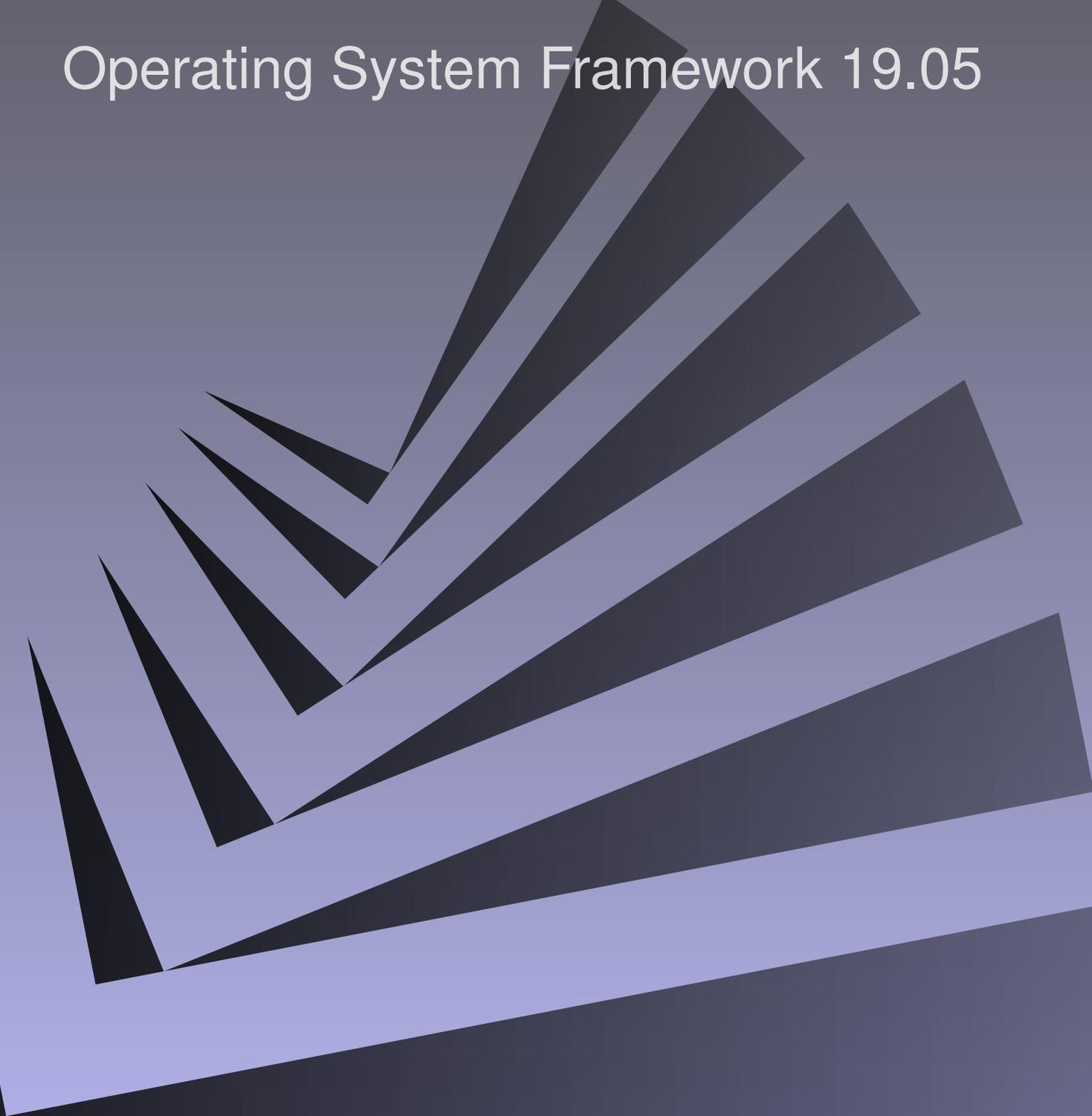


GENODE

Operating System Framework 19.05



Foundations

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1. Introduction

We are surrounded by operating systems. Each device where multiple software functions are consolidated on a single CPU employs some sort of operating system that multiplexes the physical CPU for the different functions. In our age when even mundane household items get connected to the internet, it becomes increasingly hard to find devices where this is not the case.

Our lives and our society depend on an increasing number of such devices. We have to trust them to fulfill their advertised functionality and to not perform actions that are against our interests. But are those devices trustworthy? In most cases, nobody knows that for sure. Even the device vendors are unable to guarantee the absence of vulnerabilities or hidden functions. This is not by malice. The employed commodity software stacks are simply too complex to reason about them. Software is universally known to be not perfect. So we have seemingly come to accept the common practice where vendors provide a stream of software and firmware updates that fix vulnerabilities once they become publicly known. Building moderately complex systems that are free from such issues appears to be unrealistic. Why is that?

Universal truths The past decades have provided us with enough empirical evidence about the need to be pragmatic about operating-system software. For example, high-assurance systems are known to be expensive and struggle to scale. Consequently, under cost pressure, we can live without high assurance. Security is considered as important. But at the point where the user gets bothered by it, we have to be willing to compromise. Most users would agree that guaranteed quality of service is desirable. But to attain good utilization of cheap hardware, we have to sacrifice such guarantees. Those universal truths have formed our expectations of commodity operating system software.



In markets where vendors are held liable for the correctness of their products, physical separation provides the highest assurance for the independence and protection of different functions from each other. For example, cars contain dozens of electronic control units (ECU) that can be individually evaluated and certified. However, cost considerations call for the consolidation of multiple functions on a single ECU. At this point, separation kernels are considered to partition the hardware resources into isolated compartments. Because the isolation is only as strong as the correctness of the isolation kernel, such kernels must undergo a thorough evaluation. In the face of being liable, an oversight during the evaluation may have disastrous consequences for the vendor. Each line of code to be evaluated is an expense. Hence, separation kernels are minimized to the lowest possible complexity - up to only a few thousand lines of code.

The low complexity of separation kernels comes at the cost of being inflexible. Because the hardware resources are partitioned at system-integration time, dynamic workloads are hard to accommodate. The rigidity of the approach stands in the way whenever the number of partitions, the assignment of resources to partitions, and the software running in the partitions have to be changed at runtime.

Even though the high level of assurance as provided by separation kernels is generally desirable, flexibility and the support for dynamic workloads is even more so. For this reason, commodity general-purpose OSes find their way into all kinds of devices except into those where vendors are held liable for the correctness of their products. The former include not only household appliances, network gear, consumer electronics, mobile devices, and certain comfort functions in vehicles but also the IT equipment of governments, smart-city appliances, and surveillance systems. To innovate quickly, vendors accept to make their products reliant on highly complex OS foundations. The trusted computing base (TCB) of all commodity general-purpose operating systems is measured in millions of lines of code. It comprises all the software components that must be trusted to not violate the interests of the user. This includes the kernel, the software executed at the system start, all background services with system privileges, and the actual application software. In contrast to separation kernels, any attempt to assess the correct functioning of the involved code is shallow at best. The trustworthiness of such a system remains uncertain to vendors and users alike. The uncertainty that comes with the staggering TCB complexity becomes a problem when such systems get connected to the internet: Is my internet router under control of a bot net? Is my mobile phone remotely manipulated to wiretap me? Is my TV spying on me when switched off? Are my sensitive documents stored on my computer prone to leakage? Faithfully, we hope the answers to those question to be no. But because it is impossible to reason about the trusted computing base of the employed operating systems, there are no answers.

Apparently, the lack of assurance must be the price to pay for the accommodation of feature-rich dynamic workloads.



The ease of use of software systems is often perceived as diametrical to security. There are countless mundane examples: Remembering passwords of sufficient strength is annoying. Even more so is picking a dedicated password for each different purpose. Hence, users tend to become lax about choosing and updating passwords. Another example is OpenPGP. Because setting it up for secure email communication is perceived as complicated, business-sensitive information is routinely exchanged unencrypted. Yet another example is the lack of adoption of the security frameworks such as SELinux. Even though they are readily available on commodity OS distributions, com-

prehending and defining security policies is considered as a black art, which is better left to experts.

How should an operating system strike the balance between being unusably secure and user-friendly insecure?



Current-generation general-purpose OSES are designed to utilize physical resources like memory, network bandwidth, computation time, and power in the best way possible. The common approach to maximize utilization is the over-provisioning of resources to processes. The OS kernel pretends the availability of an unlimited amount of resources to each process in the hope that processes will attempt to allocate and utilize as much resources as possible. Its holistic view on all processes and physical resources puts the kernel in the ideal position to balance resources between processes. For example, if physical memory becomes scarce, the kernel is able to uphold the illusion of unlimited memory by temporarily swapping the memory content of inactive processes to disk.

However, the optimization for high utilization comes at the price of indeterminism and effectively makes modern commodity OSES defenseless against denial-of-service attacks driven by applications. For example, because the network load is not accounted to individual network-using applications, a misbehaving network-heavy application is able to degrade the performance of other network applications. As another example, any GUI application is able to indirectly cause a huge memory consumption at the GUI server by creating an infinite amount of windows. If the system eventually runs out of memory, the kernel will identify the GUI server as the offender.

With the help of complex heuristics like process-behaviour-aware schedulers, the kernel tries hard to uphold the illusion of unlimited resources when under pressure. But since the physical resources are ultimately limited, this abstraction is destined to break sooner or later. If it breaks, the consequences may be fatal: In an out-of-memory situation, the last resort of the kernel is to rampage and kill arbitrary processes.

Can an operating system achieve high resource utilization while still being dependable?

Clean-slate approach Surprisingly, by disregarding the practical considerations of existing commodity operating systems, the contradictions outlined above can be resolved by a combination of the following key techniques:

Microkernels as a middle ground between separation kernels and monolithic kernels are able to accommodate dynamic workloads without unreasonably inflating the trusting computing base.

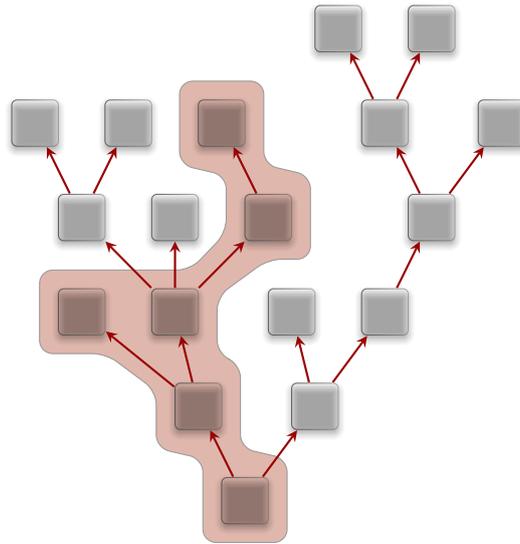


Figure 1: Application-specific trusted computing base

Capability-based security supposedly makes security easy to use by providing an intuitive way to manage authority without the need for an all-encompassing and complex global system policy.

Kernelization of software components aids the deconstruction of complex software into low-complexity security-sensitive parts and high-complexity parts. The latter no longer need to be considered as part of the trusted computing base.

Virtualization can bridge the gap between applications that expect current-generation OSes and a new operating-system design.

The management of budgets within hierarchical organizations shows how limited resources can be utilized and still be properly accounted for.

None of those techniques is new by any means. However, they have never been used as a composition of a general-purpose operating system. This is where Genode comes into the picture.

Application-specific trusted computing base A Genode system is structured as a tree of components where each component (except for the root of the tree) is owned by its parent. The notion of ownership means both responsibility and control. Being responsible for its children, the parent has to explicitly provide the resources needed by its children out of its own resources. It is also responsible to acquaint children with one another and the outside world. In return, the parent retains ultimate control over

each of its children. As the owner of a child, it has ultimate power over the child's environment, the child's view of the system, and the lifetime of the child. Each child can, in turn, have children, which yields a recursive system structure. Figure 1 illustrates the idea.

At the root of the tree, there is a low-complexity microkernel that is always part of the TCB. The kernel is solely responsible to provide protection domains, threads of execution, and the controlled communication between protection domains. All other system functions such as device drivers, network stacks, file systems, runtime environments, virtual machines, security functions, and resource multiplexers are realized as components within the tree.

The rigid organizational structure enables the system designer to tailor the trusted computing base for each component individually. For example, by hosting a cryptographic function nearby the root of the tree, the function is exposed only to the microkernel but not to complex drivers and protocol stacks that may exist in other branches of the tree. Figure 1 illustrates the TCB of one leaf node. The TCB of the yellow component comprises the chain of parents and grandparents because it is directly or indirectly owned by them. Furthermore, the TCB comprises a service used by the component. But the right branch of tree is unrelated to the component and can thereby disregarded from the yellow component's TCB.

Trading and tracking of physical resources Unlike traditional operating systems, Genode does not abstract from physical resources. Instead, each component has a budget of physical resources assigned by its parent. The budget allows the component to use the resources within the budget or to assign parts of its budget to its children. The usage and assignment of budgets is a deliberative decision by each component rather than a global policy of the OS kernel. Components are able to trade resource budgets along the branches of the tree. This way, components can offer services to other components without consuming their own resources. The dynamic trading of resource budgets between components allows for a high resource utilization without the overprovisioning of resources. Consequently, the system behavior remains deterministic at all times.

1.1. Operating-system framework

The Genode OS framework is the implementation of the Genode architecture. It is a tool kit for building highly secure special-purpose operating systems. It scales from embedded systems with as little as 4 MB of memory to highly dynamic general-purpose workloads.

The system is based on a recursive structure. Each program is executed in a dedicated sandbox and gets granted only those access rights and resources that are required to fulfill its specific purpose. Programs can create and manage sub-sandboxes out of their own resources, thereby forming hierarchies where policies can be applied at each level. The framework provides mechanisms to let programs communicate with each other and trade their resources, but only in strictly-defined manners. Thanks to this rigid regime, the attack surface of security-critical functions can be reduced by orders of magnitude compared to contemporary operating systems.

The framework aligns the construction principles of microkernels with Unix philosophy. In line with Unix philosophy, Genode is a collection of small building blocks, out of which sophisticated systems can be composed. But unlike Unix, those building blocks include not only applications but also all classical OS functionalities including kernels, device drivers, file systems, and protocol stacks.

CPU architectures

Genode supports the x86 (32 and 64 bit), ARM (32 bit), and RISC-V (64 bit) CPU architectures. On x86, modern architectural features such as IOMMUs and hardware virtualization can be utilized. On ARM, Genode is able to take advantage of TrustZone and virtualization technology.

Kernels

Genode can be deployed on a variety of different kernels including most members of the L4 family (NOVA, seL4, Fiasco.OC, OKL4 v2.1, L4ka::Pistachio, L4/Fiasco). Furthermore, it can be used on top of the Linux kernel to attain rapid development-test cycles during development. Additionally, the framework is accompanied with a custom microkernel that has been specifically developed for Genode and thereby further reduces the complexity of the trusted computing base compared to other kernels.

Virtualization

Genode supports virtualization at different levels:

- On NOVA, faithful virtualization via VirtualBox allows the execution of unmodified guest operating systems as Genode subsystems. Alternatively, the Seoul virtual machine monitor can be used to run unmodified Linux-based guest OSes.

- With Noux, there exists a runtime environment for Unix software such as GNU coreutils, bash, GCC, binutils, and findutils.
- On ARM, Genode can be used as TrustZone monitor, or as a virtual machine monitor that facilitates ARM's virtualization extensions.

Building blocks

There exist hundreds of ready-to-use components such as

- Device drivers for most common PC peripherals including networking, storage, display, USB, PS/2, Intel wireless, and audio output.
- Device drivers for a variety of ARM-based SoCs such as Texas Instruments OMAP4, Samsung Exynos5, and FreeScale i.MX.
- A GUI stack including a low-complexity GUI server, window management, and widget toolkits such as Qt5.
- Networking components such as TCP/IP stacks and packet-level network services.

1.2. Licensing and commercial support

Genode is commercially supported by the German company Genode Labs GmbH, which offers trainings, development work under contract, developer support, and commercial licensing:

Genode Labs website

<https://www.genode-labs.com>

The framework is available under two flavours of licences: an open-source license and commercial licensing. The primary license used for the distribution of the Genode OS framework is the GNU Affero General Public License Version 3 (AGPLv3). In short, the AGPLv3 grants everybody the rights to

- Use the Genode OS framework without paying any license fee,
- Freely distribute the software,
- Modify the source code and distribute modified versions of the software.

In return, the AGPLv3 requires any modifications and derived work to be published under the same or a compatible license. For the full license text, refer to

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<https://genode.org/about/LICENSE>

Note that the official license text accompanies the AGPLv3 with an additional clause that clarifies our consent to link Genode with all commonly established Open-Source licenses.

For applications that require more permissive licensing conditions than granted by the AGPLv3, Genode Labs offers the option to commercially license the technology upon request. Please write to licensing@genode-labs.com.

1.3. About this document

This document is split into two parts. Whereas the first part contains the textual description of the architectural and practical foundations, the second part serves as a reference of the framework's programming interface. This allows the first part to stay largely clear from implementation details. Cross-references between both parts are used to connect the conceptual level with the implementation level.

Chapter 2 provides engineering-minded readers with a practical jump start to explore the code and experiment with it. These practical steps are good to get a first impression and will hopefully provide the motivation to engage with the core part of the book, which are the Chapters 3 and 4.

Chapter 3 introduces Genode's high-level architecture by presenting the concept of capability-based security, the resource-trading mechanism, the root of the component tree, and the ways how components can collaborate without mutually trusting each other. Chapter 4 narrows the view on different types of components, namely device drivers, protocol stacks, resource multiplexers, runtime environments, and applications. The remaining part of the chapter focuses on the composition of components.

Chapter 5 substantiates Chapter 2 with all information needed to develop meaningful components. It covers the integration of 3rd-party software, the build system, the tool kit for automated testing, and the Git work flow of the regular Genode developers.

Chapter 6 addresses the system integration. After presenting Genode's holistic configuration concept, it details the usage of the init component, which bootstraps the static part of each Genode system.

Chapter 7 closes the first part with a look behind the scenes. It provides the details and the rationales behind technical decisions, explains the startup procedure of components, shows how Genode's concepts are mapped to kernel mechanisms, and documents known limitations.

The second part of the document gives an overview of the framework's C++ programming interface. The content is partially derived from the actual source code and supplemented with additional background information.

Acknowledgements and feedback This document greatly benefited from the feedback of the community at the Genode mailing list, the wonderful team at Genode Labs, the thorough review by Adrian-Ken Rueegsegger and Reto Buerki, and several anonymous reviewers. Thanks to everyone who contributed to the effort, be it in the form of reviews, comments, moral support, or through projects commissioned to Genode Labs.

That said, feedback from you as the reader of the document is always welcome. If you identify points you would like to see improved or if you spot grammatical errors, please do not hesitate to contact the author by writing to norman.feske@genode-labs.com or to post your feedback to the mailing list [https://genode.org/ mailing-lists](https://genode.org/community/ mailing-lists).

Part I.

Foundations

2. Getting started

Genode can be approached from two different angles: as an operating-system architecture or as a practical tool kit. This chapter assists you with exploring Genode as the latter. After introducing the recommended development environment, it guides you through the steps needed to obtain the source code (Section 2.1), to use the tool chain (Section 2.3), to test-drive system scenarios (Section 2.4), and to create your first custom component from scratch (Section 2.5).

Recommended development environment Genode is regularly used and developed on GNU/Linux. It is recommended to use the latest long-term support (LTS) version of Ubuntu. Make sure that your installation satisfies the following requirements:

- GNU Make version 3.81 (or newer) needed by the build system,
- *libSDL-dev* needed to run system scenarios directly on Linux,
- *tclsh* and *expect* needed by test-automation and work-flow tools,
- *xmllint* for validating configurations,
- *qemu*, *xorriso*, *sgdisk*, and *e2tools* needed for running system scenarios on non-Linux platforms via the Qemu emulator.

For using the entire collection of ported 3rd-party software, the following packages should be installed additionally: *byacc*, *autoconf2.64*, *autogen*, *bison*, *flex*, *g++*, *git*, *gperf*, *libxml2-utils*, *subversion*, and *xsltproc*.

Seeking help The best way to get assistance while exploring Genode is to consult the mailing list, which is the primary communication medium of regular users and developers alike. Please feel welcome to join in!

Mailing Lists

<https://genode.org/community/ mailing-lists>

If you encounter a new bug, ambiguous documentation, or a missing feature, please consider opening a corresponding issue at the issue tracker:

Issue tracker

<https://github.com/genodelabs/genode/issues>

2.1. Obtaining the source code

The centerpiece of Genode is the source code found within the official Git repository:

Source code at GitHub

<https://github.com/genodelabs/genode>

To obtain the source code, clone the Git repository:

```
git clone https://github.com/genodelabs/genode.git
```

After cloning, you can find the source code within the *genode/* directory. In the following, we refer to this directory as *<genode-dir>*.

2.2. Source-tree structure

Top-level directory At the root of the directory tree, there is the following content:

doc/ Documentation in plain text format, including the release notes of all versions.

Practical hint: The comprehensive release notes conserve most of the hands-on documentation aggregated over the lifetime of the project. When curious about a certain topic, it is often worthwhile to “grep” for the topic within the release notes to get a starting point for investigation.

tool/ Tools and scripts to support the build system, various boot loaders, the tool chain, and the management of 3rd-party source code. Please find more information in the *README* file contained in the subdirectory.

repos/ The so-called source-code repositories, which contain the actual source code of the framework components. The source code is not organized within a single source tree but multiple trees. Each tree is called a *source-code repository* and has the same principle structure. At build time, a set of source-code repositories can be selected to be incorporated into the build process. Thereby, the source-code repositories provide a coarse-grained modularization of the framework.

Repositories overview The `<genode-dir>/repos/` directory contains the following source-code repositories.

base/

The fundamental framework interfaces as well as the platform-agnostic parts of the core component (Section 3.4).

base-<platform>/ Platform-specific supplements of the *base/* repository where `<platform>` corresponds to one of the following:

linux

Linux kernel (both x86_32 and x86_64).

nova

NOVA microhypervisor. More information about the NOVA platform is provided by Section 7.8.

hw

The hw platform allows the execution of Genode on bare hardware without the need for a separate kernel. The kernel functionality is included in the core component. It supports the ARM, 64-bit x86, and 64-bit RISC-V CPU architectures. The hw platform is also used as the basis for executing Genode on top of the Muen separation kernel. More information about the hw platform can be found in Section 7.7.

sel4

The sel4 microkernel developed by NICTA in Sydney. The support for this kernel is highly experimental.

foc

Fiasco.OC is a modernized version of the L4/Fiasco microkernel with a completely revised kernel interface fostering capability-based security.

okl4

OKL4 kernel originally developed at Open-Kernel-Labs.

pistachio

L4ka::Pistachio kernel developed at University of Karlsruhe.

fiasco

L4/Fiasco kernel originally developed at Technische Universität Dresden.

os/

OS components such as the init component, device drivers, and basic system services.

demo/

Various services and applications used for demonstration purposes, for example the graphical application launcher and the tutorial browser described in Section 2.4 can be found here.

hello_tutorial/

Tutorial for creating a simple client-server scenario. This repository includes documentation and the complete source code.

libports/

Ports of popular open-source libraries, most importantly the C library. Among the 3rd-party libraries are Qt5, libSDL, freetype, Python, ncurses, Mesa, and libav.

dde_linux/

Device-driver environment for executing Linux kernel subsystems as user-level components. Among the subsystems are the USB stack, the Intel wireless stack, and the TCP/IP stack.

dde_ipxe/

Device-driver environment for executing network drivers of the iPXE project.

dde_bsd/

Device-driver environment for audio drivers ported from OpenBSD.

dde_rump/

Port of rump kernels, which are used to execute subsystems of the NetBSD kernel as user-level components. The repository contains a server that uses a rump kernel to provide various NetBSD file systems.

ports/

Ports of 3rd-party applications.

gems/

Components that use both native Genode interfaces as well as features of other high-level repositories, in particular shared libraries provided by *libports/*.

2.3. Using the build system

Genode relies on a custom tool chain, which can be downloaded at the following website:

Tool chain

<https://genode.org/download/tool-chain>

Build directory The build system never touches the source tree but generates object files, libraries, and programs in a dedicated build directory. We do not have a build directory yet. For a quick start, let us create one using the following command:

```
cd <genode-dir>
./tool/create_builddir x86_64
```

To follow the subsequent steps of test driving the Linux version of Genode, the specified platform argument should match your host OS installation. If you are using a 32-bit installation, specify `x86_32` instead of `x86_64`.

The command creates a new build directory at `build/x86_64`.

Build configuration Before using the build directory, it is recommended to revisit and possibly adjust the build configuration, which is located in the *etc/* subdirectory of the build directory, e. g., *build/x86_64/etc/*. The *build.conf* file contains global build parameters, in particular the selection of source-code repositories to be incorporated, the kernel to use (KERNEL), and the targeted board (BOARD). It is also a suitable place for adding global build options. For example, for enabling GNU make to use 4 CPU cores, use the following line in the *build.conf* file:

```
MAKE += -j4
```

Building components The recipe for building a component has the form of a *target.mk* file within the *src/* directory of one of the source-code repositories. For example, the *target.mk* file of the *init* component is located at `<genode-dir>/repos/os/src/init/target.mk`. To build the component, execute the following command from within the build directory:

```
make init
```

The argument “init” refers to the path relative to the *src/* subdirectory. The build system determines and builds all targets found under this path in all source-code repositories. When the build is finished, the resulting executable binary can be found in a subdirectory that matches the target’s path. Additionally, the build system installs a symbolic link in the *bin/* subdirectory that points to the executable binary.

If the specified path contains multiple *target.mk* files in different subdirectories, the build system builds all of them. For example, the following command builds all targets found within one of the *<repo>/src/drivers/* subdirectories:

```
make drivers
```

Furthermore, it is possible to specify multiple targets at once. The following command builds both the init component and the timer driver:

```
make init drivers/timer
```

2.4. A simple system scenario

The build directory offers much more than an environment for building components. It supports the automation of system-integration work flows, which typically include the following steps:

1. Building a set of components,
2. Configuring the static part of a system scenario,
3. Assembling a boot directory with all ingredients needed by the scenario,
4. Creating a boot image that can be loaded onto the target platform,
5. Booting the target platform with the boot image,
6. Validating the behavior of the scenario.

The recipe for such a sequence of steps can be expressed in the form of a so-called run script. Each run script represents a system scenario and entails all information required to reproduce the scenario. Run scripts can reside within the *run/* subdirectory of any source-code repository.

Genode comes with a ready-to-use run script showcasing simple graphical demo scenario. It is located at `<genode-dir>/repos/os/run/demo.run` and can be executed from within the build directory via:

```
make run/demo KERNEL=linux
```

In contrast to the building of individual components as described above, the integration of a complete system scenario requires us to select a particular OS kernel to use. The command instructs the build system to integrate and start the “run/demo” scenario on the Linux kernel. It will lookup a run script called *demo.run* in all repositories listed in *etc/build.conf*. It will eventually find the run script within the *os/* repository. After completing the build of all components needed, the command will then automatically start the scenario. Because the build directory was created for the *x86_64* platform and we specified “linux” as *KERNEL*, the scenario will be executed directly on the host system where each Genode component resides in a distinct Linux process. To explore the scenario, follow the instructions given by the graphical tutorial browser.

The terminal where the `make run/demo` command was issued displays the log output of the Genode system. To cancel the execution, hit *control-c* in the terminal.

Targeting a microkernel Whereas the ability to run system scenarios on top of Linux allows for the convenient and rapid development of components and protocols, Genode is primarily designed for the use of microkernels. The choice of the microkernel to use is up to the user of the framework and may depend on various factors like the feature set, the supported hardware architectures, the license, or the development community. To execute the demo scenario directly on the NOVA microhypervisor, the following preparatory steps are needed:

1. Download the 3rd-party source code of the NOVA microhypervisor

```
<genode-dir>/tool/ports/prepare_port nova
```

The `prepare_port` tool downloads the source code of NOVA to a subdirectory at `<genode-dir>/contrib/nova-<hash>/` where *<hash>* uniquely refers to the prepared version of NOVA.

2. On real hardware, the scenario needs a framebuffer driver. The VESA driver relies on a 3rd-party x86-emulation library in order to execute the VESA BIOS code. Download the 3rd-party source code of the `x86emu` library:

```
<genode-dir>/tool/ports/prepare_port x86emu
```

The source code will be downloaded to `<genode-dir>/contrib/x86emu-<hash>/`.

3. To boot the scenario as an operating system on a PC, a boot loader is needed. The build process produces a bootable disk or ISO image that includes the GRUB2 boot loader as well as a working boot-loader configuration. Download the boot loader as ingredient for the image-creation step.

```
<genode-dir>/tool/ports/prepare_port grub2
```

4. Since NOVA supports the `x86_64` architecture of our build directory, we can keep using the existing build directory that we just used for Linux. However, apart from enabling the parallelization of the build process as mentioned in Section 2.3, we need to incorporate the `libports` source-code repository into the build process by uncommenting the corresponding line in the configuration. Otherwise the build system would fail to build the VESA driver, which resides within `libports/`.

With those preparations in place, issue the execution of the demo run script from within the build directory:

```
make run/demo KERNEL=nova
```

This time, an instance of Qemu will be started to execute the demo scenario. The Qemu command-line arguments appear in the log output. As suggested by the arguments, the scenario is supplied to Qemu as an ISO image residing at `var/run/demo.iso`. This ISO image can not only be used with Qemu but also with a real machine. For example, creating a bootable USB stick with the system scenario is as simple as writing the ISO image onto an USB stick:

```
sudo dd if=var/run/demo.iso of=/dev/<usb-device> bs=8M conv=fsync
```

Note that `<usb-device>` refers to the device node of an USB stick. It can be determined using the `dmesg` command after plugging-in the USB stick. For booting from the USB stick, you may need to adjust the BIOS settings of the test machine accordingly.

2.5. Hello world

This section introduces the steps needed to create and execute a simple custom component that prints a hello-world message.

2.5.1. Using a custom source-code repository

In principle, it would be possible to add a new component to one of the existing source-code repositories found at `<genode-dir>/repos/`. However, unless the component is meant to be incorporated into upstream development of the Genode project, it is generally recommended to keep custom code separate from Genode's code base. This eases future updates to new versions of Genode and allows you to pick a revision-control system of your choice.

The new repository must appear within the `<genode-dir>/repos/` directory. This can be achieved by either hosting it as a subdirectory or by creating a symbolic link that points to an arbitrary location of your choice. For now, let us host a new source-code repository called "lab" directly within the `repos/` directory.

```
cd <genode-dir>
mkdir repos/lab
```

The lab repository will contain the source code and build rules for a single component as well as a run script for executing the component within Genode. Component source code reside in a `src/` subdirectory. By convention, the `src/` directory contains further subdirectories for hosting different types of components, in particular *server* (services and protocol stacks), *drivers* (hardware-device drivers), and *app* (applications). For the hello-world component, an appropriate location would be `src/app/hello/`:

```
mkdir -p repos/lab/src/app/hello
```

2.5.2. Source code and build description

The `hello/` directory contains both the source code and the build description of the component. The main part of each component typically resides in a file called `main.cc`. Hence, for a hello-world program, we have to create the `repos/lab/src/app/hello/main.cc` file with the following content:

```
#include <base/component.h>
#include <base/log.h>

void Component::construct(Genode::Env &)
{
    Genode::log("Hello world");
}
```

The *base/component.h* header contains the interface each component must implement. The `construct` function is called by the component's execution environment to initialize the component. The interface to the execution environment is passed as argument. This interface allows the application code to interact with the outside world. The simple example above merely produces a log message. The `log` function is defined in the *base/log.h* header.

The component does not exit after the `construct` function returns. Instead, it becomes ready to respond to requests or signals originating from other components. The example above does not interact with other components though. Hence, it will just keep waiting infinitely.

Please note that there exists a recommended coding style for genuine Genode components. If you consider submitting your work to the upstream development of the project, please pay attention to these common guidelines.

Coding-style guidelines

https://genode.org/documentation/developer-resources/coding_style

The source file *main.cc* is accompanied by a build-description file called *target.mk*. It contains the declarations for the source files, the libraries used by the component, and the name of the component. Create the file *repos/lab/src/app/hello/target.mk* with the following content:

```
TARGET = hello
SRC_CC = main.cc
LIBS += base
```

2.5.3. Building the component

With the build-description file in place, it is time to build the new component, for example from within the *x86_64* build directory as created in Section 2.4. To aid the build system to find the component, we have to extend the build configuration *<build-dir>/etc/build.conf* by appending the following line:

```
REPOSITORIES += $(GENODE_DIR)/repos/lab
```

By adding this line, the build system will consider our custom source-code repository. To build the component, issue the following command:

```
make app/hello
```

This step compiles the *main.cc* file and links the executable ELF binary called “hello”. The result can be found in the *<build-dir>/app/hello/* subdirectory.

2.5.4. Defining a system scenario

For testing the component, we need to define a system scenario that incorporates the component. As mentioned in Section 2.4, such a description has the form of a run script. To equip the *lab* repository with a run script, we first need to create a *lab/run/* subdirectory:

```
mkdir <genode-dir>/repos/lab/run
```

Within this directory, we create the file *<genode-dir>/repos/lab/run/hello.run* with the following content:

```
build "core init app/hello"
create_boot_directory
install_config {
  <config>
    <parent-provides>
      <service name="LOG"/>
      <service name="PD"/>
      <service name="CPU"/>
      <service name="ROM"/>
    </parent-provides>
    <default-route>
      <any-service> <parent/> </any-service>
    </default-route>
    <default caps="100"/>
    <start name="hello">
      <resource name="RAM" quantum="10M"/>
    </start>
  </config>
}
build_boot_image "core ld.lib.so init hello"
append qemu_args "-nographic -m 64"
run_genode_until {Hello world.*\n} 10
```

This run script performs the following steps:

1. It builds the components `core`, `init`, and `app/hello`.
2. It creates a fresh boot directory at `<build-dir>/var/run/hello`. This directory contains all files that will end up in the final boot image.
3. It creates a configuration for the `init` component. The configuration starts the `hello` component as the only child of `init`. Session requests originating from the `hello` component will always be directed towards the parent of `init`, which is `core`. The `<default>` node declares that each component may consume up to 100 capabilities.
4. It assembles a boot image with the executable ELF binaries `core`, `ld.lib.so` (the dynamic linker), `init`, and `hello`. The binaries are picked up from the `<build-dir>/bin/` subdirectory.
5. It instructs Qemu (if used) to disable the graphical output.
6. It triggers the execution of the system scenario and watches the log output for the given regular expression. The execution ends when the log output appears or after a timeout of 10 seconds.

The run script can be executed from within the build directory via the command:

```
make run/hello KERNEL=linux
```

After the boot output of the used kernel, the scenario will produce the following output:

```
[init -> test-printf] Hello world  
Run script execution successful.
```

The label within the brackets at the start of each line identifies the component where the message originated from. The final line is printed by the run tool after it successfully matched the log output against the regular expression specified to the `run_genode_until` command.

2.5.5. Responding to external events

Most non-trivial components respond to external events such as user input, timer events, device interrupts, the arrival of new data, or RPC requests issued by other components.

The following example presents the typical skeleton of such a component. The construct function merely creates an object representing the application as a static local variable. The actual component code lives inside the Main class.

```
#include <base/component.h>
#include <base/log.h>
#include <timer_session/connection.h>

namespace Hello { struct Main; }

struct Hello::Main
{
    Genode::Env &_env;

    Timer::Connection _timer { _env };

    void _handle_timeout()
    {
        log("woke up at ", _timer.elapsed_ms(), " ms");
    }

    Genode::Signal_handler<Main> _timeout_handler {
        _env.ep(), *this, &Main::_handle_timeout };

    Main(Genode::Env &env) : _env(env)
    {
        _timer.sigh(_timeout_handler);
        _timer.trigger_periodic(1000*1000);
        Genode::log("component constructed");
    }
};

void Component::construct(Genode::Env &env)
{
    static Hello::Main main(env);
}
```

First, note the Hello namespace. As a good practice, component code typically lives in a namespace. The component-specific namespace may incorporate other namespaces - in particular the Genode namespace - without polluting the global scope.

The constructor of the `Main` object takes the `Genode` environment as argument and stores it as the reference member variable `_env`. The member variable is prefixed with an underscore to highlight the fact that it is private to the `Main` class. In principle, `Main` could be a `class` with `_env` being part of the `private` section, but as `Main` is the top-level class of the component that is not accessed by any other parts of the program, we use a `struct` for brevity while still maintaining the convention to prefix private members with an underscore character. When spotting the use of such a prefixed variable in the code, we immediately see that it is part of the code's object context, not being an argument or a local variable.

By aggregating a `Timer::Connection` as a member variable, the `Main` object requests a session to a timer service at construction time. As this session request requires an interaction with the outside world, the `_env` needs to be passed to the `_timer` constructor.

In order to respond to events from the timer, the `Main` class hosts a `_timeout_handler` object. Its constructor arguments refer to the object and a method to be executed whenever an event occurs. The timeout handler object is registered at the `_timer` as the recipient of timeout events via the `sig` method. Finally, the timer is instructed to trigger timeout events at a rate of 1 second.

The following remarks are worth noting:

- The programming style expresses what the component *is* rather than what the component *does*.
- The component does not perform any dynamic memory allocation.
- When called, the `_handle_timeout` method has its context (the `Main` object) readily available, which makes the application of internal state changes as response to external events very natural.
- Both the `construct` function as well as the `Main::_handle_timeout` method do not block for external events.
- The component does not receive any indication about the number of occurred events, just the fact that at least one event occurred. The `_handle_timeout` code explicitly requests the current time from the timer driver via the synchronous RPC call `elapsed_ms`.

To execute the new version of the component, we need to slightly modify the run script.

```
build "core init drivers/timer app/hello"
create_boot_directory
install_config {
  <config>
    <parent-provides>
      <service name="LOG"/>
      <service name="PD"/>
      <service name="CPU"/>
      <service name="ROM"/>
    </parent-provides>
    <default-route>
      <any-service> <parent/> <any-child/> </any-service>
    </default-route>
    <default caps="100"/>
    <start name="timer">
      <resource name="RAM" quantum="1M"/>
      <provides> <service name="Timer"/> </provides>
    </start>
    <start name="hello">
      <resource name="RAM" quantum="10M"/>
    </start>
  </config>
}
build_boot_image "core ld.lib.so init timer hello"
append qemu_args "-nographic -m 64"
run_genode_until forever
```

The modifications are as follows:

- Since the hello component now relies on a timer service, we need to build and integrate a timer driver into the scenario by extending the build and build_boot_image steps accordingly.
- We instruct init to spawn the timer driver as an additional component by adding a <start> node to init's configuration. Within this node, we declare that the component provides a service of type "Timer".
- To enable the hello component to open a "Timer" session at the timer driver, the default route is modified to consider any children as servers whenever the requested service is not provided by the parent.
- This time, we let the scenario run forever so that we can watch the messages printed at periodic intervals.

When starting the run script, we can observe the periodic activation of the component in the log output:

```
[init] child "timer" announces service "Timer"  
[init -> hello] component constructed  
[init -> hello] woke up at 12 ms  
[init -> hello] woke up at 1008 ms  
[init -> hello] woke up at 2005 ms  
...
```

3. Architecture

Contemporary operating systems are immensely complex to accommodate a large variety of applications on an ever diversifying spectrum of hardware platforms. Among the functionalities provided by a commodity operating system are device drivers, protocol stacks such as file systems and network protocols, the management of hardware resources, as well as the provisioning of security functions. The latter category is meant for protecting the confidentiality and integrity of information and the lifelines of critical functionality. For assessing the effectiveness of such a security function, two questions must be considered. First, what is the potential attack surface of the function? The answer to this question yields an assessment about the likelihood of a breach. Naturally, if there is a large number of potential attack vectors, the security function is at high risk. The second question is: What is the reach of a defect? If the compromised function has unlimited access to all information processed on the system, the privacy of all users may be affected. If the function is able to permanently install software, the system may become prone to back doors.

Today's widely deployed operating systems do not isolate security-critical functions from the rest of the operating system. In contrary, they are co-located with most other operating-system functionality in a single high-complexity kernel. Thereby, those functions are exposed to the other parts of the operating system. The likelihood of a security breach is as high as the likelihood of bugs in an overly complex kernel. In other words: It is certain. Moreover, once an in-kernel function has been compromised, the defect has unlimited reach throughout the system.

The Genode architecture was designed to give more assuring answers to the two questions stated. Each piece of functionality should be exposed to only those parts of the system, on which it ultimately depends. But it remains hidden from all unrelated parts. This minimizes the attack surface on individual security functions and thereby reduces the likelihood for a security breach. In the event that one part of the system gets compromised, the scope of the defect is limited to the particular fragment and its dependent parts. Unrelated functionalities remain unaffected. To realize this idea, Genode composes the system out of many components that interact with each other. Each component serves a specific role and uses well-defined interfaces to interact with its peers. For example, a network driver accesses a physical network card and provides a bidirectional stream of network packets to another component, which, in turn, may process the packets using a TCP/IP stack and a network application. Even though the network driver and the TCP/IP stack cooperate when processing network packets, they are living in separate protection domains. So a bug in one component cannot observe or corrupt the internal state of another.

Such a component-based architecture, however, raises a number of questions, which are addressed throughout this chapter. Section 3.1 explains how components can cooperate without inherently trusting each other. Section 3.2 answers the questions of who defines the relationship between components and how components become ac-

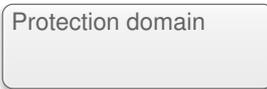
quainted with each other. An operating system ultimately acts on physical hardware resources such as memory, CPUs, and peripheral devices. Section 3.4 describes how such resources are made available to components. Section 3.5 answers the question of how a new component comes to life. The variety of relationships between components and their respective interfaces call for different communication primitives. Section 3.6 introduces Genode's inter-component communication mechanisms in detail.

3.1. Capability-based security

This section introduces the nomenclature and the general model of Genode's capability-based security concept. The Genode OS framework is not tied to one kernel but supports a variety of kernels as base platforms. On each of those base platforms, Genode uses different kernel mechanisms to implement the general model as closely as possible. Note however that not all kernels satisfy the requirements that are needed to implement the model securely. For assessing the security of a Genode-based system, the respective platform-specific implementation must be considered. Sections 7.7 and 7.8 provide details for selected kernels.

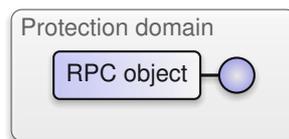
3.1.1. Capability spaces, object identities, and RPC objects

Each component lives inside a protection domain that provides an isolated execution environment.



Genode provides an object-oriented way of letting components interact with each other. Analogously to object-oriented programming languages, which have the notion of objects and pointers to objects, Genode introduces the notion of RPC objects and capabilities to RPC objects.

An *RPC object* provides a remote-procedure call (RPC) interface. Similar to a regular object, an RPC object can be constructed and accessed from within the same program. But in contrast to a regular object, it can also be called from the outside of the component. What a pointer is to a regular object, a *capability* is to an RPC object. It is a token that unambiguously refers to an RPC object. In the following, we represent an RPC object as follows.



The circle represents the capability associated with the RPC object. Like a pointer to an object, that can be used to call a function of the pointed-to object, a capability can be used to call functions of its corresponding RPC object. However, there are two important differences between a capability and a pointer. First, in contrast to a pointer that can be created out of thin air (e. g., by casting an arbitrary number to a pointer), a capability cannot be created without an RPC object. At the creation time of an RPC object, Genode creates a so-called *object identity* that represents the RPC object in the kernel. Figure 2 illustrates the relationship of an RPC object and its object identity.

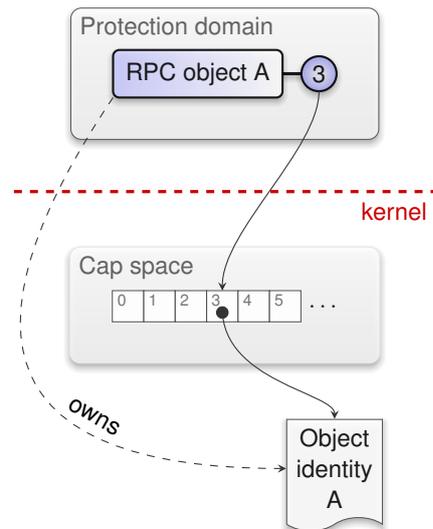


Figure 2: Relationship between an RPC object and its corresponding object identity.

For each protection domain, the kernel maintains a so-called capability space, which is a name space that is local to the protection domain. At the creation time of an RPC object, the kernel creates a corresponding object identity and lets a slot in the protection domain's capability space refer to the RPC object's identity. From the component's point of view, the RPC object A has the name 3. When interacting with the kernel, the component can use this number to refer to the RPC object A.

3.1.2. Delegation of authority and ownership

The second difference between a pointer and a capability is that a capability can be passed to different components without losing its meaning. The transfer of a capability from one protection domain to another delegates the authority to use the capability to the receiving protection domain. This operation is called *delegation* and can be performed only by the kernel. Note that the originator of the delegation does not diminish its authority by delegating a capability. It merely shares its authority with the receiving protection domain. There is no superficial notion of access rights associated with a capability. The possession of a capability ultimately enables a protection domain to use it and to delegate it further. A capability should hence be understood as an access right. Figure 3 shows the delegation of the RPC object's capability to a second protection domain and a further delegation of the capability from the second to a third protection domain. Whenever the kernel delegates a capability from one to another protection domain, it inserts a reference to the RPC object's identity into a free slot of the target's capability space. Within protection domain 2 shown in Figure 3, the RPC object can

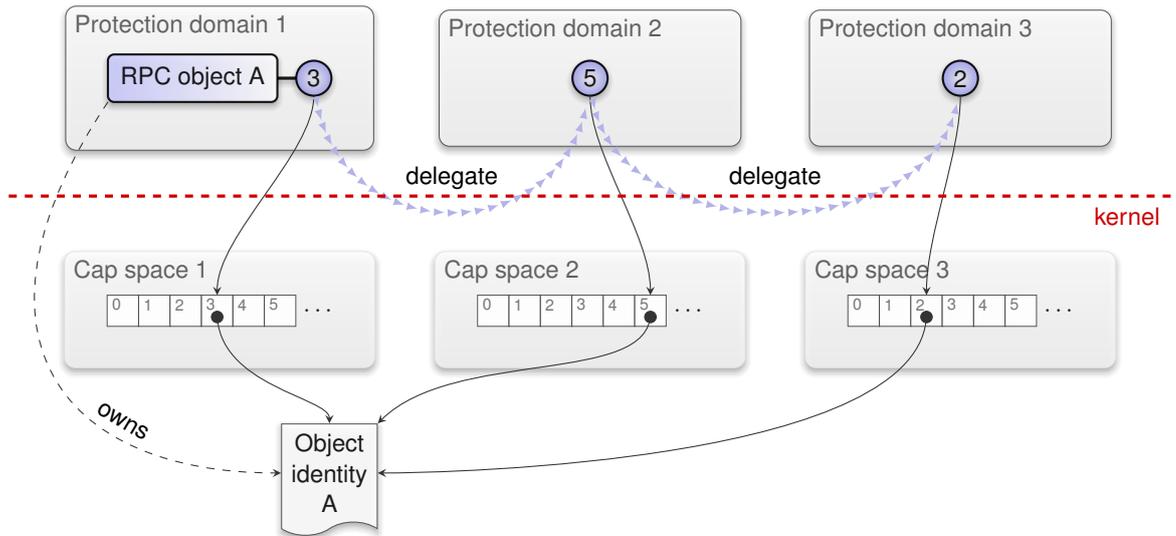


Figure 3: The transitive delegation of a capability from one protection domain to others.

be referred to by the number 5. Within protection domain 3, the same RPC object is known as 2. Note that the capability delegation does not hand over the ownership of the object identity to the target protection domain. The ownership is always retained by the protection domain that created the RPC object.

Only the owner of an RPC object is able to destroy it along with the corresponding object identity. Upon destruction of an object identity, the kernel removes all references to the vanishing object identity from all capability spaces. This effectively renders the RPC object inaccessible for all protection domains. Once the object identity for an RPC object is gone, the owner can destruct the actual RPC object.

3.1.3. Capability invocation

Capabilities enable components to call methods of RPC objects provided by different protection domains. A component that uses an RPC object plays the role of a *client* whereas a component that owns the RPC object acts in the role of a *server*. The interplay between client and server is very similar to a situation where a program calls a local function. The caller deposits the function arguments at a place where the callee will be able to pick them up and then passes control to the callee. When the callee takes over control, it obtains the function arguments, executes the function, copies the results to a place where the caller can pick them up, and finally hands back the control to the caller. In contrast to a program-local function call, however, client and server are different *threads* in their respective protection domains. The thread at the server side is called

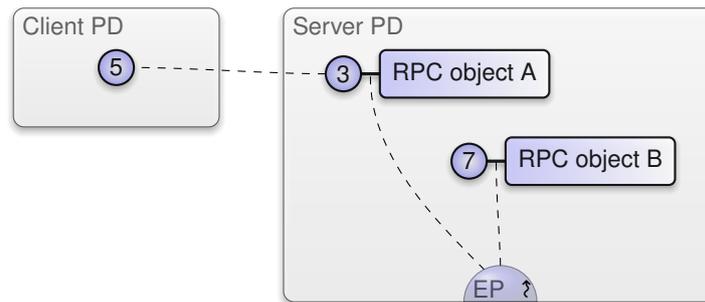


Figure 4: The RPC object A and B are associated with the server’s entrypoint. A client has a capability for A but not for B. For brevity, the kernel-protected object identities are not depicted. Instead, the dashed line between the capabilities shows that both capabilities refer to the same object identity.

entrypoint denoting the fact that it becomes active only when a call from a client enters the protection domain or when an asynchronous notification comes in. Each component has at least one initial entrypoint, which is created as part of the component’s execution environment.



The wiggly arrow denotes that the entrypoint is a thread. Besides being a thread that waits for incoming requests, the entrypoint is responsible for maintaining the association between RPC objects and their corresponding capabilities. The previous figures illustrated this association with the link between the RPC object and its capability. In order to become callable from the outside, an RPC object must be associated with a concrete entrypoint. This operation results in the creation of the object’s identity and the corresponding capability. During the lifetime of the object identity, the entrypoint maintains the association between the RPC object and its capability in a data structure called *object pool*, which allows for looking up the matching RPC object for a given capability. Figure 4 shows a scenario where two RPC objects are associated with one entrypoint in the protection domain of a server. The capability for the RPC object A has been delegated to a client.

If a protection domain is in possession of a capability, each thread executed within this protection domain can issue a call to a member function of the RPC object that is referred to by the capability. Because this is not a normal function call but the invocation of an object located in a different protection domain, this operation has to be provided by the kernel. Figure 5 illustrates the interaction of the client, the kernel, and the server. The kernel operation takes the client-local name of the invoked capability, the opcode of the called function, and the function arguments as parameters. Upon entering the kernel, the client’s thread is blocked until it receives a response. The operation of the

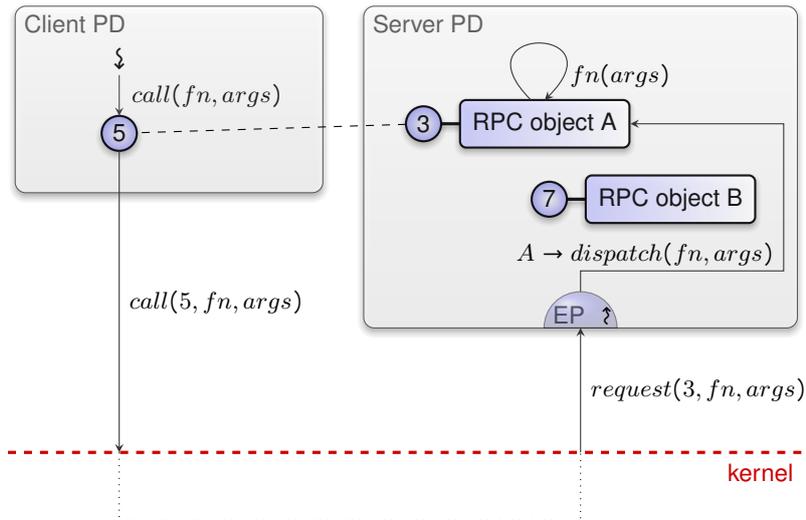


Figure 5: Control flow between client and server when the client calls a method of an RPC object.

kernel is represented by the dotted line. The kernel uses the supplied local name as an index into the client's capability space to look up the object identity, to which the capability refers. Given the object identity, the kernel is able to determine the protection domain and the corresponding entrypoint that is associated with the object identity and wakes up the entrypoint's thread with information about the incoming request. Among this information is the server-local name of the capability that was invoked. Note that the kernel has translated the client-local name to the corresponding server-local name. The capability name spaces of client and server are entirely different. The entrypoint uses this number as a key into its object pool to find the locally implemented RPC object A that belongs to the invoked capability. It then performs a method call of the so-called *dispatch* function on the RPC object. The dispatch function maps the supplied function opcode to the matching member function and calls this function with the request arguments.

The member function may produce function results. Once the RPC object's member function returns, the entrypoint thread passes the function results to the kernel by performing the kernel's *reply* operation. At this point, the server's entrypoint becomes ready for the next request. The kernel, in turn, passes the function results as return values of the original call operation to the client and wakes up the client thread.

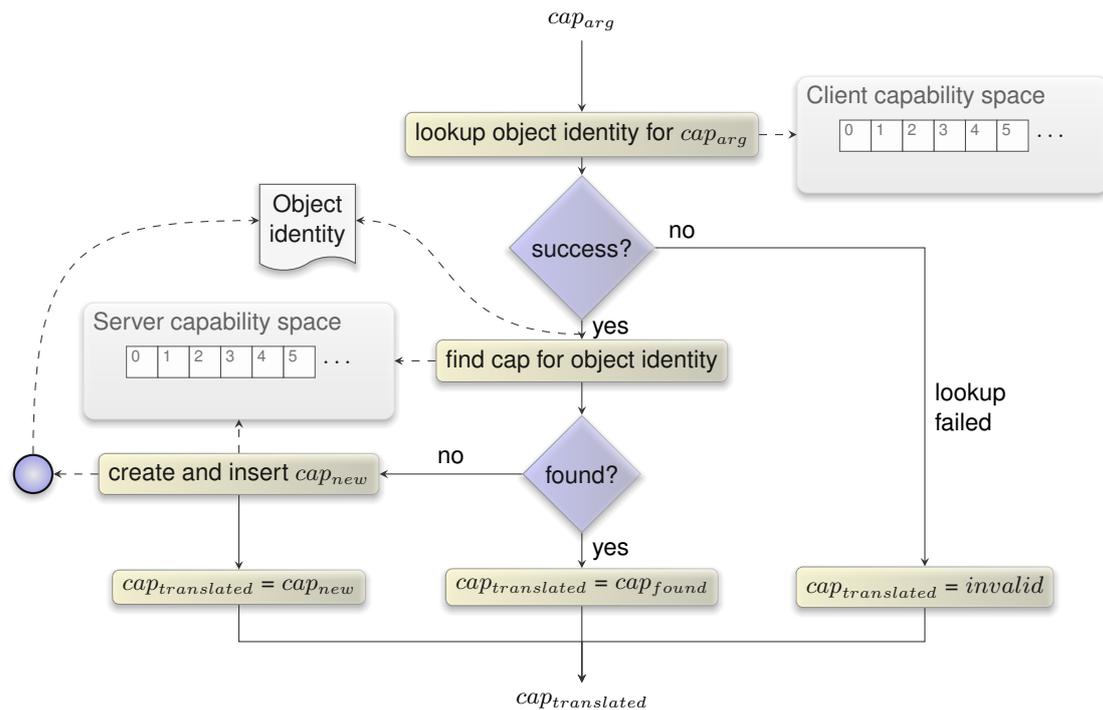


Figure 6: Procedure of delegating a capability specified as RPC argument from a client to a server.

3.1.4. Capability delegation through capability invocation

Section 3.1.2 explained that capabilities can be delegated from one protection domain to another via a kernel operation. But it left open the question of how this procedure works. The answer is the use of capabilities as RPC message payload. Similar to how a caller of a regular function can pass a pointer as an argument, a client can pass a capability as an argument to an RPC call. In fact, passing capabilities as RPC arguments or results is synonymous to delegating authority between components. If the kernel encounters a capability as an argument of a call operation, it performs the steps illustrated in Figure 6. The local names are denoted as cap , e.g., cap_{arg} is the local name of the object identity at the client side, and $cap_{translated}$ is the local name of the same object identity at the server side.

1. The kernel looks up the object identity in the capability space of the client. This lookup may fail if the client specified a number of an empty slot of its capability space. Only if the lookup succeeds is the kernel able to obtain the object identity referred to by the argument. Note that under no circumstances can the client refer to object identities, for which it has no authority because it can merely specify the object identities reachable through its capability space. For all non-empty

slots of its capability space, the protection domain was authorized to use their referenced object identities by the means of prior delegations. If the lookup fails, the translation results in an invalid capability passed to the server.

2. Given the object identity of the argument, the kernel searches the server's capability space for a slot that refers to the object identity. Note that the term "search" does not necessarily refer to an expensive linear search. The efficiency of the operation largely depends on the kernel implementation.
3. If the server already possesses a capability to the object identity, the kernel translates the argument to the server-local name when passing it as part of the request to the server. If the server does not yet possess a capability to the argument, the kernel installs a new entry into the server's capability space. The new entry refers to the object identity of the argument. At this point, the authority over the object identity has been delegated from the client to the server.
4. The kernel passes the translated or just-created local name of the argument as part of the request to the server.

Even though the above description covered the delegation of a single capability specified as argument, it is possible to delegate more than one capability with a single RPC call. Analogously to how capabilities can be delegated from a client to a server as arguments of an RPC call, capabilities can be delegated in the other direction as part of the reply of an RPC call. The procedure in the kernel is the same in both cases.

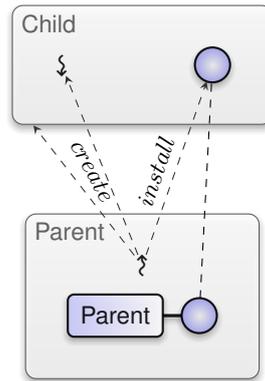


Figure 7: Initial relationship between a parent and a newly created child.

3.2. Recursive system structure

The previous section introduced capability delegation as the fundamental mechanism to share authority over RPC objects between protection domains. But in the given examples, the client was already in possession of a capability to the server's RPC object. This raises the question of how do clients get acquainted to servers?

3.2.1. Component ownership

In a Genode system, each component (except for the very first component called core) has a parent, which owns the component. The *ownership* relation between a parent and a child is two-fold.



On the one hand, ownership stands for *responsibility*. Each component requires physical resources such as the memory or in-kernel data structures that represent the component in the kernel. The parent is responsible for providing a budget of those physical resources to the child at the child's creation time but also during the child's entire lifetime. As the parent has to assign a fraction of its own physical resources to its children, it is the parent's natural interest to maintain the balance of the physical resources split between itself and each of its children. Besides being the provider of resources, the parent defines all aspects of the child's execution and serves as the child's primary point of contact for seeking acquaintances with other components.

On the other hand, ownership stands for *control*. Because the parent has created its children out of its own resources, it is in the position to exercise ultimate power over its children. This includes the decision to destruct a child at any time in order to regain the resources that were assigned to the child. But it is also in control over the relationships of the child with other components known to the parent.

Each new component is created as an empty protection domain. It is up to the parent to populate the protection domain with code and data, and to create a thread that executes the code within the protection domain. At creation time, the parent installs a single capability called *parent capability* into the new protection domain. The parent capability enables the child to perform RPC calls to the parent. The child is unaware of anything else that exists in the Genode system. It does not even know its own identity nor the identity of its parent. All it can do is issue calls to its parent using the parent capability. Figure 7 depicts the situation right after the creation of a child component. A thread in the parent component created a new protection domain and a thread residing in the protection domain. It also installed the parent capability referring to an RPC object provided by the parent. To provide the RPC object, the parent has to maintain an entrypoint. For brevity, entrypoints are not depicted in this and the following figures. Section 3.5 covers the procedure of creating a component in detail.

The ownership relation between parent and child implies that each component has to inherently trust its parent. From a child's perspective, its parent is as powerful as the kernel. Whereas the child has to trust its parent, a parent does not necessarily need to trust its children.

3.2.2. Tree of components

The parent-child relationship is not limited to a single level. Child components are free to use their resources to create further children, thereby forming a tree of components. Figure 8 shows an example scenario. The init component creates subsystems according to its configuration. In the example, it created two children, namely a GUI and a launcher. The latter allows the user to interactively create further subsystems. In the example, launcher was used to start an application.

At each position in the tree, the parent-child interface is the same. The position of a component within the tree is just a matter of composition. For example, by a mere configuration change of init, the application could be started directly by the init component and would thereby not be subjected to the launcher.

3.2.3. Services and sessions

The primary purpose of the parent interface is the establishment of communication channels between components. Any component can inform its parent about a service that it provides. In order to provide a service, a component needs to create an RPC object implementing the so-called *root interface*. The root interface offers functions for

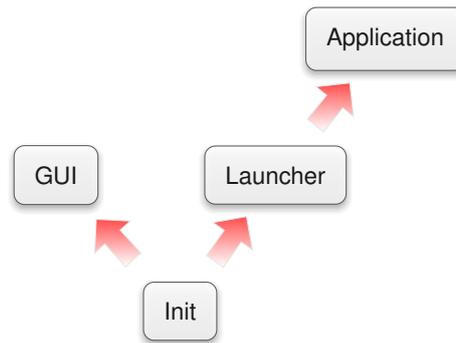


Figure 8: Example of a tree of components. The red arrow represents the ownership relation.

creating and destroying sessions of the service. Figure 9 shows a scenario where the GUI component announces its service to the init component. The announce function takes the service name and the capability for the service’s root interface as arguments. Thereby, the root capability is delegated from the GUI to init.

It is up to the parent to decide what to do with the announced information. The parent may ignore the announcement or remember that the child “GUI” provides a service “GUI”. A component can announce any number of services via subsequent announce calls.

The counterpart of the service announcement is the creation of a session by a client by issuing a *session* request to its parent. Figure 10 shows the scenario where the application requests a “GUI” session. Along with the session call, the client specifies the type of the service and a number of session arguments. The session arguments enable the client to inform the server about various properties of the desired session. In the example, the client informs the server that the client’s window should be labeled with the name “browser”. As a result of the session request, the client expects to obtain a capability to an RPC object that implements the session interface of the requested service. Such a capability is called *session capability*.

When the parent receives a session request from a child, it is free to take a policy decision on how to respond to the request. This decision is closely related to the management of resources described in Section 3.3.2. There are the following options.

Parent denies the service The parent may deny the request and thereby prevent the child from using a particular service.

Parent provides the service The parent could decide to implement the requested service by itself by handing out a session capability for a locally implemented RPC object to the child.

Server is another child If the parent has received an announcement of the service from another child, it may decide to direct the session request to the other child.

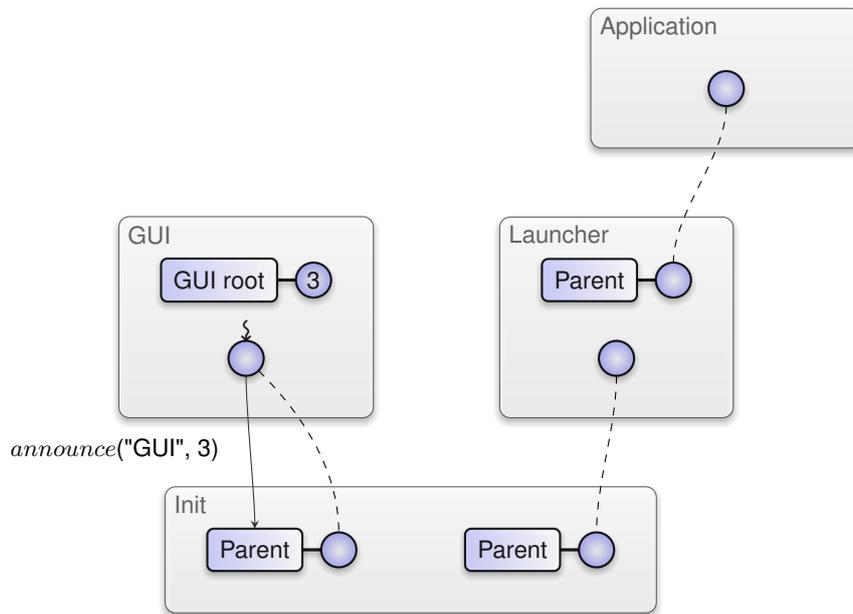


Figure 9: The GUI component announces its service to its parent using the parent interface.

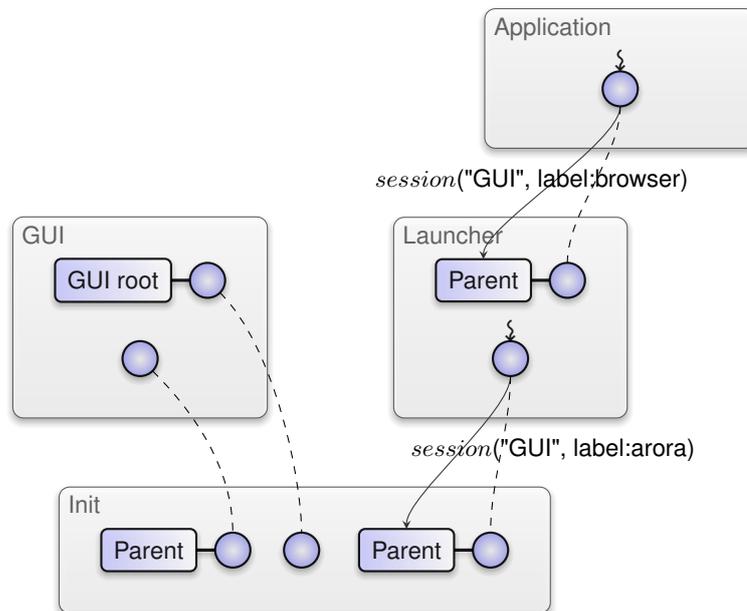


Figure 10: The application requests a GUI session using the parent interface.

Forward to grandparent The parent may decide to request a session in the name of its child from its own parent.

Figure 10 illustrates the latter option where the launcher responds to the application's session request by issuing a session request to its parent, the init component. Note that by requesting a session in the name of its child, the launcher is able to modify the session arguments according to its policy. In the example, the launcher imposes the use of a different label to the session. When init receives the session request from the launcher, it is up to init to take a policy decision with the same principle options. In fact, each component that sits in between the client and the server along the branches of the ownership tree can impose its policy onto sessions. The routing of the session request and the final session arguments as received by the server are the result of the successive application of all policies along the route.

Because the GUI announced its "GUI" service beforehand, init is in possession of the root capability, which enables it to create and destroy GUI sessions. It decides to respond to the launcher's session request by triggering the GUI-session creation at the GUI component's root interface. The GUI component responds to this request with the creation of a new GUI session and attaches the received session arguments to the new session. The accumulated session policy is thereby tied to the session's RPC object. The RPC object is accompanied with its corresponding session capability, which is delegated along the entire call chain up to the originator of the session request (Section 3.1.2). Once the application's session request returns, the application can interact directly with the GUI session using the session capability.

The differentiation between session creation and session use aligns two seemingly conflicting goals with each other, namely efficiency and the application of the security policies by potentially many components. All components on the route between client and server are involved in the creation of the session and can thereby impose their policies on the session. Once established, the direct communication channel between client and server via the session capability allows for the efficient interaction between the two components. For the actual use of the session, the intermediate components are not on the performance-critical path.

3.2.4. Client-server relationship

Whereas the role of a component as a child is dictated by the strict ownership relation that implies that the child has to ultimately trust its parent, the role of a component as client or server is more diverse.

In its *role of a client* that obtained a session capability as result of a session request from its parent, a component is unaware of the real identity of the server. It is unable to judge the trustworthiness of the server. However, it obtained the session from its parent, which the client ultimately trusts. Whichever session capability was handed out by the parent, the client is not in the position to question the parent's decision.

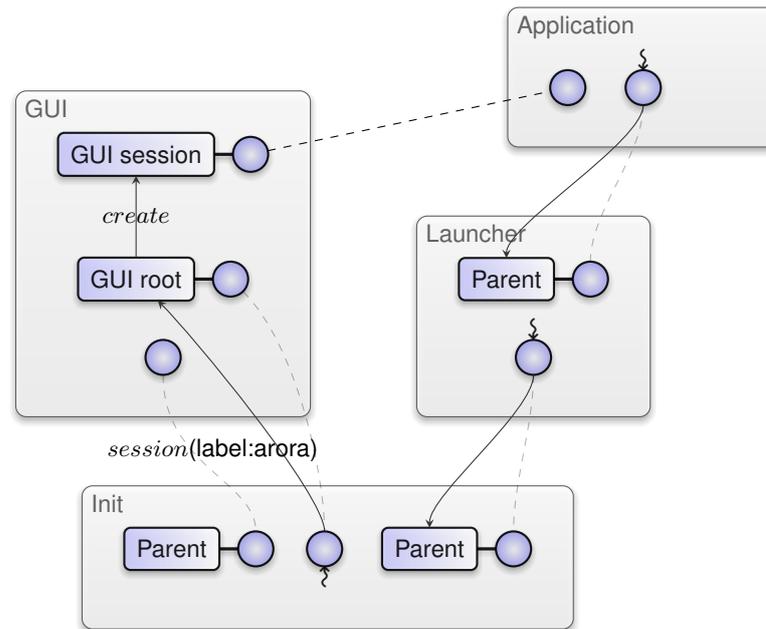


Figure 11: Session creation at the server.

Even though the integrity of the session capability can be taken for granted, the client does not need to trust the server in the same way as it trusts its parent. By invoking the capability, the client is in full control over the information it reveals to the server in the form of RPC arguments. The confidentiality and integrity of its internal state is protected. Furthermore, the invocation of a capability cannot have side effects on the client's protection domain other than the retrieval of RPC results. So the integrity of the client's internal state is protected. However, when invoking a capability, the client hands over the flow of execution to the server. The client is blocked until the server responds to the request. A misbehaving server may never respond and thereby block the client infinitely. Therefore, with respect to the liveness of the client, the client has to trust the server. To empathize with the role of a component as a client, a capability invocation can be compared to the call of a function of an opaque 3rd-party library. When calling such a library function, the caller can never be certain to regain control. It just expects that a function returns at some point. However, in contrast to a call of a library function, a capability invocation does not put the integrity and confidentiality of the client's internal state at risk.

Servers do not trust their clients When exercising the *role of a server*, a component should generally not trust its clients. On the contrary, from the server's perspective, clients should be expected to misbehave. This has two practical implications. First, a server is responsible for validating the arguments of incoming RPC requests. Second, a

server should never make itself dependent on the good will of its clients. For example, a server should generally not invoke a capability obtained from one of its clients. A malicious client could have delegated a capability to a non-responding RPC object, which may block the server forever when invoked and thereby make the server unavailable for all clients. As another example, the server must always be in control over the physical memory resources used for a shared-memory interface between itself and its clients. Otherwise, if a client was in control over the used memory, it could revoke the memory from the server at any time, possibly triggering a fault at the server. The establishment of shared memory is described in detail in Section 3.6.3. Similarly to the role as client, the internal state of a server is protected from its clients with respect to integrity and confidentiality. In contrast to a client, however, the liveness of a server is protected as well. A server never needs to wait for any response from a client. By responding to an RPC request, the server does immediately become ready to accept the next RPC request without any prior handshake with the client of the first request.

Ownership and lifetime of a session The object identity of a session RPC object and additional RPC objects that may have been created via the session is owned by the server. So the server is in control over the lifetime of those RPC objects. The client is not in the immediate position to dictate the server when to close a session because it has no power over the server. Instead, the procedure of closing a session follows the same chain of commands as involved in the session creation. The common parent of client and server plays the role of a broker, which is trusted by both parties. From the client's perspective, closing a session is a request to its parent. The client has to accept that the response to such a request is up to the policy of the parent. The closing of a session can alternatively be initiated by all nodes of the component tree that were involved in the session creation.

From the perspective of a server that is implemented by a child, the request to close a session originates from its parent, which, as the owner of the server, represents an authority that must be ultimately obeyed. If the server complies, the object identity of the session's RPC object vanishes. Since the kernel invalidates capabilities once their associated RPC object is destroyed, all capabilities referring to the RPC object - however delegated - are implicitly revoked as a side effect. Still, a server may ignore the session-close request. In this case, the parent of a server might take steps to enforce its will by destructing the server altogether.

Trustworthiness of servers Servers that are shared by clients of different security levels must be designed and implemented with special care. Besides the correct response to session-close requests, another consideration is the adherence to the security policy as configured by the parent. The mere fact that a server is a child of its parent does not imply that the parent won't need to trust it in some respects.

In cases where it is not viable to trust the server (e. g., because the server is based on ported software that is too complex for thorough evaluation), certain security properties such as the effectiveness of closing sessions could be enforced by a small (and thereby trustworthy) intermediate server that sits in-between the real server and the client. This intermediate server would then effectively wrap the server's session interface.

3.3. Resource trading

As introduced in Section 3.2.1, child components are created out of the resources of their respective parent components. This section describes the underlying mechanism. It first introduces the concept of PD sessions as resource accounts in Section 6.2.2. Section 3.3.2 explains how PD sessions are used to trade resources between components. The resource-trading mechanism ultimately allows servers to become resilient against client-driven resource-exhaustion attacks. However, such servers need to take special precautions that are explained in Section 3.3.3. Section 3.3.4 presents a mechanism for the dynamic balancing of resources among cooperative components.

3.3.1. Resource assignment

In general, it is the operating system's job to manage the physical resources of the machine in a way that enables multiple applications to utilize them in a safe and efficient manner. The physical resources are foremost the physical memory, the processing time of the CPUs, and devices.

The traditional approach to resource management Traditional operating systems usually provide abstractions of physical resources to applications running on top of the operating system. For example, instead of exposing the real interface of a device to an application, a Unix kernel provides a representation of the device as a pseudo file in the virtual file system. An application interacts with the device indirectly by operating on the respective pseudo file via a device-class-specific API (ioctl operations). As another example, a traditional OS kernel provides each application with an arbitrary amount of virtual memory, which may be much larger than the available physical memory. The application's virtual memory is backed with physical memory not before the application actually uses the memory. The pretension of unlimited memory by the kernel relieves application developers from considering memory as a limited resource. On the other hand, this convenient abstraction creates problems that are extremely hard or even impossible to solve by the OS kernel.

- The amount of physical memory that is at the disposal for backing virtual memory is limited. Traditional OS kernels employ strategies to uphold the illusion of unlimited memory by swapping memory pages to disk. However, the swap space on disk is ultimately limited, too. At one point, when the physical resources are exhausted, the pretension of unlimited memory becomes a leaky abstraction and forces the kernel to take extreme decisions such as killing arbitrary processes to free up physical memory.
- Multiple applications including critical applications as well as potentially misbehaving applications share one pool of physical resources. In the presence of a

misbehaving application that exhausts the physical memory, all applications are equally put at risk.

- Third, by granting each application the legitimate ability to consume as much memory as the application desires, applications cannot be held accountable for their consumption of physical memory. The kernel cannot distinguish a misbehaving from a well-behaving memory-demanding application.

There are several approaches to relieve those problems. For example, OS kernels that are optimized for resource utilization may employ heuristics that take the application behavior into account for parametrizing page-swapping strategies. Another example is the provisioning of a facility for pinned memory to applications. Such memory is guaranteed to be backed by physical memory. But such a facility bears the risk of allowing any application to exhaust physical memory directly. Hence, further heuristics are needed to limit the amount of pinned memory an application may use. Those counter measures and heuristics, while making the OS kernel more complex, are mere attempts to fight symptoms but unable to solve the actual problems caused by the lack of accounting. The behavior of such systems remains largely indeterministic.

As a further consequence of the abstraction from physical resources, the kernel has to entail functionality to support the abstraction. For example, for swapping memory pages to disk, the kernel has to depend on an in-kernel disk driver. For each application, whether or not it ever touches the disk, the in-kernel disk driver is part of its trusted computing base.

PD sessions and balances Genode does not abstract from physical resources. Instead, it solely arbitrates the access to such resources and provides means to delegate the authority over resources between components. Low-level physical resources are represented as services provided by the core component at the root of the component tree. The core component is described in detail in Section 3.4. The following description focuses on memory as the most prominent low-level resource managed by the operating system. Processing time is subject to the kernel's scheduling policy whereas the management of the higher-level resources such as disk space is left to the respective servers that provide those resources.

Physical memory is handed out and accounted by the PD service of core. The best way to describe the idea is to draw an analogy between the PD service and a bank. Each PD session corresponds to a bank account. Initially, when opening a new account, there is no balance. However, by having the authority over an existing bank account with a balance, one can transfer funds from the existing account to the new account. Naturally, such a transaction will decrease the balance of the originating account. Internally at the bank, the transfer does not involve any physical bank notes. The transaction is merely a change of balances of both bank accounts involved. A bank customer with the authority over a given bank account can use the value stored on the bank account to purchase

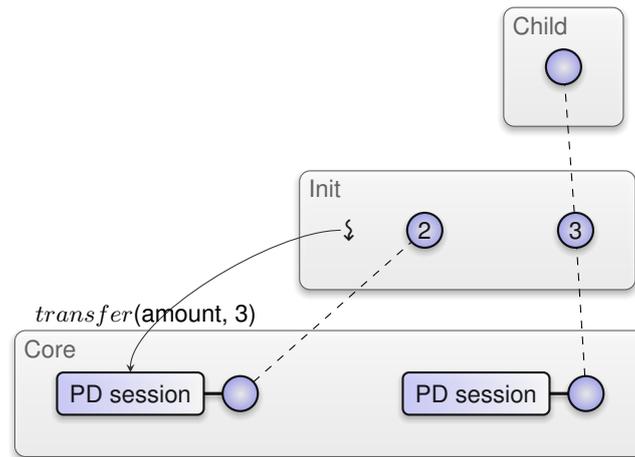


Figure 12: Init assigns a portion of its memory to a child. In addition to its own PD session (2), init has created a second PD session (3) designated for its child.

physical goods while withdrawing the costs from the account. Such a withdrawal will naturally decrease the balance on the account. If the account is depleted, the bank denies the purchase attempt. Analogously to purchasing physical goods by withdrawing balances from a bank account, physical memory can be allocated from a PD session. The balance of the PD session is the PD session's quota. A piece of allocated physical memory is represented by a so-called dataspace (see Section 3.4.1 for more details). A RAM dataspace is a container of physical memory that can be used for storing data.

Subdivision of budgets Similar to a person with a bank account, each component of a Genode system has a session at core's PD service. At boot time, the core component creates an initial PD session with the balance set to the amount of available physical memory. This PD session is designated for the init component, which is the first and only child of core. On request by init, core delegates the capability for this initial PD session to the init component.

For each child component spawned by the init component, init creates a new PD session at core. Figure 12 exemplifies this step for one child. As the result from the session creation, it obtains the capability for the new PD session. Because it has the authority over both its own and the child's designated PD session, it can transfer a certain amount of RAM quota from its own account to the child's account by invoking its own PD-session capability and specifying the beneficiary's PD-session capability as argument. Core responds to the request by atomically adjusting the quotas of both PD sessions by the specified amount. In the case of init, the amount depends on init's configuration. Thereby, init explicitly splits its own RAM budget among its child components. Each child created by init can obtain the capability for its own PD session from init via the parent interface and thereby gains the authority over the memory budget

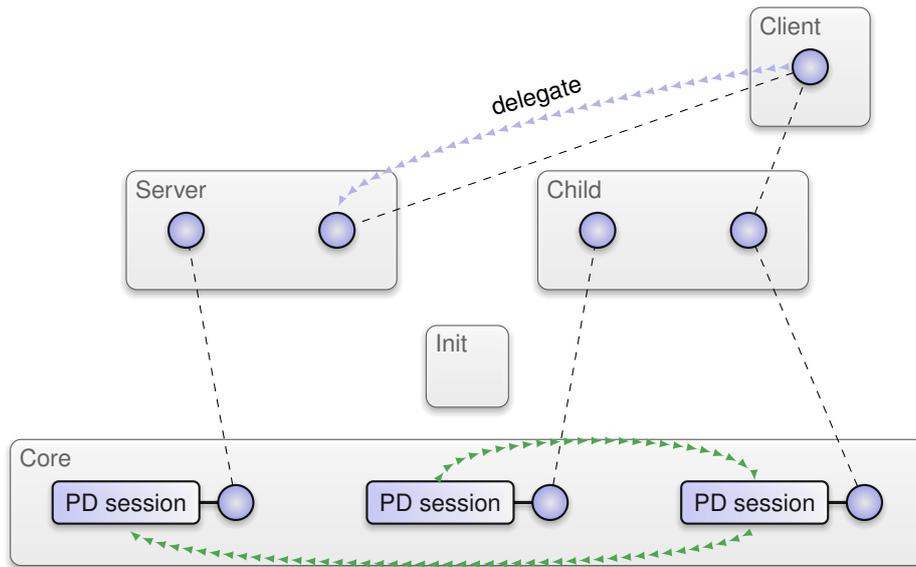


Figure 13: Memory-stealing attempt

that was assigned to it. Note however, that no child has the authority over `init`'s PD session nor the PD sessions of any siblings. The mechanism for distributing a given budget among multiple children works recursively. The children of `init` can follow the same procedure to further subdivide their budgets for spawning grandchildren.

Protection against resource stealing A parent that created a child subsystem out of its own memory resources, expects to regain the spent resources when destructing the subsystem. For this reason, it must not be possible for a child to transfer funds to another branch of the component tree without the consent of the parent. Figure 13 illustrates an example scenario that violates this expectation. The client and server components conspire to steal memory from the child. The client was created by the child and received a portion of the child's memory budget. The client requested a session for a service that was eventually routed to the server. The client-server relationship allows the client to delegate capabilities to the server. Therefore, it is able to delegate its own PD session capability to the server. The server, now in possession of the client's and its own PD session capabilities, can transfer memory from the client's to its own PD session. After this transaction, the child has no way to regain its memory resources because it has no authority over the server's PD session.

To prevent such resource-stealing scenarios, Genode restricts the quota transfer between arbitrary PD sessions. Each PD session must have a reference PD session, which can be defined only once. Transfers are permitted only between a PD session and its reference PD session. When creating the PD session of a child component, the parent

registers its own PD session as the child's reference PD session. This way, the parent becomes able to transfer budgets between its own and the child's PD session.

PD session destruction When a PD session is closed, core destroys all dataspace that were allocated from the PD session and transfers the PD session's final budget to the corresponding reference PD session.

3.3.2. Trading memory between clients and servers

An initial assignment of memory to a child is not always practical because the memory demand of a given component may be unknown at its construction time. For example, the memory needed by a GUI server over its lifetime is not known a priori but depends on the number of its clients, the number of windows on screen, or the amount of pixels that must be held at the server. In many cases, the memory usage of a server depends on the behavior of its clients. In traditional operating systems, system services like a GUI server would allocate memory on behalf of its clients. Even though the allocation was induced by a client, the server performs the allocation. The OS kernel remains unaware of the fact that the server solely needs the allocated memory for serving its client. In the presence of a misbehaving client that issues an infinite amount of requests to the server where each request triggers a server-side allocation (for example the creation of a new window), the kernel will observe the server as a resource hog. Under resource pressure, it will likely select the server to be punished. Each server that performs allocations on behalf of its clients is prone to this kind of attack. Genode solves this problem by letting clients pay for server-side allocations. Client and server may be arbitrary nodes in the component tree.

Session quotas As described in the previous section, at the creation time of a child, the parent assigns a part of its own memory quota to the new child. Since the parent retains the PD-session capabilities of all its children, it can issue further quota transfers back and forth between the children's PD sessions and its own PD session, which represents the reference account for all children. When a child requests a session at the parent interface, it can attach a fraction of its quota to the new session by specifying an amount of memory to be donated to the server as a session argument. This amount is called *session quota*. The session quota can be used by the server during the lifetime of the session. It is returned to the client when the session is closed.

When receiving a session request, the parent has to distinguish three different cases depending on its session-routing decision as described in Section 3.2.3.

Parent provides the service If the parent provides the requested service by itself, it first checks whether the session quota meets its need for providing the service. If so, it transfers the session quota from the requesting child's PD session to its own

PD session. This step may fail if the child offered a session quota larger than the available quota in the child's PD session.

Server is another child If the parent decides to route the session request to another child, it transfers the session quota from the client's PD session to the server's PD session. Because the PD sessions are not related to each other as both have the parent's PD session as reference account, this transfer from the client to the server consists of two steps. First, the parent transfers the session quota to its own PD session. If this step succeeded, it transfers the session quota from its own PD session to the server's PD session. The parent keeps track of the session quota for each session so that the quota transfers can be reverted later when closing the session. Not before the transfer of the session quota to the server's PD session succeeded, the parent issues the actual session request at the server's root interface along with the information about the transferred session quota.

Forward to grandparent The parent may decide to forward the session request to its own parent. In this case, the parent requests a session on behalf of its child. The grandparent neither knows nor cares about the actual origin of the request and will simply decrease the memory quota of the parent. For this reason, the parent transfers the session quota from the requesting child to its own PD session before issuing the session request at the grandparent.

Quota transfers may fail if there is not enough budget on the originating account. In this case, the parent aborts the session creation and reflects the lack of resources as an error to the originator of the session request.

This procedure works recursively. Once the server receives the session request along with the information about the provided session quota, it can use this information to decide whether or not to provide the session under these resource conditions. It can also use the information to tailor the quality of the service according to the provided session quota. For example, a larger session quota might enable the server to use larger caches or communication buffers for the client's session.

Session upgrades During the lifetime of a session, the initial session quota may turn out to be too scarce. Usually, the server returns such a scarcity condition as an error of operations that imply server-side allocations. The client may handle such a condition by upgrading the session quota of an existing session by issuing an upgrade request to its parent along with the targeted session capability and the additional session quota. The upgrade works analogously to the session creation. The server will receive the information about the upgrade via the root interface of the service.

Closing sessions If a child issues a session-close request to its parent, the parent determines the corresponding server, which, depending on the route of the original

session request, may be locally implemented, provided by another child, or provided by the grandparent. Once the server receives the session-close request, it is responsible for releasing all resources that were allocated from the session quota. The release of resources should revert all allocations the server has performed on behalf its client. Stressing the analogy with the bank account, the server has to sell the physical goods (i. e., RAM dataspace) it purchased from the client's session quota to restore the balance on its PD session. After the server has reverted all session-specific allocations, the server's PD session is expected to have at least as much available budget as the session quota of the to-be-closed session. As a result, the session quota can be transferred back to the client.

However, a misbehaving server may fail to release those resources by malice or because of a bug. For example, the server may be unable to free a dataspace because it mistakenly used the dataspace for another client's data. Another example would be a memory leak in the server. Such misbehavior is detected on the attempt to withdraw the session quota from the server's PD session. If the server's available RAM quota after closing a session remains lower than the session quota, the server apparently speculated memory. If the misbehaving server was locally provided by the parent, it has the full authority to not hand back the session quota to its child. If the misbehaving service was provided by the grandparent, the parent (and its whole subsystem) has to subordinate. If, however, the server was provided by another child and the child refuses to release resources, the parent's attempt to withdraw the session quota from the server's PD session will fail. It is up to the policy of the parent to handle such a failure either by punishing the server (e. g., killing the component) or by granting more of its own quota. Generally, misbehavior is against the server's own interests. A server's best interest is to obey the parent's close request to avoid intervention.

3.3.3. Component-local heap partitioning

Components that perform memory allocations on behalf of untrusted parties must take special precautions for the component-local memory management. There are two prominent examples for such components. As discussed in Section 3.3.2, a server may be used by multiple clients that must not interfere with each other. Therefore, server-side memory allocations on behalf of a particular client must strictly be accounted to the client's session quota. Second, a parent with multiple children may need to allocate memory to perform the book keeping for the individual children, for example, maintaining the information about their open sessions and their session quotas. The parent should account those child-specific allocations to the respective children. In both cases, it is not sufficient to merely keep track of the amount of memory consumed on behalf of each untrusted party but the actual allocations must be performed on independent backing stores.

Figure 14 shows a scenario where a server performs anonymous memory allocations on behalf of two session. The memory is allocated from the server's heap. Whereas allo-

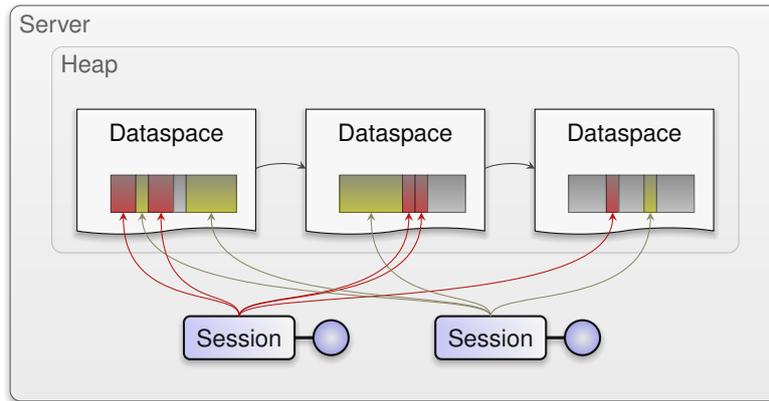


Figure 14: A server allocates anonymous memory on behalf of multiple clients from a single heap.

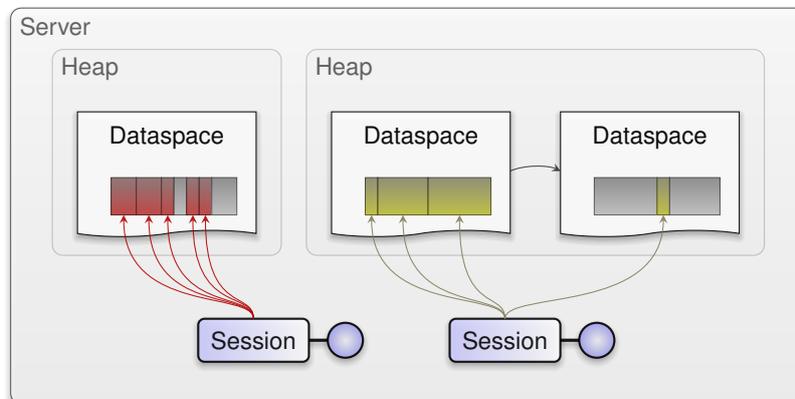


Figure 15: A server performs memory allocations from session-specific heap partitions.

cations from the heap are of byte granularity, the heap's backing store consists of several dataspaces. Those dataspaces are allocated from the server's PD session as needed but at a much larger granularity. As depicted in the figure, allocations from both sessions end up in the same dataspaces. This becomes a problem once one session is closed. As described in the previous section, the server's parent expects the server to release all resources that were allocated from the corresponding session quota. However, even if the server reverts all heap allocations that belong to the to-be-closed session, the server could still not release the underlying backing store because all dataspaces are still occupied with memory objects of another session. Therefore, the server becomes unable to comply with the parent's expectation.

The solution of this problem is illustrated in Figure 15. For each session, the server maintains a separate heap partition. Each memory allocation on behalf of a client is performed from the session-specific heap partition rather than from a global heap. This

way, memory objects of different sessions populate disjoint dataspace. When closing a session, the server reverts all memory allocations from the session's heap. After freeing the session's memory objects, the heap partition becomes empty. So it can be destroyed. By destroying the heap partition, the underlying dataspace that were used as the backing store can be properly released.

3.3.4. Dynamic resource balancing

As described in Section 6.2.2, parent components explicitly assign physical resource budgets to their children. Once assigned, the budget is at the disposal of the respective child subsystem until the subsystem gets destroyed by the parent.

However, not all components have well-defined resource demands. For example, a block cache should utilize as much memory as possible unless the memory is needed by another component. The assignment of fixed amount of memory to such a block cache cannot accommodate changes of workloads over the potentially long lifetime of the component. If dimensioned too small, there may be a lot of slack memory remaining unutilized. If dimensioned too large, the block cache would prevent other and possibly more important components to use the memory. A better alternative is to enable a component to adapt its resource use to the resource constraints of its parent. The parent interface supports this alternative with a protocol for the dynamic balancing of resources.

The resource-balancing protocol uses a combination of synchronous remote procedure calls and asynchronous notifications. Both mechanisms are described in Section 3.6. The child uses remote procedure calls to talk to its parent whereas the parent uses asynchronous notifications to signal state changes to the child. The protocol consists of two parts, which are complementary.

Resource requests By issuing a resource request to its parent, a child applies for an upgrade of its resources. The request takes the amount of desired resources as argument. A child would issue such a request if it detects scarceness of resources. A resource request returns immediately regardless of whether additional resources have been granted or not. The child may proceed working under the low resource conditions or it may block and wait for a resource-available signal from its parent. The parent may respond to this request in different ways. It may just ignore the request, possibly stalling the child. Alternatively, it may immediately transfer additional quota to the child's PD session. Or it may take further actions to free up resources to accommodate the child. Those actions may involve long-taking operations such as the destruction of subsystems or the further propagation of resource request towards the root of the component tree. Once the parent has freed up enough resources to accommodate the child's request, it transfers the new resources to the child's PD session and notifies the child by sending a resource-available signal.

Yield requests The second part of the protocol enables the parent to express its wish for regaining resources. The parent notifies the child about this condition by sending a yield signal to the child. On the reception of such a signal, the child picks up the so-called yield request at the parent using a remote procedure call. The yield request contains the amount of resources the parent wishes to regain. It is up to the child to comply with a yield request or not. Some subsystems have meaningful ways to respond to yield requests. For example, an in-memory block cache could write back the cached information and release the memory consumed by the cache. Once the child has succeeded in freeing up resources, it reports to the parent by issuing a so-called yield response via a remote procedure call to the parent. The parent may respond to a yield response by withdrawing resources from the child's PD session.

3.4. Core - the root of the component tree

Core is the first user-level component, which is directly created by the kernel. It thereby represents the root of the component tree. It has access to the raw physical resources such as memory, CPUs, memory-mapped devices, interrupts, I/O ports, and boot modules. Core exposes those low-level resources as services so that they can be used by other components. For example, physical memory is made available as so-called RAM dataspaces allocated from core's PD service, interrupts are represented by the IRQ service, and CPUs are represented by the CPU service. In order to access a resource, a component has to establish a session to the corresponding service. Thereby the access to physical resources is subjected to the routing of session requests as explained in Section 3.2.3. Moreover, the resource-trading concept described in Section 3.3.2 applies to core services in the same way as for any other service.

In addition to making hardware resources available as services, core provides all prerequisites to bootstrap the component tree. These prerequisites comprise services for creating protection domains, for managing address-space layouts, and for creating object identities.

Core is almost free from policy. There are no configuration options. The only policy of core is the startup of the init component, to which core grants all available resources. Init, in turn, uses those resources to spawn further components according to its configuration.

Section 3.4.1 introduces dataspaces as containers of memory or memory-like resources. Dataspaces form the foundation for most of the core services described in the subsequent sections. The section is followed by the introduction of each individual service provided by core. In the following, a component that has established a session to such a service is called *client*. For example, a component that obtained a session to core's CPU service is a CPU client.

3.4.1. Dataspaces

A dataspace is an RPC object¹ that resides in core and represents a contiguous physical address-space region with an arbitrary size. Its base address and size are subjected to the granularity of physical pages as dictated by the memory-management unit (MMU) hardware. Typically the granularity is 4 KiB.

Dataspaces are created and managed via core's services. Because each dataspace is a distinct RPC object, the authority over the contained physical address range is represented by a capability and can thereby be delegated between components. Each component in possession of a dataspace capability can make the dataspace content visible in its local address space. Hence, by the means of delegating dataspace capabilities, components can establish shared memory.

¹Interface specification in Section 8.1.3

On Genode, only core deals with physical memory pages. All other components use dataspace as a uniform abstraction for memory, memory-mapped I/O regions, and ROM modules.

3.4.2. Region maps

A region map¹ represents the layout of a virtual address space. The size of the virtual address space is defined at its creation time. Region maps are created implicitly as part of a PD session (Section 3.4.4) or manually via the RM service (Section 3.4.5).

Populating an address space The concept behind region maps is a generalization of the MMU's page-table mechanism. Analogously to how a page table is populated with physical page frames, a region map is populated with dataspace. Under the hood, core uses the MMU's page-table mechanism as a cache for region maps. The exact way of how MMU translations are installed depends on the underlying kernel and is opaque to Genode components. On most base platforms, memory mappings are established in a lazy fashion by core's page-fault resolution mechanism described in Section 7.3.4.

A region-map client in possession of a dataspace capability is able to *attach* the dataspace to the region map. Thereby the content of the dataspace becomes visible within the region map's virtual address space. When attaching a dataspace to a region map, core selects an appropriate virtual address range that is not yet populated with dataspace. Alternatively, the client can specify a designated virtual address. It also has the option to attach a mere window of the dataspace to the region map. Furthermore, the client can specify whether the content of the dataspace should be executable or not.

The counterpart of the *attach* operation is the *detach* operation, which enables the region-map client to remove dataspace from the region map by specifying a virtual address. Under the hood, this operation flushes the MMU mappings of the corresponding virtual address range so that the dataspace content becomes invisible.

Note that a single dataspace may be attached to any number of region maps. A dataspace may also be attached multiple times to one region map. In this case, each attach operation populates a distinct region of the virtual address space.

3.4.3. Access to boot modules (ROM)

During the initial bootstrap phase of the machine, a boot loader loads the kernel's binary and additional chunks of data called *boot modules* into the physical memory. After those preparations, the boot loader passes control to the kernel. Examples of boot modules are the ELF images of the core component, the init component, the components created by init, and the configuration of the init component. Core makes each boot

¹Interface specification in Section 8.4

module available as a ROM session¹. Because boot modules are read-only memory, they are generally called ROM modules. On session construction, the client specifies the name of the ROM module as session argument. Once created, the ROM session allows its client to obtain a ROM dataspace capability. Using this capability, the client can make the ROM module visible within its local address space. The ROM session interface is described in more detail in Section 4.5.1.

3.4.4. Protection domains (PD)

A protection domain (PD) corresponds to a unit of protection within the Genode system. Typically, there is a one-to-one relationship between a component and a PD session². Each PD consists of a virtual memory address space, a capability space (Section 3.1.1), and a budget of physical memory and capabilities. Core's PD service also plays the role of a broker for asynchronous notifications on kernels that lack the semantics of Genode's signalling API.

Physical memory and capability allocation Each PD session contains quota-bounded allocators for physical memory and capabilities. At session-creation time, its quota is zero. To make an allocator functional, it must first receive quota from another already existing PD session, which is called the *reference account*. Once the reference account is defined, quota can be transferred back and forth between the reference account and the new PD session.

Provided that the PD session is equipped with sufficient quota, the PD client can allocate RAM dataspaces from the PD session. The size of each RAM dataspace is defined by the client at the time of allocation. The location of the dataspace in physical memory is defined by core. Each RAM dataspace is physically contiguous and can thereby be used as DMA buffer by a user-level device driver. In order to set up DMA transactions, such a device driver can request the physical address of a RAM dataspace by invoking the dataspace capability.

Closing a PD session destroys all dataspaces allocated from the PD session and restores the original quota. This implies that these dataspaces disappear in all components. The quota of a closed PD session is transferred to the reference account.

Virtual memory and capability space At the hardware-level, the CPU isolates different virtual memory address spaces via a memory-management unit. Each domain is represented by a different page directory, or an address-space ID (ASID). Genode provides an abstraction from the underlying hardware mechanism in the form of region maps as introduced in Section 3.4.2. Each PD is readily equipped with three region maps. The *address space* represents the layout of the PD's virtual memory address space,

¹Interface specification in Section 8.5.2

²Interface specification in Section 8.5.1

the *stack area* represents the portion of the PD's virtual address space where stacks are located, and the *linker area* is designated for dynamically linked shared objects. The stack area and linker area are attached to the address space at the component initialisation time.

The capability space is provided as a kernel mechanism. Note that not all kernels provide equally good mechanisms to implement Genode's capability model as described in Section 3.1. On kernels with support for kernel-protected object capabilities, the PD session interface allows components to create and manage kernel-protected capabilities. Initially, the PD's capability space is empty. However, the PD client can install a single capability - the parent capability - using the *assign-parent* operation at the creation time of the PD.

3.4.5. Region-map management (RM)

As explained in Section 3.4.4, each PD session is equipped with three region maps by default. The RM service allows components to create additional region maps manually. Such manually created region maps are also referred to as *managed dataspace*s. A managed dataspace is not backed by a range of physical addresses but its content is defined by its underlying region map. This makes region maps a generalization of nested page tables. A region-map client can obtain a dataspace capability for a given region map and use this dataspace capability in the same way as any other dataspace capability, i. e., attaching it to its local address space, or delegating it to other components.

Managed dataspace)s are used in two ways. First, they allow for the manual management of portions of a component's virtual address space. For example, the so-called stack area of a protection domain is a dedicated virtual-address range preserved for stacks. Between the stacks, the virtual address space must remain empty so that stack overflows won't silently corrupt data. This is achieved by using a dedicated region map that represents the complete stack area. This region map is attached as a dataspace to the component's virtual address space. When creating a new thread along with its corresponding stack, the thread's stack is not directly attached to the component's address space but to the stack area's region map. Another example is the virtual-address range managed by a dynamic linker to load shared libraries into.

The second use of managed dataspace)s is the provision of on-demand-populated dataspace)s. A server may hand out dataspace capabilities that are backed by region maps to its clients. Once the client has attached such a dataspace to its address space and touches its content, the client triggers a page fault. Core responds to this page fault by blocking the client thread and delivering a notification to the server that created the managed dataspace along with the information about the fault address within the region map. The server can resolve this condition by attaching a dataspace with real backing store at the fault address, which prompts core to resume the execution of the faulted thread.

3.4.6. Processing-time allocation (CPU)

A CPU session¹ is an allocator for processing time that allows for the creation, the control, and the destruction of threads of execution. At session-construction time, the affinity of a CPU session with CPU cores can be defined via session arguments.

Once created, the session can be used to create, control, and kill threads. Each thread created via a CPU session is represented by a thread capability. The thread capability is used for subsequent thread-control operations. The most prominent thread-control operation is the *start* of the thread, which takes the thread's initial stack pointer and instruction pointer as arguments.

During the lifetime of a thread, the CPU client can retrieve and manipulate the *state* of the thread. This includes the register state as well as the execution state (whether the thread is paused or running). Those operations are primarily designated for realizing user-level debuggers.

To aid the graceful destruction of threads, the CPU client can issue a *cancel-blocking* operation, which causes the specified thread to cancel a current blocking operation such as waiting for an RPC response or the attempt to acquire a contended lock.

3.4.7. Access to device resources (IO_MEM, IO_PORT, IRQ)

Core's IO_MEM, IO_PORT, and IRQ services enable the realization of user-level device drivers as Genode components.

Memory mapped I/O (IO_MEM) An IO_MEM session² provides a dataspace representation for a non-memory part of the physical address space such as memory-mapped I/O regions or BIOS areas. In contrast to a memory block that is used for storing information, of which the physical location in memory is of no concern, a non-memory object has special semantics attached to its location within the physical address space. Its location is either fixed (by standard) or can be determined at runtime, for example by scanning the PCI bus for PCI resources. If the physical location of such a non-memory object is known, an IO_MEM session can be created by specifying the physical base address, the size, and the write-combining policy of the memory-mapped resource as session arguments. Once an IO_MEM session is created, the IO_MEM client can request a dataspace containing the specified physical address range.

Core hands out each physical address range only once. Session requests for ranges that intersect with physical memory are denied. Even though the granularity of memory protection is limited by the MMU page size, the IO_MEM service accepts the specification of the physical base address and size at the granularity of bytes. The rationale behind this contradiction is the unfortunate existence of platforms that host memory-mapped resources of unrelated devices on the same physical page. When driving such

¹Interface specification in Section 8.5.4

²Interface specification in Section 8.5.5

devices from different components, each of those components requires access to its corresponding device. So the same physical page must be handed out to multiple components. Of course, those components must be trusted to not touch any portion of the page that is unrelated to its own device.

Port I/O (IO_PORT) For platforms that rely on I/O ports for device access, core's IO_PORT service enables the fine-grained assignment of port ranges to individual components. Each IO_PORT session¹ corresponds to the exclusive access right to a port range specified as session arguments. Core creates the new IO_PORT session only if the specified port range does not overlap with an already existing session. This ensures that each I/O port is driven by only one IO_PORT client at a time. The IO_PORT session interface resembles the physical I/O port access instructions. Reading from an I/O port can be performed via an 8-bit, 16-bit, or 32-bit access. Vice versa, there exist operations for writing to an I/O port via an 8-bit, 16-bit, or 32-bit access. The read and write operations take absolute port addresses as arguments. Core performs the I/O-port operation only if the specified port address lies within the port range of the session.

Reception of device interrupts (IRQ) Core's IRQ service enables device-driver components to respond to device interrupts. Each IRQ session² corresponds to an interrupt. The physical interrupt number is specified as session argument. Each physical interrupt number can be specified by only one session. The IRQ session interface provides an operation to wait for the next interrupt. Only while the IRQ client is waiting for an interrupt, core unmask the interrupt at the interrupt controller. Once the interrupt occurs, core wakes up the IRQ client and masks the interrupt at the interrupt controller until the driver has acknowledged the completion of the IRQ handling and waits for the next interrupt.

3.4.8. Logging (LOG)

The LOG service is used by the lowest-level system components such as the init component for printing diagnostic output. Each LOG session³ takes a label as session argument, which is used to prefix the output of this session. This enables developers to distinguish the output of different components with each component having a unique label. The LOG client transfers the to-be-printed characters as payload of plain RPC messages, which represents the simplest possible communication mechanism between the LOG client and core's LOG service.

¹Interface specification in Section 8.5.6

²Interface specification in Section 8.5.7

³Interface specification in Section 8.5.8

3.4.9. Event tracing (TRACE)

The TRACE service provides a light-weight event-tracing facility. It is not fundamental to the architecture. However, as the service allows for the inspection and manipulation of arbitrary threads of a Genode system, TRACE sessions must not be granted to untrusted components.

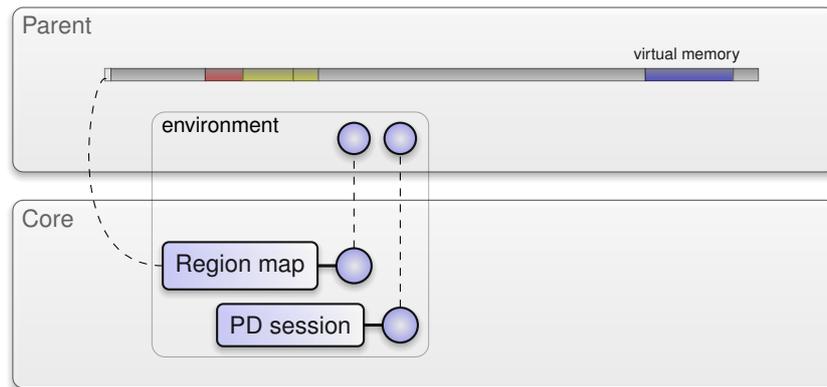


Figure 16: Starting point for creating a new component

3.5. Component creation

Each Genode component is made out of three basic ingredients:

PD session representing the component's protection domain

ROM session with the executable binary

CPU session for creating the initial thread of the component

It is the responsibility of the new component's parent to obtain those sessions. The initial situation of the parent is depicted in Figure 16. The parent's memory budget is represented by the parent's PD (Section [?]) session. The parent's virtual address space is represented by the region map contained in the parent's PD session. The parent's PD session was originally created at the parent's construction time. Along with the parent's CPU session, it forms the parent's so-called *environment*. The address space is populated with the parent's code (shown as red), the so-called stack area that hosts the stacks (shown as blue), and presumably several RAM dataspaces for the heap, the DATA segment, and the BSS segment. Those are shown as yellow.

3.5.1. Obtaining the child's ROM and PD sessions

The first step for creating a child component is obtaining the component's executable binary, e. g., by creating a session to a ROM service such as the one provided by core (Section 3.4.3). With the ROM session created, the parent can make the dataspace with the executable binary (i. e., an ELF binary) visible within its virtual address space by attaching the dataspace to its PD's region map. After this step, the parent is able to inspect the ELF header to determine the memory requirements for the binary's DATA and BSS segments.

The next step is the creation of the child's designated PD session, which holds the memory and capability budgets the child will have at its disposal. The freshly created

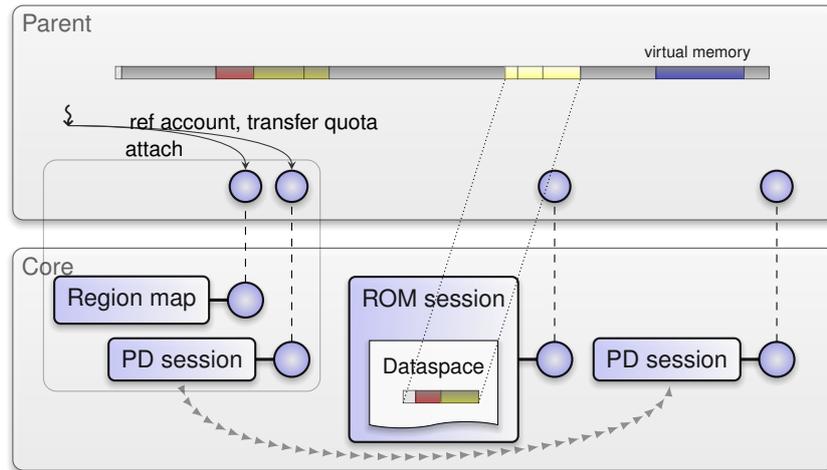


Figure 17: The parent creates the PD session of the new child and obtains the child's executable

PD session has no budget though. In order to make the PD session usable, the parent has to transfer a portion of its own RAM quota to the child's PD session. As explained in Section 6.2.2, the parent registers its own PD session as the reference account for the child's PD session in order to become able to transfer quota back and forth between both PD sessions. Figure 17 shows the situation.

3.5.2. Constructing the child's address space

With the child's PD session equipped with a memory, the parent can construct the address space for the new child and populate it with memory allocated from the child's budget (Figure 18). The address-space layout is represented as a region map that is part of each PD session (Section 3.4.4). The first page of the address space is excluded such that any attempt by the child to de-reference a null pointer will cause a fault instead of silently corrupting memory. After its creation time, the child's region map is empty. It is up to the parent to populate the virtual address space with meaningful information by attaching dataspace to the region map. The parent performs this procedure based on the information found in the ELF executable's header:

Read-only segments For each read-only segment of the ELF binary, the parent attaches the corresponding portion of the ELF dataspace to the child's address space by invoking the attach operation on the child's region-map capability. By attaching a portion of the existing ELF dataspace to the new child's region map, no memory must be copied. If multiple instances of the same executable are created, the read-only segments of all instances refer to the same physical memory pages. If the segment contains the TEXT segment (the program code), the parent specifies a so-called executable flag to the attach operation. Core passes this flag to the

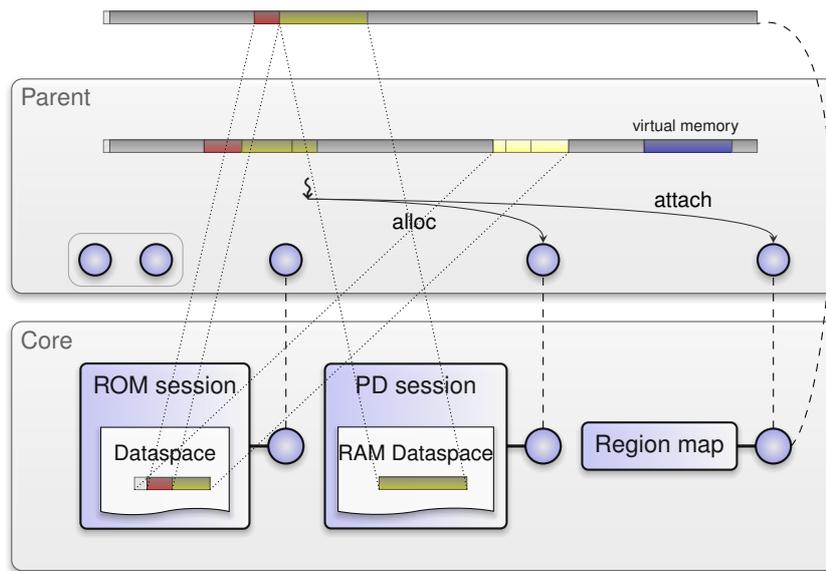


Figure 18: The parent creates and populates the virtual address space of the child using a new PD session (the parent's PD session is not depicted for brevity)

respective kernel such that the corresponding page-table entries for the new components will be configured accordingly (by setting or clearing the non-executable bit in the page-table entries). Note that the propagation of this information (or the lack thereof) depends on the kernel used. Also note that not all hardware platforms distinguish executable from non-executable memory mappings.

Read-writable segments In contrast to read-only segments, read-writable segments cannot be shared between components. Hence, each read-writable segment must be backed with a distinct copy of the segment data. The parent allocates the backing store for the copy from the child's PD session and thereby accounts the memory consumption on behalf of the child to the child's budget. For each segment, the parent performs the following steps:

1. Allocation of a RAM dataspace from the child's PD session. The size of the dataspace corresponds to the segment's memory size. The memory size may be higher than the size of the segment in the ELF binary (named file size). In particular, if the segment contains a DATA section followed by a BSS section, the file size corresponds to the size of the DATA section whereby the memory size corresponds to the sum of both sections. Core's PD service ensures that each freshly allocated RAM dataspace is guaranteed to contain zeros. Core's PD service returns a RAM dataspace capability as the result of the allocation operation.

2. Attachment of the RAM dataspace to the parent's virtual address space by invoking the attach operation on the parent's region map with the RAM dataspace capability as argument.
3. Copying of the segment content from the ELF binary's dataspace to the freshly allocated RAM dataspace. If the memory size of the segment is larger than the file size, no special precautions are needed as the remainder of the RAM dataspace is known to be initialized with zeros.
4. After filling the content of the segment dataspace, the parent no longer needs to access it. It can remove it from its virtual address space by invoking the detach operation on its own region map.
5. Based on the virtual segment address as found in the ELF header, the parent attaches the RAM dataspace to the child's virtual address space by invoking the attach operation on the child PD's region map with the RAM dataspace as argument.

This procedure is repeated for each segment. Note that although the above description refers to ELF executables, the underlying mechanisms used to load the executable binary are file-format agnostic.

3.5.3. Creating the initial thread

With the virtual address space of the child configured, it is time to create the component's initial thread. Analogously to the child's PD session, the parent creates a CPU session (Section 3.4.6) for the child. The parent may use session arguments to constrain the scheduling parameters (i. e., the priority) and the CPU affinity of the new child. Whichever session arguments are specified, the child's abilities will never exceed the parent's abilities. I. e., the child's priority is subjected to the parent's priority constraints. Once constructed, the CPU session can be used to create new threads by invoking the session's create-thread operation with the thread's designated PD as argument. Based on this association of the thread with its PD, core is able to respond to page faults triggered by the thread. The invocation of this operation results in a thread capability, which can be used to control the execution of the thread. Immediately after its creation, the thread remains inactive. In order to be executable, it first needs to be configured.

As described in Section 3.2.1, each PD has initially a single capability installed, which allows the child to communicate with its parent. Right after the creation of the PD for a new child, the parent can register a capability to a locally implemented RPC object as parent capability for the PD session. Now that the child's PD is equipped with an initial thread and a communication channel to its parent, it is the right time to kick off the execution of the thread by invoking the start operation on its thread capability. The start operation takes the initial program counter as argument, which corresponds to the program's entry-point address as found in the ELF header of the child's executable

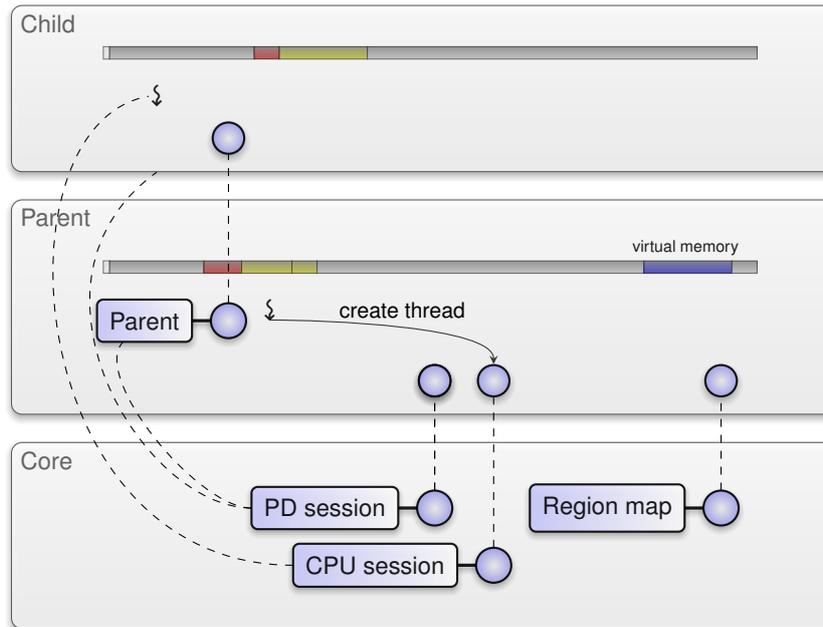


Figure 19: Creation of the child's initial thread

binary. Figure 19 illustrates the relationship between the PD session, the CPU session, and the parent capability. Note that neither the ROM dataspace containing the ELF binary nor the RAM dataspaces allocated during the ELF loading are visible in the parent's virtual address space any longer. After the initial loading of the ELF binary, the parent has detached those dataspaces from its own region map.

The child starts its execution at the virtual address defined by the ELF entrypoint. It points to a short assembly routine that sets up the initial stack and calls the low-level C++ startup code. This code, in turn, initializes the C++ runtime (such as the exception handling) along with the component's local Genode environment. The environment is constructed by successively requesting the component's CPU and PD sessions from its parent. With the Genode environment in place, the startup code initializes the stack area, sets up the real stack for the initial thread within the stack area, and returns to the assembly startup code. The assembly code, in turn, switches the stack from the initial stack to the real stack and calls the program-specific C++ startup code. This code initializes the component's initial entrypoint and executes all global constructors before calling the component's `construct` function. Section 7.1 describes the component-local startup procedure in detail.

3.6. Inter-component communication

Genode provides three principle mechanisms for inter-component communication, namely synchronous remote procedure calls (RPC), asynchronous notifications, and shared memory. Section 3.6.1 describes synchronous RPC as the most prominent one. In addition to transferring information across component boundaries, the RPC mechanism provides the means for delegating capabilities and thereby authority throughout the system.

The RPC mechanism closely resembles the semantics of a function call where the control is transferred from the caller to the callee until the function returns. As discussed in Section 3.2.4, there are situations where the provider of information does not wish to depend on the recipient to return control. Such situations are addressed by the means of an asynchronous notification mechanism explained in Section 3.6.2.

Neither synchronous RPC nor asynchronous notifications are suitable for transferring large bulks of information between components. RPC messages are strictly bound to a small size and asynchronous notifications do not carry any payload at all. This is where shared memory comes into play. By sharing memory between components, large bulks of information can be propagated without the active participation of the kernel. Section 3.6.3 explains the procedure of establishing shared memory between components.

Each of the three basic mechanisms is rarely found in isolation. Most inter-component interactions are a combination of these mechanisms. Section 3.6.4 introduces a pattern for propagating state information by combining asynchronous notifications with RPC. Section 3.6.5 shows how synchronous RPC can be combined with shared memory to transfer large bulks of information in a synchronous way. Section 3.6.6 combines asynchronous notifications with shared memory to largely decouple producers and consumers of high-throughput data streams.

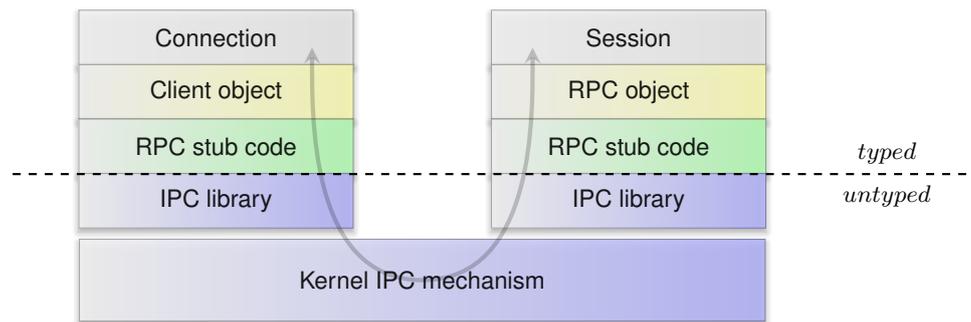


Figure 20: Layered architecture of the RPC mechanism

3.6.1. Synchronous remote procedure calls (RPC)

Section 3.1.3 introduced remote procedure calls (RPC) as Genode’s fundamental mechanism to delegate authority between components. It introduced the terminology for RPC objects, capabilities, object identities, and entrypoints. It also outlined the flow of control between a client, the kernel, and a server during an RPC call. This section complements Section 3.1.3 with the information of how the mechanism presents itself at the C++ language level. It first introduces the layered structure of the RPC mechanism and the notion of *typed capabilities*. After presenting the class structure of an RPC server, it shows how those classes interact when RPC objects are created and called.

Typed capabilities Figure 20 depicts the software layers of the RPC mechanism.

Kernel inter-process-communication (IPC) mechanism At the lowest level, the kernel’s IPC mechanism is used to transfer messages back and forth between client and server. The actual mechanism largely differs between the various kernels supported by Genode. Chapter 7 gives insights into the functioning of the IPC mechanism as used on specific kernels. Genode’s capability-based security model is based on the presumption that the kernel protects *object identities* as kernel objects, allows user-level components to refer to kernel objects via capabilities, and supports the delegation of capabilities between components using the kernel’s IPC mechanism. At the kernel-interface level, the kernel is not aware of language semantics like the C++ type system. From the kernel’s point of view, an object identity merely exists and can be referred to, but has no type.

IPC library The IPC library introduces a kernel-independent programming interface that is needed to implement the principle semantics of clients and servers. For each kernel supported by Genode, there exists a distinct IPC library that uses the respective kernel mechanism. The IPC library introduces the notions of untyped capabilities, message buffers, IPC clients, and IPC servers.

An *untyped capability* is the representation of a Genode capability at the C++ language level. It consists of the local name of the referred-to object identity as well as a means to manage the lifetime of the capability, i. e., a reference counter. The exact representation of an untyped capability depends on the kernel used.

A *message buffer* is a statically sized buffer that carries the payload of an IPC message. It distinguishes two types of payload, namely raw data and capabilities. Payloads of both kinds can be simultaneously present. A message buffer can carry up to 1 KiB of raw data and up to four capabilities. Prior to issuing the kernel IPC operation, the IPC library translates the message-buffer content to the format understood by the kernel's IPC operation.

The client side of the communication channel executes an *IPC call* operation with a destination capability, a send buffer, and a receive buffer as arguments. The send buffer contains the RPC function arguments, which can comprise plain data as well as capabilities. The IPC library transfers these arguments to the server via a platform-specific kernel operation and waits for the server's response. The response is returned to the caller as new content of the receive buffer.

At the server side of the communication channel, an entrypoint thread executes the *IPC reply* and *IPC reply-and-wait* operations to interact with potentially many clients. Analogously to the client, it uses two message buffers, a receive buffer for incoming requests and a send buffer for delivering the reply of the last request. For each entrypoint, there exists an associated untyped capability that is created with the entrypoint. This capability and can be combined with an IPC client object to perform calls to the server. The *IPC reply-and-wait* operation delivers the content of the reply buffer to the last caller and then waits for a new request using a platform-specific kernel operation. Once unblocked by the kernel, it returns the arguments for the new request in the request buffer. The server does not obtain any form of client identification along with an incoming message that could be used to implement server-side access-control policies. Instead of performing access control based on a client identification in the server, access control is solely performed by the kernel on the invocation of capabilities. If a request was delivered to the server, the client has – by definition – a capability for communicating with the server and thereby the authority to perform the request.

RPC stub code The RPC stub code complements the IPC library with the semantics of RPC interfaces and RPC functions. An RPC interface is an abstract C++ class with the declarations of the functions callable by RPC clients. Thereby each RPC interface is represented as a C++ type. The declarations are accompanied with annotations that allow the C++ compiler to generate the so-called RPC stub code on both the client side and server side. Genode uses C++ templates to generate the stub code, which avoids the crossing of a language barrier when designing RPC interfaces and alleviates the need for code-generating tools in addition to

the compiler.

The client-side stub code translates C++ method calls to IPC-library operations. Each RPC function of an RPC interface has an associated opcode (according to the order of RPC functions). This opcode along with the method arguments are inserted into the IPC client's send buffer. Vice versa, the stub code translates the content of the IPC client's receive buffer to return values of the method invocation.

The server-side stub code implements the so-called dispatch function, which takes the IPC server's receive buffer, translates the message into a proper C++ method call, calls the corresponding server-side function of the RPC interface, and translates the function results into the IPC server's send buffer.

RPC object and client object Thanks to the RPC stub code, the server-side implementation of an RPC object comes down to the implementation of the abstract interface of the corresponding RPC interface. When an RPC object is associated with an entrypoint, the entrypoint creates a unique capability for the given RPC object. RPC objects are typed with their corresponding RPC interface. This C++ type information is propagated to the corresponding capabilities. For example, when associating an RPC object that implements the LOG-session interface with an entrypoint, the resulting capability is a LOG-session capability.

This capability represents the authority to invoke the functions of the RPC object. On the client side, the client object plays the role of a proxy of the RPC object within the client's component. Thereby, the client becomes able to interact with the RPC object in a natural manner.

Sessions and connections Section 3.2.3 introduced sessions between client and server components as the basic building blocks of system composition. At the server side each session is represented by an RPC object that implements the session interface. At the client side, an open session is represented by a *connection* object. The connection object encapsulates the session arguments and also represents a client object to interact with the session.

As depicted in Figure 20, capabilities are associated with types on all levels above the IPC library. Because the IPC library is solely used by the RPC stub code but not at the framework's API level, capabilities appear as being C++ type safe, even across component boundaries. Each RPC interface implicitly defines a corresponding capability type. Figure 21 shows the inheritance graph of Genode's most fundamental capability types.

Server-side class structure Figure 22 gives an overview of the C++ classes that are involved at the server side of the RPC mechanism. As described in Section 3.1.3, each entrypoint maintains a so-called object pool. The object pool contains references to RPC objects associated with the entrypoint. When receiving an RPC request along with

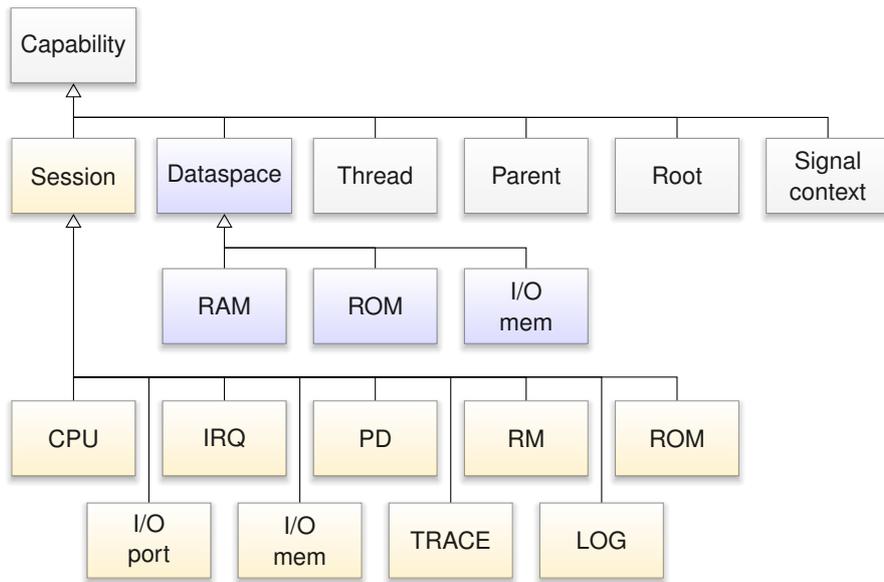


Figure 21: Fundamental capability types

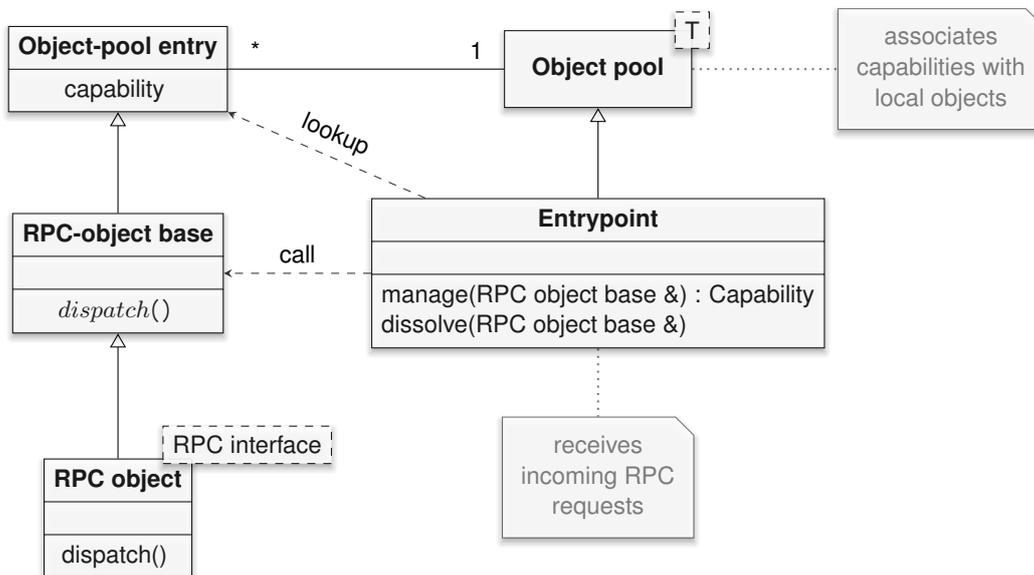


Figure 22: Server-side structure of the RPC mechanism

the local name of the invoked object identity, the entrypoint uses the object pool to lookup the corresponding RPC object. As seen in the figure, the RPC object is a class template parametrized with its RPC interface. When instantiated, the dispatch function is generated by the C++ compiler according to the RPC interface.

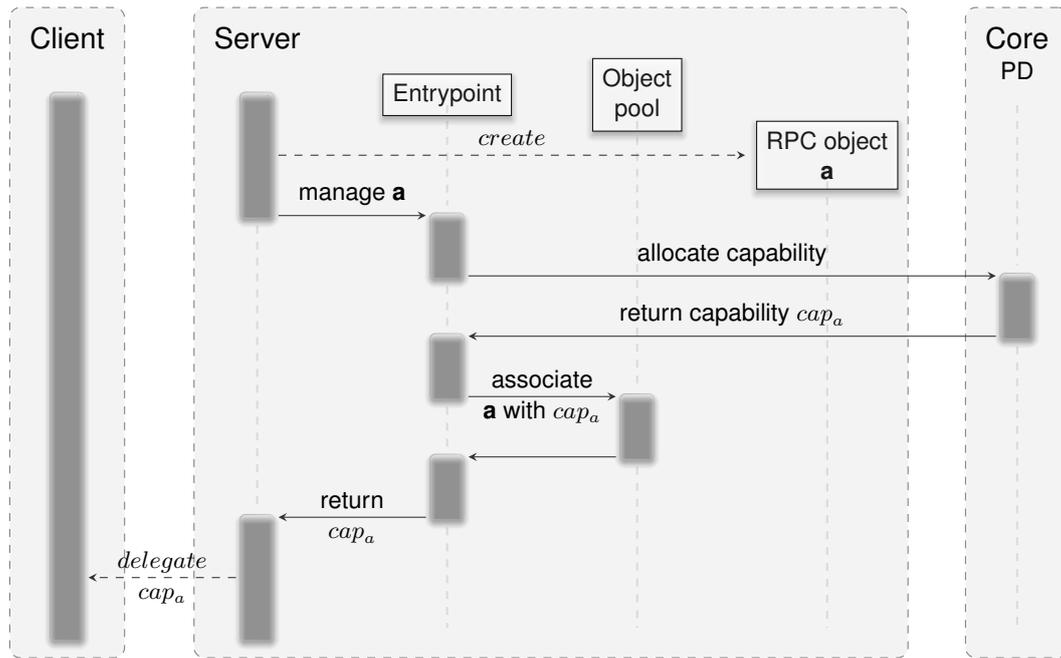


Figure 23: Creation of a new RPC object

RPC-object creation Figure 23 shows the procedure of creating a new RPC object. The server component has already created an entrypoint, which, in turn, created its corresponding object pool.

1. The server component creates an instance of an RPC object. “RPC object” denotes an object that inherits the RPC object class template typed with the RPC interface and that implements the virtual functions of this interface. By inheriting the RPC object class template, it gets equipped with a dispatch function for the given RPC interface.

Note that a single entrypoint can be used to manage any number of RPC objects of arbitrary types.

2. The server component associates the RPC object with the entrypoint by calling the entrypoint’s *manage* function with the RPC object as argument. The entrypoint responds to this call by allocating a new object identity using a session to core’s PD service (Section 3.4.4). For allocating the new object identity, the entrypoint specifies the untyped capability of its IPC server as argument. Core’s PD service responds to the request by instructing the kernel to create a new object identity associated with the untyped capability. Thereby, the kernel creates a new capability that is derived from the untyped capability. When invoked, the derived capability refers to the same IPC server as the original untyped capability. But it

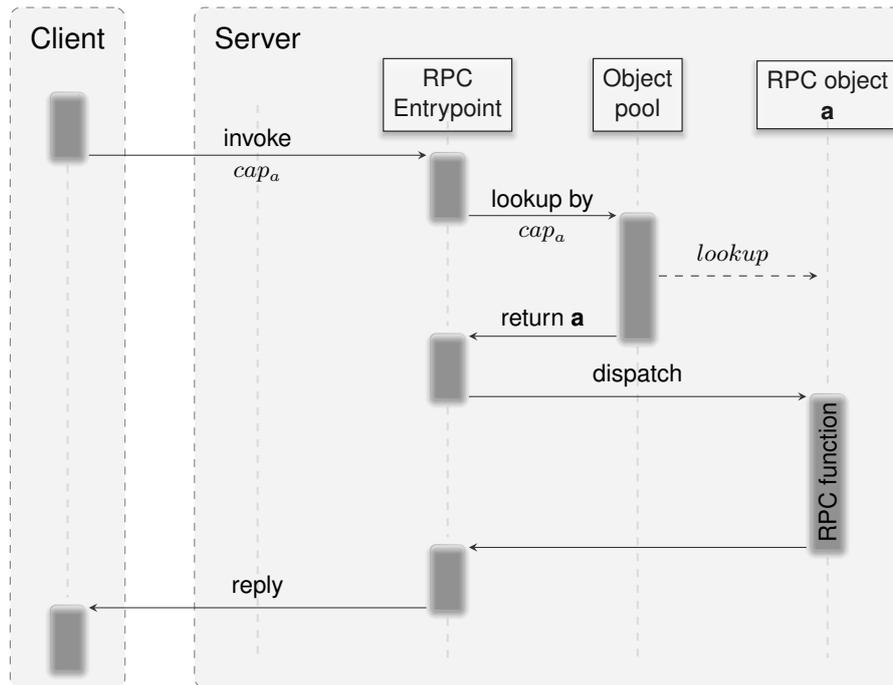


Figure 24: Invocation of an RPC object

represents a distinct object identity. The IPC server retrieves the local name of this object identity when called via the derived capability. The entrypoint stores the association of the derived capability with the RPC object in the object pool.

3. The entrypoint hands out the derived capability as return value of the manage function. At this step, the derived capability is converted into a typed capability with its type corresponding to the type of the RPC object that was specified as argument. This way, the link between the types of the RPC object and the corresponding capability is preserved at the C++ language level.
4. The server delegates the capability to another component, e. g., as payload of a remote procedure call. At this point, the client receives the authority to call the RPC object.

RPC-object invocation Figure 24 shows the flow of execution when a client calls an RPC object by invoking a capability.

1. The client invokes the given capability using an instance of an RPC client object, which uses the IPC library to invoke the kernel's IPC mechanism. The kernel delivers the request to the IPC server that belongs to the invoked capability and

- wakes up the corresponding endpoint. On reception of the request, the endpoint obtains the local name of the invoked object identity.
2. The endpoint uses the local name of the invoked object identity as a key into its object pool to look up the matching RPC object. If the lookup fails, the endpoint replies with an error.
 3. If the matching RPC object was found, the endpoint calls the RPC object's dispatch method. This method is implemented by the server-side stub code. It converts the content of the receive buffer of the IPC server to a method call. I.e., it obtains the opcode of the RPC function from the receive buffer to decide which method to call, and supplies the arguments according to the definition in the RPC interface.
 4. On the return of the RPC function, the RPC stub code populates the send buffer of the IPC server with the function results and invokes the kernel's reply operation via the IPC library. Thereby, the endpoint becomes ready to serve the next request.
 5. When delivering the reply to the client, the kernel resumes the execution of the client, which can pick up the results of the RPC call.

3.6.2. Asynchronous notifications

The synchronous RPC mechanism described in the previous section is not sufficient to cover all forms of inter-component interactions. It shows its limitations in the following situations.

Waiting for multiple conditions

In principle, the RPC mechanism can be used by an RPC client to block for a condition at a server. For example, a timer server could provide a blocking sleep function that, when called by a client, blocks the client for a certain amount of time. However, if the client wanted to respond to multiple conditions such as a timeout, incoming user input, and network activity, it would need to spawn one thread for each condition where each thread would block for a different condition. If one condition triggers, the respective thread would resume its execution and respond to the condition. However, because all threads could potentially be woken up independently from each other – as their execution depends only on their respective condition – they need to synchronize access to shared state. Consequently, components that need to respond to multiple conditions would not only waste threads but also suffer from synchronization overhead.

At the server side, the approach of blocking RPC calls is equally bad in the presence of multiple clients. For example, a timer service with the above outlined blocking interface would need to spawn one thread per client.

Signaling events to untrusted parties

With merely synchronous RPC, a server cannot deliver sporadic events to its clients. If the server wanted to inform one of its clients about such an event, it would need to act as a client itself by performing an RPC call to its own client. However, by performing an RPC call, the caller passes the control of execution to the callee. In the case of a server that serves multiple clients, it would put the availability of the server at the discretion of all its clients, which is unacceptable.

A similar situation is the interplay between a parent and a child where the parent does not trust its child but still wishes to propagate sporadic events to the child.

The solution to those problems is the use of asynchronous notifications, also named signals. Figure 25 shows the interplay between two components. The component labeled as signal handler responds to potentially many external conditions propagated as signals. The component labeled as signal producer triggers a condition. Note that both can be arbitrary components.

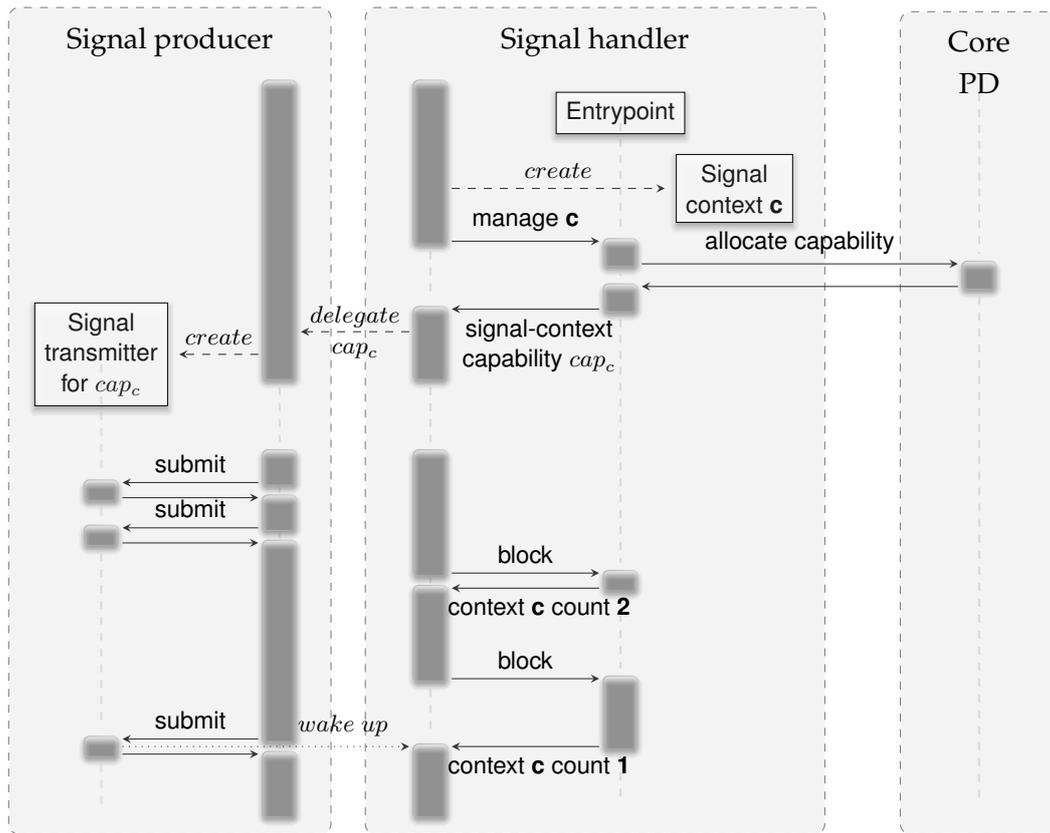


Figure 25: Interplay between signal producer and signal handler

Signal-context creation and delegation The upper part of Figure 25 depicts the steps needed by a signal handler to become able to receive asynchronous notifications.

1. Each Genode component is equipped with at least one initial entrypoint that responds to incoming RPC requests as well as asynchronous notifications. Similar to how it can handle requests for an arbitrary number of RPC objects, it can receive signals from many different sources. Within the signal-handler component, each source is represented as a so-called *signal context*. A component that needs to respond to multiple conditions creates one signal context for each condition. In the figure, a signal context “c” is created.
2. The signal-handler component associates the signal context with its entrypoint via the `manage` method. Analogous to the way how RPC objects are associated with entrypoints, the `manage` method returns a capability for the signal context. Under the hood, the entrypoint uses core’s PD service to create this kind of capability.

3. As for regular capabilities, a signal-context capability can be delegated to other components. Thereby, the authority to trigger signals for the associated context is delegated.

Triggering signals The lower part of Figure 25 illustrates the use of a signal-context capability by the signal producer.

1. Now in possession of the signal-context capability, the signal producer creates a so-called *signal transmitter* for the capability. The signal transmitter can be used to trigger a signal by calling the *submit* method. This method returns immediately. In contrast to a remote procedure call, the submission of a signal is a fire-and-forget operation.
2. At the time when the signal producer submitted the first signal, the signal handler is not yet ready to handle them. It is still busy with other things. Once the signal handler becomes ready to receive a new signal, the pending signal is delivered, which triggers the execution of the corresponding signal-handler method. Note that signals are not buffered. If signals are triggered at a high rate, multiple signals may result in only a single execution of the signal handler. For this reason, the handler cannot infer the number of events from the number of signal-handler invocations. In situations where such information is needed, the signal handler must retrieve it via another mechanism such as an RPC call to query the most current status of the server that produced the signals.
3. After handling the first batch of signals, the signal handler component blocks and becomes ready for another signal or RPC request. This time, no signals are immediately pending. After a while, however, the signal producer submits another signal, which eventually triggers another execution of the signal handler.

In contrast to remote procedure calls, signals carry no payload. If signals carried any payload, this payload would need to be buffered somewhere. Regardless of where this information is buffered, the buffer could overrun if signals are submitted at a higher rate than handled. There might be two approaches to deal with this situation. The first option would be to drop the payload once the buffer overruns, which would make the mechanism indeterministic, which is hardly desirable. The second option would be to sacrifice the fire-and-forget semantics at the producer side, blocking the producer when the buffer is full. However, this approach would put the liveliness of the producer at the whim of the signal handler. Consequently, signals are void of any payload.

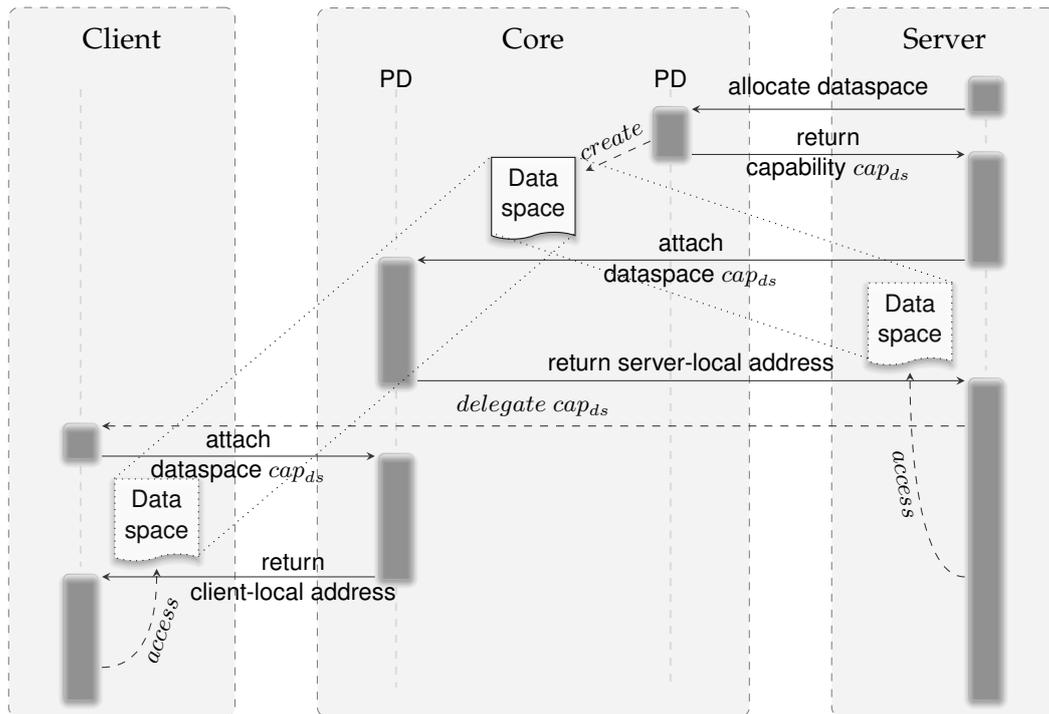


Figure 26: Establishing shared memory between client and server. The server interacts with core's PD service. Both client and server interact with the region maps of their respective PD sessions at core.

3.6.3. Shared memory

By sharing memory between components, large amounts of information can be propagated across protection-domain boundaries without the active involvement of the kernel.

Sharing memory between components raises a number of questions. First, Section 3.3 explained that physical memory resources must be explicitly assigned to components either by their respective parents or by the means of resource trading. This raises the question of which component is bound to pay for the memory shared between multiple components. Second, unlike traditional operating systems where different programs can refer to globally visible files and thereby establish shared memory by mapping a prior-agreed file into their respective virtual memory spaces, Genode does not have a global name space. How do components refer to the to-be-shared piece of memory? Figure 26 answers these questions showing the sequence of shared-memory establishment between a server and its client. The diagram depicts a client, core, and a server. The notion of a client-server relationship is intrinsic for the shared-memory mechanism. When establishing shared memory between components, the component's roles as client and server must be clearly defined.

1. The server interacts with core's PD service to allocate a new RAM dataspace. Because the server uses its own PD session for that allocation, the dataspace is paid for by the server. At first glance, this seems contradictory to the principle that clients should have to pay for using services as discussed in Section 3.3.2. However, this is not the case. By establishing the client-server relationship, the client has transferred a budget of RAM to the server via the session-quota mechanism. So the client already paid for the memory. Still, it is the server's responsibility to limit the size of the allocation to the client's session quota.

Because the server allocates the dataspace, it is the owner of the dataspace. Hence, the lifetime of the dataspace is controlled by the server.

Core's PD service returns a dataspace capability as the result of the allocation.

2. The server makes the content of the dataspace visible in its virtual address space by attaching the dataspace within the region map of its PD session. The server refers to the dataspace via the dataspace capability as returned from the prior allocation. When attaching the dataspace to the server's region map, core's PD service maps the dataspace content at a suitable virtual-address range that is not occupied with existing mappings and returns the base address of the occupied range to the server. Using this base address and the known dataspace size, the server can safely access the dataspace content by reading from or writing to its virtual memory.
3. The server delegates the authority to use the dataspace to the client. This delegation can happen in different ways, e. g., the client could request the dataspace capability via an RPC function at the server. But the delegation could also involve further components that transitively delegate the dataspace capability. Therefore, the delegation operation is depicted as a dashed line.
4. Once the client has obtained the dataspace capability, it can use the region map of its own PD session to make the dataspace content visible in its address space. Note that even though both client and server use core's PD service, each component uses a different session. Analogous to the server, the client receives a client-local address within its virtual address space as the result of the attach operation.
5. After the client has attached the dataspace within its region map, both client and server can access the shared memory using their respective virtual addresses.

In contrast to the server, the client is not in control over the lifetime of the dataspace. In principle, the server, as the owner of the dataspace, could free the dataspace at its PD session at any time and thereby revoke the corresponding memory mappings in all components that attached the dataspace. The client has to trust the server with respect to its liveness, which is consistent with the discussion in Section 3.2.4. A well-behaving server should tie the lifetime of a shared-memory dataspace to the lifetime of

the client session. When the server frees the dataspace at its PD session, core implicitly detaches the dataspace from all region maps. Thereby the dataspace will become inaccessible to the client.

3.6.4. Asynchronous state propagation

In many cases, the mere information that a signal occurred is insufficient to handle the signal in a meaningful manner. For example, a component that registers a timeout handler at a timer server will eventually receive a timeout. But in order to handle the timeout properly, it needs to know the actual time. The time could not be delivered along with the timeout because signals cannot carry any payload. But the timeout handler may issue a subsequent RPC call to the timer server for requesting the time.

Another example of this combination of asynchronous notifications and remote procedure calls is the resource-balancing protocol described in Section 3.3.4.

3.6.5. Synchronous bulk transfer

The synchronous RPC mechanism described in Section 3.6.1 enables components to exchange information via a kernel operation. In contrast to shared memory, the kernel plays an active role by copying information (and delegating capabilities) between the communication partners. Most kernels impose a restriction onto the maximum message size. To comply with all kernels supported by Genode, RPC messages must not exceed a size of 1 KiB. In principle, larger payloads could be transferred as a sequence of RPCs. But since each RPC implies the costs of two context switches, this approach is not suitable for transferring large bulks of data. But by combining synchronous RPC with shared memory, these costs can be mitigated.

Figure 27 shows the procedure of transferring large bulk data using shared memory as a communication buffer while using synchronous RPCs for arbitrating the use of the buffer. The upper half of the figure depicts the setup phase that needs to be performed only once. The lower half exemplifies an operation where the client transfers a large amount of data to the server, which processes the data before transferring a large amount of data back to the client.

1. At session-creation time, the server allocates the dataspace, which represents the designated communication buffer. The steps resemble those described in Section 3.6.3. The server uses session quota provided by the client for the allocation. This way, the client is able to aid the dimensioning of the dataspace by supplying an appropriate amount of session quota to the server. Since the server performed the allocation, the server is in control of the lifetime of the dataspace.
2. After the client established a session to the server, it initially queries the dataspace capability from the server using a synchronous RPC and attaches the dataspace

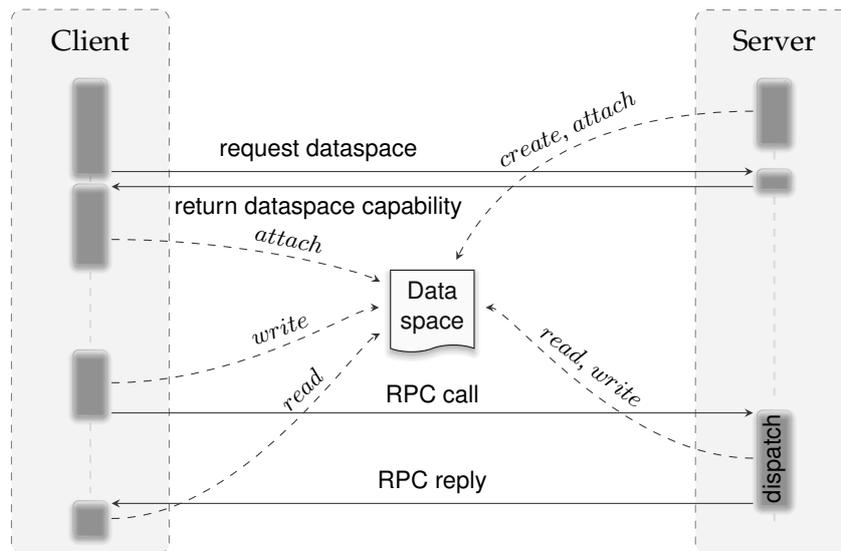


Figure 27: Transferring bulk data by combining synchronous RPC with shared memory

- to its own address space. After this step, both client and server can read and write the shared communication buffer.
3. Initially the client plays the role of the user of the dataspace. The client writes the bulk data into the dataspace. Naturally, the maximum amount of data is limited by the dataspace size.
 4. The client performs an RPC call to the server. Thereby, it hands over the role of the dataspace user to the server. Note that this handover is not enforced. The client's PD retains the right to access the dataspace, i. e., by another thread running in the same PD.
 5. On reception of the RPC, the server becomes active. It reads and processes the bulk data, and writes its results to the dataspace. The server must not assume to be the exclusive user of the dataspace. A misbehaving client may change the buffer content at any time. Therefore, the server must take appropriate precautions. In particular, if the data must be validated at the server side, the server must copy the data from the shared dataspace to a private buffer before validating and using it.
 6. Once the server has finished processing the data and written the results to the dataspace, it replies to the RPC. Thereby, it hands back the role of the user of the dataspace to the client.
 7. The client resumes its execution with the return of the RPC call, and can read the result of the server-side operation from the dataspace.

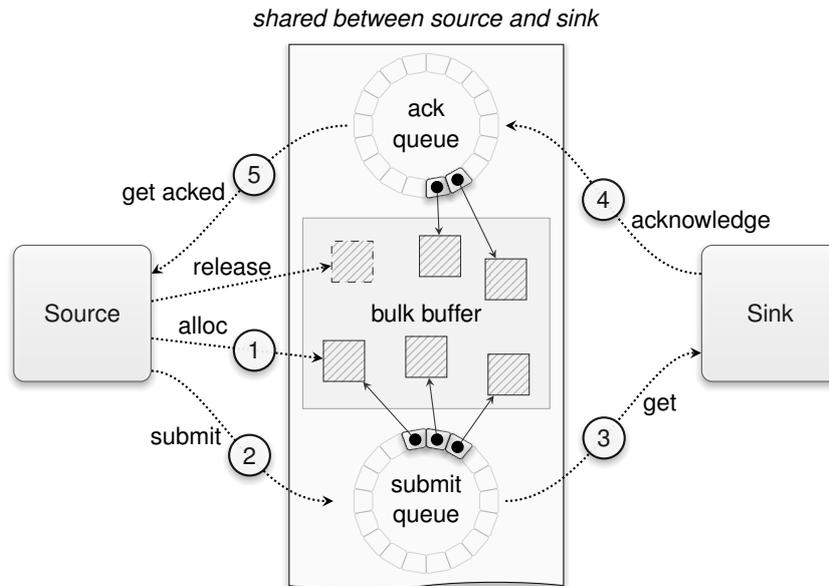


Figure 28: Life cycle of a data packet transmitted over the packet-stream interface

The RPC call may be used for carrying control information. For example, the client may provide the amount of data to process, or the server may provide the amount of data produced.

3.6.6. Asynchronous bulk transfer - packet streams

The packet-stream interface complements the facilities for the synchronous data transfer described in Sections 3.6.1 and 3.6.5 with a mechanism that carries payload over a shared memory block and employs an asynchronous data-flow protocol. It is designed for large bulk payloads such as network traffic, block-device data, video frames, and USB URB payloads.

As illustrated in Figure 28, the communication buffer consists of three parts: a submit queue, an acknowledgement queue, and a bulk buffer. The submit queue contains packets generated by the source to be processed by the sink. The acknowledgement queue contains packets that are processed and acknowledged by the sink. The bulk buffer contains the actual payload. The assignment of packets to bulk-buffer regions is performed by the source.

A packet is represented by a packet descriptor that refers to a portion of the bulk buffer and contains additional control information. Such control information may include an opcode and further arguments interpreted at the sink to perform an operation on the supplied packet data. Either the source or the sink is in charge of handling a given packet at a given time. At the points 1, 2, and 5, the packet is owned by the

source. At the points 3 and 4, the packet is owned by the sink. Putting a packet descriptor in the submit or acknowledgement queue represents a handover of responsibility. The life cycle of a single packet looks as follows:

1. The source allocates a region of the bulk buffer for storing the packet payload (*packet alloc*). It then requests the local pointer to the payload (*packet content*) and fills the packet with data.
2. The source submits the packet to the submit queue (*submit packet*).
3. The sink requests a packet from the submit queue (*get packet*), determines the local pointer to the payload (*packet content*), and processes the contained data.
4. After having finished the processing of the packet, the sink acknowledges the packet (*acknowledge packet*), placing the packet into the acknowledgement queue.
5. The source reads the packet from the acknowledgement queue and releases the packet (*release packet*). Thereby, the region of the bulk buffer that was used by the packet becomes marked as free.

This protocol has four corner cases that are handled by signals:

Submit queue is full when the source is trying to submit a new packet. In this case, the source blocks and waits for the sink to remove packets from the submit queue. If the sink observes such a condition (when it attempts to get a packet from a full submit queue), it delivers a *ready-to-submit* signal to wake up the source.

Submit queue is empty when the sink tries to obtain a packet from an empty submit queue, it may block. If the source places a packet into an empty submit queue, it delivers a *packet-avail* signal to wake up the sink.

Acknowledgement queue is full when the sink tries to acknowledge a packet at a saturated acknowledgement queue, the sink needs to wait until the source removes an acknowledged packet from the acknowledgement queue. The source notifies the sink about this condition by delivering a *ready-to-ack* signal. On reception of the signal, the sink wakes up and proceeds to submit packets into the acknowledgement queue.

Acknowledgement queue is empty when the source tries to obtain an acknowledged packet (*get acked packet*) from an empty acknowledgement queue. In this case, the source may block until the sink places another acknowledged packet into the empty acknowledgement queue and delivers an *ack-avail* signal.

If bidirectional data exchange between a client and a server is desired, there are two approaches:

One stream of operations If data transfers in either direction are triggered by the client only, a single packet stream where the client acts as the source and the server represents the sink can accommodate transfers in both directions. For example, the block session interface (Section 4.5.8) represents read and write requests as packet descriptors. The allocation of the operation's read or write buffer within the bulk buffer is performed by the client, being the source of the stream of operations. For write operations, the client populates the write buffer with the to-be-written information before submitting the packet. When the server processes the incoming packets, it distinguishes the read and write operations using the control information given in the packet descriptor. For a write operation, it processes the information contained in the packet. For a read operation, it populates the packet with new information before acknowledging the packet.

Two streams of data If data transfers in both directions can be triggered independently from client and server, two packet streams can be used. For example, the NIC session interface (Section 4.5.11) uses one packet stream for ingoing and one packet stream for outgoing network traffic. For outgoing traffic, the client plays the role of the source. For incoming traffic, the server (such as a NIC driver) is the source.

4. Components

The architecture introduced in Chapter 3 clears the way to compose sophisticated systems out of many building blocks. Each building block is represented by an individual component that resides in a dedicated protection domain and interacts with other components in a well-defined manner. Those components do not merely represent applications but all typical operating-system functionalities.

Components can come in a large variety of shape and form. Compared to a monolithic operating-system kernel, a component-based operating system challenges the system designer by enlarging the design space with the decision of the functional scope of each component and thereby the granularity of componentization. This decision depends on several factors:

Security The smaller a component, the lower the risk for bugs and vulnerabilities. The more rigid a component's interfaces, the smaller its attack surface becomes. Hence, the security of a complex system function can potentially be vastly improved by splitting it into a low-complexity component that encapsulates the security-critical part and a high-complexity component that is uncritical for security.

Performance The split of functionality into multiple components introduces inter-component communication and thereby context-switch overhead. If a functionality is known to be performance critical, such a split should clearly be motivated by a benefit for security.

Reusability Componentization can be pursued to improve reusability while sometimes disregarding performance considerations at the same time. However, reusability can also be achieved by moving functionality into libraries that can easily be reused by linking them directly against library-using components. By using a dynamic linker, linking can even happen at run time, which yields the same flexibility as the use of multiple distinct components. Therefore, the split of functionality into multiple components for the sole sake of modularization has to be questioned.

Sections 4.1, 4.2, 4.3, and 4.4 aid the navigation within the componentization design space by discussing the different roles a component can play within a Genode system. This can be the role of a device driver, protocol stack, resource multiplexer, runtime environment, and that of an application. By distinguishing those roles, it becomes possible to assess the possible security implications of each individual component.

The versatility of a component-based system does not come from the existence of many components alone. Even more important is the composability of components. Components can be combined only if their interfaces match. To maximize composability, the number of interfaces throughout the system should be as low as possible, and

all interfaces should be largely orthogonal to each other. Section 4.5 reviews Genode's common session interfaces.

Components can be used in different ways depending on their configuration and their position within the component tree. Section 4.6 explains how a component obtains and processes its configuration. Section 4.7 discusses the most prominent options of composing components.

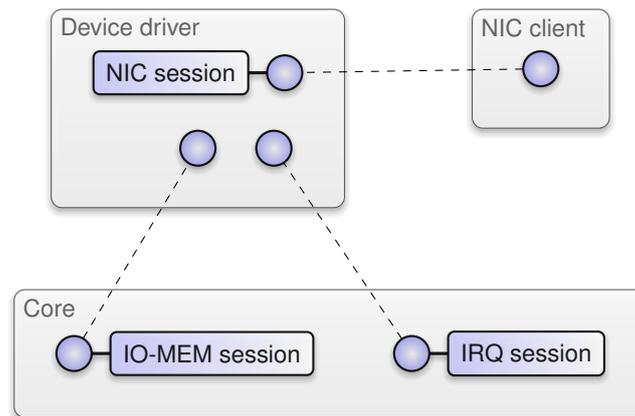


Figure 29: A network device driver provides a NIC service to a single client and uses core’s IO-MEM and IRQ services to interact with the physical network adaptor.

4.1. Device drivers

A device driver translates a device interface to a Genode session interface. Figure 29 illustrates the typical role of a device driver.

The device interface is defined by the device vendor and typically comprises the driving of state machines of the device, the notification of device-related events via interrupts, and the means to transfer data from and to the device. A device-driver component accesses the device interface via sessions to the core services IO_MEM, IO_PORT, and IRQ as described in Section 3.4.7.

In general, a physical device cannot safely be driven by multiple users at the same time. If multiple users accessed one device concurrently, the device state would eventually become inconsistent. A device driver should not attempt to multiplex a hardware device. Instead, to keep its complexity low, it should act as a server that serves only a single client per physical device. Whereas a device driver for a simple device usually accepts only one client, a device driver for a complex device with multiple sub devices (such as a USB driver) may hand out each sub device to a different client.

A device driver should be largely void of built-in policy. If it merely translates the interface of a single device to a session interface, there is not much room for policy anyway. If, however, a device driver hands out multiple sub devices to different clients, the assignment of sub devices to clients must be subjected to a policy. In this case, the device driver should obtain policy information from its configuration as provided by the driver’s parent.

4.1.1. Platform driver

There are three problems that are fundamentally important for running an operating system on modern hardware but that lie outside the scope of an ordinary device driver because they affect the platform as a whole rather than a single device. Those problems are the enumeration of devices, the discovery of interrupt routing, and the initial setup of the platform.

Problem 1: Device enumeration Modern hardware platforms are rather complex and vary a lot. For example, the devices attached to the PCI bus of a PC are usually not known at the build time of the system but need to be discovered at run time. Technically, each individual device driver could probe its respective device at the PCI bus. But in the presence of multiple drivers, this approach would hardly work. First, the configuration interface of the PCI bus is a device itself. The concurrent access to the PCI configuration interface by multiple drivers would ultimately yield undefined behaviour. Second, for being able to interact directly with the PCI configuration interface, each driver would need to carry with it the functionality to interact with PCI.

Problem 2: Interrupt routing On PC platforms with multiple processors, the use of legacy interrupts as provided by the Intel 8259 programmable interrupt controller (PIC) is not suitable because there is no way to express the assignment of interrupts to CPUs. To overcome the limitations of the PIC, Intel introduced the Advanced Programmable Interrupt Controller (APIC). The APIC, however, comes with a different name space for interrupt numbers, which creates an inconsistency between the numbers provided by the PCI configuration (interrupt lines) and interrupt numbers as understood by the APIC. The assignment of legacy interrupts to APIC interrupts is provided by the Advanced Configuration and Power Interface (ACPI) tables. Consequently, in order to support multi-processor PC platforms, the operating system needs to interpret those tables. Within a component-based system, we need to answer the question of which component is responsible to interpret the ACPI tables and how this information is applied to individual device drivers.

Problem 3: Initial hardware setup In embedded systems, the interaction of the SoC (system on chip) with its surrounding peripheral hardware is often not fixed in hardware but rather a configuration issue. For example, the power supply and clocks of certain peripherals may be enabled by speaking an I2C protocol with a separate power-management chip. Also, the direction and polarity of the general-purpose I/O pins depends largely on the way how the SoC is used. Naturally, such hardware setup steps could be performed by the kernel. But this would require the kernel to become aware of potentially complex platform intrinsics.

Central platform driver The natural solution to these problems is the introduction of a so-called platform driver, which encapsulates the peculiarities outlined above. On PC platforms, the role of the platform driver is executed by the ACPI driver. The ACPI driver provides an interface to the PCI bus in the form of a PCI service. Device drivers obtain the information about PCI devices by creating a PCI session at the ACPI driver. Furthermore, the ACPI driver provides an IRQ service that transparently applies the interrupt routing based on the information provided by the ACPI tables. Furthermore, the ACPI driver provides the means to allocate DMA buffers, which is further explained in Section 4.1.3.

On ARM platforms, the corresponding component is named platform driver and provides a so-called platform service. Because of the large variety of ARM-based SoCs, the session interface for this service differs from platform to platform.

4.1.2. Interrupt handling

Most device drivers need to respond to sporadic events produced by the device and propagated to the CPU as interrupts. In Genode, a device-driver component obtains device interrupts via core's IRQ service introduced in Section 3.4.7. On PC platforms, device drivers usually do not use core's IRQ service directly but rather use the IRQ service provided by the platform driver (Section 4.1.1).

4.1.3. Direct memory access (DMA) transactions

Devices that need to transfer large amounts of data usually support a means to issue data transfers from and to the system's physical memory without the active participation of the CPU. Such transfers are called *direct memory access (DMA) transactions*. DMA transactions relieve the CPU from actively copying data between device registers and memory, optimize the throughput of the system bus by the effective use of burst transfers, and may even be used to establish direct data paths between devices. However, the benefits of DMA come at the risk of corrupting the physical memory by misguided DMA transactions. Because those DMA-capable devices can issue bus requests that target the physical memory directly while not involving the CPU altogether, such requests are naturally not subjected to the virtual-memory mechanism implemented in the CPU in the form of a memory-management unit (MMU). Figure 30 illustrates the problem. From the device's point of view, there is just physical memory. Hence, if a driver sets up a DMA transaction, e. g., if a disk driver wants to read a block from the disk, it programs the memory-mapped registers of the device with the address and size of a physical-memory buffer where it expects to receive the data. If the driver lives in a user-level component, as is the case for a Genode-based system, it still needs to know the physical address of the DMA buffer to program the device correctly. Unfortunately, there is nothing to prevent the driver from specifying any physical address to the device. A malicious driver could misuse the device to read and manipulate all

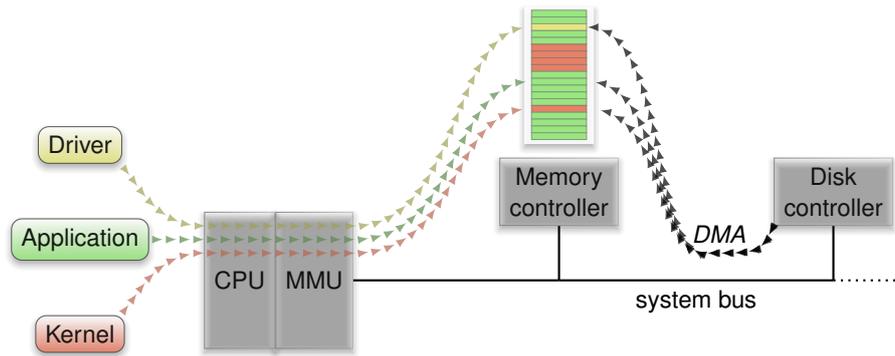


Figure 30: The MMU restricts the access of physical memory pages by different components according to their virtual address spaces. However, direct memory accesses issued by the disk controller are not subjected to the MMU. The disk controller can access the entirety of the physical memory present in the system.

parts of the physical memory, including the kernel. Consequently, device drivers and devices should ideally be trustworthy. However, there are several scenarios where this is ultimately not the case.

Scenario 1: Direct device assignment to virtual machines When hosting virtual machines as Genode components, the direct assignment of a physical device such as a USB controller, a GPU, or a dedicated network card to the guest OS running in the virtual machine can be useful in two ways. First, if the guest OS is the sole user of the device, direct assignment of the device maximizes the I/O performance of the guest OS using the device. Second, the guest OS may be equipped with a proprietary device driver that is not present as a Genode component otherwise. In this case, the guest OS may be used as a runtime that executes the device driver, and thus, provides a driver interface to the Genode world. In both cases the guest OS should not be considered as trustworthy. On the contrary, it bears the risk of subverting the isolation between components. A misbehaving guest OS could issue DMA requests referring to the physical memory used by other components or even the kernel, and thereby break out of its virtual machine.

Scenario 2: Firmware-driven attacks Modern peripherals such as wireless LAN adaptors, network cards, or GPUs employ firmware executed on the peripheral device. This firmware is executed on a microcontroller on the device, and is thereby not subjected to the policy of the normal operating system. Such firmware may either be built-in by the device vendor, or is loaded by the device driver at initialization time of the device. In both cases, the firmware tends to be a black box that remains obscure with the exception of the device vendor. Hidden functionality or vulnerabilities might be

present in it. By the means of DMA transactions, such firmware has unlimited access to the system. For example, a back door implemented in the firmware of a network adaptor could look for special network packets to activate and control arbitrary spyware. Because malware embedded in the firmware of the device can neither be detected nor controlled by the operating system, both monolithic and microkernel-based operating systems are powerless against such attacks.

Scenario 3: Bus-level attacks The previous examples misuse a DMA-capable device as a proxy to drive an attack. However, the system bus can be attacked directly with no hardware tinkering at all. There are ready-to-exploit interfaces that are featured on most PC systems. For example, most laptops come with PCMCIA / Express-Card slots, which allow expansion cards to access the system bus. Furthermore, serial bus interfaces, e. g., IEEE 1394 (Firewire), enable connected devices to indirectly access the system bus via the peripheral bus controller. If the bus controller allows the device to issue direct system bus requests by default, a connected device becomes able to gain control over the whole system.

DMA transactions in component-based systems Direct memory access (DMA) of devices looks like the Achilles heel of component-based operating systems. The most compelling argument in favor of componentization is that by encapsulating each system component within a dedicated user-level address space, the system as a whole becomes more robust and secure compared to a monolithic operating-system kernel. In the event that one component fails due to a bug or an attack, other components remain unaffected. The prime example for such buggy components are, however, device drivers. By empirical evidence, those remain the most prominent trouble makers in today's operating systems, which suggests that the DMA loophole renders the approach of component-based systems largely ineffective. However, there are three counter arguments to this observation.

First, by encapsulating each driver in a dedicated address space, classes of bugs that are unrelated to DMA remain confined in the driver component. In practice most driver-related problems stem from issues like memory leaks, synchronization problems, deadlocks, flawed driver logic, wrong state machines, or incorrect device-initialization sequences. For those classes of problems, the benefits of isolating the driver in a dedicated component still apply.

Second, executing a driver largely isolated from other operating-system code minimizes the attack surface onto the driver. If the driver interface is rigidly small and well-defined, it is hard to compromise the driver by exploiting its interface.

Third, modern PC hardware has closed the DMA loophole by incorporating so-called IOMMUs into the system. As depicted in Figure 31, the IOMMU sits between the physical memory and the system bus where the devices are attached to. So each DMA request has to go through the IOMMU, which is not only able to arbitrate the access of DMA

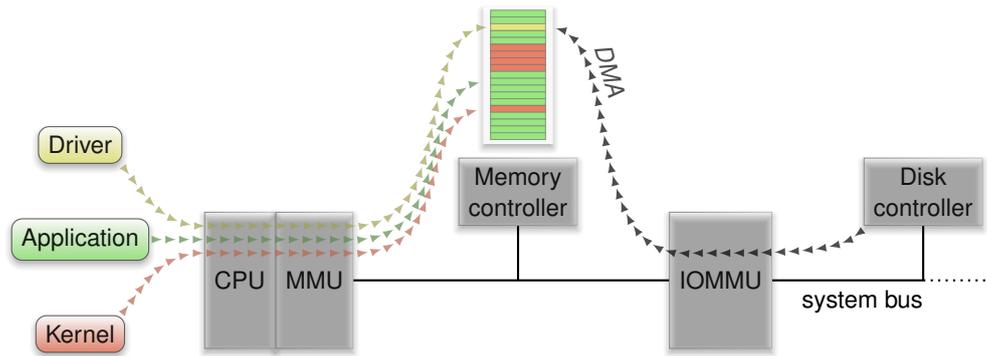


Figure 31: An IOMMU arbitrates and virtualizes DMA accesses issued by a device to the RAM. Only if a valid IOMMU mapping exists for a given DMA access, the memory access is performed.

requests to the RAM but is also able to virtualize the address space per device. Similar to how an MMU confines each process running on the CPU within a distinct virtual address space, the IOMMU is able to confine each device within a dedicated virtual address space. To tell the different devices apart, the IOMMU uses the PCI device's bus-device-function triplet as unique identification.

With an IOMMU in place, the operating system can effectively limit the scope of actions the given device can execute on the system. I.e., by restricting all accesses originating from a particular PCI device to the DMA buffers used for the communication, the operating system becomes able to detect and prevent any unintended bus accesses initiated by the device.

When executed on the NOVA kernel, Genode subjects all DMA transactions to the IOMMU, if present. Section 7.8.7 discusses the use of IOMMUs in more depth.

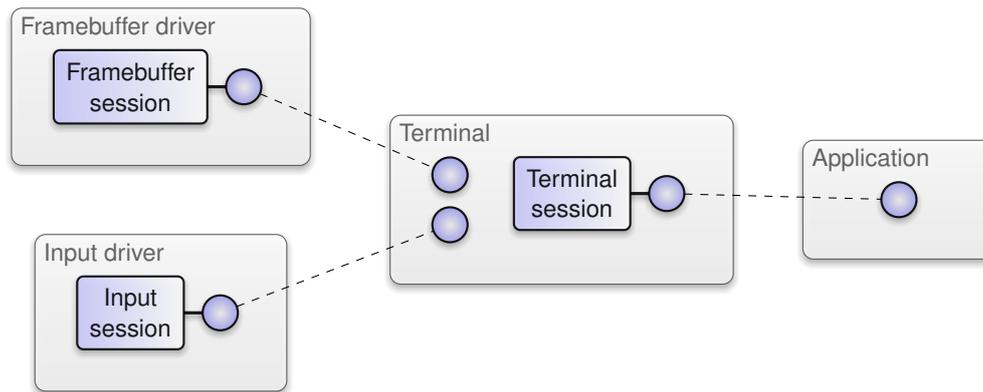


Figure 32: Example of a protocol stack. The terminal provides the translation between the terminal-session interface (on the right) and the driver interfaces (on the left).

4.2. Protocol stacks

A protocol stack *translates* one session interface to another (or the same) session interface. For example, a terminal component may provide a command-line application with a service for obtaining textual user input and for printing text. To implement this service, the terminal uses an input session and a framebuffer session. Figure 32 depicts the relationship between the terminal, its client application, and the used drivers. For realizing the output of a stream of characters on screen, it implements a parser for escape sequences, maintains a state machine for the virtual terminal, and renders the pixel representation of characters onto the framebuffer. For the provisioning of textual user input, it responds to key presses reported by the input session, maintains the state of modifier keys, and applies a keyboard layout to the stream of incoming events. When viewed from the outside of the component, the terminal translates a terminal session to a framebuffer session as well as an input session.

Similar to a device driver, a protocol stack typically serves a single client. In contrast to device drivers, however, protocol stacks are not bound to physical devices. Therefore, a protocol stack can be instantiated any number of times. For example, if multiple terminals are needed, one terminal component could be instantiated per terminal. Because each terminal uses an independent instance of the protocol stack, a bug in the protocol stack of one terminal does not affect any other terminal. However complex the implementation of the protocol stack may be, it is not prone to leaking information to another terminal because it is connected to a single client only. The leakage of information is constrained to interfaces used by the individual instance. Hence, in cases like this, the protocol-stack component is suitable for hosting highly complex untrusted code if such code cannot be avoided.

Note that the example above cannot be generalized for all protocol stacks. There are protocol stacks that are critical for the confidentiality of information. For example, an

in-band encryption component may translate plain-text network traffic to encrypted network traffic designated to be transported over a public network. Even though the component is a protocol stack, it may still be prone to leaking unencrypted information to the public network.

Whereas protocol stacks are not necessarily critical for integrity and confidentiality, they are almost universally critical for availability.

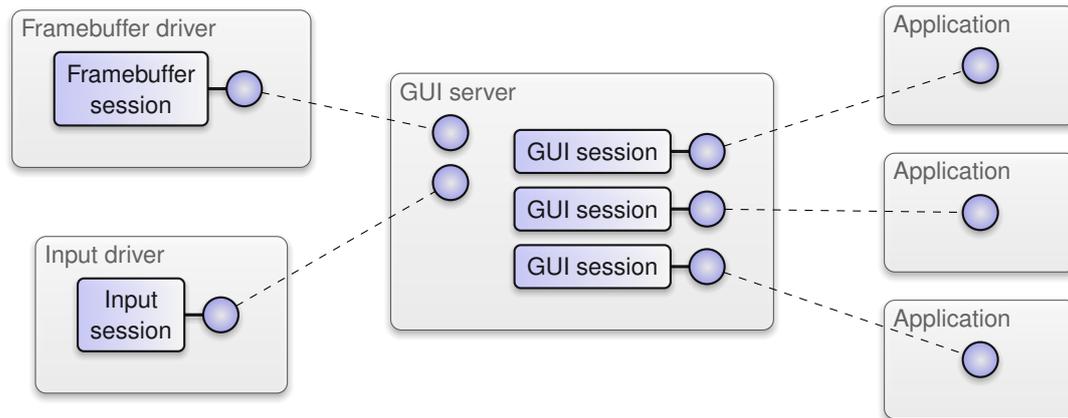


Figure 33: A GUI server multiplexes the physical framebuffer and input devices among multiple applications.

4.3. Resource multiplexers

A resource multiplexer transforms one resource into a number of virtual resources. A resource is typically a session to a device driver. For example, a NIC-switch component may use one NIC session to a NIC driver as uplink and, in turn, provide a NIC service where each session represents a virtual NIC. Another example is a GUI server as depicted in Figure 33, which enables multiple applications to share the same physical framebuffer and input devices by presenting each client in a window or a virtual console.

In contrast to a typical device driver or protocol stack that serves only a single client, a resource multiplexer is shared by potentially many clients. In the presence of untrusted clients besides security-critical clients, a resource multiplexer ultimately becomes a so-called *multi-level* component. This term denotes that the component is cross-cutting the security levels of all its clients. This has the following ramifications.

Covert channels Because the component is a shared resource that is accessed by clients of different security levels, it must maintain the strict isolation between its clients unless explicitly configured otherwise. Hence, the component's client interface as well as the internal structure must be designed to prevent the leakage of information across clients. I.e., two clients must never share the same namespace of server-side objects if such a namespace can be modified by the clients. For example, a window server that hands out global window IDs to its clients is prone to unintended information leakage because one client could observe the allocation of window IDs by another client. The ID allocation could be misused as a covert channel that circumvents security policies. In the same line, a resource multiplexer is prone to timing channels if the operations provided via its client interface depends on the behavior of other clients. For this reason, blocking RPC

calls should be avoided because the duration of a blocking operation may reveal information about the internal state such as the presence of other clients of the resource multiplexer.

Complexity is dangerous As a resource multiplexer is shared by clients of different security levels, the same considerations apply as for the OS kernel: high complexity poses a major risk for bugs. Such bugs may, in turn, result in the unintended flow of information between clients or degrade the quality of service for all clients. Hence, in terms of complexity, resource multiplexers must be as simple as possible.

Denial of service The exposure of a resource multiplexer to untrusted and even malicious clients makes it a potential target for denial-of-service attacks. Some operations provided by the resource multiplexer may require the allocation of memory. For example, a GUI server may need memory for the book keeping of each window created by its clients. If the resource multiplexer performed such allocations from its own memory budget, a malicious client could trigger the exhaustion of server-side memory by creating new windows in an infinite loop. To mitigate this category of problems, a resource multiplexer should perform memory allocations exclusively from client-provided resources, i. e., using the session quota as provided by each client at session-creation time. Section 3.3 describes Genode's resource-trading mechanism in detail. In particular, resource multiplexers should employ heap partitioning as explained in Section 3.3.3.

Avoiding built-in policies A resource multiplexer can be understood as a microkernel for a higher-level resource. Whereas a microkernel multiplexes or arbitrates the CPU and memory between multiple components, a resource multiplexer does the same for sessions. Hence, the principles for constructing microkernels equally apply for resource multiplexers. In the line of those principles, a resource multiplexer should ideally implement sole mechanisms but should be void of built-in policy.

Enforcement of policy Instead of providing a built-in policy, a resource multiplexer obtains policy information from its configuration as supplied by its parent. The resource multiplexer must enforce the given policy. Otherwise, the security policy expressed in the configuration remains ineffective.

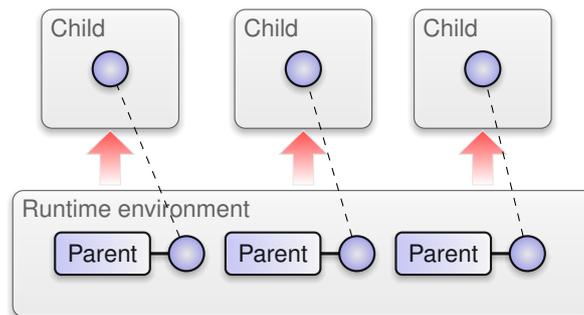


Figure 34: A runtime environment manages multiple child components.

4.4. Runtime environments and applications

The component types discussed in the previous sections have in common that they deliberately lack built-in policy but act according to a policy supplied by their respective parents by the means of configuration. This raises the question where those policies should come from. The answer comes in the form of runtime environments and applications.

A *runtime environment* as depicted in Figure 34 is a component that hosts child components. As explained in the Sections 3.2 and 3.3, it is thereby able to exercise control over its children but is also responsible to manage the children’s resources. A runtime environment controls its children in three ways:

Session routing It is up to the runtime environment to decide how to route session requests originating from a child. The routing of sessions is discussed in Section 3.2.3.

Configuration Each child obtains its configuration from its parent in the form of a ROM session as described in Section 4.6. Using this mechanism, the runtime environment is able to feed policy information to its children. Of course, in order to make the policy effective, the respective child has to interpret and enforce the configuration accordingly.

Lifetime The lifetime of a child ultimately depends on its parent. Hence, a runtime environment can destroy and possibly restart child components at any time.

With regard to the management of child resources, a runtime environment can employ a large variety of policies using two principal approaches:

Quota management Using the resource-trading mechanisms introduced in Section 3.3, the runtime environment can assign resources to each child individually. Moreover, if a child supports the dynamic rebalancing protocol described in Section 3.3.4, the runtime environment may even change those assignments over the lifetime of its children.

Interposing services Because the runtime environment controls the session routing of each child, it is principally able to interpose the child's use of any service including those normally provided by core such as PD (Section 3.4.4), and CPU (Section 3.4.6). The runtime environment may provide a locally implemented version of those session interfaces instead of routing session requests directly towards the core component. Internally, each session of such a local service may create a session to the real core service, thereby effectively wrapping core's sessions. This way, the runtime environment can not only observe the interaction of its child with core services but also implement custom resource-management strategies, for example, sharing one single budget among multiple children.

Canonical examples of runtime environments are the init component that applies a policy according to its configuration, the noux runtime that presents itself as a Unix kernel to its children, a debugger that interposes all core services for the debugging target, or a virtual machine monitor.

A typical *application* is a leaf node in the component tree that merely uses services. In practice, however, the boundary between applications and runtime environments can be blurry. As illustrated in Section 4.7, Genode fosters the internal split of applications into several components, thereby forming *multi-component applications*. From the outside, such a multi-component application appears as a leaf node of the component tree but internally, it employs an additional level of componentization by executing portions of its functionality in separate child components. The primary incentive behind this approach is the sandboxing of untrusted application functionality. For example, a video player may execute the video codec within a separate child component so that a bug in the complex video codec will not compromise the entire video-player application.

4.5. Common session interfaces

The core services described in Section 3.4 principally enable the creation of a recursively structured system. However, their scope is limited to the few low-level resources provided by core, namely processing time, memory, and low-level device resources. Device drivers (Section 4.1) and protocol stacks (Section 4.2) transform those low-level resources into higher-level resources. Analogously to how core's low-level resources are represented by the session interfaces of core's services, higher-level resources are represented by the session interfaces provided by device drivers and protocol stacks. In principle, each device driver could introduce a custom session interface representing the particular device. But as discussed in the introduction of Chapter 4, a low number of orthogonal session interfaces is desirable to maximize the composability of components. This section introduces the common session interfaces that are used throughout Genode.

4.5.1. Read-only memory (ROM)

The ROM session interface makes a piece of data in the form of a dataspace available to the client.

Session creation At session-creation time, the client specifies the name of a ROM module as session argument. One server may hand out different ROM modules depending on the name specified. Once a ROM session has been created, the client can request the capability of the dataspace that contains the ROM module. Using this capability and the region map of the client's PD session, the client can attach the ROM module to its local address space and thereby access the information. The client is expected to merely read the data, hence the name of the interface.

ROM module updates In contrast to the intuitive assumption that read-only data is immutable, ROM modules may mutate during the lifetime of the session. The server may update the content of the ROM module with new versions. However, the server does not do so without the consent of the client. The protocol between client and server consists of the following steps.

1. The client registers a signal handler at the server to indicate that it is interested in receiving updates of the ROM module.
2. If the server has a new version of the ROM module, it does not immediately change the dataspace shared with the client. Instead, it maintains the new version separately and informs the client by submitting a signal to the client's signal handler.

3. The client continues working with the original version of the dataspace. Once it receives the signal from the server, it may decide to update the dataspace by calling the *update* function at the server.
4. The server responds to the update request. If the new version fits into the existing dataspace, the server copies the content of the new version into the existing dataspace and returns this condition with the reply of the update call. Thereby, the ROM session interface employs synchronous bulk transfers as described in Section 3.6.5.
5. The client evaluates the result of the update call. If the new version did fit into the existing dataspace, the update is complete at this point. However, if the new version is larger than the existing dataspace, the client requests a new dataspace from the server.
6. Upon reception of the dataspace request, the server destroys the original dataspace (thereby making it invisible to the client), and returns the new version of the ROM module as a freshly allocated dataspace.
7. The client attaches the new dataspace capability to its local address space to access the new version.

The protocol is designed in such a way that neither the client nor the server need to support updates. A server with no support for updating ROM modules such as core's ROM service simply ignores the registration of a signal handler by a client. A client that is not able to cope with ROM-module updates never requests the dataspace twice.

However, if both client and server support the update protocol, the ROM session interface provides a means to propagate large state changes from the server to the client in a transactional way. In the common case where the new version of a ROM module fits into the same dataspace as the old version, the update does not require any memory mappings to be changed.

Use cases The ROM session interface is used wherever data shall be accessed in a memory mapped fashion.

- Boot time data comes in the form of the ROM sessions provided by core's ROM service. On some kernels, core exports kernel-specific information such as the kernel version in the form of special ROM modules.
- If an executable binary is provided as a ROM module, the binary's text segment can be attached directly to the address space of a new process (Section 3.5). So multiple instances of the same component effectively share the same text segment. The same holds true for shared libraries. For this reason, executable binaries and shared libraries are requested in the form of ROM sessions.

- Components obtain their configuration by requesting a ROM session for the “config” ROM module at their respective parent (Section 4.6). This way, configuration information can be propagated using a simple interface with no need for a file system. Furthermore, the update mechanism allows the parent to dynamically change the configuration of a component during its lifetime.
- As described in Section 4.7.5, multi-component applications may obtain data models in the form of ROM sessions. In such scenarios, the ROM session’s update mechanism is used to propagate model updates in a transactional way.

4.5.2. Report

The report session interface allows a client to report its internal state to the outside using synchronous bulk transfers (Section 3.6.5).

Session creation At session-creation time, the client specifies a label and a buffer size. The label aids the routing of the session request but may also be used to select a policy at the report server. The buffer size determines the size of the dataspace shared between the report server and its client.

Use cases

- Components may use report sessions to export their internal state for monitoring purposes or for propagating exceptional events.
- Device drivers may report information about detected devices or other resources. For example, a bus driver may report a list of devices attached on the bus, or a wireless driver may report the list of available networks.
- In multi-component applications, components that provide data models to other components may use the report-session interface to propagate model updates.

4.5.3. Terminal and UART

The terminal session interface provides a bi-directional communication channel between client and server using synchronous bulk transfers (Section 3.6.5). It is primarily meant to be used for textual interfaces but may also be used to transfer other serial streams of data.

The interface uses the two RPC functions *read* and *write* to arbitrate the access to a shared-memory communication buffer between client and server as described in Section 3.6.5. The read function never blocks. When called, it copies new input into the communication buffer and returns the number of new characters. If there is no new input, it returns 0. To avoid the need to poll for new input at the client side, the client can

register a signal handler that gets notified upon the arrival of new input. The write function takes the number of to-be-written characters as argument. The server responds to this function by processing the specified amount of characters from the communication buffer.

Besides the actual read and write operations, the terminal supports the querying of the number of new available input events (without reading it) and the terminal size in rows and columns.

Session creation At session-creation time, the terminal session may not be ready to use. For example, a TCP terminal session needs an established TCP connection first. In such a situation, the use of the terminal session by a particular client must be deferred until the session becomes ready. Delaying the session creation at the server side is not an option because this would render the server's entry point unavailable for all other clients until the TCP connection is ready. Instead, the client blocks until the server delivers a connected signal. This signal is emitted when the session becomes ready to use. The client waits for this signal right after creating the session.

Use cases

- Device drivers that provide streams of characters in either direction.
- A graphical terminal.
- Transfer of streams of data over TCP (using the TCP terminal).
- Writing streams of data to a file (using a file terminal).
- User input and output of traditional command-line based software, i. e., programs executed in the noux runtime environment.
- Multiplexing of multiple textual user interfaces (using the terminal-mux component).
- Headless operation and management of subsystems (using the CLI monitor).

UART The UART session interface complements the terminal session interface with additional control functions, e. g., for setting the baud rate. Because UART sessions are compatible to terminal sessions, a UART device driver can be used as both UART server and terminal server.

4.5.4. Input

The input session interface is used to communicate low-level user-input events from the server to the client using synchronous bulk transfers (Section 3.6.5). Such an event can be of one of the following types:

press or release of a button or key. Each physical button (such as a mouse button) or key (such as a key on a keyboard) is represented by a unique value. At the input-session level, key events are reported as raw hardware events. They are reported without a keyboard layout applied and without any interpretation of meta keys (like shift, alt, and control). This gives the client the flexibility to handle arbitrary combinations of keys.

relative motion of pointer devices such as a mouse. Such events are generated by device drivers.

absolute motion of pointer devices such as a touch screen or graphics tablet. Furthermore absolute motion events are generated by virtual input devices such as the input session provided by a GUI server.

wheel motion of scroll wheels in vertical and horizontal directions.

focus of the session. Focus events are artificially generated by servers to indicate a gained or lost keyboard focus of the client. The client may respond to such an event by changing its graphical representation accordingly.

leave of the pointer position. Leave events are artificially generated by servers to indicate a lost pointer focus.

character associated with a pressed key. This type of event is usually not generated by low-level device drivers but by a higher-level service - like the input-filer component - that applies keyboard-layout rules to sequences of low-level events. Each character event encodes a single UTF-8 symbol, which is ready to be consumed by components that operate on textual input rather than low-level hardware events.

Use cases

- Drivers for user-input devices play the roles of input servers.
- Providing user input from a GUI server to its clients, e. g., the interface of the nitpicker GUI server provides an input session as part of the server's interface.
- Merging multiple streams of user input into one stream (using an input merger).
- Virtual input devices can be realized as input servers that generate artificial input events.

4.5.5. Framebuffer

The framebuffer session interface allows a client to supply pixel data to a framebuffer server such as a framebuffer driver or a virtual framebuffer provided by a GUI server. The client obtains access to the framebuffer as a dataspace, which is shared between

client and server. The client may update the pixels within the dataspace at any time. Once a part of the framebuffer has been updated, the client informs the server by calling a *refresh* RPC function. Thereby, the framebuffer session interface employs a synchronous bulk transfer mechanism (Section 3.6.5).

Session creation In general, the screen mode is defined by the framebuffer server, not the client. The mode may be constrained by the physical capabilities of the hardware or depend on the driver configuration. Some framebuffer servers, however, may take a suggestion by the client into account. At session-creation time, the client may specify a preferred mode as session argument. Once the session is constructed, however, the client must request the actually used mode via the *mode* RPC function.

Screen-mode changes The session interface supports dynamic screen-mode changes during the lifetime of the session using the following protocol:

1. The client may register a signal handler using the *mode_sigh* RPC function. This handler gets notified in the event of server-side mode changes.
2. Similarly to the transactional protocol used for updating ROM modules (Section 4.5.1), the dataspace shared between client and server stays intact until the client acknowledges the mode change by calling the *mode* RPC function.
3. The server responds to the *mode* function by applying the new mode and returns the corresponding mode information to the client. This step may destroy the old framebuffer dataspace.
4. The client requests a new version of the framebuffer dataspace by calling the *dataspace* RPC function and attaches the dataspace to its local address space. Note that each subsequent call of the *dataspace* RPC function may result in the replacement of the existing dataspace by a new dataspace. Hence, calling *dataspace* twice may invalidate the dataspace returned from the first call.

Frame-rate synchronization To enable framebuffer clients to synchronize their operations with the display frequency, a client can register a handler for receiving display-synchronization events as asynchronous notifications (Section 3.6.2).

Use cases

- Framebuffer device drivers are represented as framebuffer servers.
- A virtual framebuffer may provide both the framebuffer and input session interfaces by presenting a window on screen. The resizing of the window may be reflected to the client as screen-mode changes.

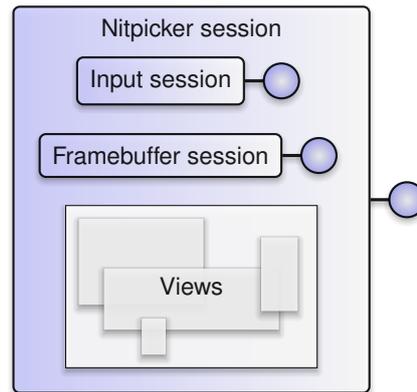


Figure 35: A nitpicker session aggregates a framebuffer session, an input session, and a session-local view stack.

- A filter component requests a framebuffer session and, in turn, provides a framebuffer session to a client. This way, pixel transformations can be applied to pixels produced by a client without extending the client.

4.5.6. Nitpicker GUI

The nitpicker session interface combines an input session and a framebuffer session into a single session (Figure 35). Furthermore, it supplements the framebuffer session with the notion of views, which allows the creation of flexible multi-window user interfaces. The interface is generally suited for resource multiplexers of the framebuffer and input sessions. A view is a rectangular area on screen that displays a portion of the client's virtual framebuffer. The position, size, and viewport of each view is defined by the client. Views can overlap, thereby creating a view stack. The stacking order of the views of one client can be freely defined by the client.

The size of the virtual framebuffer can be freely defined by the client but the required backing store must be provided in the form of session quota. Clients may request the screen mode of the physical framebuffer and are able to register a signal handler for mode changes of the physical framebuffer. This way, nitpicker clients are able to adapt themselves to changing screen resolutions.

Use cases

- The nitpicker GUI server allows multiple GUI applications to share a pair of a physical framebuffer session and an input session in a secure way.
- A window manager implementing the nitpicker session interface may represent each view as a window with window decorations and a placement policy. The

resizing of a window by the user is reflected to the client as a screen-mode change.

- A loader (Section 4.5.14) virtualizes the nitpicker session interface for the loaded subsystem.

4.5.7. Platform

The platform session interface (on ARM-based devices) and the PCI session interface (on x86-based machines) provide the client with access to the devices present on the hardware platform. See Section 4.1.1 for more information on the role of platform drivers.

4.5.8. Block

The block session interface allows a client to access a storage server at the block level. The interface is based on a packet stream (Section 3.6.6). Each packet represents a block-access command, which can be either read or write. Thanks to the use of the packet-stream mechanism, the client can issue multiple commands at once and thereby hide access latencies by submitting batches of block requests. The server acknowledges each packet after completing the corresponding block-command operation.

The packet-stream interface for submitting commands is complemented by the *info* RPC function for querying the properties of the block device, i. e., the supported operations, the block size, and the block count. Furthermore, a client can call the *sync* RPC function to flush caches at the block server.

Session creation At session-creation time, the client can dimension the size of the communication buffer as session argument. The server allocates the shared communication buffer from the session quota.

Use cases

- Block-device drivers implement the block-session interface.
- The part-block component requests a single block session, parses a partition table, and hands out each partition as a separate block session to its clients. There can be one client for each partition.
- File-system servers use block sessions as their back end.

4.5.9. Regulator

The regulator session represents an adjustable value in the hardware platform. Examples are runtime-configurable frequencies and voltages. The interface is a plain RPC interface.

4.5.10. Timer

The timer session interface provides a client with a session-local time source. A client can use it to schedule timeouts that are delivered as signals to a previously registered signal handler. Furthermore, the client can request the elapsed number of milliseconds since the creation of the timer session.

4.5.11. NIC

A NIC session represents a network interface that operates at network-packet level. Each session employs two independent packet streams (Section 3.6.6), one for receiving network packets and one for transmitting network packets. Furthermore, the client can query the MAC address of the network interface.

Session creation At session-creation time, the communication buffers of both packet streams are dimensioned via session arguments. The communication buffers are allocated by the server using the session quota provided by the client.

Use cases

- Network drivers are represented as NIC servers.
- A NIC switch uses one NIC session connected to a NIC driver, and provides multiple virtual NIC interfaces to its clients by managing a custom name space of virtual MAC addresses.
- A TCP/IP stack uses a NIC session as back end.

4.5.12. Audio output

The audio output interface allows for the transfer of audio data from the client to the server. One session corresponds to one channel. I.e., for stereo output, two audio-out sessions are required.

Session construction At session-construction time, the client specifies the type of channel (e. g., front left) as session argument.

Interface design For the output of streamed audio data, a codec typically decodes a relatively large portion of an audio stream and submits the sample data to a mixer. The mixer, in turn, mixes the samples of multiple sources and forwards the result to the audio driver. The codec, the mixer, and the audio driver are separate components. By using large buffer sizes between them, there is only very little context-switching

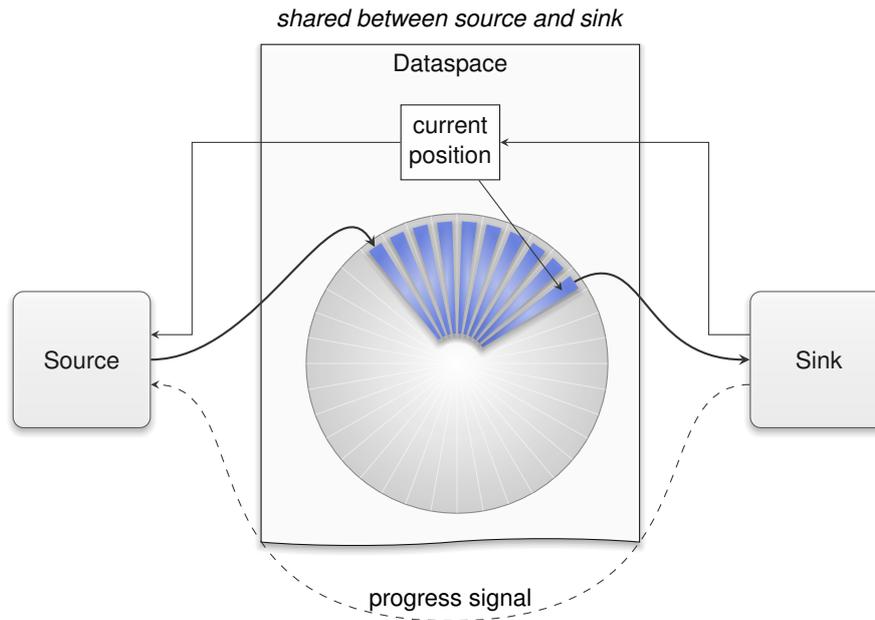


Figure 36: The time-driven audio-out session interface uses shared memory to transfer audio frames and propagate progress information.

overhead. Also, the driver can submit large buffers of sample data to the sound device without any further intervention needed. In contrast, sporadic sounds are used to inform the user about an immediate event. An example is the acoustic feedback to certain user input in games. The user ultimately expects that such sounds are played back without much latency. Otherwise the interactive experience would suffer. Hence, using large buffers between the audio source, the mixer, and the driver is not an option. The audio-out session interface was specifically designed to accommodate both corner cases of audio output.

Similarly to the packet-stream mechanism described in Section 3.6.6, the audio-out session interface depicted in Figure 36 employs a combination of shared memory and asynchronous notifications. However, in contrast to the packet-stream mechanism, it has no notion of ownership of packets. When using the normal packet-stream protocol, either the source or the sink is in charge of handling a given packet at a given time, not both. The audio-out session interface weakens this notion of ownership by letting the source update once submitted audio frames even after submitting them. If there are solely continuous streams of audio arriving at the mixer, the mixer can mix those large batches of audio samples at once and pass the result to the driver.

Now, if a sporadic sound comes in, the mixer checks the current output position reported by the audio driver, and re-mixes those portions that haven't been played back yet by incorporating the sporadic sound. So the buffer consumed by the driver

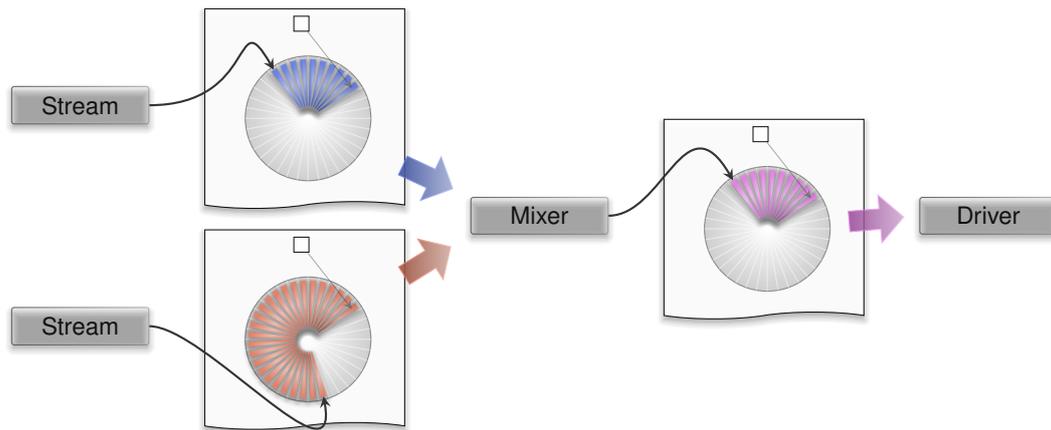


Figure 37: The mixer processes batches of incoming audio frames from multiple sources.

gets updated with new data.

Besides the way of how packets are populated with data, the second major difference to the packet-stream mechanism is its time-triggered mode of operation. The driver produces periodic signals that indicate the completeness of a played-back audio packet. This signal triggers the mixer to become active, which in turn serves as a time base for its clients. The current playback position is denoted alongside the sample data as a field in the memory buffer shared between source and sink.

Use cases

- The audio-out session interface is provided by audio drivers.
- An audio mixer combines incoming audio streams of multiple clients into one audio stream transferred to an audio driver.

4.5.13. File system

The file-system session interface provides the client with a storage facility at the file and directory-level. Compared to the block session interface (Section 4.5.8), it operates on a higher abstraction level that is suited for multiplexing the storage device among multiple clients. Similar to the block session, the file-system session employs a single packet stream interface (Section 3.6.6) for issuing read and write operations. This way, read and write requests can be processed in batches and even out of order.

In contrast to read and write operations that carry potentially large amounts of payload, the directory functions provided by the file-system session interface are syn-

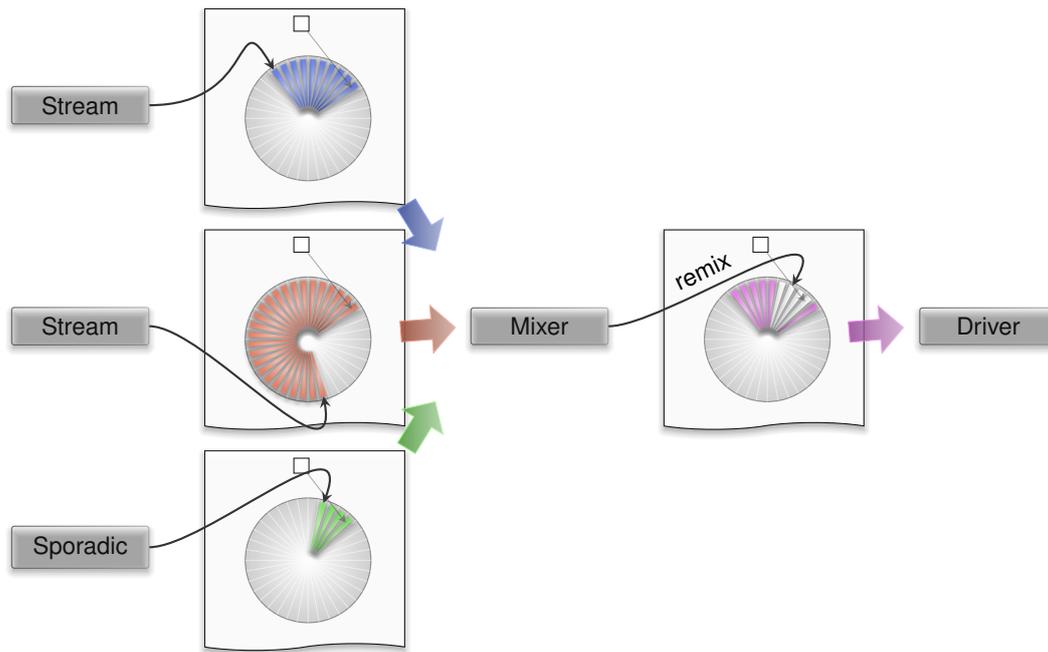


Figure 38: A sporadic occurring sound prompts the mixer to remix packets that were already submitted in the output queue.

chronous RPC functions. Those functions are used for opening, creating, renaming, moving, deleting, and querying files, directories and symbolic links.

The directory functions are complemented with an interface for receiving notifications upon file or directory changes using asynchronous notifications.

Use cases

- A file-system operates on a block session to provide file-system sessions to its clients.
- A RAM file system keeps the directory structure and files in memory and provides file-system sessions to multiple clients. Each session may be restricted in different ways (such as the root directory as visible by the respective client, or the permission to write). Thereby the clients can communicate using the RAM file system as a shared storage facility but are subjected to an information-flow policy.
- A file-system component may play the role of a filter that transparently encrypts the content of the files of its client and stores the encrypted files at another file-system server.

- A pseudo file system may use the file-system interface as an hierarchic control interface. For example, a trace file system provides a pseudo file system as a front end to interact with core's TRACE service.

4.5.14. Loader

The loader session interface allows clients to dynamically create Genode subsystems to be hosted as children of a loader service. In contrast to a component that is spawning a new subsystem as an immediate child, a loader client has very limited control over the spawned subsystem. It can merely define the binaries and configuration to start, define the position where the loaded subsystem will appear on screen, and kill the subsystem. But it is not able to interfere with the operation of the subsystem during its lifetime.

Session creation At session-creation time, the client defines the amount of memory to be used for the new subsystem as session quota. Once the session is established, the client equips the loader session with ROM modules that will be presented to the loaded subsystem. From the perspective of the subsystem, those ROM modules can be requested in the form of ROM sessions from its parent.

Visual integration of the subsystem The loaded subsystem may implement a graphical user interface by creating a nitpicker session (Section 4.5.6). The loader responds to such a session request by providing a locally implemented session. The loader subordinates the nitpicker session of the loaded subsystem to a nitpicker view (called parent view) defined by the loader client. The loader client can use the loader session interface to position the view relative to the parent-view position. Thereby, the graphical user interface of the loaded subsystem can be seamlessly integrated with the user interface of the loader client.

Use case The most illustrative use case is the execution of web-browser plugins where neither the browser trusts the plugin nor the plugin trusts the browser (Section 4.7.4).

4.6. Component configuration

By convention, each component obtains its configuration in the form of a ROM module named “config”. The ROM session for this ROM module is provided by the parent of the component. For example, for the `init` component, which is the immediate child of `core`, its “config” ROM module is provided by `core`’s ROM service. `Init`, in turn, provides a different config ROM module to each of its children by a locally implemented ROM service per child.

4.6.1. Configuration format

In principle, being a mere ROM module, a component configuration can come in an arbitrary format. However, throughout Genode, there exists the convention to use XML as syntax and wrap the configuration within a `<config>` node. The definition of sub nodes of the configuration depends on the respective component.

4.6.2. Server-side policy selection

Servers that serve multiple clients may apply a different policy to each client. In general, the policy may be defined by the session arguments aggregated on the route of the session request as explained in Section 3.2.3. However, in the usual case, the policy is dictated by the common parent of client and server. In this case, the parent may propagate its policy as the server’s configuration and deliver a textual label as session argument for each session requested at the server. The configuration contains a list of policies whereas the session label is used as a key to select the policy from the list. For example, the following snippet configures a RAM file system with different policies.

```
<config>
  <!-- constrain sessions according to their labels -->
  <policy label="noux -> root" root="/" />
  <policy label="noux -> home" root="/home/user" />
  <policy label="noux -> tmp" root="/tmp" writeable="yes" />
</config>
```

Each time a session is created, the server matches the supplied session label against the configured policies. Only if a policy matches, the parameters of the matching policy come into effect. The way how the session label is matched against the policies depends on the implementation of the server. However, by convention, servers usually select the policy depending on the attributes `label`, `label_prefix`, and `label_suffix`. If present, the `label` attribute must perfectly match the session label whereby the suffix and prefix counterparts allow for partially matching the session label. If multiple `<policy>` nodes match at the server side, the most specific policy is selected. Exact matches are considered as most specific, prefixes as less specific, and suffixes as least

specific. If multiple prefixes or suffixes match, the longest is considered as the most specific. If multiple policies have the same label, the selection is undefined. This is a configuration error.

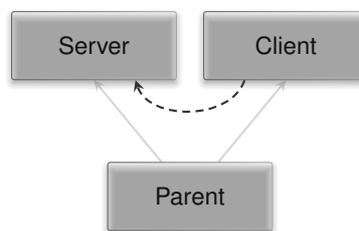
4.6.3. Dynamic component reconfiguration at runtime

As described in Section 4.5.1, a ROM module can be updated during the lifetime of the ROM session. This principally enables a parent to dynamically reconfigure a child component without the need to restart it. If a component supports its dynamic reconfiguration, it installs a signal handler at its “config” ROM session. Each time, the configuration changes, the component will receive a signal. It responds to such a signal by obtaining the new version of the ROM module using the steps described in Section 4.5.1 and applying the new configuration.

4.7. Component composition

Genode provides a playground for combining components in many different ways. The best composition of components often depends on the goal of the system integrator. Among possible goals are the ease of use for the end user, the cost-efficient reuse of existing software, and good application performance. However, the most prominent goal is the mitigation of security risks. This section presents composition techniques that leverage Genode's architecture to dramatically reduce the trusted computing base of applications and to solve rather complicated problems in surprisingly easy ways.

The figures presented throughout this section use a simpler nomenclature than the previous sections. A component is depicted as box. Parent-child relationships are represented as light-gray arrows. A session between a client and a server is illustrated by a dashed arrow pointing to the server.



4.7.1. Sandboxing

The functionality of existing applications and libraries is often worth reusing or economically downright infeasible to reimplement. Examples are PDF rendering engines, libraries that support commonly used video and audio codecs, or libraries that decode hundreds of image formats.

However, code of such rich functionality is inherently complex and must be assumed to contain security flaws. This is empirically evidenced by the never ending stream of security exploits targeting the decoders of data formats. But even in the absence of bugs, the processing of data by third-party libraries may have unintended side effects. For example, a PDF file may contain code that accesses the file system, which the user of a PDF reader may not expect. By linking such a third-party library to a security-critical application, the application's security is seemingly traded against the functional value that the library offers.

Fortunately, Genode's architecture principally allows every component to encapsulate untrusted functionality in child components. So instead of directly linking a third-party library to an application, the application executes the library code in a dedicated sub component. By imposing a strict session-routing policy onto the component, the untrusted code is restricted to its sandbox. Figure 39 shows a video player as a practical example of this approach.

The video player uses the nitpicker GUI server to present a user interface with the graphical controls of the player. Furthermore, it has access to a media file containing

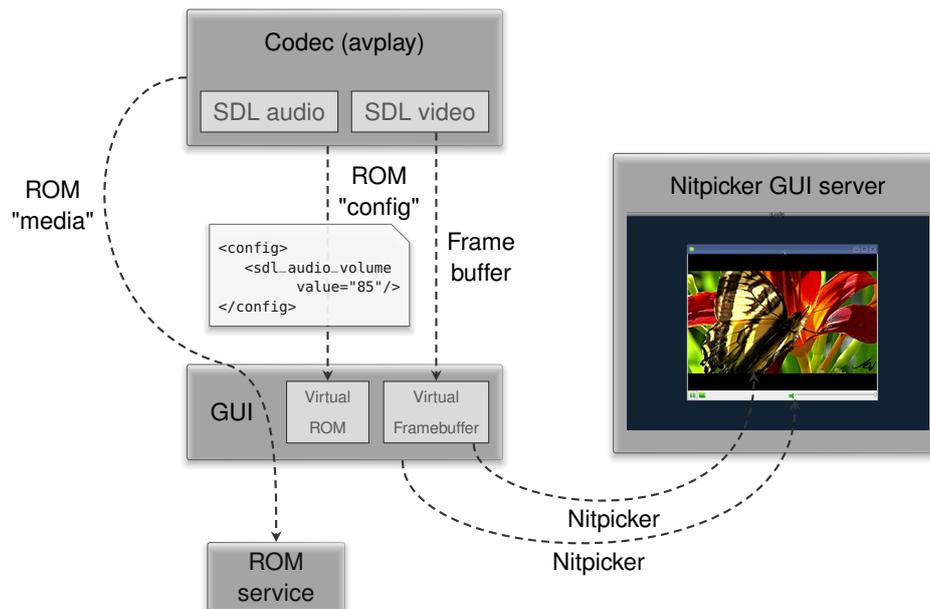


Figure 39: A video player executes the video and audio codecs inside a dedicated sandbox.

video and audio data. Instead of linking the media-codec library (libav) directly to the video-player application, it executes the codec as a child component. Thereby the application effectively restricts the execution environment of the codec to only those resources that are needed by the codec. Those resources are the media file that is handed out to the codec as a ROM module, a facility to output video frames in the form of a framebuffer session, and a facility to output an audio stream in the form of an audio-out session.

In order to reuse as much code as possible, the video player executes an existing example application called `avplay` that comes with the codec library as child component. The `avplay` example uses `libSDL` as back end for video and audio output and responds to a few keyboard shortcuts for controlling the video playback such as pausing the video. Because there exists a Genode version of `libSDL`, `avplay` can be executed as a Genode component with no modifications. This version of `libSDL` requests a framebuffer session (Section 4.5.5) and an audio-out session (Section 4.5.12) to perform the video and audio output. To handle user input, `libSDL` opens an input session (Section 4.5.4). Furthermore, it opens a ROM session for obtaining a configuration. This configuration parametrizes the audio back end of `libSDL`. Because `avplay` is a child of the video-player application, all those session requests are directed to the application. It is entirely up to the application how to respond to those requests. For accommodating the request for a framebuffer session, the application creates a second nitpicker session, configures a virtual framebuffer, and embeds this virtual framebuffer into its GUI. It keeps the nitpicker session capability for itself and merely hands out the virtual

framebuffer's session capability to avplay. For accommodating the request for the input session, it hands out a capability to a locally-implemented input session. Using this input session, it becomes able to supply artificial input events to avplay. For example, when the user clicks on the play button of the application's GUI, the application would submit a sequence of press and release events to the input sessions, which appear to avplay as the keyboard shortcut for starting the playback. To let the user adjust the audio parameters of libSDL during playback, the video-player application dynamically changes the avplay configuration using the mechanism described in Section 4.6.3. As a response to a configuration update, libSDL's audio back end picks up the changed configuration parameters and adjusts the audio playback accordingly.

By sandboxing avplay as a child component of the video player, a bug in the video or audio codecs can no longer compromise the application. The execution environment of avplay is tailored to the needs of the codec. In particular, it does not allow the codec to access any files or the network. In the worst case, if avplay becomes corrupted, the possible damage is restricted to producing wrong video or audio frames but a corrupted codec can neither access any of the user's data nor can it communicate to the outside world.

4.7.2. Component-level and OS-level virtualization

The sandboxing technique presented in the previous section tailors the execution environment of untrusted third-party code by applying an application-specific policy to all session requests originating from the untrusted code. However, the tailoring of the execution environment by the parent can even go a step further by providing the all-encompassing virtualization of all services used by the child, including core's services such as PD, CPU, and LOG. This way, the parent can not just tailor the execution environment of a child but completely define all aspects of the child's execution. This clears the way for introducing custom operating-system interfaces at any position within the component tree, or for monitoring the behavior of subsystems.

Introducing a custom OS interface By implementing all session interfaces normally provided by core, a runtime environment becomes able to handle all low-level interactions of the child with core. This includes the allocation of memory using the PD service, the spawning and controlling of threads using the CPU service, and the management of the child's address space using the PD service.

The noux runtime illustrated in Figure 40 is the canonical example of this approach. It appears as a Unix kernel to its children and thereby enables the use of Unix software on top of Genode. Normally, several aspects of Unix would contradict with Genode's architecture:

- The Unix system-call interface supports files and sockets as first-level citizens.
- There is no global virtual file system in Genode.

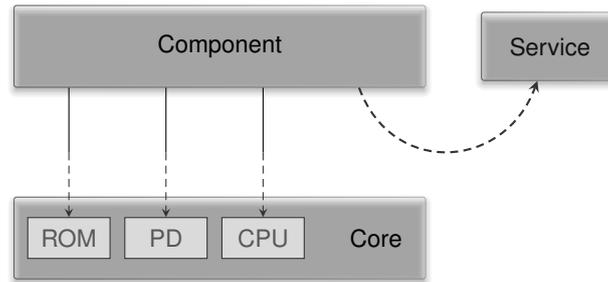


Figure 41: Each Genode component is created out of basic resources provided by core.

- Any Unix process can allocate memory as needed. There is no necessity for explicit assignment of memory resources to Unix processes.
- Processes are created by forking existing processes. The new process inherits the roles (in the form of open file descriptors) of the forking process.

Noux resolves these contradictions by providing the interfaces of core's low-level services alongside a custom RPC interface. By providing a custom noux session interface to its children, noux can accommodate all kinds of abstractions including the notion of files and sockets. Noux maintains a virtual file system that appears to be global among all the children of the noux instance. Since noux handles all the children's interaction with the PD service, it can hand out memory allocations from a pool of memory shared among all children. Finally, because noux observes all the interactions of each child with the PD service, it is able to replay the address-space layout of an existing process to a new process when fork is called.

Monitoring the behavior of subsystems Besides hosting arbitrary OS personalities as a subsystem, the interception of core's services allows for the all-encompassing monitoring of subsystems without the need for special support in the kernel. This is useful for failsafe monitoring or for user-level debugging.

As described in Section 3.5, any Genode component is created out of low-level resources in the form of sessions provided by core. Those sessions include at least a PD session, a CPU session, and a ROM session with the executable binary as depicted in Figure 41. In addition to those low-level sessions, the component may interact with sessions provided by other components.

For debugging a component, a debugger would need a way to inspect the internal state of the component. As the complete internal state is usually known by the OS kernel only, the traditional approach to user-level debugging is the introduction of a debugging interface into the kernel. For example, Linux has the ptrace mechanism and several microkernels of the L4 family come with built-in kernel debuggers. Such a debugging interface, however, introduces security risks. Besides increasing the com-

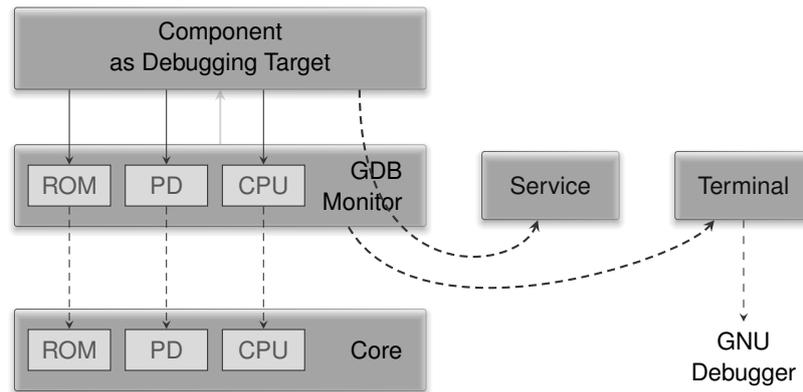


Figure 42: By intercepting all sessions to core’s services, a debug monitor obtains insights into the internal state of its child component. The debug monitor, in turn, is controlled from a remote debugger.

plexity of the kernel, access to the kernel’s debugging mechanisms needs to be strictly subjected to a security policy. Otherwise any program could use those mechanisms to inspect or manipulate other programs. Most L4 kernels usually exclude debugging features in production builds altogether.

In a Genode system, the component’s internal state is represented in the form of core sessions. Hence, by intercepting those sessions of a child, a parent can monitor all interactions of the child with core and thereby record the child’s internal state. Figure 42 shows a scenario where a debug monitor executes a component (debugging target) as a child while intercepting all sessions to core’s services. The interception is performed by providing custom implementations of core’s session interfaces as locally implemented services. Under the hood, the local services realize their functionality using actual core sessions. But by sitting in the middle between the debugging target and core, the debug monitor can observe the target’s internal state including the memory content, the virtual address-space layout, and the state of all threads running inside the component. Furthermore, since the debug monitor is in possession of all the session capabilities of the debugging target, it can *manipulate* it in arbitrary ways. For example, it can change thread states (e.g., pausing the execution or enable single-stepping) and modify the memory content (e.g., inserting breakpoint instructions). The figure shows that those debugging features can be remotely controlled over a terminal connection.

Using this form of component-level virtualization, a problem that used to require special kernel additions in traditional operating systems can be solved via Genode’s regular interfaces. Furthermore, Figure 43 shows that by combining the solution with OS-level virtualization, the connection to a remote debugger can actually be routed to an on-target instance of the debugger, thereby enabling on-target debugging.

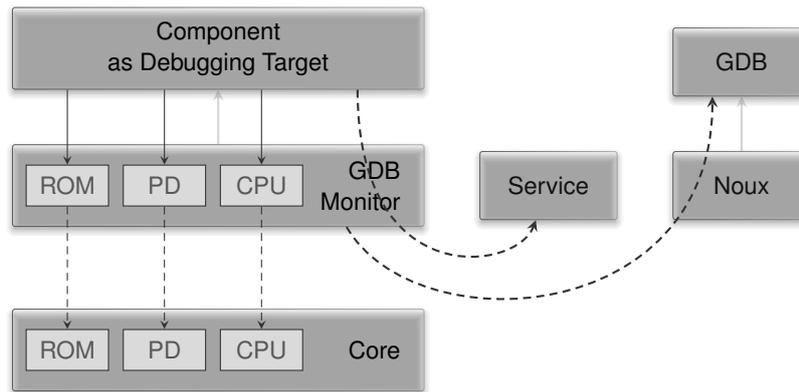


Figure 43: The GNU debugger is executed within a dedicated noux instance, thereby providing an on-target debugging facility.

4.7.3. Interposing individual services

The design of Genode's fundamental services, in particular resource multiplexers, is guided by the principle of minimalism. Because such components are security critical, complexity must be avoided. Functionality is added to such components only if it cannot be provided outside the component.

However, components like the nitpicker GUI server are often confronted with feature requests. For example, users may want to move a window on screen by dragging the window's title bar. Because nitpicker has no notion of windows or title bars, such functionality is not supported. Instead, nitpicker moves the burden to implement window decorations to its clients. However, this approach sacrifices functionality that is taken for granted on modern graphical user interfaces. For example, the user may want to switch the application focus using a keyboard shortcut or perform window operations and the interactions with virtual desktops in a consistent way. If each application implemented the functionality of virtual desktops individually, the result would hardly be usable. For this reason, it is tempting to move window-management functionality into the GUI server and to accept the violation of the minimalism principle.

The nitpicker GUI server is not the only service challenged by feature requests. The problem is present even at the lowest-level services provided by core. Core's region-map mechanism is used to manage the virtual address spaces of components via their respective PD sessions. When a dataspace is attached to a region map, the region map picks a suitable virtual address range where the dataspace will be made visible in the virtual address space. The allocation strategy depends on several factors such as alignment constraints and the address range that fits best. But eventually, it is deterministic. This contradicts the common wisdom that address spaces shall be randomized. Hence core's PD service is challenged with the request for adding address-space randomization as a feature. Unfortunately, the addition of such a feature into core raises two

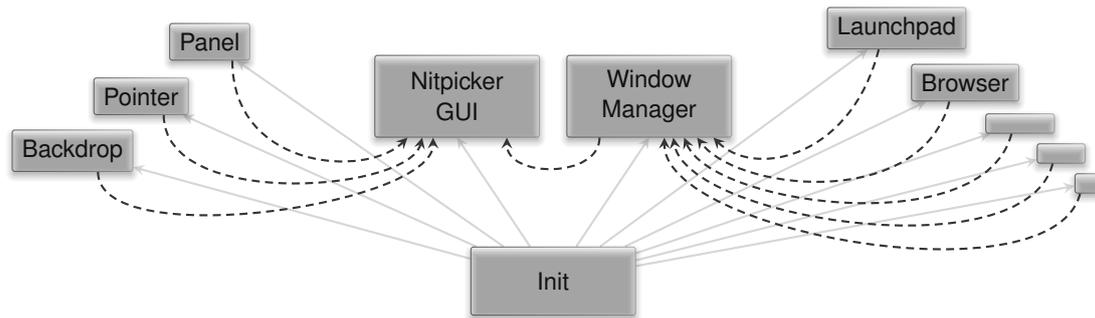


Figure 44: The nitpicker GUI accompanied with a window manager that interposes the nitpicker session interface for the applications on the right. The applications on the left are still able to use nitpicker directly and thereby avoid the complexity added by the window manager.

issues. First, core would need to have a source of good random numbers. But core does not contain any device drivers where to draw entropy from. With weak entropy, the randomization might be not random enough. In this case, the pretension of a security mechanism that is actually ineffective may be worse than not having it in the first place. Second, the feature would certainly increase the complexity of core. This is acceptable for components that potentially benefit from the added feature, such as outward-facing network applications. But the complexity eventually becomes part of the TCB of all components including those that do not benefit from the feature.

The solution to those kind of problems is the enrichment of existing servers by interposing their sessions. Figure 44 shows a window manager implemented as a separate component outside of nitpicker. Both the nitpicker GUI server and the window manager provide the nitpicker session interface. But the window manager enriches the semantics of the interface by adding window decorations and a window-layout policy. Under the hood, the window manager uses the real nitpicker GUI server to implement its service. From the application's point of view, the use of either service is transparent. Security-critical applications can still be routed directly to the nitpicker GUI server. So the complexity of the window manager comes into effect only for those applications that use it.

The same approach can be applied to the address-space randomization problem. A component with access to good random numbers may provide a randomized version of core's PD service. Outward-facing components can benefit from this security feature by having their PD session requests routed to this component instead of core.

4.7.4. Ceding the parenthood

When using a shell to manage subsystems, the complexity of the shell naturally becomes a security risk. A shell can be a text-command interpreter, a graphical desktop

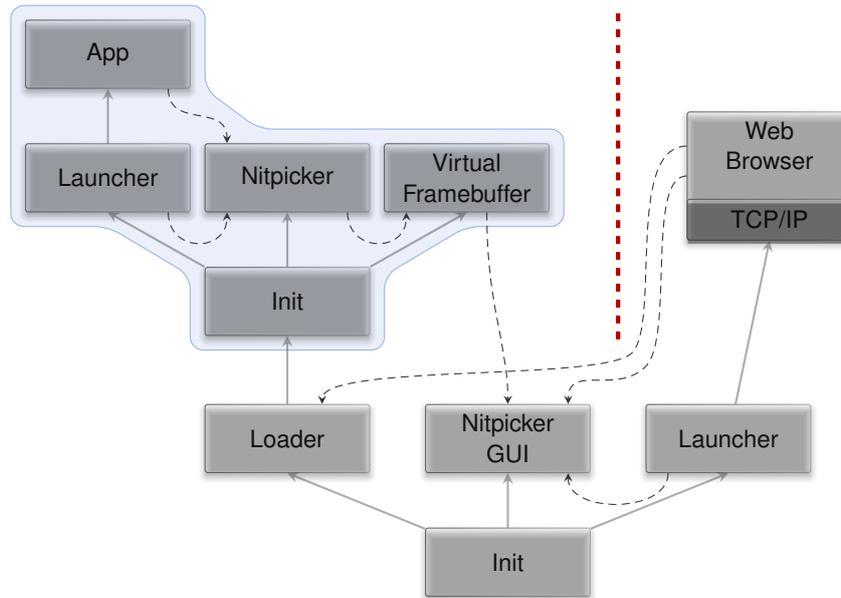


Figure 45: A web browser spawns a plugin by ceding the parenthood of the plugin to the trusted loader service.

shell, a web browser that launches subsystems as plugins, or a web server that provides a remote administration interface. What all those kinds of shells have in common is that they contain an enormous amount of complexity that can be attributed to convenience. For example, a textual shell usually depends on `libreadline`, `ncurses`, or similar libraries to provide a command history and to deal with the peculiarities of virtual text terminals. A graphical desktop shell is even worse because it usually depends on a highly complex widget toolkit, not to mention using a web browser as a shell. Unfortunately, the functionality provided by these programs cannot be dismissed as it is expected by the user. But the high complexity of the convenience functions fundamentally contradicts the security-critical role of the shell as the common parent of all spawned subsystems. If the shell gets compromised, all the spawned subsystems will suffer.

The risk of such convoluted shells can be mitigated by moving the parent role for the started subsystems to another component, namely a loader service. In contrast to the shell, which should be regarded as untrusted due to its complexity, the loader is a small component that is orders of magnitude less complex. Figure 45 shows a scenario where a web browser is used as a shell to spawn a Genode subsystem. Instead of spawning the subsystem as the child of the browser, the browser creates a loader session. Using the loader-session interface described in Section 4.5.14, it can initially import the to-be-executed subsystem into the loader session and kick off the execution of the subsystem. However, once the subsystem is running, the browser can no longer

interfere with the subsystem's operation. So security-sensitive information processed within the loaded subsystem are no longer exposed to the browser. Still, the lifetime of the loaded subsystem depends on the browser. If it decides to close the loader session, the loader will destroy the corresponding subsystem.

By ceding the parenthood to a trusted component, the risks stemming from the complexity of various kinds of shells can be mitigated.

4.7.5. Publishing and subscribing

All the mechanisms for transferring data between components presented in Section 3.6 have in common that data is transferred in a peer-to-peer fashion. A client transfers data to a server or vice versa. However, there are situations where such a close coupling of both ends of communication is not desired. In multicast scenarios, the producer of information desires to propagate information without the need to interact (or even depend on a handshake) with each individual recipient. Specifically, a component might want to publish status information about itself that might be useful for other components. For example, a wireless-networking driver may report the list of detected wireless networks along with their respective SSIDs and reception qualities such that a GUI component can pick up the information and present it to the user. Each time, the driver detects a change in the ether, it wants to publish an updated version of the list. Such a scenario could principally be addressed by introducing a use-case-specific session interface, i. e., a “wlan-list” session. But this approach has two disadvantages.

1. It forces the wireless driver to play an additional server role. Instead of pushing information anytime at the discretion of the driver, the driver has to actively support the pulling of information from the wlan-list client. This is arguably more complex.
2. The wlan-list session interface ultimately depends on the capabilities of the driver implementation. If an alternative wireless driver is able to supplement the list with further details, the wlan-list session interface of the alternative driver might look different. As a consequence, the approach is likely to introduce many special-purpose session interfaces. This contradicts with the goal to promote the composability of components as stated at the beginning of Section 4.5.

As an alternative to introducing special-purpose session interfaces for addressing the scenarios outlined above, two existing session interfaces can be combined, namely ROM and report.

Report-ROM server The *report-rom* server is both a ROM service and a report service. It acts as an information broker between information providers (clients of the report service) and information consumers (clients of the ROM service).

To propagate its internal state to the outside, a component creates a report session. From the client's perspective, the posting of information via the report session's *submit* function is a fire-and-forget operation, similar to the submission of a signal. But in contrast to a signal, which cannot carry any payload, a report is accompanied with arbitrary data. For the example above, the wireless driver would create a report session. Each time, the list of networks changes, it would submit an updated list as a report to the report-ROM server.

The report-ROM server stores incoming reports in a database using the client's session label as key. Therefore, the wireless driver's report will end up in the database under the name of the driver component. If one component wishes to post reports of different kinds, it can do so by extending the session label by a component-provided label suffix supplied as session-construction argument (Section 4.5.2). The memory needed as the backing store for the report at the report-ROM server is accounted to the report client via the session-quota mechanism described in Section 3.3.2.

In its role of a ROM service, the report-ROM server hands out the reports stored in its database as ROM modules. The association of reports with ROM sessions is based on the session label of the ROM client. The configuration of the report-ROM server contains a list of policies as introduced in Section 4.6.2. Each policy entry is accompanied with a corresponding key into the report database.

When a new report comes in, all ROM clients that are associated with the report are informed via a ROM-update signal (Section 4.5.1). Each client can individually respond to the signal by following the ROM-module update procedure and thereby obtain the new version of the report. From the client's perspective, the origin of the information is opaque. It cannot decide whether the ROM module is provided by the report-ROM server or an arbitrary other ROM service.

Coming back to the wireless-driver example, the use of the report-ROM server effectively decouples the GUI application from the wireless driver. This has the following benefits:

- The application can be developed and tested with an arbitrary ROM server supplying an artificially created list of networks.
- There is no need for the introduction of a special-purpose session interface between both components.
- The wireless driver can post state updates in an intuitive fire-and-forget way without playing an additional server role.
- The wireless driver can be restarted without affecting the application.

Poly-instantiation of the report-ROM mechanism The report-ROM server is a canonical example of a protocol stack (Section 4.2). It performs a translation between the report-session interface and the ROM-session interface. Being a protocol stack, it

can be instantiated any number of times. It is up to the system integrator whether to use one instance for gathering the reports of many report clients, or to instantiate multiple report-ROM servers. Taken to the extreme, one report-ROM server could be instantiated per report client. The routing of ROM-session requests restricts the access of the ROM clients to the different instances. Even in the event that the report-ROM server is compromised, the policy for the information flows between the producers and consumers of information stays in effect.

4.7.6. Enslaving services

In the scenarios described in the previous sections, the relationships between clients and servers have been one of the following:

- The client is a sibling of the server within the component tree, or
- The client is a child of a parent that provides a locally-implemented service to its child.

However, the Genode architecture allows for a third option: The parent can be a client of its own child. Given the discussion in Section 3.2.4, this arrangement looks counter-intuitive at first because the discussion concluded that a client has to trust the server with respect to the client's liveliness. Here, a call to the server would be synonymous to a call to the child. Even though the parent is the owner of the child, it would make itself dependent on the child, which is generally against the interest of the parent.

That said, there is a plausible case where the parent's trust in a child is justified: If the parent uses an existing component like a 3rd-party library. When calling code of a 3rd-party library, the caller implicitly agrees to yield control to the library and trusts the called function to return at some point. The call of a service that is provided by a child corresponds to such a library call.

By providing the option to host a server as a child component, Genode's architecture facilitates the use of arbitrary server components in a library-like fashion. Because the server performs a useful function but is owned by its client, it is called *slave*. An application may aggregate existing protocol-stack components as slaves without the need to incorporate the code of the protocol stacks into the application. For example, by enslaving the report-ROM server introduced in Section 4.7.5, an application becomes able to use it as a local publisher-subscriber mechanism. Another example would be an application that aggregates an instance of the nitpicker GUI server for the sole purpose of composing an image out of several source images. When started, the nitpicker slave requests a framebuffer and an input session. The application responds to these requests by handing out locally-implemented sessions so that the output of the nitpicker slave becomes visible to the application. To perform the image composition, the application creates a nitpicker session for each source image and supplies the image data to the virtual framebuffer of the respective session. After configuring nitpicker views according

to the desired layout of the final image, the application obtains the composed image from nitpicker's framebuffer.

Note that by calling the slave, the parent does not need to trust the slave with respect to the integrity and confidentiality of its internal state (see the discussion in Section 3.2.4). By performing the call, only the liveness of the parent is potentially affected. If not trusting the slave to return control once called, the parent may take special precautions: A watchdog thread inside the parent could monitor the progress of the slave and cancel the call after the expiration of a timeout.

5. Development

The Genode OS framework is accompanied by a scalable build system and tooling infrastructure that is designed for the creation of highly modular and portable systems software. Understanding the underlying concepts is important for leveraging the full potential of the framework. This chapter complements Chapter 2 with the explanation of the coarse-grained source-tree structure (Section 5.1), the integration of 3rd-party software (Section 5.2), the build system (Section 5.3), and system-integration tools (Section 5.4). Furthermore, it describes the project's development process in Section 5.7.

5.1. Source-code repositories

As briefly introduced in Section 2.2, Genode's source tree is organized in the form of several source-code repositories. This coarse-grained modularization of the source code has the following benefits:

- Source codes of different concerns remain well separated. For example, the platform-specific code for each base platform is located in a dedicated *base-
<platform>* repository.
- Different abstraction levels and features of the system can be maintained in different source-code repositories. Whereby the source code contained in the *os* repository is free from any dependency from 3rd-party software, the components hosted in the *libports* repository are free to use foreign code.
- Custom developments and experimental features can be hosted in dedicated source-code repositories, which do not interfere with Genode's source tree. Such a custom repository can be managed independently from Genode using arbitrary revision-control systems.

The build-directory configuration defines the set of repositories to incorporate into the build process. At build time, the build system overlays the directory structures of all selected repositories to form a single logical source tree. The selection of source-code repositories ultimately defines the view of the build system on the source tree.

Note that the order of the repositories as configured in the build configuration (in *etc/build.conf*) is important. Front-most repositories shadow subsequent repositories. This makes the repository mechanism a powerful tool for tweaking existing repositories: By adding a custom repository in front of another one, customized versions of single files (e. g., header files or target description files) can be supplied to the build system without changing the original repository.

Each source-code repository has the principle structure shown in Table 1.

Directory	Description
<i>doc/</i>	Documentation, specific for the repository
<i>etc/</i>	Default configuration for the build process
<i>mk/</i>	Build-system supplements
<i>include/</i>	Globally visible header files
<i>src/</i>	Source codes and target build descriptions
<i>lib/mk/</i>	Library build descriptions
<i>lib/import/</i>	Library import descriptions
<i>ports/</i>	Port descriptions of 3rd-party software

Table 1: Structure of a source-code repository. Depending on the repository, only a subset of those directories may be present.

5.2. Integration of 3rd-party software

Downloaded 3rd-party source code resides outside of the actual repository at the central `<genode-dir>/contrib/` directory. This structure has the following benefits over hosting 3rd-party source code along with Genode's genuine source code:

- Working with `grep` within the repositories works very efficient because downloaded and extracted 3rd-party code is not in the way. Such code resides next to the repositories.
- Storing all build directories and downloaded 3rd-party source code somewhere outside the Genode source tree, e. g., on different disk partitions, can be easily accomplished by creating symbolic links for the `build/` and `contrib/` directories.

The `contrib/` directory is managed using the tools at `<genode-dir>/tool/ports/`.

Obtain a list of available ports

```
tool/ports/list
```

Download and install a port

```
tool/ports/prepare_port <port-name>
```

The `prepare_port` tool scans all repositories under `repos/` for the specified port and installs the port into `contrib/`. Each version of an installed port resides in a dedicated subdirectory within the `contrib/` directory. The port-specific directory is called port directory. It is named `<port-name>-<fingerprint>`. The `<fingerprint>` uniquely identifies the version of the port (it is a SHA256 hash of the ingredients of the port). If two versions of the same port are installed, each of them will have a different fingerprint. So they end up in different directories.

Within a source-code repository, a port is represented by two files, a `<port-name>.port` and a `<port-name>.hash` file. Both files reside at the `ports/` subdirectory of the corresponding repository. The `<port-name>.port` file is the port description, which declares the ingredients of the port, e. g., the archives to download and the patches to apply. The `<port-name>.hash` file contains the fingerprint of the corresponding port description, thereby uniquely identifying a version of the port as expected by the checked-out Genode version.

For step-by-step instructions on how to add a port using the mechanism, please refer to the porting guide:

Genode Porting Guide

<https://genode.org/documentation/developer-resources/porting>

5.3. Build system

5.3.1. Build directories

The build system is supposed to never touch the source tree. The procedure of building components and integrating them into system scenarios is performed within a distinct *build directory*. One build directory targets a specific kernel and hardware platform. Because the source tree is decoupled from the build directory, one source tree can have many different build directories associated, each targeted at a different platform.

The recommended way for creating a build directory is the use of the *create_builddir* tool located at `<genode-dir>/tool/`. The tool prints usage information along with a list of supported base platforms when started without arguments. For creating a new build directory, one of the listed target platforms must be specified. By default, the new build directory is created at `<genode-dir>/build/<platform>/` where `<platform>` corresponds to the specified argument. Alternatively, the default location can be overridden via the optional `BUILD_DIR=` argument. For example:

```
cd <genode-dir>
./tool/create_builddir x86_64 BUILD_DIR=/tmp/build.x86_64
```

This command creates a new build directory for the 64-bit x86 platform at `/tmp/build.x86_64/`. For the basic operations available from within the build directory, please refer to Section 2.3.

Configuration Each build directory contains a *Makefile*, which is a symbolic link to `tool/builddir/build.mk`. The makefile is the front end of the build system and not supposed to be edited. Besides the makefile, there is an *etc/* subdirectory that contains the build-directory configuration. For most platforms, there exists merely a single *build.conf* file, which defines the source-code repositories to be incorporated into the build process along with the parameters for the run tool explained in Section 5.4.1.

The selection of source-code repositories is defined by the `REPOSITORIES` declaration, which contains a list of directories. The `etc/build.conf` file as found in a freshly created build directory is preconfigured to select the source-code repositories *base-<platform>*, *base*, *os*, and *demo*. There are a number of commented-out lines that can be uncommented for enabling additional repositories.

Cleaning To remove all but kernel-related generated files, use

```
make clean
```

To remove all generated files, use

```
make cleanall
```

Both `clean` and `cleanall` won't remove any files from the `bin/` subdirectory. This makes the `bin/` a safe place for files that are unrelated to the build process, yet are required for the integration stage, e. g., binary data.

Controlling the verbosity To understand the inner workings of the build process in more detail, you can tell the build system to display each directory change by specifying

```
make VERBOSE_DIR=
```

If you are interested in the arguments that are passed to each invocation of `make`, you can make them visible via

```
make VERBOSE_MK=
```

Furthermore, you can observe each single shell-command invocation by specifying

```
make VERBOSE=
```

Of course, you can combine these verbosity toggles for maximizing the noise.

5.3.2. Target descriptions

Each build target is represented by a corresponding `target.mk` file within the `src/` subdirectory of a source-code repository. This file declares the name of the target, the source codes to be incorporated into the target, and the libraries the target depends on. The build system evaluates target descriptions using `make`. Hence, the syntax corresponds to the syntax of makefiles and the principle functionality of `make` is available for `target.mk` files. For example, it is possible to define custom rules as done in Section 5.3.5.

Target declarations

TARGET is the name of the binary to be created. This is the only **mandatory variable** to be defined in each `target.mk` file.

LIBS is the list of libraries that are used by the target.

SRC_CC contains the list of `.cc` source files. The default search location for source codes is the directory where the `target.mk` file resides.

SRC_C contains the list of .c source files.

SRC_S contains the list of assembly .s source files.

SRC_BIN contains binary data files to be linked to the target.

INC_DIR is the list of include search locations. Directories should always be appended by using +=.

REQUIRES expresses the requirements that must be satisfied in order to build the target. More details about the underlying mechanism is provided by Section 5.3.4.

CC_OPT contains additional compiler options to be used for .c as well as for .cc files.

CC_CXX_OPT contains additional compiler options to be used for the C++ compiler only.

CC_C_OPT contains additional compiler options to be used for the C compiler only.

EXT_OBJECTS is a list of external objects or libraries. This declaration is merely used for interfacing Genode with legacy software components.

Specifying search locations When specifying search locations for header files via the **INC_DIR** variable or for source files via **vpath**, the use of relative pathnames is illegal. Instead, the following variables can be used to reference locations within the source-code repository where the target resides:

REP_DIR is the base directory of the target's source-code repository. Normally, specifying locations relative to the base of the repository is rarely used by *target.mk* files but needed by library descriptions.

PRG_DIR is the directory where the *target.mk* file resides. This variable is always to be used when specifying a relative path.

\$(call select_from_repositories, path/relative/to/repo) This function returns the absolute path for the given repository-relative path by looking at all source-code repositories in their configured order. Hereby, it is possible to access files or directories that are outside the target's source-code repository.

\$(call select_from_ports, <port-name>) This function returns the absolute path for the *contrib* directory of the specified *<port-name>*. The *contrib* directory is located at *<genode-dir>/contrib/<port-name>-<fingerprint>* whereby *<fingerprint>* uniquely identifies the version of the port as expected by the current state of the Genode source tree.

5.3.3. Library descriptions

In contrast to target descriptions that are scattered across the whole source tree, library descriptions are located at the central place *lib/mk*. Each library corresponds to a *<libname>.mk* file. The base of the description file is the name of the library. Therefore, no `TARGET` variable needs to be defined. The location of source-code files is usually defined relative to `$(REP_DIR)`. Library-description files support the following additional declaration:

SHARED_LIB = yes declares that the library should be built as a shared object rather than a static library. The resulting object will be called *<libname>.lib.so*.

5.3.4. Platform specifications

Building components for different platforms likely implicates that portions of code are tied to certain aspects of the target platform. For example, target platforms may differ in the following respects:

- The API of the used kernel,
- The hardware architecture such as x86, ARMv7,
- Certain hardware facilities such as a custom device, or
- Other considerations such as software license requirements.

Each of those aspects may influence the build process in different ways. The build system provides a generic mechanism to steer the build process according to such aspects. Each aspect is represented by a tag called *spec value*. Any platform targeted by Genode can be characterized by a set of such spec values.

The **developer** of a software component knows the constraints of his software and thus specifies these requirements in the build-description file of the component. The **system integrator** defines the platform the software will be built for by specifying the targeted platform in the SPECS declaration in the build directory's *etc/specs.conf* file. In addition to the (optional) *etc/specs.conf* file within the build directory, the build system incorporates all *etc/specs.conf* files found in the enabled repositories. For example, when using the Linux kernel as a platform, the *base-linux/etc/specs.conf* file is picked up automatically. The build directory's *specs.conf* file can still be used to extend the SPECS declarations, for example to enable special features.

Each *<spec>* in the SPECS variable instructs the build system to

- Include the make-rules of a corresponding *base/mk/spec/<specname>.mk* file. This enables the customization of the build process for each platform.

- Search for `<libname>.mk` files in the `lib/mk/spec/<specname>/` subdirectory. This way, alternative implementations of one and the same library interface can be selected depending on the platform specification.

Before a target or library gets built, the build system checks if the `REQUIRES` entries of the build description file are satisfied by entries of the `SPECS` variable. The compilation is executed only if each entry in the `REQUIRES` variable is present in the `SPECS` variable as supplied by the build directory configuration.

5.3.5. Building tools to be executed on the host platform

Sometimes, software requires custom tools that are used to generate source code or other ingredients for the build process, for example IDL compilers. Such tools won't be executed on top of Genode but on the host platform during the build process. Hence, they must be compiled with the tool chain installed on the host, not the Genode tool chain.

The build system accommodates the building of such host tools as a side effect of building a library or a target. Even though it is possible to add the tool-compilation step to a regular build description file, it is recommended to introduce a dedicated pseudo library for building such tools. This way, the rules for building host tools are kept separate from rules that refer to regular targets. By convention, the pseudo library should be named `<package>_host_tools` and the host tools should be built at `<build-dir>/tool/<package>/` where `<package>` refers to the name of the software package the tool belongs to, e. g., `qt5` or `mupdf`. To build a tool named `<tool>`, the pseudo library contains a custom make rule like the following:

```
$(BUILD_BASE_DIR)/tool/<package>/<tool>:
  $(MSG_BUILD)$(!notdir $@)
  $(VERBOSE)mkdir -p $(dir $@)
  $(VERBOSE)...build commands...
```

To let the build system trigger the rule, add the custom target to the `HOST_TOOLS` variable:

```
HOST_TOOLS += $(BUILD_BASE_DIR)/tool/<package>/<tool>
```

Once the pseudo library for building the host tools is in place, it can be referenced by each target or library that relies on the respective tools via the `LIBS` declaration. The tool can be invoked by referring to `$(BUILD_BASE_DIR)/tool/<package>/tool`.

For an example of using custom host tools, please refer to the `mupdf` package found within the `libports` repository. During the build of the `mupdf` library, two custom tools `fontdump` and `cmappedump` are invoked. The tools are built via the

lib/mk/mupdf_host_tools.mk library description file. The actual mupdf library (*lib/mk/mupdf.mk*) has the pseudo library `mupdf_host_tools` listed in its LIBS declaration and refers to the tools relative to `$(BUILD_BASE_DIR)`.

5.3.6. Building 3rd-party software

The source code of 3rd-party software is managed by the mechanism presented in Section 5.2. Once prepared, such source codes resides in a subdirectory of `<genode-dir>/contrib/`.

If the build system encounters a target that incorporates ported source code (that is, a build-description file that calls the `select_from_ports` function), it looks up the respective `<port-name>.hash` file in the repositories as specified in the build configuration. The fingerprint found in the hash file is used to construct the path to the port directory under `contrib/`. If that lookup fails, a meaningful error is printed. Any number of versions of the same port can be installed at the same time. I.e., when switching Git branches that use different versions of the same port, the build system automatically finds the right port version as expected by the currently active branch.

5.4. System integration and automated testing

Genode's portability across kernels and hardware platforms is one of the prime features of the framework. However, each kernel or hardware platform requires different considerations when it comes to system configuration, integration, and booting. When using a particular kernel, profound knowledge about the boot concept and the kernel-specific tools is required. To streamline the testing of system scenarios across the many different supported kernels and hardware platforms, the framework is equipped with tools that relieve the system integrator from these peculiarities.

5.4.1. Run tool

The centerpiece of the system-integration infrastructure is the so-called run tool. Directed by a script (run script), it performs all the steps necessary to test a system scenario. Those steps are:

1. **Building** the components of a scenario
2. **Configuration** of the init component
3. Assembly of the **boot directory**
4. Creation of the **boot image**
5. **Powering-on** the test machine
6. **Loading** of the boot image
7. Capturing the **LOG output**
8. **Validation** of the scenario's behavior
9. **Powering-off** the test machine

Each of those steps depends on various parameters such as the used kernel, the hardware platform used to execute the scenario, the way the test hardware is connected to the test infrastructure (e. g., UART, AMT, JTAG, network), the way the test hardware is powered or reset, or the way of how the scenario is loaded into the test hardware. To accommodate the variety of combinations of these parameters, the run tool consists of an extensible library of modules. The selection and configuration of the modules is expressed in the run-tool configuration. The following types of modules exist:

boot-dir modules These modules contain the functionality to populate the boot directory and are specific to each kernel. It is mandatory to always include the module corresponding to the used kernel.

(the available modules are: linux, hw, okl4, fiasco, pistachio, nova, sel4, foc)

image modules These modules are used to wrap up all components used by the run script in a specific format and thereby prepare them for execution. Depending on the used kernel, different formats can be used. With these modules, the creation of ISO and disk images is also handled.

(the available modules are: uboot, disk, iso)

load modules These modules handle the way the components are transferred to the target system. Depending on the used kernel there are various options to pass on the components. For example, loading from TFTP or via JTAG is handled by the modules of this category.

(the available modules are: tftp, jtag, fastboot, ipxe)

log modules These modules handle how the output of a currently executed run script is captured.

(the available modules are: qemu, linux, serial, amt)

power_on modules These modules are used for bringing the target system into a defined state, e. g., by starting or rebooting the system.

(the available modules are: qemu, linux, softreset, amt, netio)

power_off modules These modules are used for turning the target system off after the execution of a run script.

Each module has the form of a script snippet located under the `tool/run/<step>/` directory where `<step>` is a subdirectory named after the module type. Further instructions about the use of each module (e. g., additional configuration arguments) can be found in the form of comments inside the respective script snippets. Thanks to this modular structure, an extension of the tool kit comes down to adding a file at the corresponding module-type subdirectory. This way, custom work flows (such as tunneling JTAG over SSH) can be accommodated fairly easily.

5.4.2. Run-tool configuration examples

To execute a run script, a combination of modules may be used. The combination is controlled via the `RUN_OPT` declaration contained in the build directory's `etc/build.conf` file. The following examples illustrate the selection and configuration of different run modules:

Executing NOVA in Qemu

```
RUN_OPT = --include boot_dir/nova \  
          --include power_on/qemu --include log/qemu --include image/iso
```

By including `boot_dir/nova`, the run tool assembles a boot directory equipped with a boot loader and a boot-loader configuration that is able to bootstrap the NOVA kernel. The combination of the modules `power_on/qemu` and `log/qemu` prompts the run tool to spawn the Qemu emulator with the generated boot image and fetch the log output of the emulated machine from its virtual comport. The specification of `image/iso` tells the run tool to use a bootable ISO image as a boot medium as opposed to a disk image.

Executing NOVA on a real x86 machine using AMT The following example uses Intel's advanced management technology (AMT) to remotely reset a physical target machine (`power_on/amt`) and capture the serial output over network (`log/amt`). In contrast to the example above, the system scenario is supplied via TFTP (`load/tftp`). Note that the example requires a working network-boot setup including a TFTP server, a DHCP server, and a PXE boot loader.

```
RUN_OPT = --include boot_dir/nova \  
          --include power_on/amt \  
            --power-on-amt-host 10.23.42.13 \  
            --power-on-amt-password 'foo!' \  
          --include load/tftp \  
            --load-tftp-base-dir /var/lib/tftpboot \  
            --load-tftp-offset-dir /x86 \  
          --include log/amt \  
            --log-amt-host 10.23.42.13 \  
            --log-amt-password 'foo!'
```

If the test machine has a comport connection to the machine where the run tool is executed, the `log/serial` module may be used instead of `log/amt`:

```
--include log/serial --log-serial-cmd 'picocom -b 115200 /dev/ttyUSB0'
```

Executing base-hw on a Raspberry Pi The following example boots a system scenario based on the `base-hw` kernel on a Raspberry Pi that is powered via a network-controllable power plug (`netio`). The Raspberry Pi is connected to a JTAG debugger, which is used to load the system image onto the device.

```
RUN_OPT = --include boot_dir/hw \  
          --include power_on/netio \  
            --power-on-netio-ip 10.23.42.5 \  
            --power-on-netio-user admin \  
            --power-on-netio-password secret \  
            --power-on-netio-port 1 \  
          --include power_off/netio \  
            --power-off-netio-ip 10.23.42.5 \  
            --power-off-netio-user admin \  
            --power-off-netio-password secret \  
            --power-off-netio-port 1 \  
          --include load/jtag \  
          --load-jtag-debugger \  
            /usr/share/openocd/scripts/interface/flyswatter2.cfg \  
          --load-jtag-board \  
            /usr/share/openocd/scripts/interface/raspberrypi.cfg \  
          --include log/serial \  
            --log-serial-cmd 'picocom -b 115200 /dev/ttyUSB0'
```

5.4.3. Meaningful default behaviour

The `create_builddir` tool introduced in Section 2.3 equips a freshly created build directory with a meaningful default configuration that depends on the selected platform and the used kernel. For example, when creating a build directory for the `x86_64` base platform and building a scenario with `KERNEL=linux`, `RUN_OPT` is automatically defined as

```
RUN_OPT = --include boot_dir/linux \  
          --include power_on/linux --include log/linux
```

5.4.4. Run scripts

Using run scripts, complete system scenarios can be described in a concise and kernel-independent way. As described in Section 2.4, a run script can be used to integrate and test-drive the scenario directly from the build directory. The best way to get acquainted with the concept is by reviewing the run script for the hello-world example presented in Section 2.5.4. It performs the following steps:

1. Building the components needed for the system using the `build` command. This command instructs the build system to compile the targets listed in the brace block. It has the same effect as manually invoking `make` with the specified argument from within the build directory.

2. Creating a new boot directory using the `create_boot_directory` command. The integration of the scenario is performed in a dedicated directory at `<build-dir>/var/run/<run-script-name>/`. When the run script is finished, this boot directory will contain all components of the final system.
3. Installing the configuration for the init component into the boot directory using the `install_config` command. The argument to this command will be written to a file called `config` within the boot directory. It will eventually be loaded as boot module and made available by core's ROM service to the init component. The configuration of init is explained in Chapter 6.
4. Creating a bootable system image using the `build_boot_image` command. This command copies the specified list of files from the `<build-dir>/bin/` directory to the boot directory and executes the steps needed to transform the content of the boot directory into a bootable form. Under the hood, the run tool invokes the run-module types `boot_dir` and `boot_image`. Depending on the run-tool configuration, this form may be an ISO image, a disk image, or a bootable ELF image.
5. Executing the system image using the `run_genode_until` command. Depending on the run-tool configuration, the system image is executed using an emulator or a physical machine. Under the hood, this step invokes the run modules of the types `power_on`, `load`, `log`, and `power_off`. For most platforms, Qemu is used by default. On Linux, the scenario is executed by starting core directly from the boot directory. The `run_genode_until` command takes a regular expression as argument. If the log output of the scenario matches the specified pattern, the `run_genode_until` command returns. If specifying `forever` as argument, this command will never return. If a regular expression is specified, an additional argument determines a timeout in seconds. If the regular expression does not match until the timeout is reached, the run script will abort.

After the successful completion of a run script, the run tool prints the message "Run script execution successful."

Note that the `hello.run` script does not contain kernel-specific information. Therefore it can be executed from the build directory of any base platform via the command `make run/hello KERNEL=<kernel>`. When invoking `make` with an argument of the form `run/<run-script>`, the build system searches all repositories for a run script with the specified name. The run script must be located in one of the repositories' `run/` subdirectories and have the file extension `.run`.

5.4.5. The run mechanism explained

The run tool is based on `expect`, which is an extension of the Tcl scripting language that allows for the scripting of interactive command-line-based programs. When the

user invokes a run script via *make run/<run-script>*, the build system invokes the run tool at *<genode-dir>/tool/run/run* with the run script and the content of the `RUN_OPT` definition as arguments. The run tool is an expect script that has no other purpose than defining several commands used by run scripts and including the run modules as specified by the run-tool configuration. Whereas *tool/run/run* provides the generic commands, the run modules under *tool/run/<module>/* contain all the peculiarities of the various kernels and boot strategies. The run modules thereby document precisely how the integration and boot concept works for each kernel platform.

Run modules Each module consist of an expect source file located in one of the existing directories of a category. It is named implicitly by its location and the name of the source file, e. g. *image/iso* is the name of the image module that creates an ISO image. The source file contains one mandatory function:

```
run_<module> { <module-args> }
```

The function is called if the step is executed by the run tool. If its execution was successful, it returns true and otherwise false. Certain modules may also call exit on failure.

A module may have arguments, which are - by convention - prefixed with the name of the module, e. g., *power_on/amt* has an argument called *-power-on-amt-host*. By convention, the modules contain accessor functions for argument values. For example, the function *power_on_amt_host* in the run module *power_on/amt* returns the value supplied to the argument *-power-on-amt-host*. Thereby, a run script can access the value of such arguments in a defined way by calling *power_on_amt_host*. Also, arguments without a value are treated similarly. For example, for querying the presence of the argument *-image-uboot-no-gzip*, the run module *run/image/uboot* provides the corresponding function *image_uboot_use_no_gzip*. In addition to these functions, a module may have additional public functions. Those functions may be used by run scripts or other modules. To enable a run script or module to query the presence of another module, the run tool provides the function *have_include*. For example, the presence of the *load/tftp* module can be checked by calling *have_include* with the argument "load/tftp".

5.4.6. Using run scripts to implement integration tests

Because run scripts are actually expect scripts, the whole arsenal of language features of the Tcl scripting language is available to them. This turns run scripts into powerful tools for the automated execution of test cases. A good example is the run script at *repos/lib-ports/run/lwip.run*, which tests the lwIP stack by running a simple Genode-based HTTP server on the test machine. It fetches and validates a HTML page from this server. The run script makes use of a regular expression as argument to the *run_genode_until*

command to detect the state when the web server becomes ready, subsequently executes the lynx shell command to fetch the web site, and employs Tcl's support for regular expressions to validate the result. The run script works across all platforms that have network support. To accommodate a high diversity of platforms, parts of the run script depend on the *spec* values as defined for the build directory. The spec values are probed via the *have_spec* function. Depending on the probed spec values, the run script uses the *append_if* and *lappend_if* commands to conditionally assemble the init configuration and the list of boot modules.

To use the run mechanism efficiently, a basic understanding of the Tcl scripting language is required. Furthermore the functions provided by *tool/run/run* and the run modules at *tool/run/* should be studied.

5.4.7. Automated testing across base platforms

To execute one or multiple test cases on more than one base platform, there exists a dedicated tool at *tool/autopilot*. Its primary purpose is the nightly execution of test cases. The tool takes a list of platforms and of run scripts as arguments and executes each run script on each platform. The build directory for each platform is created at */tmp/autopilot.<username>/<platform>* and the output of each run script is written to a file called *<platform>.<run-script>.log*. On *stderr*, autopilot prints the statistics about whether or not each run script executed successfully on each platform. If at least one run script failed, autopilot returns a non-zero exit code, which makes it straight forward to include autopilot into an automated build-and-test environment.

5.5. Package management

The established system-integration work flow with Genode is based on the *run* tool as explained in the previous section. It automates the building, configuration, integration, and testing of Genode-based systems. Whereas the run tool succeeds in overcoming the challenges that come with Genode's diversity of kernels and supported hardware platforms, its scalability is somewhat limited to appliance-like system scenarios: The result of the integration process is a system image with a certain feature set. Whenever requirements change, the system image is replaced with a freshly created image that takes those requirements into account. In practice, there are two limitations of this system-integration approach:

First, since the run tool implicitly builds all components required for a system scenario, the system integrator has to compile all components from source. For example, if a system includes a component based on Qt5, one needs to compile the entire Qt5 application framework, which induces significant overhead to the actual system-integration tasks of composing and configuring components.

Second, general-purpose systems tend to become too complex and diverse to be treated as system images. When looking at commodity OSes, each installation differs with respect to the installed set of applications, user preferences, used device drivers and system preferences. A system based on the run tool's work flow would require the user to customize the run script of the system for each tweak. To stay up to date, the user would need to re-create the system image from time to time while manually maintaining any customizations. In practice this is a burden very few end users are willing to endure.

The primary goal of Genode's package management is to overcome these scalability limitations, in particular:

- Alleviating the need to build everything that goes into system scenarios from scratch,
- Facilitating modular system compositions while abstracting from technical details,
- On-target system update and system development,
- Assuring the user that system updates are safe to apply by providing the ability to easily roll back the system or parts thereof to previous versions,
- Securing the integrity of the deployed software,
- Low friction for existing developers.

The design of Genode's package-management concept is largely influenced by Git as well as the <https://nixos.org/nix/> package manager. In particular the latter opened

our eyes to discover the potential that lies beyond the package management employed in state-of-the-art commodity systems. Even though we considered adapting Nix for Genode and actually conducted intensive experiments in this direction, we settled on a custom solution that leverages Genode's holistic view on all levels of the operating system including the build system and tooling, source structure, ABI design, framework API, system configuration, inter-component interaction, and the components itself. Whereby Nix is designed for being used on top of Linux, Genode's whole-systems view led us to simplifications that eliminated the needs for Nix' powerful features like its custom description language.

5.5.1. Nomenclature

When speaking about "package management", one has to clarify what a "package" in the context of an operating system represents. Traditionally, a package is the unit of delivery of a bunch of "dumb" files, usually wrapped up in a compressed archive. A package may depend on the presence of other packages. Thereby, a dependency graph is formed. To express how packages fit with each other, a package is usually accompanied with meta data (description). Depending on the package manager, package descriptions follow certain formalisms (e. g., package-description language) and express more-or-less complex concepts such as versioning schemes or the distinction between hard and soft dependencies.

Genode's package management does not follow this notion of a "package". Instead of subsuming all deliverable content under one term, we distinguish different kinds of content, each in a tailored and simple form. To avoid the clash of the notions of the common meaning of a "package", we speak of "archives" as the basic unit of delivery. The following subsections introduce the different categories. Archives are named with their version as suffix, appended via a slash. The suffix is maintained by the author of the archive. The recommended naming scheme is the use of the release date as version suffix, e. g., `report_rom/2017-05-14`.

Raw-data archive A raw-data archive contains arbitrary data that is - in contrast to executable binaries - independent from the processor architecture. Examples are configuration data, game assets, images, or fonts. The content of raw-data archives is expected to be consumed by components at runtime. It is not relevant for the build process of executable binaries. Each raw-data archive contains merely a collection of data files. There is no meta data.

API archive An API archive has the structure of a Genode source-code repository. It may contain all the typical content of such a source-code repository such as header files (in the `include/` subdirectory), source codes (in the `src/` subdirectory), library-description files (in the `lib/mk/` subdirectory), or ABI symbols (`lib/symbols/` subdirectory). At the top

level, a LICENSE file is expected that clarifies the license of the contained source code. There is no meta data contained in an API archive.

An API archive is meant to provide *ingredients* for building components. The canonical example is the public programming interface of a library (header files) and the library's binary interface in the form of an ABI-symbols file. One API archive may contain the interfaces of multiple libraries. For example, the interfaces of `libc` and `libm` may be contained in a single "libc" API archive because they are closely related to each other. Conversely, an API archive may contain a single header file only. The granularity of those archives may vary. But they have in common that they are used at build time only, not at runtime.

Source archive Like an API archive, a source archive has the structure of a Genode source-tree repository and is expected to contain all the typical content of such a source repository along with a LICENSE file. But unlike an API archive, it contains descriptions of actual build targets in the form of Genode's usual `target.mk` files.

In addition to the source code, a source archive contains a file called `used_apis`, which contains a list of API-archive names with each name on a separate line. For example, the `used_apis` file of the `report_rom` source archive looks as follows:

```
base/2017-05-14
os/2017-05-13
report_session/2017-05-13
```

The `used_apis` file declares the APIs needed to incorporate into the build process when building the source archive. Hence, they represent *build-time dependencies* on the specific API versions.

A source archive may be equipped with a top-level file called `api` containing the name of exactly one API archive. If present, it declares that the source archive *implements* the specified API. For example, the `libc/2017-05-14` source archive contains the actual source code of the `libc` and `libm` as well as an `api` file with the content `libc/2017-04-13`. The latter refers to the API implemented by this version of the `libc` source package (note the differing versions of the API and source archives)

Binary archive A binary archive contains the build result of the equally-named source archive when built for a particular architecture. That is, all files that would appear in the `<build-dir>/bin/` subdirectory when building all targets present in the source archive. There is no meta data present in a binary archive.

A binary archive is created out of the content of its corresponding source archive and all API archives listed in the source archive's `used_apis` file. Note that since a binary archive depends on only one source archive, which has no further dependencies, all binary archives can be built independently from each other. For example, a `libc`-using

application needs the source code of the application as well as the libc's API archive (the libc's header file and ABI) but it does not need the actual libc library to be present.

Package archive A package archive contains an `archives` file with a list of archive names that belong together at runtime. Each listed archive appears on a separate line. For example, the `archives` file of the package archive for the window manager `wm/2018-02-26` looks as follows:

```
genodelabs/raw/wm/2018-02-14
genodelabs/src/wm/2018-02-26
genodelabs/src/report_rom/2018-02-26
genodelabs/src/decorator/2018-02-26
genodelabs/src/floating_window_layouter/2018-02-26
```

In contrast to the list of `used_apis` of a source archive, the content of the `archives` file denotes the origin of the respective archives ("genodelabs"), the archive type, followed by the versioned name of the archive.

An `archives` file may specify raw archives, source archives, or package archives (as type `pkg`). It thereby allows the expression of `_runtime dependencies_`. If a package archive lists another package archive, it inherits the content of the listed archive. This way, a new package archive may easily customize an existing package archive.

A package archive does not specify binary archives directly as they differ between the architecture and are already referenced by the source archives.

In addition to an `archives` file, a package archive is expected to contain a `README` file explaining the purpose of the collection.

5.5.2. Depot structure

Archives are stored within a directory tree called *depot/*. The depot is structured as follows:

```
<user>/pubkey
<user>/download
<user>/src/<name>/<version>/
<user>/api/<name>/<version>/
<user>/raw/<name>/<version>/
<user>/pkg/<name>/<version>/
<user>/bin/<arch>/<src-name>/<src-version>/
```

The `<user>` stands for the origin of the contained archives. For example, the official archives provided by Genode Labs reside in a *genodelabs/* subdirectory. Within this

directory, there is a `pubkey` file with the user's public key that is used to verify the integrity of archives downloaded from the user. The file `download` specifies the download location as an URL.

Subsuming archives in a subdirectory that correspond to their origin (user) serves two purposes. First, it provides a user-local name space for versioning archives. E.g., there might be two versions of a `nitpicker/2017-04-15` source archive, one by "genodelabs" and one by "nfske". However, since each version resides in its origin's subdirectory, version-naming conflicts between different origins cannot happen. Second, by allowing multiple archive origins in the depot side-by-side, package archives may incorporate archives of different origins, which fosters the goal of a federalistic development, where contributions of different origins can be easily combined.

The actual archives are stored in the subdirectories named after the archive types (`raw`, `api`, `src`, `bin`, `pkg`). Archives contained in the `bin/` subdirectories are further subdivided in the various architectures (like `x86_64`, or `arm_v7`).

5.5.3. Depot management

The tools for managing the depot content reside under the `tool/depot/` directory. When invoked without arguments, each tool prints a brief description of the tool and its arguments.

Unless stated otherwise, the tools are able to consume any number of archives as arguments. By default, they perform their work sequentially. This can be changed by the `-j <N>` argument, where `<N>` denotes the desired level of parallelization. For example, by specifying `-j 4` to the `tool/depot/build` tool, four concurrent jobs are executed during the creation of binary archives.

Downloading archives The depot can be populated with archives in two ways, either by creating the content from locally available source codes as explained by Section 5.5.4, or by downloading ready-to-use archives from a web server.

In order to download archives originating from a specific user, the depot's corresponding user subdirectory must contain two files:

pubkey contains the public key of the GPG key pair used by the creator (aka "user") of the to-be-downloaded archives for signing the archives. The file contains the ASCII-armored version of the public key.

download contains the base URL of the web server where to fetch archives from. The web server is expected to mirror the structure of the depot. That is, the base URL is followed by a sub directory for the user, which contains the archive-type-specific subdirectories.

If both the public key and the download locations are defined, the download tool can be used as follows:

```
./tool/depot/download genodelabs/src/zlib/2018-01-10
```

The tool automatically downloads the specified archives and their dependencies. For example, as the `zlib` depends on the `libc` API, the `libc` API archive is downloaded as well. All archive types are accepted as arguments including binary and package archives. Furthermore, it is possible to download all binary archives referenced by a package archive. For example, the following command downloads the `window-manager` (`wm`) package archive, including all binary archives, for the 64-bit x86 architecture. Downloaded binary archives are always accompanied with their corresponding source and used API archives.

```
./tool/depot/download genodelabs/pkg/x86_64/wm/2018-02-26
```

Archive content is not downloaded directly to the depot. Instead, the individual archives and signature files are downloaded to a quarantine area in the form of a *public/* directory located in the root of Genode's source tree. As its name suggests, the *public/* directory contains data that is imported from or to-be exported to the public. The download tool populates it with the downloaded archives in their compressed form accompanied with their signatures.

The compressed archives are not extracted before their signature is checked against the public key defined at `depot/<user>/pubkey`. If however the signature is valid, the archive content is imported to the target destination within the depot. This procedure ensures that depot content - whenever downloaded - is blessed by the cryptographic signature of its creator.

Building binary archives from source archives With the depot populated with source and API archives, one can use the `tool/depot/build` tool to produce binary archives. The arguments have the form `<user>/bin/<arch>/<src-name>` where `<arch>` stands for the targeted CPU architecture. For example, the following command builds the `zlib` library for the 64-bit x86 architecture. It executes four concurrent jobs during the build process.

```
./tool/depot/build genodelabs/bin/x86_64/zlib/2018-01-10 -j4
```

Note that the command expects a specific version of the source archive as argument. The depot may contain several versions. So the user has to decide, which one to build.

After the tool is finished, the freshly built binary archive can be found in the depot within the `genodelabs/bin/<arch>/<src>/<version>/` subdirectory. Only the final result of the built process is preserved. In the example above, that would be the `zlib.lib.so` library.

For debugging purposes, it might be interesting to inspect the intermediate state of the build. This is possible by adding `KEEP_BUILD_DIR=1` as argument to the build command. The binary's intermediate build directory can be found besides the binary archive's location named with a `.build` suffix.

By default, the build tool won't attempt to rebuild a binary archive that is already present in the depot. However, it is possible to force a rebuild via the `REBUILD=1` argument.

Publishing archives Archives located in the depot can be conveniently made available to the public using the `tool/depot/publish` tool. Given an archive path, the tool takes care of determining all archives that are implicitly needed by the specified one, wrapping the archive's content into compressed tar archives, and signing those.

As a precondition, the tool requires you to possess the private key that matches the `depot/<you>/pubkey` file within your depot. The key pair should be present in the key ring of your GNU privacy guard.

To publish archives, one needs to provide the specific version to publish. For example:

```
./tool/depot/publish <you>/pkg/x86_64/wm/2018-02-26
```

The command checks that the specified archive and all dependencies are present in the depot. It then proceeds with the archiving and signing operations. For the latter, the pass phrase for your private key will be requested. The publish tool outputs the information about the processed archives, e. g.:

```
publish /.../public/<you>/api/base/2018-02-26.tar.xz
publish /.../public/<you>/api/framebuffer_session/2017-05-31.tar.xz
publish /.../public/<you>/api/gems/2018-01-28.tar.xz
publish /.../public/<you>/api/input_session/2018-01-05.tar.xz
publish /.../public/<you>/api/nitpicker_gfx/2018-01-05.tar.xz
publish /.../public/<you>/api/nitpicker_session/2018-01-05.tar.xz
publish /.../public/<you>/api/os/2018-02-13.tar.xz
publish /.../public/<you>/api/report_session/2018-01-05.tar.xz
publish /.../public/<you>/api/scout_gfx/2018-01-05.tar.xz
publish /.../public/<you>/bin/x86_64/decorator/2018-02-26.tar.xz
publish /.../public/<you>/bin/x86_64/floating_window_layouter/2018-02-26.tar.xz
publish /.../public/<you>/bin/x86_64/report_rom/2018-02-26.tar.xz
publish /.../public/<you>/bin/x86_64/wm/2018-02-26.tar.xz
publish /.../public/<you>/pkg/wm/2018-02-26.tar.xz
publish /.../public/<you>/raw/wm/2018-02-14.tar.xz
publish /.../public/<you>/src/decorator/2018-02-26.tar.xz
publish /.../public/<you>/src/floating_window_layouter/2018-02-26.tar.xz
publish /.../public/<you>/src/report_rom/2018-02-26.tar.xz
publish /.../public/<you>/src/wm/2018-02-26.tar.xz
```

According to the output, the tool populates a directory called *public/* at the root of the Genode source tree with the to-be-published archives. The content of the *public/* directory is now ready to be copied to a web server, e. g., by using `rsync`.

5.5.4. Automated extraction of archives from the source tree

Genode users are expected to populate their local depot with content obtained via the `tool/depot/download` tool. However, Genode developers need a way to create depot archives locally in order to make them available to users. Thanks to the `tool/depot/extract` tool, the assembly of archives does not need to be a manual process. Instead, archives can be conveniently generated out of the source codes present in the Genode source tree and the *contrib/* directory.

However, the granularity of splitting source code into archives, the definition of what a particular API entails, and the relationship between archives must be augmented by the archive creator as this kind of information is not present in the source tree as is. This is where so-called “archive recipes” enter the picture. An archive recipe defines the content of an archive. Such recipes can be located at an *recipes/* subdirectory of any source-code repository, similar to how port descriptions and run scripts are organized. Each *recipe/* directory contains subdirectories for the archive types, which, in turn, contain a directory for each archive. The latter is called a *recipe directory*.

Recipe directory The recipe directory is named after the archive *omitting the archive version* and contains at least one file named *hash*. This file defines the version of the

archive along with a hash value of the archive's content separated by a space character. By tying the version name to a particular hash value, the *extract* tool is able to detect the appropriate points in time whenever the version should be increased due to a change of the archive's content.

API, source, and raw-data archive recipes Recipe directories for API, source, or raw-data archives contain a *content.mk* file that defines the archive's content in the form of make rules. The *content.mk* file is executed from the archive's location within the depot. Hence, the contained rules can refer to archive-relative files as targets. The first (default) rule of the *content.mk* file is executed with a customized make environment:

GENODE_DIR A variable that holds the path to the root of the Genode source tree,

REP_DIR A variable with the path to the source code repository where the recipe is located

port_dir A make function that returns the directory of a port within the *contrib/* directory. The function expects the location of the corresponding port file as argument, for example, the *zlib* recipe residing in the *libports/* repository may specify `$(REP_DIR)/ports/zlib` to access the 3rd-party *zlib* source code.

Source archive recipes contain simplified versions of the *used_apis* and (for libraries) *api* files as found in the archives. In contrast to the depot's counterparts of these files, which contain version-suffixed names, the files contained in recipe directories omit the version suffix. This is possible because the *extract* tool always extracts the *current* version of a given archive from the source tree. This current version is already defined in the corresponding recipe directory.

Package-archive recipes The recipe directory for a package archive contains the verbatim content of the to-be-created package archive except for the *archives* file. All other files are copied verbatim to the archive. The content of the recipe's *archives* file may omit the version information from the listed ingredients. Furthermore, the user part of each entry can be left blank by using `_` as a wildcard. When generating the package archive from the recipe, the *extract* tool will replace this wildcard with the user that creates the archive.

5.5.5. Convenience front-end to the *extract*, *build* tools

For developers, the work flow of interacting with the depot is most often the combination of the *extract* and *build* tools whereas the latter expects concrete version names as arguments. The *create* tool accelerates this common usage pattern by allowing the user to omit the version names. Operations implicitly refer to the *current* version of the archives as defined in the recipes.

Furthermore, the *create* tool is able to manage version updates for the developer. If invoked with the argument `UPDATE_VERSIONS=1`, it automatically updates hash files of the involved recipes by taking the current date as version name. This is a valuable assistance in situations where a commonly used API changes. In this case, the versions of the API and all dependent archives must be increased, which would be a labour-intensive task otherwise. If the depot already contains an archive of the current version, the create tools won't re-create the depot archive by default. Local modifications of the source code in the repository do not automatically result in a new archive. To ensure that the depot archive is current, one can specify `FORCE=1` when executing the create tool. With this argument, existing depot archives are replaced by freshly extracted ones and version updates are detected. When specified for binary archives, `FORCE=1` normally implies `REBUILD=1`. To prevent the superfluous rebuild of binary archives whose source versions remain unchanged, `FORCE=1` can be combined with the argument `REBUILD=`.

5.5.6. Accessing depot content from run scripts

The depot tools are not meant to replace the run tool but rather to complement it. When both tools are combined, the run tool implicitly refers to "current" archive versions as defined for the archive's corresponding recipes. This way, the regular run-tool work flow can be maintained while attaining a productivity boost by fetching content from the depot instead of building it.

Run scripts can use the `import_from_depot` function to incorporate archive content from the depot into a scenario. It must be called after the `create_boot_directory` function and takes any number of `pkg`, `src`, or `raw` archives as arguments. An archive is specified as depot-relative path of the form `<user>/<type>/name`. Run scripts may call `import_from_depot` repeatedly. Each argument can refer to a specific version of an archive or just the version-less archive name. In the latter case, the current version (as defined by a corresponding archive recipe in the source tree) is used.

If a `src` archive is specified, the run tool integrates the content of the corresponding binary archive into the scenario. The binary archives are selected according the spec values as defined for the build directory.

The following excerpt of a run script incorporates the content of several binary archives into a system scenario. The `base_src` function is provided by the run tool and returns the name of an archive with the kernel-specific ingredients. It depends on the `KERNEL` and `BOARD` definition in the build directory.

```
import_from_depot [depot_user]/src/[base_src] \  
                  [depot_user]/src/report_rom \  
                  [depot_user]/src/fs_rom \  
                  [depot_user]/src/vfs \  
                  [depot_user]/src/init
```

The `depot_user` function returns the name of the depot sub directory from where the archives should be obtained. It returns “genodelabs” by default. This default can be overridden via the `-depot-user` argument of the run tool. For example, the following line in the `<build-dir>/etc/build.conf` file instructs the `import_from_depot` call above to obtain the depot content from `depot/test/`.

```
RUN_OPT += --depot-user test
```

Automated depot management When using the `import_from_depot` mechanism of the run tool, one frequently encounters a situation where the depot lacks a particular archive. Whenever the run tool detects such a situation, it prompts the user to manually curate the depot content via the `tool/depot/create` tool. The need for such manual steps negatively interferes with the development workflow. The right manual steps are sometimes not straight-forward to find, in particular after switching between Git branches.

To relieve the developer from this uncreative manual labor, the run tool provides the option `-depot-auto-update` for managing the depot automatically according to the needs of the executed run script. To enable this option, use the following line in the build configuration:

```
RUN_OPT += --depot-auto-update
```

If enabled, the run tool automatically invokes the right depot-management commands to populate the depot with the required archives, and to ensure the consistency of the depot content with the current version of the source tree. The feature comes at the price of a delay when executing the run script because the consistency check involves the extraction of all used source archives from the source tree. In regular run scripts, this delay is barely noticeable. Only when working with a run script of a large system, it may be better to leave the depot auto update disabled.

Please note that the use of the automated depot update may result in version updates of the corresponding depot recipes in the source tree (recipe hash files). It is a good practice to review and commit those hash files once the local changes in the source tree have reached a good shape.

Selectively overriding depot content While working on a component that is embedded in a complex system scenario, the advantages of the run-tool’s work flow and the depot can easily be combined. The majority of the scenario’s content may come from the depot via the `import_from_depot` mechanism. Because fetching content from the depot sidesteps the build system for those components, the system integration step becomes very quick. It is still possible to override selected components by freshly built

ones. For example, while working on the graphical *terminal* component, one may combine the following lines in one run script:

```
create_boot_directory
...
import_from_depot genodelabs/pkg/terminal
...
build { server/terminal }
build_boot_image { terminal }
```

Since, the *pkg/terminal* package is imported from the depot, the scenario obtains all ingredients needed to spawn a graphical terminal such as font and configuration data. The package also contains the `terminal` binary. However, as we want to use our freshly compiled binary instead, we override the `terminal` with our customized version by specifying the binary name in the `build_boot_image` step.

The same approach is convenient for instrumenting low-level parts of the framework while debugging a larger scenario. As the low-level parts reside within the dynamic linker, we can explicitly build the dynamic linker *lib/ld* and integrate the resulting *ld.lib.so* binary as boot module:

```
create_boot_directory
...
import_from_depot genodelabs/src/[base_src]
...
build { lib/ld }
build_boot_image { ld.lib.so }
```

5.6. Static code analysis

The Clang static analyzer tool can analyze source code in C and C++ projects to find bugs at compile time:

Clang static analyzer <https://clang-analyzer.llvm.org>

With this tool enabled, Genode users can check and ensure the quality of Genode components. It can be invoked during make invocations and during the creation of packages.

For the invocation of *make* within a Genode build directory, the `STATIC_ANALYZE` variable on the command line prompts the static analyzer to run next to the actual build step.

```
STATIC_ANALYZE=1 make -C build/x86_64 KERNEL=... run/...
```

For analyzing packages, the wrapper tool *tool/depot/static_analyze* becomes handy. It can be combined with the *tool/depot/** tools to take effect:

```
tool/depot/static_analyze tool/depot/create <user>/pkg/...
```

The results of the static-analyzer tool are generated in the form of HTML pages and can be inspected afterwards. The following example output showcases a run of the static analyzer tool:

```
make: Entering directory '../genode/build/x86_64'
checking library dependencies...
scan-build: Using '/usr/lib/llvm-6.0/bin/clang' for static analysis
...

LINK    init
scan-build: 0 bugs found.
scan-build: The analyzer encountered problems on some source files.
scan-build: Preprocessed versions of these sources were deposited in
              '/tmp/scan-build-2018-11-28-111203-20081-1/failures'.
```

This feature is known to work well with Clang 6.0 on Ubuntu 16.04. The steps to provide the required tools on Linux are like follows.

```
sudo apt install clang-tools-6.0
cd $HOME/bin
ln -s $(which scan-build-6.0) scan-build
```

5.7. Git flow

The official Genode Git repository is available at the project's GitHub site:

GitHub project

<https://github.com/genodelabs/genode>

5.7.1. Master and staging

The official Git repository has two branches “master” and “staging”.

Master branch The master branch is the recommended branch for users of the framework. It is known to have passed quality tests. The existing history of this branch is fixed and will never change.

Staging branch The staging branch contains the commits that are scheduled for inclusion into the master branch. However, before changes are merged into the master branch, they are subjected to quality-assurance measures conducted by Genode Labs. Those measures include the successful building of the framework for all base platforms and the passing of automated tests. After changes enter the staging branch, those quality-assurance measures are expected to fail. If so, the changes are successively refined by a series of *fixup* commits. Each fixup commit should refer to the commit it is refining using a commit message as follows:

```
fixup "<commit message of the refined commit>"
```

If the fixup is non-trivial, change the “fixup” prefix to “squash” and add a more elaborative description to the commit message.

Once the staging branch passes the quality-assurance measures, the Genode maintainers tidy-up the history of the staging branch by merging all fixup commits with their respective original commit. The resulting commits are then merged on top of the master branch and the staging branch is reset to the new master branch.

Note that the staging branch is volatile. In contrast to the master branch, its history is not stable. Hence, it should not be used to base developments on.

Release version The version number of a Genode release refers to the release date. The two-digit major number corresponds to the last two digits of the year and the two-digit minor number corresponds to the month. For example, “17.02”.

Each Genode release represents a snapshot of the master branch taken at release time. It is complemented by the following commits:

- “Release notes for version <version>” containing the release documentation in the form of a text file at *doc/release_notes*,
- “News item for Genode <version>” containing the release announcement as published at the *genode.org* website,
- “Version: <version>” with the adaptation of the *VERSION* file.

The latter commit is tagged with the version number. The tag is signed by one of the mainline developers.

5.7.2. Development practice

Each developer maintains a fork of Genode’s Git repository. To facilitate close collaboration with the developer community, it is recommended to host the fork on GitHub. Open a GitHub account, use GitHub’s web interface to create a new fork, and follow the steps given by GitHub to fetch the cloned repository to your development machine.

In the following, we refer to the official Genode repository as “genodelabs/genode”. To conveniently follow the project’s mainline development, it is recommended to register the official repository as a “remote” in your Git repository:

```
git remote add genodelabs https://github.com/genodelabs/genode.git
```

Once, the official repository is known to your clone, you can fetch new official revisions via

```
git fetch genodelabs
```

Topic branches As a rule of thumb, every line of development has a corresponding topic in the issue tracker. This is the place where the developers discuss and review the ongoing work. Hence, when starting a new line of development, the first step should be the creation of a new topic.

Issue tracker

<https://github.com/genodelabs/genode/issues>

The new topic should be accompanied with a short description about the motivation behind the line of work and the taken approach. The second step is the creation of a dedicated topic branch in the developer’s fork of Genode’s Git repository.

```
git checkout -b issue<number> genodelabs/master
```

The new topic branch should be based on the most current *genodelabs/master* branch. This eases the later integration of the topic branch into the mainline development.

While working on a topic branch, it is recommended to commit many small intermediate steps. This is useful to keep track of the line of thoughts during development. This history is regarded as volatile. That is, it is not set in stone. Hence, you as developer do not have to spend too much thoughts on the commits during the actual development.

Once the work on the topic is completed and the topic branch is going to get integrated into the mainline development, the developer curates the topic-branch history so that a short and well-arranged sequence of commits remains. This step is usually performed by interactively editing the topic-branch history via the `git rebase -i` command. In many cases, the entire topic branch can be squashed into a single commit. The goal behind this curating step is to let the mainline history document the progress at a level of detail that is meaningful for the users of the framework. The mainline history should satisfy the following:

- The relationship of a commit with an issue at the issue tracker should be visible. For this reason, GitHub's annotations "Issue #n" and "Fixed #n" are added to the commit messages.
- Revisiting the history between Genode releases should clearly reveal the changes that potentially interest the users. I.e., when writing the quarterly release notes, the Genode developers go through the history and base the release-notes documentation on the information contained in the commit messages. This works best if each topic is comprised by a few commits with meaningful descriptions. This becomes hard if the history contains too many details.
- Each commit should represent a kind of "transaction" that can be reviewed independently without knowing too much context. This is hardly possible if intermediate steps that subsequently touch the same code are present as individual commits.
- It should be easy to selectively revert individual topics/features using `git revert` (e. g., when trouble-shooting). This is simple when each topic is represented by one or just a few commits.

Coding conventions Genode's source code follows time-tested conventions regarding the coding style and code pattern, which are important to follow. The coding style is described in the following document:

Coding-style Guidelines

https://genode.org/documentation/developer-resources/coding_style

Writing a commit message Commit messages should adhere the following convention. The first line summarizes the commit using not more than 50 characters. This line will be displayed by various tools. So it should express the basic topic and eventually refer to an issue. For example:

```
Add sanity checks in tool/tool_chain, fix #62
```

If the patch refers to an existing issue, add a reference to the corresponding issue. If not, please consider opening an issue first. In the case the patch is supposed to close an existing issue, add this information using GitHub's conventions, e. g., by stating "Fix #45" in your commit message, the issue will be closed automatically, by stating "Issue #45", the commit will be displayed in the stream of discussion of the corresponding issue.

After a blank line, a description of the patch follows. The description should consider the following questions:

- Why is the patch needed?
- How does the patch achieve the goal?
- What are known consequences of this patch? Will it break API compatibility, or produce a follow-up issue?

Reconsider the documentation related to your patch: If the commit message contains important information not present in the source code, this information should better be placed into the code or the accompanied documentation (e. g., in the form of a README file).

6. System configuration

There are manifold principal approaches to configure different aspects of an operating system and the applications running on top. At the lowest level, there exists the opportunity to pass configuration information to the boot loader. This information may be evaluated directly by the boot loader or passed to the booted system. As an example for the former, some boot loaders allow for setting up a graphics mode depending on its configuration. Hence, the graphics mode to be used by the OS could be defined right at this early stage of booting. More prominently, however, is the mere passing of configuration information to the booted OS, e. g., in the form of a kernel command line or as command-line arguments to boot modules. The OS interprets boot-loader-provided data structures (i. e., multiboot info structures) to obtain such information. Most kernels interpret certain configuration arguments passed via this mechanism. At the OS-initialization level, before any drivers are functioning, the OS behavior is typically governed by configuration information provided along with the kernel image, i. e., an initial file-system image (initrd). On Linux-based systems, this information comes in the form of configuration files and init scripts located at well-known locations within the initial file-system image. Higher up the software stack, configuration becomes an even more diverse topic. I. e., the runtime behavior of a GNU/Linux-based system is defined by a conglomerate of configuration files, daemons and their respective command-line arguments, environment variables, collections of symlinks, and plenty of heuristics.

The diversity and complexity of configuration mechanisms, however, is problematic for high-assurance computing. To attain a high level of assurance, Genode's architecture must be complemented by a low-complexity yet scalable configuration concept. The design of this concept takes the following considerations into account:

Uniformity across platforms To be applicable across a variety of kernels and hardware platforms, the configuration mechanism must not rely on a particular kernel or boot loader. Even though boot loaders for x86-based machines usually support the multiboot specification and thereby the ability to supplement boot modules with additional command lines, boot loaders on ARM-based platforms generally lack this ability. Furthermore, even if a multiboot compliant boot loader is used, the kernel - once started - must provide a way to reflect the boot information to the system on top, which is not the case for most microkernels.

Low complexity The configuration mechanism is an intrinsic part of each component. Hence, it affects the trusted computing base of every Genode-based system. For this reason, the mechanism must be easy to understand and implementable without the need for complex underlying OS infrastructure. As a negative example, the provision of configuration files via a file system would require each Genode-based system to support the notion of a file system and to define the naming of configuration files.

Expressiveness Passing configuration information as command-line arguments to components at their creation time seems like a natural way to avoid the complexity of a file-based configuration mechanism. However, whereas command-line arguments are the tried and tested way for supplying program arguments in a concise way, the expressiveness of the approach is limited. In particular, it is ill-suited for expressing structured information as often found in configurations. Being a component-based system, Genode requires a way to express relationships between components, which lends itself to the use of a structural representation.

Common syntax The requirement of a low-complexity mechanism mandates a common syntax across components. Otherwise, each component would need to come with a custom parser. Each of those parsers would eventually inflate the complexity of the trusted computing base. In contrast, a common syntax that is both expressive and simple to parse helps to avoid such redundancies by using a single parser implementation across all components.

Least privilege Being the guiding motive behind Genode's architecture, the principle of least privilege needs to be applied to the access of configuration information. Each component needs to be able to access its own configuration but must not observe configuration information concerning unrelated components. A system-global registry of configurations or even a global namespace of keys for such a database would violate this principle.

Accommodation of dynamic workloads Supplying configuration information at the construction time of a component is not sufficient for long-living components, whose behavior might need to be adapted at runtime. For example, the assignment of resources to the clients of a resource multiplexer might change over the lifetime of the resource multiplexer. Hence, the configuration concept should provide a means to update the configuration information of a component after it has been constructed.

```

<config>
  <parent-provides> ... </parent-provides>
  <default-route> ... </default-route>
  ...
  <start name="nitpicker" caps="100">
    ...
  </start>
  <start name="launchpad" caps="2000">
    ...
    <config>
      <launcher name="Virtualbox">
        <binary name="init"/>
        <config>
          <parent-provides> ... </parent-provides>
          <default-route>
            <any-service> <any-child/> <parent/> </any-service>
          </default-route>
          <start name="nit_fb" caps="100">
            <resource name="RAM" quantum="6M"/>
            <config xpos="400" ypos="270" width="300" height="200" />
          </start>
          <provides>
            <service name="Input"/>
            <service name="Framebuffer"/>
          </provides>
        </start>
        <start name="virtualbox" caps="1000">
          <resource name="RAM" quantum="1G"/>
          <config vbox_file="test.vbox" vm_name="TestVM">
            ...
          </config>
        </start>
      </launcher>
    </config>
  </start>
</config>

```

Figure 46: Nested system configuration

6.1. Nested configuration concept

Genode's configuration concept is based on the ROM session interface described in Section 4.5.1. In contrast to a file-system interface, the ROM session interface is extremely simple. The client of a ROM service specifies the requested ROM module by its name as known by the client. There is neither a way to query a list of available ROM modules, nor are ROM modules organized in a hierarchic name space.

The ROM session interface is implemented by core's ROM service to make boot modules available to other components. Those boot modules comprise the executable binaries of the init component as well as those of the components created by init. Furthermore, a ROM module called "config" contains the configuration of the init process in XML format. To obtain its configuration, init requests a ROM session for the ROM module "config" from its parent, which is core. Figure 46 shows an example of such a

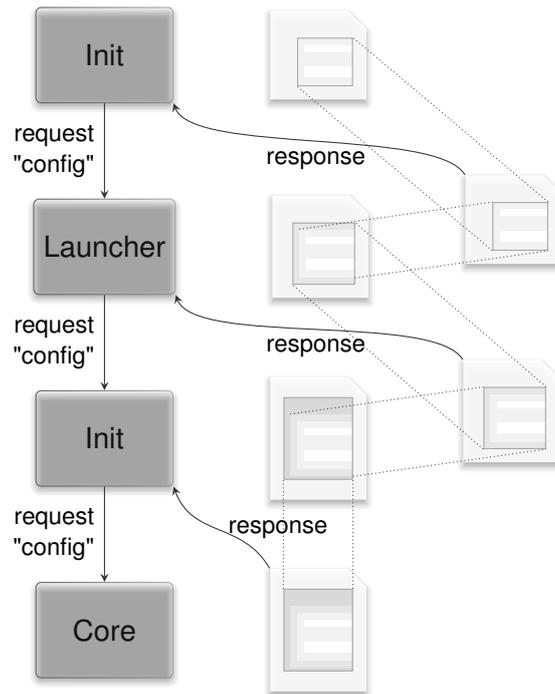


Figure 47: Successive interception of “config” ROM requests

config ROM module.

The config ROM module uses XML as syntax, which supports the expression of arbitrary structural data while being simple to parse. I.e., Genode’s XML parser comes in the form of a single header file with less than 400 lines of code. Init’s configuration is contained within a single `<config>` node.

Each component started by init obtains its configuration by requesting a ROM module named “config” from its parent. Init responds to this request by handing out a locally-provided ROM session. Instead of handing out the “config” ROM module as obtained from core, it creates a new dataspace that solely contains the portion of init’s config ROM module that refers to the respective child. Analogously to init’s configuration, each child’s configuration has the form of a single `<config>` node. This works recursively. From each component’s perspective, including the init component, the mechanism for obtaining its configuration is identical – it obtains a ROM session for a ROM module named “config” from its parent. The parent interposes the ROM session request as described in Section 4.7.3. Figure 47 shows the successive interposing of “config” ROM requests according to the example configuration given in Figure 46. At each level, the information structure within the `<config>` node can be different. Besides following the convention that a configuration has the form of a single `<config>` node, each component can introduce arbitrary custom tags and attributes.

Besides being simple, the use of the ROM session interface for supplying configuration information has the benefit of supporting dynamic configuration updates over the lifetime of the config ROM session. Section 4.5.1 describes the update protocol between client and server of a ROM session. This way, the configuration of long-living components can be dynamically changed.

6.2. The init component

The init component plays a special role within Genode's component tree. It gets started directly by core, gets assigned all physical resources, and controls the execution of all subsequent component nodes, which can be further instances of init. Init's policy is driven by an XML-based configuration, which declares a number of children, their relationships, and resource assignments.

6.2.1. Session routing

At the parent-child interface, there are two operations that are subject to policy decisions of the parent: the child announcing a service and the child requesting a service. If a child announces a service, it is up to the parent to decide if and how to make this service accessible to its other children. When a child requests a service, the parent may deny the session request, delegate the request to its own parent, implement the requested service locally, or open a session at one of its other children. This decision may depend on the service requested or the session-construction arguments provided by the child. Apart from assigning resources to children, the central element of the policy implemented in the parent is a set of rules to route session requests. Therefore, init's configuration concept is laid out around child components and the routing of session requests originating from those components. The mechanism is best illustrated by an example:

```

<config>
  <parent-provides>
    <service name="PD"/>
    <service name="ROM"/>
    <service name="CPU"/>
    <service name="LOG"/>
  </parent-provides>
  <start name="timer" caps="100">
    <resource name="RAM" quantum="1M"/>
    <provides> <service name="Timer"/> </provides>
    <route>
      <service name="PD"> <parent/> </service>
      <service name="ROM"> <parent/> </service>
      <service name="CPU"> <parent/> </service>
      <service name="LOG"> <parent/> </service>
    </route>
  </start>
  <start name="test-timer" caps="200">
    <resource name="RAM" quantum="1M"/>
    <route>
      <service name="Timer"> <child name="timer"/> </service>
      <service name="PD"> <parent/> </service>
      <service name="ROM"> <parent/> </service>
      <service name="CPU"> <parent/> </service>
      <service name="LOG"> <parent/> </service>
    </route>
  </start>
</config>

```

First, there is the declaration of services provided by the parent of the configured init instance. In this case, we declare that the parent provides a LOG service. For each child to start, there is a `<start>` node describing the assigned RAM and capability budget, declaring services provided by the child, and holding a routing table for session requests originating from the child. The first child is called “timer” and implements the “Timer” service. The second component called “test-timer” is a client of the timer service. In its routing table, we see that requests for “Timer” sessions are routed to the “timer” child whereas requests for core’s services are routed to init’s parent. Per-child service routing rules provide a flexible way to express arbitrary client-server relationships. For example, service requests may be transparently mediated through special policy components acting upon session-construction arguments. There might be multiple children implementing the same service, each targeted by different routing tables. If there exists no valid route to a requested service, the service is denied. In the example above, the routing tables act effectively as a white list of services the child is allowed to use.

Routing based on session labels Access-control policies in Genode systems are based on session labels. When a server receives a new session request, the session label is passed along with the request.

A session label is a string that is assembled by the components that are involved with routing the session request from the client along the branches of the component tree to the server. The client may specify the least significant part of the label by itself. This part gives the parent a hint for routing the request. For example, a client may create two file-system sessions, one labeled with “home” and one labeled with “bin”. The parent may take this information into account and route the individual requests to different file-system servers. The label is successively superseded (prefixed) by additional parts along the chain of components on the route of the session request. The first part of the label is the most significant part as it is imposed by the component in the intermediate proximity of the server. The last part is the least trusted part of the label because it originated from the client. Once the session request arrives at the server, the server takes the session label as the key to select a server-side policy as described in Section 4.6.2.

In most cases, routing decisions are simply based on the type of the requested sessions. However, by equipping `<service>` nodes with the following attributes, it is possible to take session labels as a criterion for the routing of session requests into account.

label="<string>" The session label must perfectly match the specified string.

label_prefix="<string>" The first part of the label must match the specified string.

label_suffix="<string>" The end of the label must match the specified string.

unscoped_label="<string>" The session label including the child’s name prefix must perfectly match the specified string. In contrast to the `label` attribute, which refers to the child-defined label, the `unscoped_label` can refer to the child’s environment sessions, which have no client-defined label because they are initiated by `init` itself.

label_last="<string>" The part after the last “→” delimiter must match the specified string. This part usually refers to a requested resource such as the name of a ROM module. If no delimiter is present, the label must be an exact match.

If no attributes are present, the route matches. The attributes can be combined. If any of the specified attributes mismatch, the route is neglected. If multiple `<service>` nodes match in `init`’s routing configuration, the first matching rule is taken. So the order of the nodes is important.

Wildcards In practice, usage scenarios become more complex than the basic example, increasing the size of routing tables. Furthermore, in many practical cases, multiple children may use the same set of services and require duplicated routing tables within the configuration. In particular during development, the elaborative specification of routing tables tend to become an inconvenience. To alleviate this problem, there are two mechanisms, namely wildcards and a default route. Instead of specifying a list of individual service routes targeting the same destination, the wildcard `<any-service>` becomes handy. For example, instead of specifying

```
<route>
  <service name="ROM"> <parent/> </service>
  <service name="LOG"> <parent/> </service>
  <service name="PD"> <parent/> </service>
  <service name="CPU"> <parent/> </service>
</route>
```

the following shorthand can be used:

```
<route>
  <any-service> <parent/> </any-service>
</route>
```

The latter version is not as strict as the first one because it permits the child to create sessions at the parent, which were not white listed in the elaborative version. Therefore, the use of wildcards is discouraged for configuring untrusted components. Wildcards and explicit routes may be combined as illustrated by the following example:

```
<route>
  <service name="LOG"> <child name="nitlog"/> </service>
  <any-service> <parent/> </any-service>
</route>
```

The routing table is processed starting with the first entry. If the route matches the service request, it is taken, otherwise the remaining routing-table entries are visited. This way, the explicit service route of “LOG” sessions to the “nitlog” child shadows the LOG service provided by the parent.

To allow a child to use services provided by arbitrary other children, there is a further wildcard called `<any-child>`. Using this wildcard, such a policy can be expressed as follows:

```
<route>
  <any-service> <parent/> </any-service>
  <any-service> <any-child/> </any-service>
</route>
```

This rule would delegate all session requests referring to one of the parent's services to the parent. If no parent service matches the session request, the request is routed to any child providing the service. The rule can be further abbreviated to:

```
<route>
  <any-service> <parent/> <any-child/> </any-service>
</route>
```

Init detects potential ambiguities caused by multiple children providing the same service. In this case, the ambiguity must be resolved using an explicit route preceding the wildcards.

Default routing To reduce the need to specify the same routing table for many children in one configuration, there is a `<default-route>` mechanism. The default route is declared within the `<config>` node and used for each `<start>` entry with no `<route>` node. In particular during development, the default route becomes handy to keep the configuration tidy and neat.

The combination of explicit routes and wildcards is designed to scale well from being convenient to use during development towards being highly secure at deployment time. If only explicit rules are present in the configuration, the permitted relationships between all processes are explicitly defined and can be easily verified.

6.2.2. Resource assignment

Physical memory budget Each `<start>` node must be equipped with a declaration of the amount of RAM assigned to the child via a `<resource>` sub node.

```
<resource name="RAM" quantum="1M"/>
```

If the specified amount exceeds the available resources, the available resources are assigned almost completely to the child. This makes it possible to assign all remaining resources to the last child by simply specifying an overly large quantum. In this case, init retains only a small amount of quota for itself, which is used to cover indirect costs such as a few capabilities created on behalf of the children, or memory used for buffering configuration data. The preserved amount can be configured as follows:

```
<config>
  ...
  <resource name="RAM" preserve="1M"/>
  ...
</config>
```

If not specified, init has a reasonable default of 160K (on 32 bit) and 320K (on 64 bit).

Capability budget Each component requires a certain amount of capabilities to live. At startup, several capabilities are created along with the component's environment sessions, in particular its PD session. At lifetime, the component consumes capabilities when creating signal handlers or RPC objects. Since the system-global amount of capabilities is a bounded resource, which depends on the used kernel and the kernel configuration, Genode subjects the allocation of capabilities to the same rigid regime as for physical memory. First, the creation of capabilities is restricted by resource quotas explicitly assigned to components. Second, capability budgets can be traded between clients and servers such that servers are able to account capability allocations to their clients.

Each `<start>` node can be equipped with a `caps` attribute with the amount of capabilities assigned to the component. As a rule of thumb, the setup costs of a component are 35 capabilities. Hence, for typical components, an amount of 100 is a practical value. To alleviate the need to equip each `<start>` node with the same default value, the `init` configuration accepts a default declaration as follows:

```
<default caps="100"/>
```

Unless a `<start>` node is equipped with a custom `caps` attribute, the default value is used.

If a component runs out of capabilities, `core`'s PD service prints a warning to the log. To observe the consumption of capabilities per component in detail, `core`'s PD service is equipped with a diagnostic mode, which can be enabled via the `diag` attribute in the target node of `init`'s routing rules. E.g., the following route enables the diagnostic mode for the PD session:

```
<route>
  <service name="PD"> <parent diag="yes"/> </service>
  ...
</route>
```

With the `diag` attribute enabled, `core` prints a log message each time the PD consumes, frees, or transfers its capability budget.

6.2.3. Multiple instantiation of a single ELF binary

Each `<start>` node requires a unique name attribute. By default, the value of this attribute is used as ROM module name for obtaining the ELF binary from the parent. If multiple instances of a component with the same ELF binary are needed, the binary name can be explicitly specified using a `<binary>` sub node of the `<start>` node:

```
<binary name="filename"/>
```

This way, a unique child name can be defined independently from the binary name.

6.2.4. Session-label rewriting

As explained in section 6.2.1, init routes session requests by taking the requested service type and the session label into account. The latter may be used by the server as a key for selecting a policy at the server side. To simplify server-side policies, init supports the rewriting of session labels in the target node of a matching session route. For example, a interactive shell (“noux”) may have the following session route for the “home” file system:

```
<route>
  <service name="File_system" label="home">
    <child name="vfs"/>
  </service>
  ...
</route>
```

At the “vfs” file-system server, the label of the file-system session will appear as “noux → home”. This information may be evaluated by the vfs’s server-side policy. However, when renaming the noux instance, we’d need to update this server-side policy.

With the label-rewriting mechanism, the client’s identity can be hidden from the server. The label can instead represent the role of the client, or a name of a physical resource. For example, the route could be changed to this:

```
<route>
  <service name="File_system" label="home">
    <child name="vfs" label="primary_user"/>
  </service>
  ...
</route>
```

When the vfs receives the session request, it is presented with the label “primary_user”. The fact that the client is “noux” is not taken into account for the server-side policy selection.

6.2.5. Nested configuration

Each <start> node can host a <config> sub node. As described in Section 6.1, the content of this sub node is provided to the child when a ROM session for the module name “config” is requested. Thereby, arbitrary configuration parameters can be passed

to the child. For example, the following configuration starts the `timer-test` within an `init` instance within another `init` instance. To show the flexibility of `init`'s service routing facility, the "Timer" session of the second-level `timer-test` child is routed to the `timer` service started at the first-level `init` instance.

```
<config>
  <parent-provides>
    <service name="LOG"/>
    <service name="ROM"/>
    <service name="CPU"/>
    <service name="PD"/>
  </parent-provides>
  <start name="timer" caps="100">
    <resource name="RAM" quantum="1M"/>
    <provides><service name="Timer"/></provides>
    <route>
      <any-service> <parent/> </any-service>
    </route>
  </start>
  <start name="init" caps="1000">
    <resource name="RAM" quantum="10M"/>
    <config>
      <parent-provides>
        <service name="Timer"/>
        <service name="LOG"/>
        <service name="ROM"/>
        <service name="CPU"/>
        <service name="PD"/>
      </parent-provides>
      <start name="test-timer" caps="200">
        <resource name="RAM" quantum="1M"/>
        <route>
          <any-service> <parent/> </any-service>
        </route>
      </start>
    </config>
    <route>
      <service name="Timer"> <child name="timer"/> </service>
      <any-service> <parent/> </any-service>
    </route>
  </start>
</config>
```

The services `ROM`, `LOG`, `CPU`, and `PD` are required by the second-level `init` instance to create the `timer-test` component. As illustrated by this example, the use of nested configurations enables the construction of arbitrarily complex component trees via a

single configuration.

6.2.6. Configuring components from distinct ROM modules

As an alternative to specifying the component configurations of all `<start>` nodes via `<config>` sub nodes, component configurations may be placed in separate ROM modules by facilitating the session-label rewriting mechanism described in Section 6.2.4:

```
<start name="nitpicker">
  <resource name="RAM" quantum="1M"/>
  <route>
    <service name="ROM" label="config">
      <parent label="nitpicker.config"/>
    </service>
    ...
  </route>
  ...
</start>
```

With this routing rule in place, a ROM session request for the module “config” is routed to the parent and appears at the parent’s ROM service under the label “nitpicker.config”.

6.2.7. Assigning subsystems to CPUs

Most multi-processor (MP) systems have topologies that can be represented on a two-dimensional coordinate system. CPU nodes close to each other are expected to have closer relationship than distant nodes. In a large MP system, it is natural to assign clusters of closely related nodes to a given workload. As described in Section 3.2, Genode’s architecture is based on a strictly hierarchic organizational structure. Thereby, it lends itself to the idea of applying this successive virtualization of resources to the problem of clustering CPU nodes.

Each component within the component tree has a component-local view on a so-called *affinity space*, which is a two-dimensional coordinate space. If the component creates a new subsystem, it can assign a portion of its own affinity space to the new subsystem by imposing a rectangular affinity location to the subsystem’s CPU session. Figure 48 illustrates the idea.

Following from the expression of affinities as a rectangular location within a component-local affinity space, the assignment of subsystems to CPU nodes consists of two parts: the definition of the affinity space dimensions as used for the init instance, and the association of subsystems with affinity locations relative to the affinity space. The affinity space is configured as a sub node of the `<config>` node. For example, the following declaration describes an affinity space of 4x2:

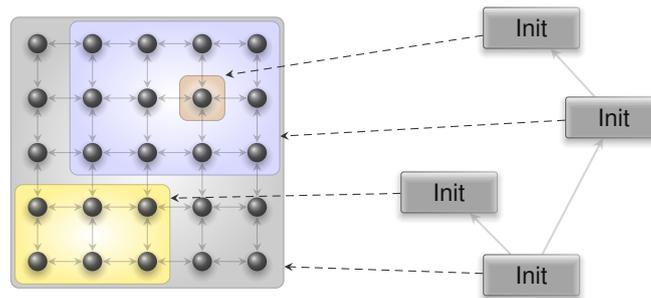


Figure 48: Successive virtualization of CPU affinity spaces by nested instances of `init`

```
<config>
...
<affinity-space width="4" height="2" />
...
</config>
```

Subsystems can be constrained to parts of the affinity space using the `<affinity>` sub node of a `<start>` entry:

```
<config>
...
<start name="loader">
  <affinity xpos="0" ypos="1" width="2" height="1" />
  ...
</start>
...
</config>
```

As illustrated by this example, the numbers used in the declarations for this instance of `init` are not directly related to physical CPUs. If the machine has merely two cores, `init`'s affinity space would be mapped to the range 0,1 of physical CPUs. However, in a machine with 16x16 CPUs, the loader would obtain 8x8 CPUs with the upper-left CPU at position (4,0).

6.2.8. Priority support

The number of CPU priorities to be distinguished by `init` can be specified with the `prio_levels` attribute of the `<config>` node. The value must be a power of two. By default, no priorities are used. To assign a priority to a child process, a priority value can be specified as `priority` attribute of the corresponding `<start>` node. Valid priority

values lie in the range of `-prio_levels + 1` (maximum priority degradation) to 0 (no priority degradation).

6.2.9. Propagation of exit events

A component can notify its parent about its graceful exit via the exit RPC function of the parent interface. By default, init responds to such a notification from one of its children by merely printing a log message but ignores it otherwise. However, there are scenarios where the exit of a particular child should result in the exit of the entire init component. To propagate the exit of a child to the parent of init, start nodes can host the optional sub node `<exit>` with the attribute `propagate` set to "yes".

```
<config>
  <start name="noux">
    <exit propagate="yes"/>
    ...
  </start>
</config>
```

The exit value specified by the exiting child is forwarded to init's parent.

6.2.10. State reporting

When used in a nested fashion, init can be configured to report its internal state in the form of a "state" report by placing a `<report>` node into init's configuration. The report node accepts the following arguments (with their default values shown):

delay_ms="100" specifies the number of milliseconds to wait before producing a new report. This way, many consecutive state changes - like they occur during startup - do not result in an overly large number of reports but are merged into one final report.

buffer="4K" the maximum size of the report in bytes. The attribute accepts the use of K/M/G as units.

init_ram="no" if enabled, the report will contain a `<ram>` node with the memory statistics of init.

init_caps="no" if enabled, the report will contain a `<caps>` node with the capability-allocation statistics of init.

ids="no" supplement the children in the report with unique IDs, which may be used to infer the lifetime of children across configuration updates in the future.

requested="no" if enabled, the report will contain information about all session requests initiated by the children.

provided="no" if enabled, the report will contain information about all sessions provided by all servers.

session_args="no" level of detail of the session information generated via requested or provided.

child_ram="no" if enabled, the report will contain a <ram> node for each child based on the information obtained from the child's PD session.

child_caps="no" if enabled, the report will contain a <caps> node for each child based on the information obtained from the child's PD session.

Note that the state reporting feature cannot be used for the initial instance of init started by core. It depends on the "Timer" and "Report" services, which are provided by higher-level components only.

6.2.11. Init verbosity

To ease debugging, init can be instructed to print diverse status information as LOG output. To enable the verbose mode, assign the value "yes" to the verbose attribute of the <config> node.

6.2.12. Service forwarding

In nested scenarios, init is able to act as a server that forwards session requests to its children. Session requests can be routed depending on the requested service type and the session label originating from init's parent.

The feature is configured by one or multiple <service> nodes hosted in init's <config> node. The routing policy is selected via the regular server-side policy-selection mechanism, for example:

```
<config>
...
<service name="LOG">
  <policy label="noux">
    <child name="terminal_log" label="important"/>
  </policy>
  <default-policy> <child name="nitlog"/> </default-policy>
</service>
...
</config>
```

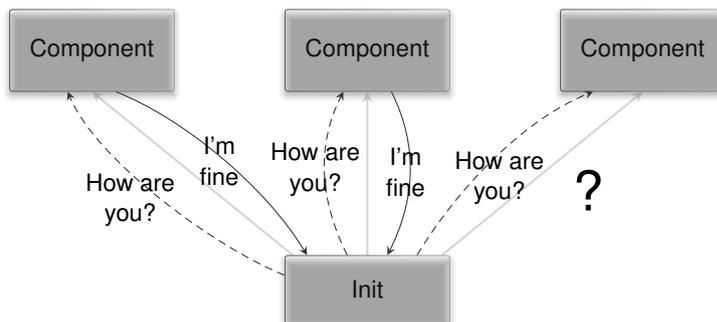


Figure 49: Init queries the responsiveness of its children

Each policy node must have a `<child>` sub node, which denotes the name of the server with the name attribute. The optional `label` attribute defines the session label presented to the server, analogous to how the rewriting of session labels works in session routes. If not specified, the client-provided label is presented to the server as is.

6.2.13. Component health monitoring

Scenarios where components are known to sometimes fail call for a mechanism that continuously checks the health of components and reports anomalies. To accommodate such use cases, Genode provides a built-in health-monitoring mechanism. Each component registers a heartbeat signal handler during its initialization at its parent. This happens under the hood and is thereby transparent to application code. Each time the signal is triggered by the parent, the default heartbeat handler invokes the `heartbeat_response` function at the parent interface and thereby confirms that the component is still able to respond to external events.

Thanks to this low-level mechanism, the `init` component is able to monitor its child components as depicted in Figure 49. A global (for this `init` instance) heartbeat rate can be configured via a `<heartbeat rate_ms="1000"/>` node at the top level of `init`'s configuration. The heartbeat rate can be specified in milliseconds. If configured, `init` uses a dedicated timer session for performing health checks periodically. Each component that hosts a `<heartbeat>` node inside its `<start>` node is monitored. In each period, `init` requests heartbeat responses from all monitored children and maintains a count of outstanding heartbeats for each component. The counter is incremented in each period and reset whenever the child responds to `init`'s heartbeat request. Whenever the number of outstanding heartbeats of a child becomes higher than 1, the child may be in trouble. `Init` reports this information in its state report via the new attribute `skipped_heartbeats="N"` where `N` denotes the number of periods since the child became unresponsive.

Of course, the mechanism won't deliver 100% accuracy. There may be situations like long-running calculations where long times of unresponsiveness are expected from a

healthy component. Vice versa, in a multi-threaded application, the crash of a secondary thread may go undetected if the primary (checked) thread stays responsive. However, in the majority of cases where a component crashes (page fault, stack overflow), gets stuck in a busy loop, produces a deadlock, or throws an unhandled exception (abort), the mechanism nicely reflects the troublesome situation to the outside.

7. Under the hood

This chapter gives insight into the inner workings of the Genode OS framework. In particular, it explains how the concepts explained in Chapter 3 are realized on different kernels and hardware platforms.

7.1. Component-local startup code and linker scripts

All Genode components including core rely on the same startup code, which is roughly outlined at the end of Section 3.5. This section revisits the required steps in more detail and refers to the corresponding points in the source code. Furthermore, it provides background information about the linkage of components, which is closely related to the startup code.

7.1.1. Linker scripts

Under the hood, the Genode build system uses three different linker scripts located at *repos/base/src/ld/*:

genode.ld is used for statically linked components, including core,

genode_dyn.ld is used for dynamically linked components, i. e., components that are linked against at least one shared library,

genode_rel.ld is used for shared libraries.

Additionally, there exists a special linker script for the dynamic linker (Section 7.6).

Each program image generated by the linker generally consists of three parts, which appear consecutively in the component's virtual memory.

1. A read-only "text" part contains sections for code, read-only data, and the list of global constructors and destructors.

The startup code is placed in a dedicated section `.text.crt0`, which appears right at the start of the segment. Thereby the link address of the component is known to correspond to the ELF entrypoint (the first instruction of the assembly startup code). This is useful when converting the ELF image of the base-hw version of core into a raw binary. Such a raw binary can be loaded directly into the memory of the target platform without the need for an ELF loader.

The mechanisms for generating the list of constructors and destructors differ between CPU architecture and are defined by the architecture's ABI. On x86, the lists are represented by `.ctors.*` and `.dtors.*`. On ARM, the information about global constructors is represented by `.init_array` and there is no visible information about global destructors.

2. A read-writable "data" part that is pre-populated with data.
3. A read-writable "bss" part that is not physically present in the binary but known to be zero-initialized when the ELF image is loaded.

The link address is not defined in the linker script but specified as linker argument. The default link address is specified in a platform-specific spec file, e. g., *repos/base-nova/mk/spec/nova.mk* for the NOVA platform. Components that need to organize their virtual address space in a special way (e. g., a virtual machine monitor that co-locates the guest-physical address space with its virtual address space) may specify link addresses that differ from the default one by overriding the `LD_TEXT_ADDR` value.

ELF entry point As defined at the start of the linker script via the `ENTRY` directive, the ELF entrypoint is the function `_start`. This function is located at the very beginning of the `.text.crt0` section. See the Section 7.1.2 for more details.

Symbols defined by the linker script The following symbols are defined by the linker script and used by the base framework.

`_prog_img_beg`, `_prog_img_data`, `_prog_img_end` Those symbols mark the start of the “text” part, the start of the “data” part (the end of the “text” part), and the end of the “bss” part. They are used by core to exclude those virtual memory ranges from the core’s virtual-memory allocator (core-region allocator).

`_parent_cap`, `_parent_cap_thread_id`, `_parent_cap_local_name` Those symbols are located at the beginning of the “data” part. During the ELF loading of a new component, the parent writes information about the parent capability to this location (the start of the first read-writable ELF segment). See the corresponding code in the `Loaded_executable` constructor in *base/src/lib/base/child_process.cc*. The use of the information depends on the base platform. E.g., on a platform where a capability is represented by a tuple of a global thread ID and an object ID such as OKL4 and L4ka::Pistachio, the information is taken as verbatim values. On platforms that fully support capability-based security without the use of any form of a global name to represent a capability, the information remains unused. Here, the parent capability is represented by the same known local name in all components.

Even though the linker scripts are used across all base platforms, they contain a few platform-specific supplements that are needed to support the respective kernel ABIs. For example, the definition of the symbol `__l4sys_invoke_indirect` is needed only on the Fiasco.OC platform and is unused on the other base platforms. Please refer to the comments in the linker script for further explanations.

7.1.2. Startup code

The execution of the initial thread of a new component starts at the ELF entry point, which corresponds to the `_start` function. This is an assembly function defined in

repos/base/src/lib/startup/spec/<arch>/crt0.s where *<arch>* is the CPU architecture (x86_32, x86_64, or ARM).

Assembly startup code The assembly startup code is position-independent code (PIC). Because the Genode base libraries are linked against both statically-linked and dynamically linked executables, they have to be compiled as PIC code. To be consistent with the base libraries, the startup code needs to be position-independent, too.

The code performs the following steps:

1. Saving the initial state of certain CPU registers. Depending on the used kernel, these registers carry information from the kernel to the core component. More details about this information are provided by Section 7.3.2. The initial register values are saved in global variables named `_initial_<register>`. The global variables are located in the BSS segment. Note that those variables are used solely by core.
2. Setting up the initial stack. Before the assembly code can call any higher-level C function, the stack pointer must be initialized to point to the top of a valid stack. The initial stack is located in the BSS section and referred to by the symbol `_stack_high`. However, having a stack located within the BSS section is dangerous. If it overflows (e. g., by declaring large local variables, or by recursive function calls), the stack would silently overwrite parts of the BSS and DATA sections located below the lower stack boundary. For prior known code, the stack can be dimensioned to a reasonable size. But for arbitrary application code, no assumption about the stack usage can be made. For this reason, the initial stack cannot be used for the entire lifetime of the component. Before any component-specific code is called, the stack needs to be relocated to another area of the virtual address space where the lower bound of the stack is guarded by empty pages. When using such a “real” stack, a stack overflow will produce a page fault, which can be handled or at least immediately detected. The initial stack is solely used to perform the steps required to set up the real stack. Because those steps are the same for all components, the usage of the initial stack is bounded.
3. Because the startup code is used by statically linked components as well as the dynamic linker, the startup immediately calls the `init_rtd` hook function. For regular components, the function does not do anything. The default implementation in *init_main_thread.cc* at *repos/base/src/lib/startup/* is a weak function. The dynamic linker provides a non-weak implementation, which allows the linker to perform initial relocations of itself very early at the dynamic linker’s startup.
4. By calling the `init_main_thread` function defined in *repos/base/src/lib/startup/init_main_thread.cc*, the assembly code triggers the execution of all the steps needed for the creation

of the real stack. The function is implemented in C++, uses the initial stack, and returns the address of the real stack.

5. With the new stack pointer returned by `init_main_thread`, the assembly startup code is able to switch the stack pointer from the initial stack to the real stack. From this point on, stack overflows cannot easily corrupt any data.
6. With the real stack in place, the assembly code finally passes the control over to the C++ startup code provided by the `_main` function.

Initialization of the real stack along with the Genode environment As mentioned above, the assembly code calls the `init_main_thread` function (located in `repos/base/src/lib/startup/init_main_thread.cc`) for setting up the real stack for the program. For placing a stack in a dedicated portion of the component's virtual address space, the function needs to overcome two principle problems:

- It needs to obtain the backing store used for the stack, i. e., allocating a dataspace from the component's PD session as initialized by the parent.
- It needs to preserve a portion of its virtual address space for placing the stack and make the allocated memory visible within this portion.

In order to solve both problems, the function needs to obtain the capability for its PD session from its parent. This comes down to the need to perform RPC calls. First, for requesting the PD session capability from the parent, and second, for invoking the session capability to perform the RAM allocation and region-map attach operations.

The RPC mechanism is based on C++. In particular, the mechanism supports the propagation of C++ exceptions across RPC interfaces. Hence, before being able to perform RPC calls, the program must initialize the C++ runtime including the exception-handling support. The initialization of the C++ runtime, in turn, requires support for dynamically allocating memory. Hence, a heap must be available. This chain of dependencies ultimately results in the need to construct the entire Genode environment as a side effect of initializing the real stack of the program.

During the construction of the Genode environment, the program requests its own CPU, PD, and LOG sessions from its parent.

With the environment constructed, the program is able to interact with its own PD session and can principally realize the initialization of the real stack. However, instead of merely allocating a new RAM dataspace and attaching the dataspace to the address space of the PD session, a so-called stack area is used. The stack area is a secondary region map that is attached as a dataspace to the component's address-space region map. This way, virtual-memory allocations within the stack area can be managed manually. I.e., the spaces between the stacks of different threads are guaranteed to remain free from any attached dataspaces. The stack area of a component is created as part of the

component's PD session. The environment initialization code requests its region-map capability via `Pd_session::stack_area` and attaches it as a managed dataspace to the component's address space.

Component-dependent startup code With the Genode environment constructed and the initial stack switched to a proper stack located in the stack area, the component-dependent startup code of the `_main` function in `repos/base/src/lib/startup/_main.cc` can be executed. This code is responsible for calling the global constructors of the program before calling the program's main function.

In accordance to the established signature of the `main` function, taking an argument list and an environment as arguments, the startup code supplies these arguments but uses dummy default values. However, since the values are taken from the global variables `genode_argv`, `genode_argc`, and `genode_envp`, a global constructor is able to override the default values.

The startup code in `_main.cc` is accompanied with support for `atexit` handling. The `atexit` mechanism allows for the registration of handlers to be called at the exit of the program. It is provided in the form of a POSIX API by the C runtime. But it is also used by the compiler to schedule the execution of the destructors of function-local static objects. For the latter reason, the `atexit` mechanism cannot be merely provided by the (optional) C runtime but must be supported by the base library.

7.2. C++ runtime

Genode is implemented in C++ and relies on all C++ features required to use the language in its idiomatic way. This includes the use of exceptions and runtime-type information.

7.2.1. Rationale behind using exceptions

Compared to return-based error handling as prominently used in C programs, the C++ exception mechanism is much more complex. In particular, it requires the use of a C++ runtime library that is called as a back-end by the exception handling code and generated by the compiler. This library contains the functionality needed to unwind the stack and a mechanism for obtaining runtime type information (RTTI). The C++ runtime libraries that come with common tool chains, in turn, rely on a C library for performing dynamic memory allocations, string operations, and I/O operations. Consequently, C++ programs that rely on exceptions and RTTI implicitly depend on a C library. For this reason, the use of those C++ features is universally disregarded for low-level operating-system code that usually does not run in an environment where a complete C library is available.

In principle, C++ can be used without exceptions and RTTI (by passing the arguments `-fno-exceptions` and `-fno-rtti` to GCC). However, without those features, it is hardly possible to use the language as designed.

For example, when the operator `new` is used, it performs two steps: Allocating the memory needed to hold the to-be-created object and calling the constructor of the object with the return value of the allocation as `this` pointer. In the event that the memory allocation fails, the only way for the allocator to propagate the out-of-memory condition is throwing an exception. If such an exception is not thrown, the constructor would be called with a null as `this` pointer.

Another example is the handling of errors during the construction of an object. The object construction may consist of several consecutive steps such as the construction of base classes and aggregated objects. If one of those steps fails, the construction of the overall object remains incomplete. This condition must be propagated to the code that issued the object construction. There are two principle approaches:

1. The error condition can be kept as an attribute in the object. After constructing the object, the user of the object may detect the error condition by requesting the attribute value. However, this approach is plagued by the following problems.

First, the failure of one step may cause subsequent steps to fail as well. In the worst case, if the failed step initializes a pointer that is passed to subsequent steps, the subsequent steps may use an uninitialized pointer. Consequently, the error condition must eventually be propagated to subsequent steps, which, in turn, need to be implemented in a defensive way.

Second, if the construction failed, the object exists but it is inconsistent. In the worst case, if the user of the object misses to check for the successful construction, it will perform operations on an inconsistent object. But even in the good case, where the user detects the incomplete construction and decides to immediately destruct the object, the destruction is error prone. The already performed steps may have had side effects such as resource allocations. So it is important to revert all the successful steps by invoking their respective destructors. However, when destructing the object, the destructors of the incomplete steps are also called. Consequently, such destructors need to be implemented in a defensive manner to accommodate this situation.

Third, objects cannot have references that depend on potentially failing construction steps. In contrast to a pointer that may be marked as uninitialized by being a null pointer, a reference is, by definition, initialized once it exists. Consequently, the result of such a step can never be passed as reference to subsequent steps. Pointers must be used.

Fourth, the mere existence of incompletely constructed objects introduces many variants of possible failures that need to be considered in the code. There may be many different stages of incompleteness. Because of the third problem, every time a construction step takes the result of a previous step as an argument, it explicitly has to consider the error case. This, in turn, tremendously inflates the test space of the code.

Furthermore, there needs to be a convention of how the completion of an object is indicated. All programmers have to learn and follow the convention.

2. The error condition triggers an exception. Thereby, the object construction immediately stops at the erroneous step. Subsequent steps are not executed at all. Furthermore, while unwinding the stack, the exception mechanism reverts all already completed steps by calling their respective destructors. Consequently, the construction of an object can be considered as a transaction. If it succeeds, the object is known to be completely constructed. If it fails, the object immediately ceases to exist.

Thanks to the transactional semantics of the second variant, the state space for potential error conditions (and thereby the test space) remains small. Also, the second variant facilitates the use of references as class members, which can be safely passed as arguments to subsequent constructors. When receiving such a reference as argument (as opposed to a pointer), no validity checks are needed. Consequently, by using exceptions, the robustness of object-oriented code (i. e., code that relies on C++ constructors) can be greatly improved over code that avoids exceptions.

7.2.2. Bare-metal C++ runtime

Acknowledging the rationale given in the previous section, there is still the problem of the complexity added by the exception mechanism. For Genode, the complexity of the trusted computing base is a fundamental metric. The C++ exception mechanism with its dependency to the C library arguably adds significant complexity. The code complexity of a C library exceeds the complexity of the fundamental components (such as the kernel, core, and init) by an order of magnitude. Making the fundamental components depend on such a C library would jeopardize one of Genode's most valuable assets, which is its low complexity.

To enable the use of C++ exceptions and runtime type information but avoid the incorporation of an entire C library into the trusted computing base, Genode comes with a customized C++ runtime that does not depend on a C library. The C++ runtime libraries are provided by the tool chain, which interface with the symbols provided by Genode's C++ support code (*repos/base/src/lib/cxx*).

Unfortunately, the interface used by the C++ runtime does not reside in a specific namespace but it is rather a subset of the POSIX API. When linking a real C library to a Genode component, the symbols present in the C library would collide with the symbols present in Genode's C++ support code. For this reason, the C++ runtime (of the compiler) and Genode's C++ support code are wrapped in a single library (*repos/base/lib/mk/cxx.mk*) in a way that all POSIX functions remain hidden. All the references of the C++ runtime are resolved by the C++ support code, both wrapped in the *cxx* library. To the outside, the *cxx* library solely exports the CXA ABI as required by the compiler.

7.3. Interaction of core with the underlying kernel

Core is the root of the component tree. It is initialized and started directly by the underlying kernel and has two purposes. First, it makes the low-level physical resources of the machine available to other components in the form of services. These resources are physical memory, processing time, device resources, initial boot modules, and protection mechanisms (such as the MMU, IOMMU, and virtualization extensions). It thereby hides the peculiarities of the used kernel behind an API that is uniform across all kernels supported by Genode. Core's second purpose is the creation of the init component by using its own services and following the steps described in Section 3.5.

Even though core is executed in user mode, its role as the root of the component tree makes it as critical as the kernel. It just happens to be executed in a different processor mode. Whereas regular components solely interact with the kernel when performing inter-component communication, core interplays with the kernel more intensely. The following subsections go into detail about this interplay.

The description tries to be general across the various kernels supported by Genode. Note, however, that a particular kernel may deviate from the general description.

7.3.1. System-image assembly

A Genode-based system consists of potentially many boot modules. But boot loaders - in particular on ARM platforms - usually support the loading of a single system image only. To unify the boot procedure across kernels and CPU architectures, on all kernels except Linux, Genode merges boot modules together with the core component into a single image.

The core component is actually built as a library. The library description file is specific for each platform and located at `lib/mk/spec/<pf>/core.mk` where `<pf>` corresponds to the hardware platform used. It includes the platform-agnostic `lib/mk/core.inc` file. The library contains everything core needs (including the C++ runtime and the core code) except the following symbols:

`_boot_modules_headers_begin` and `_boot_modules_headers_end` Between those symbols, core expects an array of boot-module header structures. A boot-module header contains the name, core-local address, and size of a boot module. This meta data is used by core's initialization code in `src/core/platform.cc` to populate the ROM service with modules.

`_boot_modules_binaries_begin` and `_boot_modules_binaries_end` Between those symbols, core expects the actual module data. This range is outside the core image (beyond `_prog_img_end`). In contrast to the boot-module headers, the modules reside in a separate section that remains unmapped within core's virtual address space. Only when access to a boot module is required by core (i. e., the ELF binary

of init during the creation of the init component), core makes the module visible within its virtual address space.

Making the boot modules invisible to core has two benefits. The integrity of the boot modules does not depend on core. Even in the presence of a bug in core, the boot modules cannot be accidentally overwritten. Second, no page-table entries are needed to map the modules into the virtual address space of core. This is particularly beneficial when using large boot modules such as a complete disk image. If incorporated into the core image, page-table entries for the entire disk image would need to be allocated at the initialization time of core.

These symbols are defined in an assembly file called *boot_modules.s*. When building core stand-alone, the final linking stage combines the core library with the dummy *boot_modules.s* file located at *src/core/boot_modules.s*. But when using the run tool (Section 5.4.1) to integrate a bootable system image, the run tool dynamically generates a version of *boot_modules.s* depending on the boot modules listed in the run script and repeats the final linking stage of core by combining the core library with the generated *boot_modules.s* file. The generated file is placed at *<build-dir>/var/run/<scenario>/* and incorporates the boot modules using the assembler's `.incbin` directive. The result of the final linking stage is an executable ELF binary that contains both core and the boot modules.

7.3.2. Bootstrapping and allocator setup

At boot time, the kernel passes information about the physical resources and the initial system state to core. Even though the mechanism and format of this information varies from kernel to kernel, it generally covers the following aspects:

- A list of free physical memory ranges
- A list of the physical memory locations of the boot modules along with their respective names
- The number of available CPUs
- All information needed to enable the initial thread to perform kernel operations

Core's allocators Core's kernel-specific platform initialization code (*core/platform.cc*) uses this information to initialize the allocators used for keeping track of physical resources. Those allocators are:

RAM allocator contains the ranges of the available physical memory

I/O memory allocator contains the physical address ranges of unused memory-mapped I/O resources. In general, all ranges not initially present in the RAM allocator are considered to be I/O memory.

I/O port allocator contains the I/O ports on x86-based platforms that are currently not in use. This allocator is initialized with the entire I/O port range of 0 to 0xffff.

IRQ allocator contains the IRQs that are associated with IRQ sessions. This allocator is initialized with the entirety of the available IRQ numbers.

Core-region allocator contains the virtual memory regions of core that are not in use.

The RAM allocator and core-region allocator are subsumed in the so-called core-memory allocator. In addition to aggregating both allocators, the core-memory allocator allows for the allocation of core-local virtual-memory regions that can be used for holding core-local objects. Each region allocated from the core-memory allocator has to satisfy three conditions:

1. It must be backed by a physical memory range (as allocated from the RAM allocator)
2. It must have assigned a core-local virtual memory range (as allocated from the core-region allocator)
3. The physical-memory range must have the same size as the virtual-memory range
4. The virtual memory range must be mapped to the physical memory range using the MMU

Internally, the core-memory allocator maintains a so-called mapped-memory allocator that contains ranges of ready-to-use core-local memory. If a new allocation exceeds the available capacity, the core-memory allocator expands its capacity by allocating a new physical memory region from the RAM allocator, allocating a new core-virtual memory region from the core-region allocator, and installing a mapping from the virtual region to the physical region.

All memory allocations mentioned above are performed at the granularity of physical pages, i. e., 4 KiB.

The core-memory allocator is expanded on demand but never shrunk. This makes it unsuitable for allocating objects on behalf of core's clients because allocations could not be reverted when closing a session. It is solely used for dynamic memory allocations at startup (e. g., the memory needed for keeping the information about the boot modules), and for keeping meta data for the allocators themselves.

7.3.3. Kernel-object creation

Kernel objects are objects maintained within the kernel and used by the kernel. The exact notion of what a kernel object represents depends on the actual kernel as the various kernels differ with respect to the abstractions they provide. Typical kernel objects are threads and protection domains. Some kernels have kernel objects for memory

mappings while others provide page tables as kernel objects. Whereas some kernels represent scheduling parameters as distinct kernel objects, others subsume scheduling parameters to threads. What all kernel objects have in common, though, is that they consume kernel memory. Most kernels of the L4 family preserve a fixed pool of memory for the allocation of kernel objects.

If an arbitrary component were able to perform a kernel operation that triggers the creation of a kernel object, the memory consumption of the kernel would depend on the good behavior of all components. A misbehaving component may exhaust the kernel memory.

To counter this problem, on Genode, only core triggers the creation of kernel objects and thereby guards the consumption of kernel memory. Note, however, that not all kernels are able to prevent the creation of kernel objects outside of core.

7.3.4. Page-fault handling

Each time a thread within the Genode system triggers a page fault, the kernel reflects the page fault along with the fault information as a message to the user-level page-fault handler residing in core. The fault information comprises the identity and instruction pointer of the faulted thread, the page-fault address, and the fault type (read, write, execute). The page-fault handler represents each thread as a so-called *pager object*, which encapsulates the subset of the thread's interface that is needed to handle page faults. For handling the page fault, the page-fault handler first looks up the pager object that belongs to the faulting thread's identity, analogously to how an RPC entry-point looks up the RPC object for an incoming RPC request. Given the pager object, the fault is handled by calling the pager function with the fault information as argument. This function is implemented by the so-called `Rm_client` (`repos/base/src/core/region_map_component.cc`), which represents the association of the pager object with its virtual address space (region map). Given the context information about the region map of the thread's PD, the pager function looks up the region within the region map, on which the page fault occurred. The lookup results in one of the following three cases:

Region is populated with a dataspace If a dataspace is attached at the fault address, the backing store of the dataspace is determined. Depending on the kernel, the backing store may be a physical page, a core-local page, or another reference to a physical memory page. The pager function then installs a memory mapping from the virtual page where the fault occurred to the corresponding part of the backing store.

Region is populated with a managed dataspace If the fault occurred within a region where a managed dataspace is attached, the fault handling is forwarded to the region map that represents the managed dataspace.

Region is empty If no dataspace could be found at the fault address, the fault cannot be resolved. In this case, core submits an region-map-fault signal to the region map where the fault occurred. This way, the region-map client has the chance to detect and possibly respond to the fault. Once the signal handler receives a fault signal, it is able to query the fault address from the region map. As a response to the fault, the region-map client may attach a dataspace at this address. This attach operation, in turn, will prompt core to wake up the thread (or multiple threads) that faulted within the attached region. Unless a dataspace is attached at the page-fault address, the faulting thread remains blocked. If no signal handler for region-map faults is registered for the region map, core prints a diagnostic message and blocks the faulting thread forever.

To optimize the TLB footprint and the use of kernel memory, region maps do not merely operate at the granularity of memory pages but on address ranges whose size and alignment are arbitrary power-of-two values (at least as large as the size of the smallest physical page). The source and destinations of memory mappings may span many pages. This way, depending on the kernel and the architecture, multiple pages may be mapped at once, or large page-table mappings can be used.

7.4. Asynchronous notification mechanism

Section 3.6.2 introduces asynchronous notifications (signals) as one of the fundamental inter-component communication mechanisms. The description covers the semantics of the mechanism but the question of how the mechanism relates to core and the underlying kernel remains unanswered. This section complements Section 3.6.2 with those implementation details.

Most kernels do not directly support the semantics of asynchronous notifications as presented in Section 3.6.2. As a reminder, the mechanism has the following features:

- The authority for triggering a signal is represented by a signal-context capability, which can be delegated via the common capability-delegation mechanism described in Section 3.1.4.
- The submission of a signal is a fire-and-forget operation. The signal producer is never blocked.
- On the reception of a signal, the signal handler can obtain the context to which the signal refers. This way, it is able to distinguish different sources of events.
- A signal receiver can wait or poll for potentially many signal contexts. The number of signal contexts associated with a single signal receiver is not limited.

The gap between this feature set and the mechanisms provided by the underlying kernel is bridged by core as part of the PD service. This service plays the role of a proxy between the producers and receivers of signals. Each component that interacts with signals has a session to this service.

Within core, a signal context is represented as an RPC object. The RPC object maintains a counter of signals pending for this context. Signal contexts can be created and destroyed by the clients of the PD service using the *alloc_context* and *free_context* RPC functions. Upon the creation of a signal context, the PD client can specify an integer value called *imprint* with a client-local meaning. Later, on the reception of signals, the imprint value is delivered along with the signal to enable the client to tell the contexts of the incoming signals apart. As a result of the allocation of a new signal context, the client obtains a signal-context capability. This capability can be delegated to other components using the regular capability-delegation mechanism.

Signal submission A component in possession of a signal-context capability is able to trigger signals using the *submit* function of its PD session. The submit function takes the signal context capability of the targeted context and a counter value as arguments. The capability as supplied to the submit function does not need to originate from the called session. It may have been created and delegated by another component. Note that even though a signal context is an RPC object, the submission of a signal is not realized as an invocation of this object. The signal-context capability is merely used

as an RPC function argument. This design accounts for the fact that signal-context capabilities may originate from untrusted peers as is the case for servers that deliver asynchronous notifications to their clients. A client of such a server supplies a signal-context capability as argument to one of the server's RPC functions. An example is the input session interface (Section 4.5.4) that allows the client to get notified when new user input becomes available. A malicious client may specify a capability that was not created via core's PD service but that instead refers to an RPC object local to the client. If the submit function was an RPC function of the signal context, the server's call of the submit RPC function would eventually invoke the RPC object of the client. This would put the client in a position where it may block the server indefinitely and thereby make the server unavailable to all clients. In contrast to the untrusted signal-context capability, the PD session of a signal producer is by definition trusted. So it is safe to invoke the submit RPC function with the signal-context capability as argument. In the case where an invalid signal-context capability is delegated to the signal producer, core will fail to look up a signal context for the given capability and omit the signal.

Signal reception For receiving signals, a component needs a way to obtain information about pending signals from core. This involves two steps: First, the component needs a way to block until signals are available. Second, if a signal is pending, the component needs a way to determine the signal context and the signal receiver associated with the signal and wake up the thread that blocks the `Signal_receiver::block_for_signal` API function.

Both problems are solved by a dedicated thread that is spawned during component startup. This signal thread blocks at core's PD service for incoming signals. The blocking operation is not directly performed on the PD session but on a decoupled RPC object called *signal source*. In contrast to the PD session interface that is kernel agnostic, the underlying kernel mechanism used for blocking the signal thread at the signal source depends on the used base platform.

The signal-source RPC object implements an RPC interface, on which the PD client issues a blocking `wait_for_signal` RPC function. This function blocks as long as no signal that refers to the session's signal contexts is pending. If the function returns, the return value contains the imprint that was assigned to the signal context at its creation and the number of signals pending for this context. On most base platforms, the implementation of the blocking RPC interface is realized by processing RPC requests and responses out of order to enable one entrypoint in core to serve all signal sources. Core uses a dedicated entrypoint for the signal-source handling to decouple the delivery of signals from potentially long-taking operations of the other core services.

Given the imprint value returned by the signal source, the signal thread determines the signal context and signal receiver that belongs to the pending signal (using a data structure called `Signal_context_registry`) and locally submits the signal to the signal-receiver object. This, in turn, unblocks the `Signal_receiver::block_for_signal`

function at the API level.

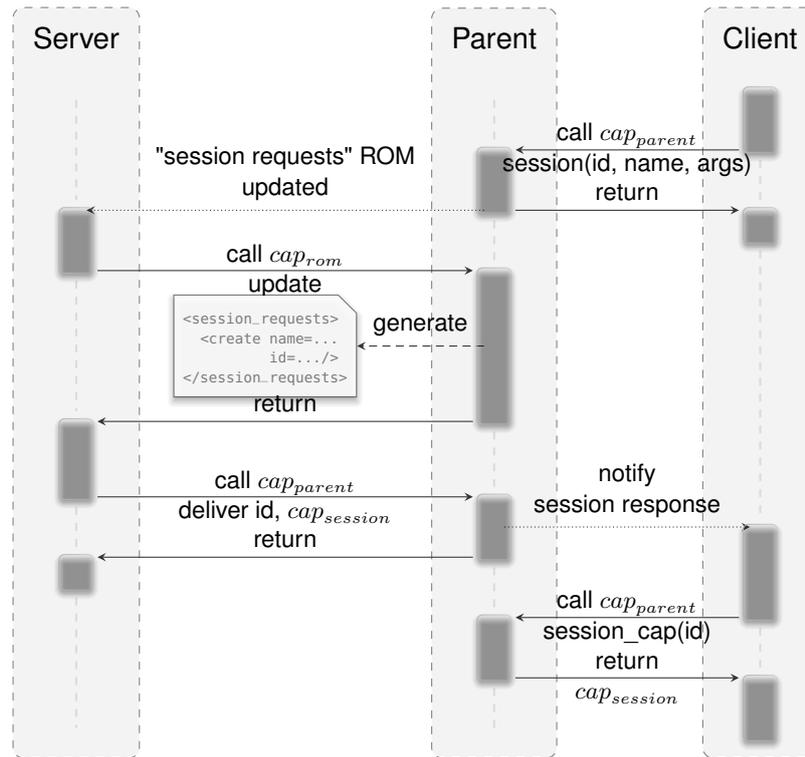


Figure 50: Parent-child interplay during the creation of a new session. The dotted lines are asynchronous notifications, which have fire-and-forget semantics. A component that triggers a signal does not block.

7.5. Parent-child interaction in detail

On a conceptual level, the session-creation procedure as described in Section 3.2.3 appears as a synchronous interaction between the parent and its child components. The interaction serves three purposes. First, it is used to communicate information between different protection domains, in this case the parent, the client, and the server. Second, it implicitly dictates the flow of control between the involved parties because the caller blocks until the callee replies. Third, the interplay delegates authority (in particular authority to access the server's session object) between protection domains. The latter is realized with the kernel's ability to carry capabilities as IPC message payload.

On the surface, the interaction looks like a sequence of synchronous RPC calls. However, under the hood, the interplay between the parent and its children is based on a combination of asynchronous notifications from the parent to the children and synchronous RPC from the children to the parent. The protocol is designed such that the parent's liveliness remains independent from the behavior of its children, which must generally be regarded as untrusted from the parent's perspective. The sequence of cre-

ating a session is depicted in Figure 50. The following points are worth noting:

- Sessions are identified via IDs, which are plain numbers as opposed to capabilities. The IDs as seen by the client and server belong to different ID name spaces. IDs of sessions requested by the client are allocated by the client. IDs of sessions requested at the server are allocated by the parent.
- The parent does not issue RPC calls to any of its children.
- Each activation of the parent merely applies a state change of the session's meta data structures maintained at the parent, which capture the entire state of session requests.
- The information about pending session requests is communicated from the parent to the server via a ROM session. At startup, the server requests a ROM session for the ROM module "session_requests" from its parent. The parent implements this ROM session locally. Since ROM sessions support versions, the parent can post version updates of the "session_requests" ROM with the regular mechanisms already present in Genode.
- The parties involved can potentially run in parallel.

7.6. Dynamic linker

The dynamic linker is a mechanism for loading ELF binaries that are dynamically-linked against shared libraries.

7.6.1. Building dynamically-linked programs

The build system automatically decides whether a program is linked statically or dynamically depending on the use of shared libraries. If the target is linked against at least one shared library, the resulting ELF image is a dynamically-linked program. Almost all Genode components are linked against the Genode application binary interface (ABI), which is a shared library. Therefore, components are dynamically-linked programs unless a kernel-specific base library is explicitly used.

The entrypoint of a dynamically-linked program is the `Component::construct` function.

7.6.2. Startup of dynamically-linked programs

When creating a new component, the parent first detects whether the to-be-loaded ELF binary represents a statically-linked program or a dynamically-linked program by inspecting the ELF binary's program-header information (see *repos/base/src/lib/base/elf_binary.cc*). If the program is statically linked, the parent follows the procedure as described in Section 3.5. If the program is dynamically linked, the parent remembers the dataspace of the program's ELF image but starts the ELF image of the dynamic linker instead.

The dynamic linker is a regular Genode component that follows the startup procedure described in Section 7.1.2. However, because of its hybrid nature, it needs to take special precautions before using any data that contains relocations. Because the dynamic linker is a shared library, it contains data relocations. Even though the linker's code is position independent and can principally be loaded to an arbitrary address, global data objects may contain pointers to other global data objects or code. For example, vtable entries contain pointers to code. Those pointers must be relocated depending on the load address of the binary. This step is performed by the `init_rtl` hook function, which was already mentioned in Section 7.1.2. Global data objects must not be used before calling this function. For this reason, `init_rtl` is called at the earliest possible time directly from the assembly startup code. Apart from the call of this hook function, the startup of the dynamic linker is the same as for statically-linked programs.

The main function of the dynamic linker obtains the binary of the actual dynamically-linked program by requesting a ROM session for the module "binary". The parent responds to this request by handing out a locally-provided ROM session that contains the dataspace of the actual program. Once the linker has obtained the dataspace containing the dynamically-linked program, it loads the program and all required shared libraries. The dynamic linker requests each shared library as a ROM session from its parent.

After completing the loading of all ELF objects, the dynamic linker determines the entry point of the loaded binary by looking up the `Component::construct` symbol and calls it as a function. Note that this particular symbol is ambiguous as both the dynamic linker and the loaded program have such a function. Hence, the lookup is performed explicitly on the loaded program.

7.6.3. Address-space management

To load the binary and the associated shared libraries, the linker does not directly attach dataspace to its address space. Instead, it manages a dedicated part of the component's virtual address space called *linker area* manually. The linker area is a region map that is created as part of a PD session. The dynamic linker attaches the linker area as a managed dataspace to its address space. This way, the linker can precisely control the layout within the virtual-address range covered by the managed dataspace. This control is needed because the loading of an ELF object does not correspond to an atomic attachment of a single dataspace but it involves consecutive attach operations for multiple dataspace, one for each ELF segment. When attaching one segment, the linker must make sure that there is enough space beyond the segment to host the next segment. The use of a managed dataspace allows the linker to manually allocate large-enough portions of virtual memory and populate them in multiple steps.

7.7. Execution on bare hardware (base-hw)

The code specific to the base-hw platform is located within the *repos/base-hw/* directory. In the following description, unless explicitly stated otherwise, all paths are relative to this directory.

In contrast to classical L4 microkernels where Genode's core process runs as user-level roottask on top of the kernel, base-hw executes Genode's core directly on the hardware with no distinct kernel underneath. Core and the kernel are melted into one hybrid component. Although all threads of core are running in privileged processor mode, they call a kernel library to synchronize hardware interaction. However, most work is done outside of that library. This design has several benefits. First, the kernel part becomes much simpler. For example, there are no allocators needed within the kernel. Second, base-hw side-steps long-standing difficult kernel-level problems, in particular the management of kernel resources. For the allocation of kernel objects, the hybrid core/kernel can employ Genode's user-level resource trading concepts as described in Section 3.3. Finally and most importantly, merging the kernel with roottask removes a lot of redundancies between both programs. Traditionally, both kernel and roottask perform the book keeping of physical-resource allocations and the existence of kernel objects such as address spaces and threads. In base-hw, those data structures exist only once. The complexity of the combined kernel/core is significantly lower than the sum of the complexities of a traditional self-sufficient kernel and a distinct roottask on top. This way, base-hw helps to make Genode's TCB less complex.

The following subsections detail the problems that base-hw had to address to become a self-sufficient base platform for Genode.

7.7.1. Bootstrapping of base-hw

Startup of the base-hw kernel Core on base-hw uses Genode's regular linker script. Like any regular Genode component, its execution starts at the `_start` symbol. But unlike a regular component, core is started by the bootstrap component as a kernel running in privileged mode. Instead of directly following the startup procedure described in Section 7.1.2, base-hw uses custom startup code that initializes the kernel part of core first. For example, the startup code for the ARM architecture is located at *src/core/spec/arm/crt0.s*. It calls the kernel initialization code in *src/core/kernel/init.cc*. Core's regular C++ startup code (the `_main` function) is executed by the first thread created by the kernel (see the thread setup in the `Core_thread::Core_thread()` constructor).

7.7.2. Kernel entry and exit

The execution model of the kernel can be roughly characterized as a single-stack kernel. In contrast to traditional L4 kernels that maintain one kernel thread per user thread, the base-hw kernel is a mere state machine that never blocks in the kernel. State transitions are triggered by core or user-level threads that enter the kernel via a system

call, by device interrupts, or by a CPU exception. Once entered, the kernel applies the state change depending on the event that caused the kernel entry, and leaves the kernel again. The transition between normal threads and kernel execution depends on the concrete architecture. For ARM, the corresponding code is located at *src/core/spec/arm/exception_vector.s*.

7.7.3. Interrupt handling and preemptive multi-threading

In order to respond to interrupts, base-hw has to contain a driver for the interrupt controller. The interrupt-controller driver for a particular hardware platform can be found at *src/core/spec/<spec>/pic.h* and the corresponding *src/core/spec/<spec>/pic.cc*. Whereby *<spec>* refers to a particular platform (e. g., *imx53*) or an IP block that is used across different platforms (e. g., *arm_gic* for ARM's generic interrupt controller). Each of the drivers implement the same interface. When building core, the build system uses the build-spec mechanism explained in Section 5.3 to incorporate the single driver needed for the targeted SoC.

To support preemptive multi-threading, base-hw requires a hardware timer. The timer is programmed with the time slice length of the currently executed thread. Once the programmed timeout elapses, the timer device generates an interrupt that is handled by the kernel. Similarly to interrupt controllers, there exist a variety of different timer devices for different CPUs. Therefore, base-hw contains different timer drivers. The timer drivers are located at *src/core/spec/<spec>/timer_driver.h* where *<spec>* refers to the timer variant.

The in-kernel handler of the timer interrupt invokes the thread scheduler (*src/core/kernel/cpu_scheduler.h*). The scheduler maintains a list of so-called scheduling contexts where each context refers to a thread. Each time the kernel is entered, the scheduler is updated with the passed duration. When updated, it takes a scheduling decision by making the next to-be-executed thread the head of the list. At kernel exit, the control is passed to the user-level thread that corresponds to the head of the scheduler list.

7.7.4. Split kernel interface

The system-call interface of the base-hw kernel is split into two parts. One part is usable by all components and solely contains system calls for inter-component communication and thread synchronization. The definition of this interface is located at *include/kernel/interface.h*. The second part is exposed only to core. It supplements the public interface with operations for the creation, the management, and the destruction of kernel objects. The definition of the core-private interface is located at *src/core/kernel/core_interface.h*.

The distinction between both parts of the kernel interface is enforced by the function `Thread::_call` in *src/core/kernel/thread.cc*.

7.7.5. Public part of the kernel interface

Threads do not run independently but interact with each other via synchronous inter-component communication as detailed in Section 3.6. Within base-hw, this mechanism is referred to as IPC (for inter-process communication). To allow threads to perform calls to other threads or to receive RPC requests, the kernel interface is equipped with system calls for performing IPC (*send_request_msg*, *await_request_msg*, *send_reply_msg*). To keep the kernel as simple as possible, IPC is performed using so-called user-level thread-control blocks (UTCB). Each thread has a corresponding memory page that is always mapped in the kernel. This UTCB page is used to carry IPC payload. The largely simplified procedure of transferring a message is as follows. (In reality, the state space is more complex because the receiver may not be in a blocking state when the sender issues the message)

1. The sender marshals its payload into its UTCB and invokes the kernel,
2. The kernel transfers the payload from the sender's UTCB to the receiver's UTCB and schedules the receiver,
3. The receiver retrieves the incoming message from its UTCB.

Because all UTCBs are always mapped in the kernel, no page faults can occur during the second step. This way, the flow of execution within the kernel becomes predictable and no kernel exception handling code is needed.

In addition to IPC, threads interact via the synchronization primitives provided by the Genode API. To implement these portions of the API, the kernel provides system calls for managing the execution control of threads (*stop_thread*, *restart_thread*, *yield_thread*).

To support asynchronous notifications as described in Section 3.6.2, the kernel provides system calls for the submission and reception of signals (*await_signal*, *cancel_next_await_signal*, *submit_signal*, *pending_signal*, and *ack_signal*) as well as the lifetime management of signal contexts (*kill_signal_context*). In contrast to other base platforms, Genode's signal API is directly supported by the kernel so that the propagation of signals does not require any interaction with core's PD service. However, the creation of signal contexts is arbitrated by the PD service. This way, the kernel objects needed for the signalling mechanism are accounted to the corresponding clients of the PD service.

The kernel provides an interface to make the kernel's scheduling timer available as time source to the user land. Using this interface, components can bind signal contexts to timeouts (*timeout*) and follow the progress of time (*time* and *timeout_max_us*).

7.7.6. Core-private part of the kernel interface

The core-private part of the kernel interface allows core to perform privileged operations. Note that even though the kernel and core provide different interfaces, both are executed in privileged CPU mode, share the same address space and ultimately trust each other. The kernel is regarded a mere support library of core that executes those functions that shall be synchronized between different CPU cores and core's threads. In particular, the kernel does not perform any allocation. Instead, the allocation of kernel objects is performed as an interplay of core and the kernel.

1. Core allocates physical memory from its physical-memory allocator. Most kernel-object allocations are performed in the context of one of core's services. Hence, those allocations can be properly accounted to a session quota (Section 3.3). This way, kernel objects allocated on behalf of core's clients are "paid for" by those clients.
2. Core allocates virtual memory to make the allocated physical memory visible within core and the kernel.
3. Core invokes the kernel to construct the kernel object at the location specified by core. This kernel invocation is actually a system call that enters the kernel via the kernel-entry path.
4. The kernel initializes the kernel object at the virtual address specified by core and returns to core via the kernel-exit path.

The core-private kernel interface consists of the following operations:

- The creation and destruction of protection domains (*new_pd*, *update_pd*, *delete_pd*), invoked by the PD service
- The creation, manipulation, and destruction of threads (*new_thread*, *start_thread*, *resume_thread*, *thread_quota*, *pause_thread*, *delete_thread*, *thread_pager*, and *cancel_thread_blocking*), used by the CPU service and the core-specific back end of the Genode::Thread API
- The creation and destruction of signal receivers and signal contexts (*new_signal_receiver*, *delete_signal_receiver*, *new_signal_context*, and *delete_signal_context*), invoked by the PD service
- The creation and destruction of kernel-protected object identities (*new_obj*, *delete_obj*)
- The creation, manipulation, and destruction of interrupt kernel objects (*new_irq*, *ack_irq*, and *delete_irq*)

7.7.7. Scheduler of the base-hw kernel

CPU scheduling in traditional L4 microkernels is based on static priorities. The scheduler always picks the runnable thread with highest priority for execution. If multiple threads share one priority, the kernel schedules those threads in a round-robin fashion. Whereas being pretty fast and easy to implement, this scheme has disadvantages: First, there is no way to prevent high-prioritized threads from starving lower-prioritized ones. Second, CPU time cannot be granted to threads and passed between them by the means of quota. To cope with these problems without much loss of performance, base-hw employs a custom scheduler that deviates from the traditional approach.

The base-hw scheduler introduces the distinction between high-throughput-oriented scheduling contexts - called *fills* - and low-latency-oriented scheduling contexts - called *claims*. Examples for typical fills would be the processing of a compiler job or the rendering computations of a sophisticated graphics program. They shall obtain as much CPU time as the system can spare but there is no demand for a high responsiveness. In contrast, an example for the claim category would be a typical GUI-software stack covering the control flow from user-input drivers through a chain of GUI components to the drivers of the graphical output. Another example is a user-level device driver that must quickly respond to sporadic interrupts but is otherwise untrusted. The low latency of such components is a key factor for usability and quality of service. Besides introducing the distinction between claim and fill scheduling contexts, base-hw introduces the notion of a so-called *super period*, which is a multiple of typical scheduling time slices, e. g., one second. The entire super period corresponds to 100% of the CPU time of one CPU. Portions of it can be assigned to scheduling contexts. A CPU quota thereby corresponds to a percentage of the super period.

At the beginning of a super period, each claim has its full amount of assigned CPU quota. The priority defines the absolute scheduling order within the super period among those claims that are active and have quota left. As long as there exist such claims, the scheduler stays in the claim mode and the quota of the scheduled claims decreases. At the end of a super period, the quota of all claims is replenished to the initial value. Every time the scheduler can't find an active claim with CPU-quota left, it switches to the fill mode. Fills are scheduled in a simple round-robin fashion with identical time slices. The proceeding of the super period doesn't affect the scheduling order and time-slices of this mode. The concept of quota and priority that is implemented through the claim mode aligns nicely with Genode's way of hierarchical resource management: Through CPU sessions, each process becomes able to assign portions of its CPU time and subranges of its priority band to its children without knowing the global meaning of CPU time or priority.

7.7.8. Sparsely populated core address space

Even though core has the authority over all physical memory, it has no immediate access to the physical pages. Whenever core requires access to a physical memory page, it first has to explicitly map the physical page into its own virtual memory space. This way, the virtual address space of core stays clean from any data of other components. Even in the presence of a bug in core (e. g., a dangling pointer), information cannot accidentally leak between different protection domains because the virtual memory of the other components is not necessarily visible to core.

7.7.9. Multi-processor support of base-hw

On uniprocessor systems, the base-hw kernel is single-threaded. Its execution model corresponds to a mere state machine. On SMP systems, it maintains one kernel thread and one scheduler per CPU core. Access to kernel objects gets fully serialized by one global spin lock that is acquired when entering the kernel and released when leaving the kernel. This keeps the use of multiple cores transparent to the kernel model, which greatly simplifies the code compared to traditional L4 microkernels. Given that the kernel is a simple state machine providing lightweight non-blocking operations, there is little contention for the global kernel lock. Even though this claim may not hold up when scaling to a large number of cores, current platforms can be accommodated well.

Cross-CPU inter-component communication Regarding synchronous and asynchronous inter-processor communication - thanks to the global kernel lock - there is no semantic difference to the uniprocessor case. The only difference is that on a multiprocessor system, one processor may change the schedule of another processor by unblocking one of its threads (e. g., when an RPC call is received by a server that resides on a different CPU as the client). This condition may rescind the current scheduling choice of the other processor. To avoid lags in this case, the kernel lets the unaware target processor trap into an inter-processor interrupt (IPI). The targeted processor can react to the IPI by taking the decision to schedule the receiving thread. As the IPI sender does not have to wait for an answer, the sending and receiving CPUs remain largely decoupled. There is no need for a complex IPI protocol between sender and receiver.

TLB shutdown With respect to the synchronization of core-local hardware, there are two different situations to deal with. Some hardware components like most ARM caches and branch predictors implement their own coherence protocol and thus need adaption in terms of configuration only. Others, like the TLBs lack this feature. When for instance a page table entry gets invalid, the TLB invalidation of the affected entries must be performed locally by each core. To signal the necessity of TLB maintenance

work, an IPI is sent to all other cores. Once all cores have completed the cleaning, the thread that invoked the TLB invalidation resumes its execution.

7.7.10. Asynchronous notifications on base-hw

The base-hw platform improves the mechanism described in Section 7.4 by introducing signal receivers and signal contexts as first-class kernel objects. Core's PD service is merely used to arbitrate the creation and destruction of those kernel objects but it does not play the role of a signal-delivery proxy. Instead, signals are communicated directly by using the public kernel operations *await_signal*, *cancel_next_await_signal*, *submit_signal*, and *ack_signal*.

7.8. Execution on the NOVA microhypervisor (base-nova)

NOVA is a so-called microhypervisor, denoting the combination of microkernel and a virtualization platform (hypervisor). It is a high-performance microkernel for the x86 architecture. In contrast to other microkernels, it has been designed for hardware-based virtualization via user-level virtual-machine monitors. In line with Genode's architecture, NOVA's kernel interface is based on capability-based security. Hence, the kernel fully supports the model of a Genode kernel as described in Section 3.1.

NOVA website

<http://hypervisor.org>

NOVA kernel-interface specification

<https://github.com/udosteinberg/NOVA/raw/master/doc/specification.pdf>

7.8.1. Integration of NOVA with Genode

The NOVA kernel is available via Genode's ports mechanism detailed in Section 5.2. The port description is located at *repos/base-nova/ports/nova.port*.

Building the NOVA kernel Even though NOVA is a third-party kernel with a custom build system, the kernel is built directly by the Genode build system. NOVA's build system remains unused.

From within a Genode build directory configured for one of the *nova_x86_32* or *nova_x86_64* platforms, the kernel can be built via

```
make kernel
```

The build description for the kernel is located at *repos/base-nova/src/kernel/target.mk*.

System-call bindings NOVA is not accompanied with bindings to its kernel interface. There only is a description of the kernel interface in the form of the kernel specification available. For this reason, Genode maintains the kernel bindings for NOVA within the Genode source tree. The bindings are located at *repos/base-nova/include/* in the subdirectories *nova/*, *spec/32bit/nova/*, and *spec/64bit/nova/*.

7.8.2. Bootstrapping of a NOVA-based system

After finishing its initialization, the kernel starts the second boot module, the first being the kernel itself, as root task. The root task is Genode's core. The virtual address space of core contains the text and data segments of core, the UTCB of the initial execution context (EC), and the hypervisor info page (HIP). Details about the HIP are provided in Section 6 of the NOVA specification.

BSS section of core The kernel's ELF loader does not support the concept of a BSS segment. It simply maps the physical pages of core's text and data segments into the virtual memory of core but does not allocate any additional physical pages for backing the BSS. For this reason, the NOVA version of core does not use the *genode.ld* linker script as described in Section 7.1.1 but the linker script located at *repos/base-nova/src/core/core.ld*. This version hosts the BSS section within the data segment. Thereby, the BSS is physically present in the core binary in the form of zero-initialized data.

Initial information provided by NOVA to core The kernel passes a pointer to the HIP to core as the initial value of the ESP register. Genode's startup code saves this value in the global variable `_initial_sp` (Section 7.1.2).

7.8.3. Log output on modern PC hardware

Because transmitting information over legacy comports does not require complex device drivers, serial output over comports is still the predominant way to output low-level system logs like kernel messages or the output of core's LOG service.

Unfortunately, most modern PCs lack dedicated comports. This leaves two options to obtain low-level system logs.

1. The use of vendor-specific platform-management features such as Intel VPro / Intel Advanced Management Technology (AMT) or Intel Platform Management Interface (IPMI). These platform features are able to emulate a legacy comport and provide the serial output over the network. Unfortunately, those solutions are not uniform across different vendors, difficult to use, and tend to be unreliable.
2. The use of a PCI card or an Express Card that provides a physical comport. When using such a device, the added comport appears as PCI I/O resource. Because the device interface is compatible to the legacy comports, no special drivers are needed.

The latter option allows the retrieval of low-level system logs on hardware that lacks special management features. In contrast to the legacy comports, however, it has the minor disadvantage that the location of the device's I/O resources is not known beforehand. The I/O port range of the comport depends on the device-enumeration procedure of the BIOS. To enable the kernel to output information over this comport, the kernel must be configured with the I/O port range as assigned by the BIOS on the specific machine. One kernel binary cannot simply be used across different machines.

The Bender chain boot loader To alleviate the need to adapt the kernel configuration to the used comport hardware, the bender chain boot loader can be used.

Bender is part of the MORBO tools

<https://github.com/TUD-OS/morbo>

Instead of starting the NOVA hypervisor directly, the multi-boot-compliant boot loader (such as GRUB) starts bender as the kernel. All remaining boot modules including the real kernel have already been loaded into memory by the original boot loader. Bender scans the PCI bus for a comport device. If such a device is found (e. g., an Express Card), it writes the information about the device’s I/O port range to a known offset within the BIOS data area (BDA).

After the comport-device probing is finished, bender passes control to the next boot module, which is the real kernel. The comport device driver of the kernel does not use a hard-coded I/O port range for the comport but looks up the comport location in the BDA. The use of bender is optional. When not used, the BDA always contains the I/O port range of the legacy comport 1.

The Genode source tree contains a pre-compiled binary of bender at *tool/boot/bender*. This binary is automatically incorporated into boot images for the NOVA base platform when the run tool (Section 5.4.1) is used.

7.8.4. Relation of NOVA’s kernel objects to Genode’s core services

For the terminology of NOVA’s kernel objects, refer to the NOVA specification mentioned in the introduction of Section 7.8. A brief glossary for the terminology used in the remainder of this section is given in table 2.

NOVA term	
PD	Protection domain
EC	Execution context (thread)
SC	Scheduling context
HIP	Hypervisor information page
IDC	Inter-domain call (RPC call)
portal	communication endpoint

Table 2: Glossary of NOVA’s terminology

NOVA capabilities are not Genode capabilities Both NOVA and Genode use the term “capability”. However, the term does not have the same meaning in both contexts. A Genode capability refers to an RPC object or a signal context. In the context of NOVA, a capability refers to a NOVA kernel object. To avoid confusing both meanings of the term, Genode refers to NOVA’s term as “capability selector”, or simply “selector”. A Genode signal context capability corresponds to a NOVA semaphore, all other Genode capabilities correspond to NOVA portals.

PD service A PD session corresponds to a NOVA PD.

A Genode capability being a NOVA portal has a defined IP and an associated local EC (the Genode entrypoint). The invocation of a such a Genode capability is an IDC call to a portal. A Genode capability is delegated by passing its corresponding portal or semaphore selector as IDC argument.

Page faults are handled as explained in Section 7.8.5. Each memory mapping installed in a component implicitly triggers the allocation of a node in the kernel's mapping database.

CPU service NOVA distinguishes between so-called global ECs and local ECs. A global EC can be equipped with CPU time by associating it with an SC. It can perform IDC calls but it cannot receive IDC calls. In contrast to a global EC, a local EC is able to receive IDC calls but it has no CPU time. A local EC is not executed before it is called by another EC.

A regular Genode thread is a global EC. A Genode entrypoint is a local EC. Core distinguishes both cases based on the instruction-pointer (IP) argument of the CPU session's start function. For a local EC, the IP is set to zero.

IO_MEM services Core's RAM and IO_MEM allocators are initialized based on the information found in NOVA's HIP.

ROM service Core's ROM service provides all boot modules as ROM modules. Additionally, a copy of NOVA's HIP is provided as a ROM module named "hypervisor_info_page".

IRQ service NOVA represents each interrupt as a semaphore created by the kernel. By registration of a Genode signal context capability via the `sigh` method of the `Irq_session` interface, the semaphore of the signal context capability is bound to the interrupt semaphore. Genode signals and NOVA semaphores are handled as described in 7.8.6.

Upon the initial IRQ session's `ack_irq` call, a NOVA semaphore-down operation is issued within core on the interrupt semaphore, which implicitly unmask the interrupt at the CPU. When the interrupt occurs, the kernel masks the interrupt at the CPU and performs the semaphore-up operation on the IRQ's semaphore. Thereby, the chained semaphore, which is the beforehand registered Genode signal context, is triggered and the interrupt is delivered as Genode signal. The interrupt gets acknowledged and unmasked by calling the IRQ session's `ack_irq` method.

7.8.5. Page-fault handling on NOVA

On NOVA, each EC has a pre-defined range of portal selectors. For each type of exception, the range has a dedicated portal that is entered in the event of an exception. The page-fault portal of a Genode thread is defined at the creation time of the thread and points to a pager EC per CPU within core. Hence, for each CPU, a pager EC in core pages all Genode threads running on the same CPU.

The operation of pager ECs When an EC triggers a page fault, the faulting EC implicitly performs an IDC call to its pager. The IDC message contains the fault information. For resolving the page fault, core follows the procedure described in 7.3.4. If the lookup for a dataspace within the faulter's region map succeeds, core establishes a memory mapping into the EC's PD by invoking the asynchronous map operation of the kernel and replies to the IDC message. In the case where the region lookup within the thread's corresponding region map fails, the faulted thread is retained in a blocked state via a kernel semaphore. In the event that the fault is later resolved by a region-map client as described in the paragraph "Region is empty" of Section 7.3.4, the semaphore gets released, thus resuming the execution of the faulted thread. The faulter will immediately trigger another fault at the same address. This time, however, the region lookup succeeds.

Mapping database NOVA tracks memory mappings in a data structure called *mapping database* and has the notion of the delegation of memory mappings (rather than the delegation of memory access). Memory access can be delegated only if the originator of the delegation has a mapping. Core is the only exception because it can establish mappings originating from the physical memory space. Because mappings can be delegated transitively between PDs, the mapping database is a tree where each node denotes the delegation of a mapping. The tree is maintained in order to enable the kernel to rescind the authority. When a mapping is revoked, the kernel implicitly cancels all transitive mappings that originated from the revoked node.

7.8.6. Asynchronous notifications on NOVA

To support asynchronous notifications as described in Section 3.6.2, we extended the NOVA kernel semaphores to support signalling via chained NOVA semaphores. This extension enables the creation of kernel semaphores with a per-semaphore value, which can be bound to another kernel semaphore. Each bound semaphore corresponds to a Genode signal context. The per-semaphore value is used to distinguish different sources of signals.

On this base platform, the blocking of the signal thread at the signal source is realized by using a kernel semaphore shared by the PD session and the PD client. All chained semaphores (Signal contexts) are bound to this semaphore. When first issuing

a *wait-for-signal* operation at the signal source, the client requests a capability selector for the shared semaphore (*repos/base-nova/include/signal_session/source_client.h*). It then performs a *down* operation on this semaphore to block.

If a signal sender issues a submit operation on a Genode signal capability, then a regular NOVA kernel semaphore-up syscall is used. If the kernel detects that the used semaphore is chained to another semaphore, the up operation is delegated to the one received during the initial *wait-for-signal* operation of the signal receiving thread.

In contrast to other base platforms, Genode's signal API is supported by the kernel so that the propagation of signals does not require any interaction with core's PD service. However, the creation of signal contexts is arbitrated by the PD service.

7.8.7. IOMMU support

As discussed in Section 4.1.3, misbehaving device drivers may exploit DMA transactions to circumvent their component boundaries. When executing Genode on the NOVA microhypervisor, however, bus-master DMA is subjected to the IOMMU.

The NOVA kernel applies a subset of the (MMU) address space of a protection domain to the (IOMMU) address space of a device. So the device's address space can be managed in the same way as one normally manages the address space of a PD. The only missing link is the assignment of device address spaces to PDs. This link is provided by the dedicated system call *assign_pci* that takes a PD capability selector and a device identifier as arguments. The PD capability selector represents the authorization over the protection domain, which is going to be targeted by DMA transactions. The device identifier is a virtual address where the extended PCI configuration space of the device is mapped in the specified PD. Only if a user-level device driver has access to the extended PCI configuration space of the device, is it able to get the assignment in place.

To make NOVA's IOMMU support available to Genode, the ACPI driver has the ability to lookup the extended PCI configuration space region for all devices and reports it via a Genode ROM. The platform driver on x86 evaluates the reported ROM and uses the information to obtain transparently for platform clients (device drivers) the extended PCI configuration space per device. The platform driver uses a NOVA-specific extension (*assign_pci*) to the PD session interface to associate a PCI device with a protection domain.

Even though these mechanisms combined should in theory suffice to let drivers operate with the IOMMU enabled, in practice, the situation is a bit more complicated. Because NOVA uses the same virtual-to-physical mappings for the device as it uses for the process, the DMA addresses the driver needs to supply to the device must be virtual addresses rather than physical addresses. Consequently, to be able to make a device driver usable on systems without IOMMU as well as on systems with IOMMU, the driver needs to become IOMMU-aware and distinguish both cases. This is an unfortunate consequence of the otherwise elegant mechanism provided by NOVA. To re-

lieve the device drivers from worrying about both cases, Genode decouples the virtual address space of the device from the virtual address space of the driver. The former address space is represented by a dedicated protection domain called *device PD* independent from the driver. Its sole purpose is to hold mappings of DMA buffers that are accessible by the associated device. By using one-to-one physical-to-virtual mappings for those buffers within the device PD, each device PD contains a subset of the physical address space. The platform driver performs the assignment of device PDs to PCI devices. If a device driver intends to use DMA, it allocates a new DMA buffer for a specific PCI device at the platform driver. The platform driver responds to such a request by allocating a RAM dataspace at core, attaching it to the device PD using the dataspace's physical address as virtual address, and by handing out the dataspace capability to the client. If the driver requests the physical address of the dataspace, the address returned will be a valid virtual address in the associated device PD. This design implies that a device driver must allocate DMA buffers at the platform driver (specifying the PCI device the buffer is intended for) instead of using core's PD service to allocate buffers anonymously.

7.8.8. Genode-specific modifications of the NOVA kernel

NOVA is not ready to be used as a Genode base platform as is. This section compiles the modifications that were needed to meet the functional requirements of the framework. All modifications are maintained at the following repository:

Genode's version of NOVA

<https://github.com/alex-ab/NOVA.git>

The repository contains a separate branch for each version of NOVA that has been used by Genode. When preparing the NOVA port using the port description at *repos/base-nova/ports/nova.port*, the NOVA branch that matches the used Genode version is checked out automatically. The port description refers to a specific commit ID. The commit history of each branch within the NOVA repository corresponds to the history of the original NOVA kernel followed by a series of Genode-specific commits. Each time NOVA is updated, a new branch is created and all Genode-specific commits are rebased on top of the history of the new NOVA version. This way, the differences between the original NOVA kernel and the Genode version remain clearly documented. The Genode-specific modifications solve the following problems:

Destruction of kernel objects

NOVA does not support the destruction of kernel objects. I.e., PDs and ECs can be created but not destroyed. With Genode being a dynamic system, kernel-object destruction is a mandatory feature.

Inter-processor IDC

On NOVA, only local ECs can receive IDC calls. Furthermore each local EC is bound to a particular CPU (hence the name “local EC”). Consequently, synchronous inter-component communication via IDC calls is possible only between ECs that both reside on the same CPU but can never cross CPU boundaries. Unfortunately, IDC is the only mechanism for the delegation of capabilities. Consequently, authority cannot be delegated between subsystems that reside on different CPUs. For Genode, this scheme is too rigid.

Therefore, the Genode version of NOVA introduces inter-CPU IDC calls. When calling an EC on another CPU, the kernel creates a temporary EC and SC on the target CPU as a representative of the caller. The calling EC is blocked. The temporary EC uses the same UTCB as the calling EC. Thereby, the original IDC message is effectively transferred from one CPU to the other. The temporary EC then performs a local IDC to the destination EC using NOVA’s existing IDC mechanism. Once the temporary EC receives the reply (with the reply message contained in the caller’s UTCB), the kernel destroys the temporary EC and SC and unblocks the caller EC.

Support for priority-inheriting spinlocks

Genode’s lock mechanism relies on a yielding spinlock for protecting the lock meta data. On most base platforms, there exists the invariant that all threads of one component share the same CPU priority. So priority inversion within a component cannot occur. NOVA breaks this invariant because the scheduling parameters (SC) are passed along IDC call chains. Consequently, when a client calls a server, the SCs of both client and server reside within the server. These SCs may have different priorities. The use of a naive spinlock for synchronization will produce priority inversion problems. The kernel has been extended with the mechanisms needed to support the implementation of priority-inheriting spinlocks in userland.

Combination of capability delegation and translation

As described in Section 3.1.4, there are two cases when a capability is specified as an RPC argument. The callee may already have a capability referring to the specified object identity. In this case, the callee expects to receive the corresponding local name of the object identity. In the other case, when the callee does not yet have a capability for the object identity, it obtains a new local name that refers to the delegated capability.

NOVA does not support this mechanism per se. When specifying a capability selector as map item for an IDC call, the caller has to specify whether a new mapping should be created or the translation of the local names should be performed by the kernel. However, in the general case, this question is not decidable by the

caller. Hence, NOVA had to be changed to take the decision depending on the existence of a valid translation for the specified capability selector.

Support for deferred page-fault resolution

With the original version of NOVA, the maximum number of threads is limited by core's stack area: NOVA's page-fault handling protocol works completely synchronously. When a page fault occurs, the faulting EC enters its page-fault portal and thereby activates the corresponding pager EC in core. If the pager's lookup for a matching dataspace within the faulting EC's region map succeeds, the page fault is resolved by delegating a memory mapping as the reply to the page-fault IDC call. However, if a page fault occurs on a managed dataspace, the pager cannot resolve it immediately. The resolution must be delayed until the region-map fault handler (outside of core) responds to the fault signal. In order to enable core to serve page faults of other threads in the meantime, each thread has its dedicated pager EC in core.

Each pager EC, in turn, consumes a slot in the stack area within core. Since core's stack area is limited, the maximum number of ECs within core is limited too. Because one core EC is needed as pager for each thread outside of core, the available stacks within core become a limited resource shared by all CPU-session clients. Because each Genode component is a client of core's CPU service, this bounded resource is effectively shared among all components. Consequently, the allocation of threads on NOVA's version of core represents a possible covert storage channel.

To avoid the downsides described above, we extended the NOVA IPC reply system call to specify an optional semaphore capability selector. The NOVA kernel validates the capability selector and blocks the faulting thread in the semaphore. The faulted thread remains blocked even after the pager has replied to the fault message. But the pager immediately becomes available for other page-fault requests. With this change, it suffices to maintain only one pager thread per CPU for all client threads.

The benefits are manifold. First, the *base-nova* implementation converges more closely to other Genode base platforms. Second, core can not run out of threads anymore as the number of threads in core is fixed for a given setup. And the third benefit is that the helping mechanism of NOVA can be leveraged for concurrently faulting threads.

Remote revocation of memory mappings In the original version of NOVA, roottask must retain mappings to all memory used throughout the system. In order to be able to delegate a mapping to another PD as response of a page fault, it must possess a local mapping of the physical page. Otherwise, it would not be able to revoke the mapping later on because the kernel expects roottask's mapping node

as a proof of the authorization for the revocation of the mapping. Consequently, even though roottask never touches memory handed out to other components, it needs to have memory mappings with full access rights installed within its virtual address space.

To relieve Genode's roottask (core) from the need to keep local mappings for all memory handed out to other components and thereby let core benefit from a sparsely populated address space as described in Section 7.7.8 for base-hw, we changed the kernel's revoke operation to take a PD selector and a virtual address within the targeted PD as argument. By presenting the PD selector as a token of authorization over the entire PD, we do no longer need core-locally installed mappings as the proof of authorization. Hence, memory mappings can always be installed directly from the physical address space to the target PD.

Support for write-combined access to memory-mapped I/O resources The original version of NOVA is not able to benefit from write combining because the kernel interface does not allow the userland to specify cacheability attributes for memory mappings. To achieve good throughput to the framebuffer, write combining is crucial. Hence, we extended the kernel interface to allow the userland to propagate cacheability attributes to the page-table entries of memory mappings and set up the x86 page attribute table (PAT) with a configuration for write combining.

Support for the virtualization of 64-bit guest operating systems The original version of NOVA supports 32-bit guest operations only. We enhanced the kernel to also support 64-bit guests.

Resource quotas for kernel resources The NOVA kernel lacks the ability to adopt the kernel memory pool to the behavior of the userland. The kernel memory pool has a fixed size, which cannot be changed at runtime. Even though we have not removed this principal limitation, we extended the kernel with the ability to subject kernel-memory allocations to a userlevel policy at the granularity of PDs. Each kernel operation that consumes kernel memory is accounted to a PD whereas each PD has a limited quota of kernel memory. This measure prevents arbitrary userland programs to bring down the entire system by exhausting the kernel memory. The reach of damage is limited to the respective PD.

Asynchronous notification mechanism We extended the NOVA kernel semaphores to support signalling via chained NOVA semaphores. This extension enables the creation of kernel semaphores with a per-semaphore value, which can be bound to another kernel semaphore. Each bound semaphore corresponds to a Genode signal context. The per-semaphore value is used to distinguish different sources of signals. Now, a signal sender issues a submit operation on a Genode signal capability via a regular NOVA semaphore-up syscall. If the kernel detects that the

used semaphore is chained to another semaphore, the up operation is delegated to the chained one. If a thread is blocked, it gets woken up directly and the per-semaphore value of the bound semaphore gets delivered. In case no thread is currently blocked, the signal is stored and delivered as soon as a thread issues the next semaphore-down operation.

Chaining semaphores is an operation that is limited to a single level, which avoids attacks targeting endless loops in the kernel. The creation of such signals can solely be performed if the issuer has a NOVA PD capability with the semaphore-create permission set. On Genode, this effectively reserves the operation to core. Furthermore, our solution preserves the invariant of the original NOVA kernel that a thread may be blocked in only one semaphore at a time.

Interrupt delivery We applied the same principle of the asynchronous notification extension to the delivery of interrupts by the NOVA kernel. Interrupts are delivered as ordinary Genode signals, which alleviate of the need for one thread per interrupt as required by the original NOVA kernel. The interrupt gets directly delivered to the address space of the driver in case of a Message Signalled Interrupt (MSI), or in case of a shared interrupt, to the x86 platform driver.

7.8.9. Known limitations of NOVA

This section summarizes the known limitations of NOVA and the NOVA version of core.

Fixed amount of kernel memory NOVA allocates kernel objects out of a memory pool of a fixed size. The pool is dimensioned in the kernel's linker script *nova/src/hypervisor.ld* (at the symbol `_mempool_f`).

Bounded number of object capabilities within core For each capability created via core's PD service, core allocates the corresponding NOVA portal or NOVA semaphore and maintains the capability selector during the lifetime of the associated object identity. Each allocation of a capability via core's PD service consumes one entry in core's capability space. Because the space is bounded, clients of the service could misuse core's capability space as covert storage channel.

Part II. Reference

8. Functional specification

This chapter complements the architectural information of Chapters 3 and 4 with a thorough description of the framework's C++ programming interface. The material is partially generated from the source code, specifically the public header files of the *base* and *os* source-code repositories. The location of the headers in either both repositories depends on role of the respective header. Only if the interface is fundamentally required by the core component or by the base framework itself, it is contained in the base repository. Otherwise, the header is found in the *os* repository.

Scope of the API The Genode API covers everything needed by Genode to be self-sufficient without any dependency on 3rd-party code. It does not even depend on a C runtime. It is possible to create components that solely use the raw Genode API, as is the case for the ones hosted within the *repos/os/* repository. Because such components do not rely on any library code except for the low-complexity Genode base libraries, they are relatively easy to evaluate. That said, the API must not be mistaken as an application-level API. It does not present an alternative to established application-level libraries like the standard C++ library. For example, even though the framework contains a few utilities for processing strings, those utilities do merely exist to support the use cases present in Genode.

General conventions The functional specification adheres to the following general conventions:

- Static member functions are called *class functions*. All other member functions are called *methods*.
- Both structs and classes are referred to as *classes*. There is no distinction between both at the API level.
- Constant functions with no argument and a return value are called *accessors*. Technically, they are “getters” but since Genode does not have any “setters”, accessors are synonymous to “getters”. Because those functions are so simple, they are listed in the class overview and are not described separately.
- Classes that merely inherit other classes are called *sub types*. In contrast to the use of a typedef, such classes are not mere name aliases but represent a new type. The type is compatible to the base class but not vice versa. For example, exception types are sub types of the `Exception` class.
- Namespace-wide information is presented with a light yellow background.
- Each non-trivial class is presented in the form of a class diagram on a blue-shaded background. The diagram shows the public base classes and the list of public

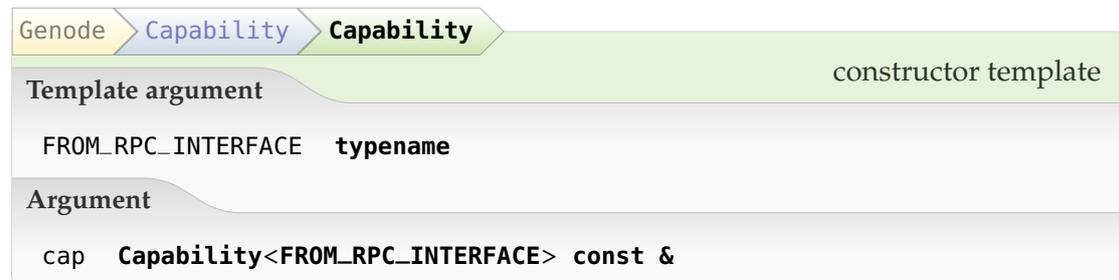
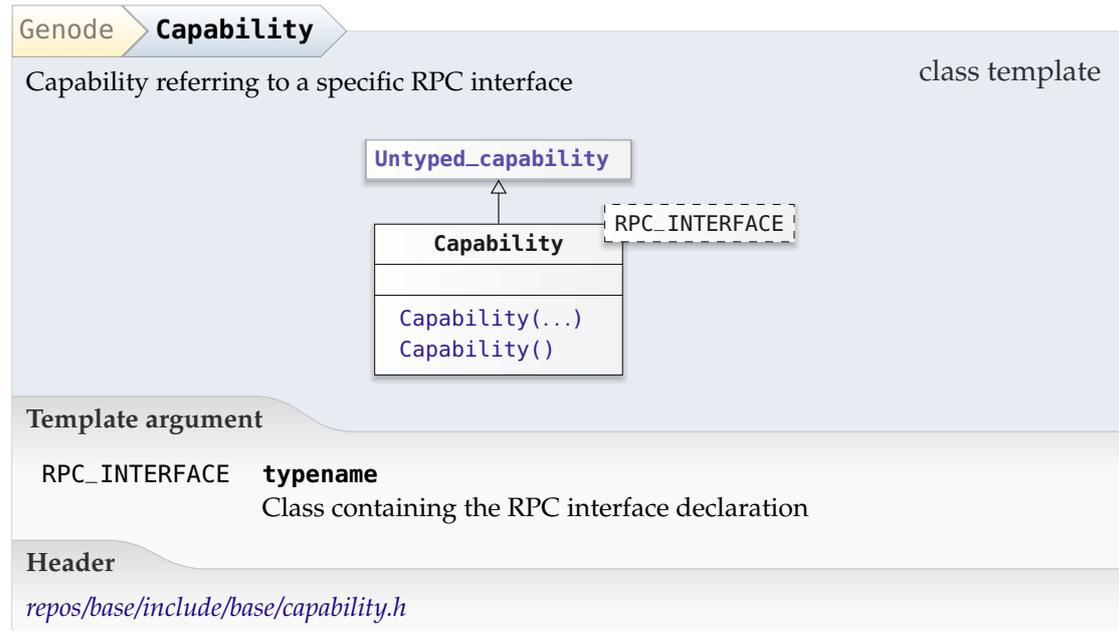
class functions and methods. If the class is a template, the template arguments are annotated at the top-right of corner of the class. If the class represents an RPC interface, an information box is attached. The methods listed in the diagram can be used as hyperlinks to further descriptions if available.

- Method descriptions are presented on a green-shaded background, global functions are presented on an orange-shaded background.
- The directory path presented under “Header” sections is a hyperlink to the corresponding source code at GitHub.

8.1. API primitives

8.1.1. Capability types

As described in Section 3.1, inter-component communication is based on capabilities. A capability refers to a system-wide unique object identity and can be delegated among components. At API level, each capability is associated with the type of the RPC interface the capability refers to - similar to how a C++ reference refers to the type of a specific C++ object.



This implicit constructor checks at compile time for the compatibility of the source and target capability types. The construction is performed only if the target capability type is identical to or a base type of the source capability type.



8.1.2. Sessions and connections

Servers provide their services over session-based communication channels. A `Session` type is defined as an abstract interface inherited from the `Session` base class.



Each session interface has to provide an implementation of the following class function that returns the name of the service as constant string.

```
static const char *service_name();
```

This function is used by the framework for the announcement of the service's root interface at the component's parent. The string returned by this function corresponds to the service name as used in the system configuration (Section 6).

The interaction of a client with a server involves the definition of session-construction arguments, the request of the session creation via its parent, the initialization of the matching RPC-client stub code with the received session capability, the actual use of the session interface, and the closure of the session. The `Connection` template class provides a way to greatly simplify the handling of session arguments, session creation, and destruction on the client side. By implementing a service-specific connection class inherited from `Connection`, session arguments become plain constructor arguments, session functions can be called directly on the `Connection` object, and the session gets properly closed when destructing the `Connection`.

Genode > **Connection** class template

Representation of an open connection to a service

```

classDiagram
    class Connection_base
    class Connection {
        Connection(...)
        ~Connection()
        cap() Capability<SESSION_TYPE>
        session(...) Capability<SESSION_TYPE>
        session(...) Capability<SESSION_TYPE>
    }
    Connection_base <|-- Connection
    
```

Template argument

SESSION_TYPE **typename**

Header

repos/base/include/base/connection.h

Genode > Connection > **Connection** constructor

Arguments

env **Env &**

- **Capability<SESSION_TYPE>**

Genode > Connection > **cap** const method

Return value

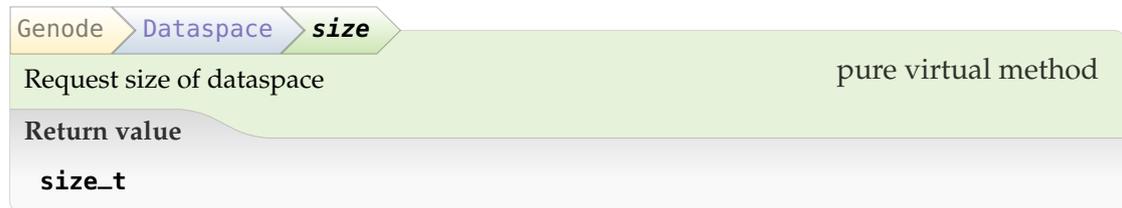
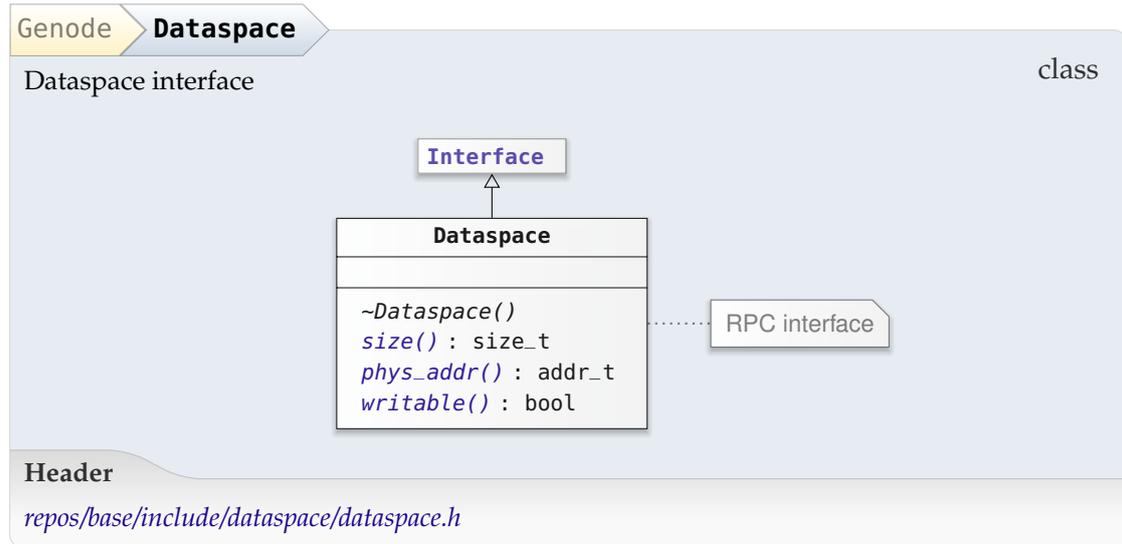
Capability<SESSION_TYPE> Session capability

Genode	Connection	session	
Issue session request to the parent			method
Arguments			
parent		Parent &	
format_args		const char *	
-		...	
Return value			
Capability<SESSION_TYPE>			

Genode	Connection	session	
Issue session request to the parent			method
Arguments			
parent		Parent &	
affinity		Affinity const &	
format_args		char const *	
-		...	
Return value			
Capability<SESSION_TYPE>			

8.1.3. Dataspace interface

The dataspace abstraction described in Section 3.4.1 is the fundamental API primitive for representing a container of memory as provided by core's PD, IO_MEM, or ROM services. Each dataspace is referenced by a capability that can be passed among components. Each component with the capability to a dataspace can access the dataspace's content by attaching the dataspace to the region map of its PD session. In addition to the use as arguments for region-map operations, dataspaces provide the following interface.



Genode	Dataspace	writable	
Return value			pure virtual method
bool	True if dataspace is writable		

Attached dataspace As a utility for handling the common case where a dataspace is attached to the component's address space as long as a certain object (like a session) exists, an instance of an `Attached_dataspace` can be hosted as a member variable. When destructed, the dataspace will be automatically detached from the component's address space.

Genode	Attached_dataspace			
Utility to attach a dataspace to the local address space		class		
<table border="1"> <thead> <tr> <th>Attached_dataspace</th> </tr> </thead> <tbody> <tr> <td> <pre>Attached_dataspace(...) ~Attached_dataspace() cap() : Dataspace_capability local_addr() : T * local_addr() : T const * size() : size_t invalidate()</pre> </td> </tr> </tbody> </table>			Attached_dataspace	<pre>Attached_dataspace(...) ~Attached_dataspace() cap() : Dataspace_capability local_addr() : T * local_addr() : T const * size() : size_t invalidate()</pre>
Attached_dataspace				
<pre>Attached_dataspace(...) ~Attached_dataspace() cap() : Dataspace_capability local_addr() : T * local_addr() : T const * size() : size_t invalidate()</pre>				
Header				
<i>repos/base/include/base/attached_dataspace.h</i>				

Genode	Attached_dataspace	Attached_dataspace	constructor
Arguments			
rm	Region_map &		
ds	Dataspace_capability		
Exceptions			
	Region_map::Region_conflict		
	Region_map::Invalid_dataspace		
	Out_of_caps		
	Out_of_ram		

Genode	Attached_dataspace	cap	const method
Return value			
	Dataspace_capability	Capability of the used dataspace	

Genode	Attached_dataspace	local_addr	method template
Request local address			
Template argument			
T	typename		
Return value			
T	*		

This is a template to avoid inconvenient casts at the caller. A newly attached dataspace is untyped memory anyway.

Genode	Attached_dataspace	local_addr	const method template
Template argument			
T	typename		
Return value			
T	const *		

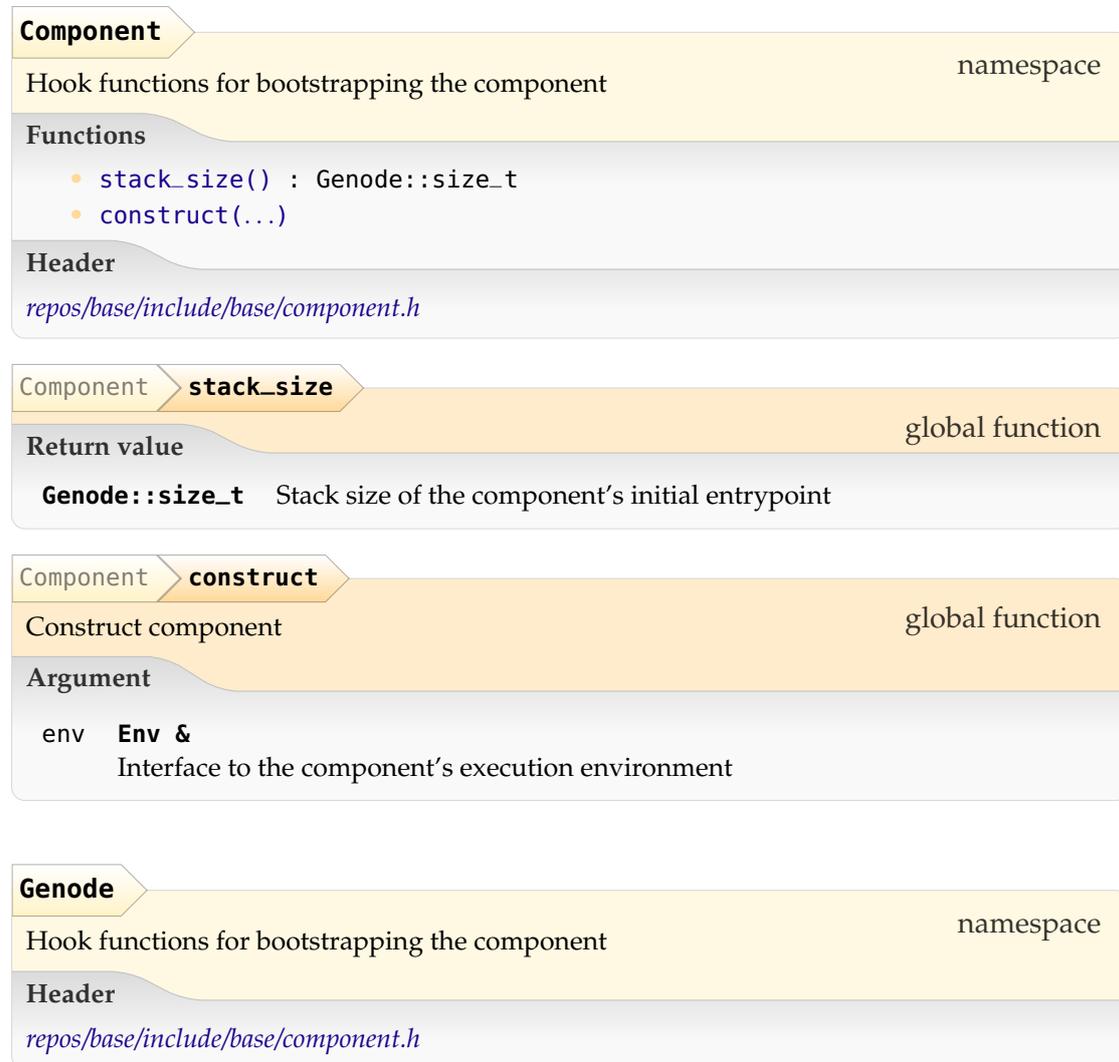
Genode	Attached_dataspace	size	const method
Return value			
size_t	Size		



This method can be called if the the dataspace is known to be physically destroyed, e. g., because the session where the dataspace originated from was closed. In this case, core will already have removed the memory mappings of the dataspace. So we have to omit the detach operation in `~Attached_dataspace`.

8.2. Component execution environment

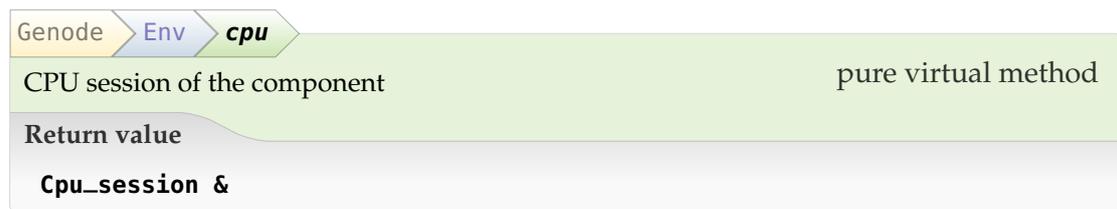
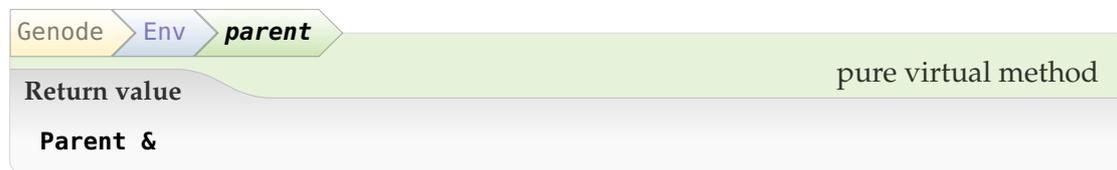
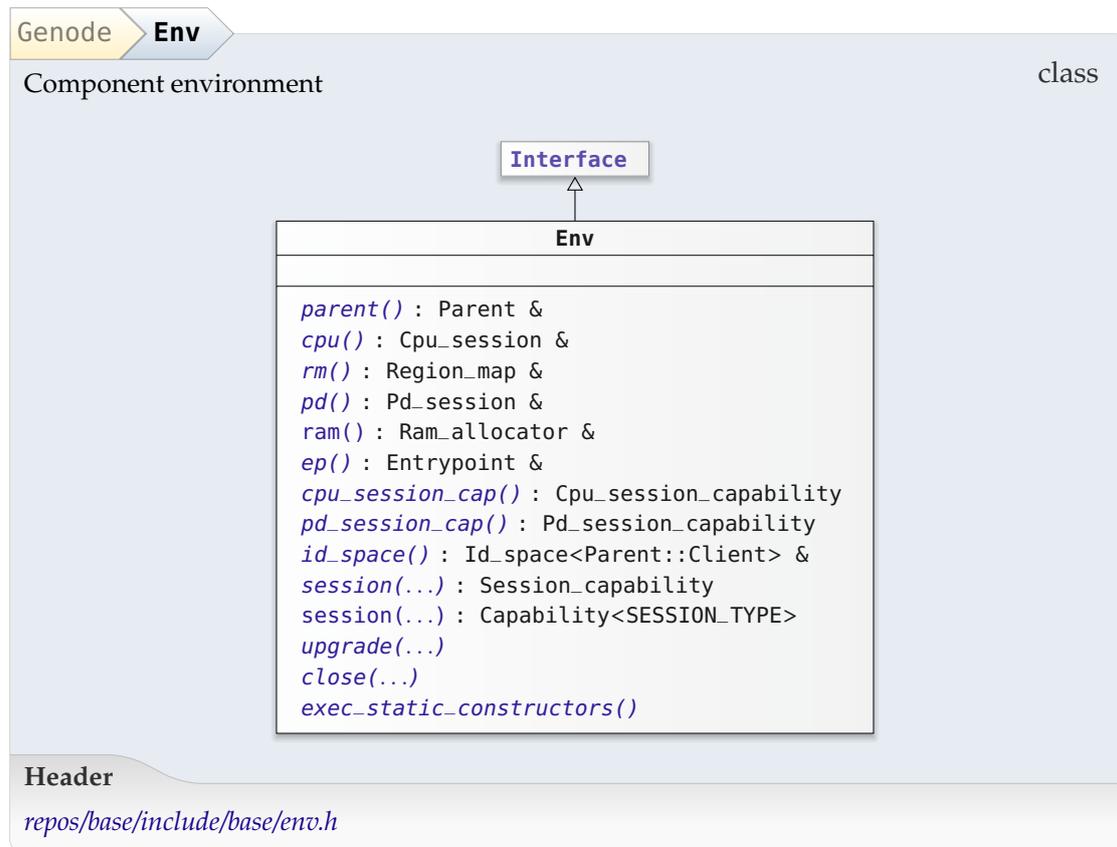
Each component has to provide an implementation of the Component interface as illustrated by the example given in Section 2.5.2.



8.2.1. Interface to the component's environment

As described in Section 3.5, each component consists of a protection domain (PD session), a LOG session, a ROM session with the component's executable binary, and a CPU session, from which the main thread is created. These sessions form the *environment* of the component, which is represented by the `Env` interface class. The environment is provided to the component as argument to the `Component::construct`

function.



This session is used to create the threads of the component.

Genode	Env	rm	
Region map of the component's address space			pure virtual method
Return value			
Region_map &			
Genode	Env	pd	
PD session of the component as created by the parent			pure virtual method
Return value			
Pd_session &			
Genode	Env	ram	
Memory allocator			method
Return value			
Ram_allocator &			
Genode	Env	ep	
Entrypoint for handling RPC requests and signals			pure virtual method
Return value			
Entrypoint &			
Genode	Env	cpu_session_cap	
Return value			pure virtual method
Cpu_session_capability			The CPU-session capability of the component
Genode	Env	pd_session_cap	
Return value			pure virtual method
Pd_session_capability			The PD-session capability of the component
Genode	Env	id_space	
ID space of sessions obtained from the parent			pure virtual method
Return value			
Id_space<Parent::Client> &			

Genode	Env	session	pure virtual method
Arguments			
<ul style="list-style-type: none"> - Service_name const & - Id - Session_args const & - Affinity const & 			
Return value			
Session_capability			

Genode	Env	session	method template
Create session to a service			
Template argument			
SESSION_TYPE	typename	Session interface type	
Arguments			
id	Id	Session ID of new session	
args	Session_args const &	Session constructor arguments	
affinity	Affinity const &	Preferred CPU affinity for the session	
Exceptions			
Service_denied Insufficient_cap_quota Insufficient_ram_quota Out_of_caps Out_of_ram			
Return value			
Capability<SESSION_TYPE>			

See the documentation of `Parent::session`.

This method blocks until the session is available or an error occurred.

Genode	Env	upgrade	
Upgrade session quota			pure virtual method
Arguments			
id	Id	ID of recipient session	
args	Upgrade_args const &	Description of the amount of quota to transfer	
Exceptions			
Out_of_ram			
Out_of_caps			

See the documentation of `Parent::upgrade`.

The `args` argument has the same principle format as the `args` argument of the `session` operation.

Genode	Env	close	
Close session and block until the session is gone			pure virtual method
Argument			
-	Id		

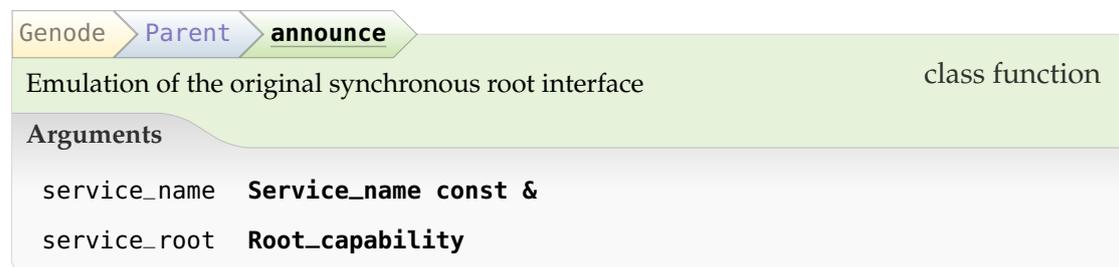
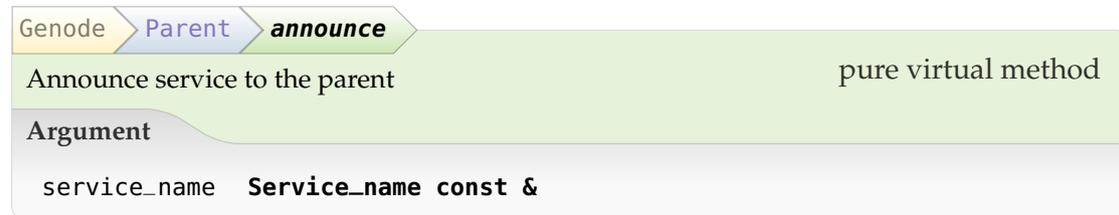
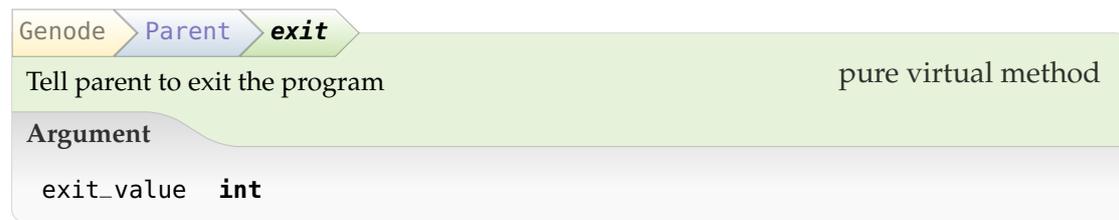
Genode	Env	exec_static_constructors	
Execute pending static constructors			pure virtual method

On component startup, the dynamic linker does not call possible static constructors in the binary and shared libraries the binary depends on. If the component requires static construction it needs to call this function at construction time explicitly. For example, the `libc` implementation executes this function before constructing `libc` components.

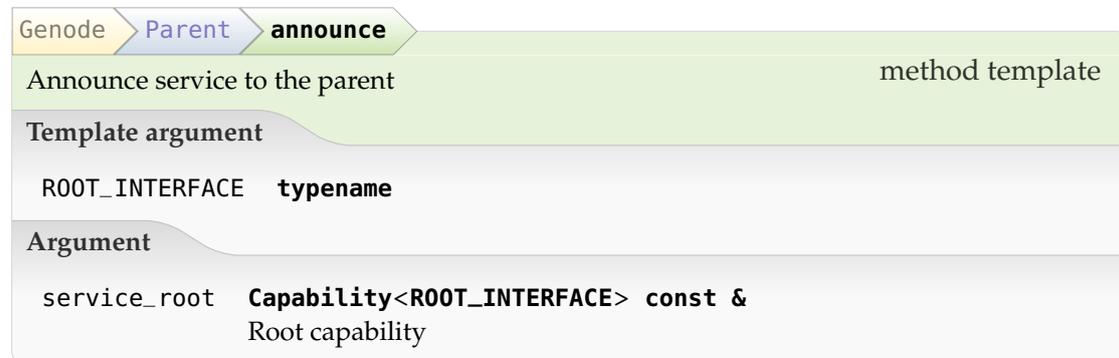
8.2.2. Parent interface

At its creation time, the only communication partner of a component is its immediate parent. The parent can be reached via interface returned by `Env::parent()`.





This method transparently spawns a proxy “root” endpoint that dispatches asynchronous session-management operations (as issued by the parent) to the local root interfaces via component-local RPC calls. The method solely exists for API compatibility.



The type of the specified service_root capability match with an interface that provides a Session_type type (i. e., a Typed_root interface). This Session_type is expected to host a class function called service_name returning the name of the provided interface as null-terminated string.

Genode	Parent	<i>session_sigh</i>	
Register signal handler for session notifications			pure virtual method
Argument			
- Signal_context_capability			
Genode	Parent	<i>session</i>	
Create session to a service			pure virtual method
Arguments			
id	Id	Client-side ID of new session	
service_name	Service_name const &	Name of the requested interface	
args	Session_args const &	Session constructor arguments	
affinity	Affinity const &	Preferred CPU affinity for the session <i>Default is Affinity()</i>	
Exceptions			
Service_denied	Parent denies session request		
Insufficient_cap_quota	Donated cap quota does not suffice		
Insufficient_ram_quota	Donated RAM quota does not suffice		
Out_of_caps	Session CAP quota exceeds our resources		
Out_of_ram	Session RAM quota exceeds our resources		
Return value			
Session_capability	Session capability if the new session is immediately available, or an invalid capability		

If the returned capability is invalid, the request is pending at the server. The parent delivers a signal to the handler as registered via `session_sigh` once the server responded to the request. Now the session capability can be picked up by calling `session_cap`.

Genode	Parent	session_cap	
Request session capability			pure virtual method
Argument			
id	Id		
Exceptions			
Service_denied			
Insufficient_cap_quota			
Insufficient_ram_quota			
Return value			
Session_capability			

See `session` for more documentation.

In the exception case, the parent implicitly closes the session.

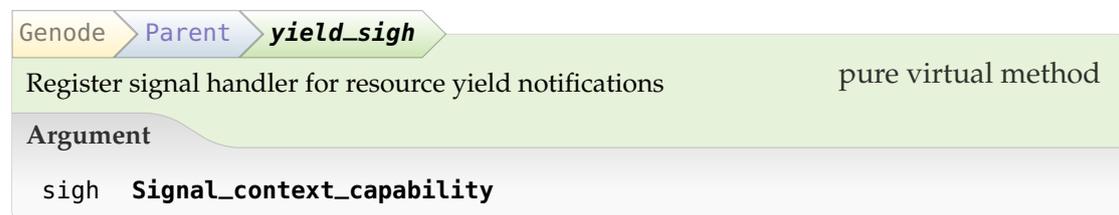
Genode	Parent	upgrade	
Transfer our quota to the server that provides the specified session			pure virtual method
Arguments			
to_session	Id		
args	Upgrade_args const & Description of the amount of quota to transfer		
Exceptions			
Out_of_caps			
Out_of_ram			
Return value			
Upgrade_result			

The `args` argument has the same principle format as the `args` argument of the `session` operation.

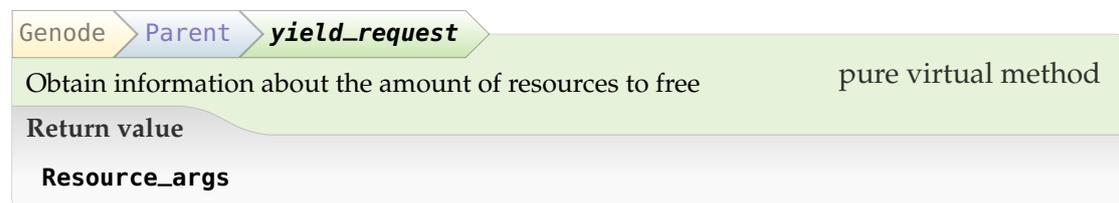
Genode	Parent	close	
Close session			pure virtual method
Argument			
- Id			
Return value			
Close_result			
Genode	Parent	session_response	
Set state of a session provided by the child service			pure virtual method
Arguments			
- Id			
- Session_response			
Genode	Parent	deliver_session_cap	
Deliver capability for a new session provided by the child service			pure virtual method
Arguments			
- Id			
- Session_capability			
Genode	Parent	main_thread_cap	
Provide thread_cap of main thread			pure virtual const method
Return value			
Thread_capability			
Genode	Parent	resource_avail_sigh	
Register signal handler for resource notifications			pure virtual method
Argument			
sigh Signal_context_capability			



By invoking this method, a component is able to inform its parent about the need for additional resources. The argument string contains a resource description in the same format as used for session-construction arguments. In particular, for requesting additional RAM quota, the argument looks like "ram_quota=<amount>" where amount is the amount of additional resources expected from the parent. If the parent complies with the request, it submits a resource-available signal to the handler registered via `resource_avail_sigh()`. On the reception of such a signal, the component can re-evaluate its resource quota and resume execution.



Using the yield signal, the parent is able to inform the component about its wish to regain resources.



The amount of resources returned by this method is the goal set by the parent. It is not commanded but merely meant as a friendly beg to cooperate. The component is not obligated to comply. If the component decides to take action to free resources, it can inform its parent about the availability of freed up resources by calling `yield_response()`.



The parent may issue heartbeat signals to the child at any time and expects a call of the `heartbeat_response` RPC function as response. When observing the RPC call, the parent infers that the child is still able to respond to external events.

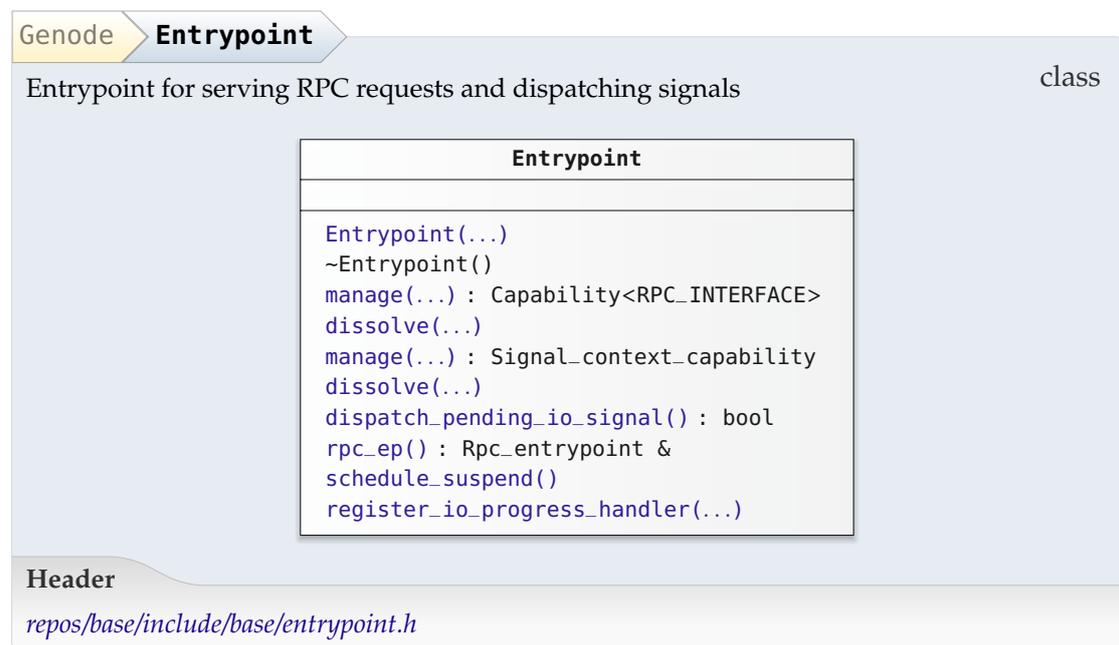


8.3. Entrypoint

An entrypoint is a thread that is able to respond to RPC requests and signals. Each component has at least one initial entrypoint that is created as part of the component's environment. It can be accessed via the `Env::ep()` method.

The `Entrypoint::manage` and `Entrypoint::dissolve` methods are used to associate respectively disassociate signal handlers and RPC objects with the entrypoint. Under the hood, those operations interact with the component's PD session in order to bind the component's signal handlers and RPC objects to capabilities.

Note that the current version of the Entrypoint utilizes the former 'Rpc_entrypoint' and Signal_receiver APIs. The entrypoint is designated to eventually replace those APIs. Hence, application code should no longer use the Rpc_entrypoint and Signal_receiver directly.



Genode > Entrypoint > **Entrypoint** constructor

Arguments

env	Env &
stack_size	size_t
name	char const *
-	Location

Genode > Entrypoint > **manage** method template

Associate RPC object with the entry point

Template arguments

RPC_INTERFACE	typename
RPC_SERVER	typename

Argument

obj **Rpc_object<RPC_INTERFACE, RPC_SERVER> &**

Return value

Capability<RPC_INTERFACE>

Genode > Entrypoint > **dissolve** method template

Dissolve RPC object from entry point

Template arguments

RPC_INTERFACE	typename
RPC_SERVER	typename

Argument

obj **Rpc_object<RPC_INTERFACE, RPC_SERVER> &**

Genode	Entrypoint	manage	
Associate signal dispatcher with entry point			method
Argument			
- Signal_dispatcher_base &			
Return value			
Signal_context_capability			

Genode	Entrypoint	dissolve	
Disassociate signal dispatcher from entry point			method
Argument			
- Signal_dispatcher_base &			

Genode	Entrypoint	dispatch_pending_io_signal	
Dispatch single pending I/O-level signal (non-blocking)			method
Return value			
bool True if a pending signal was dispatched, false if no signal was pending			

Genode	Entrypoint	rpc_ep	
			method
Return value			
Rpc_entrypoint & RPC entrypoint			

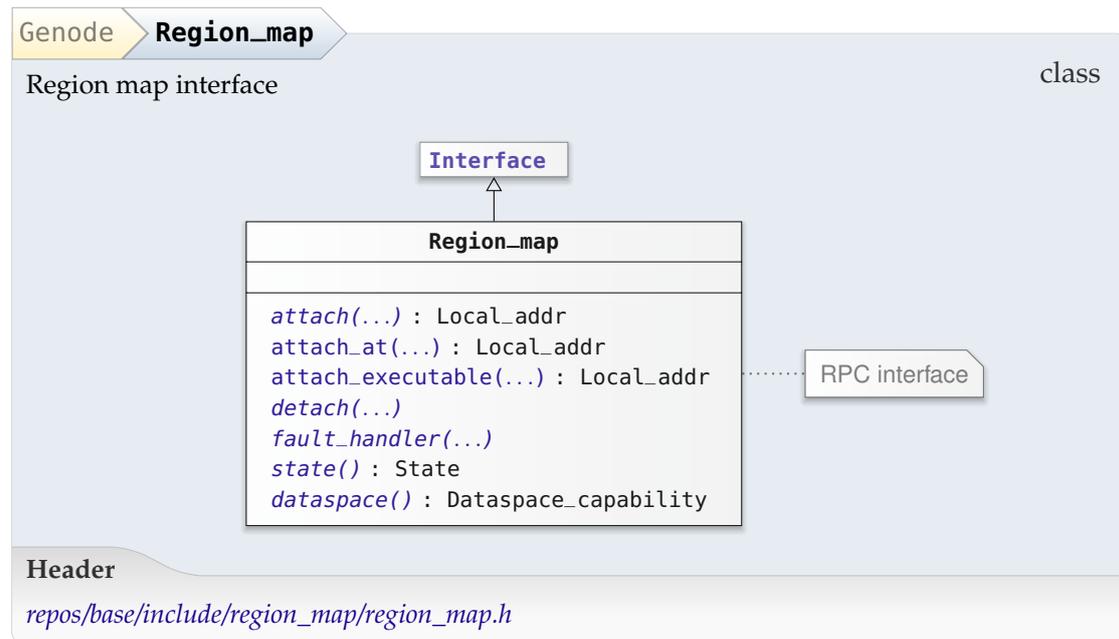
Genode	Entrypoint	schedule_suspend	
Trigger a suspend-resume cycle in the entrypoint			method

The suspended callback is called after the entrypoint entered the safe suspend state. The resumed callback is called when the entrypoint is fully functional again.

Genode	Entrypoint	register_io_progress_handler	
Register hook functor to be called after I/O signals are dispatched			method
Argument			
handler Io_progress_handler &			

8.4. Region-map interface

A region map represents a (portion of) a virtual memory address space (Section 3.4.2). By attaching dataspace to a region map, the content of those dataspace becomes visible in the component's virtual address space. Furthermore, a region map can be used as a dataspace. Thereby, the nesting of region maps becomes possible. This allows a component to manage portions of its own virtual address space manually as done for the stack area and linker area (Section 8.5.1). The use of region maps as so-called managed dataspace makes it even possible to manage portions of the virtual address space of other components (Section 8.5.3).



Genode	Region_map	attach	
Map dataspace into region map			pure virtual method
Arguments			
ds	Dataspace_capability	Capability of dataspace to map	
size	size_t	Size of the locally mapped region default (0) is the whole dataspace <i>Default is 0</i>	
offset	off_t	Start at offset in dataspace (page-aligned) <i>Default is 0</i>	
use_local_addr	bool	If set to true, attach the dataspace at the specified <code>local_addr</code> <i>Default is false</i>	
local_addr	Local_addr	Local destination address <i>Default is (void *)0</i>	
executable	bool	If the mapping should be executable <i>Default is false</i>	
writable	bool	If the mapping should be writable <i>Default is true</i>	
Exceptions			
Invalid_dataspace			
Region_conflict			
Out_of_ram		RAM quota of meta-data backing store is exhausted	
Out_of_caps		Cap quota of meta-data backing store is exhausted	
Return value			
Local_addr		Address of mapped dataspace within region map	

Genode > Region_map > **attach_at** method

Shortcut for attaching a dataspace at a predefined local address

Arguments

ds	Dataspace_capability
local_addr	addr_t
size	size_t <i>Default is 0</i>
offset	off_t <i>Default is 0</i>

Return value

Local_addr

Genode > Region_map > **attach_executable** method

Shortcut for attaching a dataspace executable at a predefined local address

Arguments

ds	Dataspace_capability
local_addr	addr_t
size	size_t <i>Default is 0</i>
offset	off_t <i>Default is 0</i>

Return value

Local_addr

Genode > Region_map > **detach** pure virtual method

Remove region from local address space

Argument

local_addr	Local_addr
------------	-------------------

Genode	Region_map	fault_handler	
Register signal handler for region-manager faults			pure virtual method
Argument			
handler	Signal_context_capability		

On Linux, this signal is never delivered because page-fault handling is performed by the Linux kernel. On microkernel platforms, unresolvable page faults (traditionally called segmentation fault) will result in the delivery of the signal.

Genode	Region_map	state	
Request current state of region map			pure virtual method
Return value			
State			

Genode	Region_map	dataspace	
			pure virtual method
Return value			
Dataspace_capability	Dataspace representation of region map		

8.5. Session interfaces of the base API

8.5.1. PD session interface

The protection-domain (PD) service (Section 3.4.4) enables the creation of address spaces that are isolated from each other. Each PD session corresponds to a protection domain. Each PD session is equipped with three region maps, one representing the PD's virtual address space, one for the component's stack area, and one for the component's linker area designated for shared objects. Of those region maps, only the virtual address space is needed by application code directly. The stack area and linker area are used by the framework internally. The PD service is rarely needed by applications directly but it is internally.

The PD session also represents a resource partition with a budget of physical memory and capabilities. Within the bounds of its RAM budget, it allows the client to allocate physical memory in the form of dataspaces.

Analogously, within the bounds of its capability budget, capabilities can be allocated and associated with a local object or a signal handler. Such a capability can be passed to another protection domain via an RPC call whereby the receiving protection domain obtains the right to send messages to the associated object or to trigger the associated signal handler respectively. The capability-management operations are not used directly by components at the API level but are used indirectly via the RPC mechanism described in Section 8.15 and the signalling API described in Section 8.14.



Genode	Pd_session	assign_parent	
Assign parent to protection domain			pure virtual method
Argument			
parent	Capability<Parent>		Capability of parent interface

Genode	Pd_session	assign_pci	
Assign PCI device to PD			pure virtual method
Arguments			
pci_config_memory_address	addr_t		
bdf	uint16_t		
Return value			
bool			

The specified address has to refer to the locally mapped PCI configuration space of the device.

This function is solely used on the NOVA kernel.

Genode	Pd_session	map	
Trigger eager insertion of page frames to page table within specified virtual range.			pure virtual method
Arguments			
virt	addr_t	Virtual address within the address space to start	
size	addr_t	The virtual size of the region	
Exceptions			
Out_of_ram			
Out_of_caps			

If the used kernel don't support this feature, the operation will silently ignore the request.

Genode	Pd_session	alloc_signal_source	
Create a new signal source			pure virtual method
Exceptions			
Out_of_ram Out_of_caps			
Return value			
Signal_source_capability A cap that acts as reference to the created source			

The signal source provides an interface to wait for incoming signals.

Genode	Pd_session	free_signal_source	
Free a signal source			pure virtual method
Argument			
cap	Signal_source_capability Capability of the signal source to destroy		

Genode	Pd_session	alloc_context	
Allocate signal context			pure virtual method
Arguments			
source	Signal_source_capability Signal source that shall provide the new context		
imprint	unsigned long Opaque value that gets delivered with signals originating from the allocated signal-context capability		
Exceptions			
Out_of_ram Out_of_caps Invalid_signal_source			
Return value			
Capability<Signal_context> New signal-context capability			

Genode	Pd_session	free_context	
Free signal-context			pure virtual method
Argument			
cap	Capability<Signal_context> Capability of signal-context to release		

Genode	Pd_session	submit	
Submit signals to the specified signal context			pure virtual method
Arguments			
context	Capability<Signal_context> Signal destination		
cnt	unsigned Number of signals to submit at once <i>Default is 1</i>		

The context argument does not necessarily belong to this PD session. Normally, it is a capability obtained from a potentially untrusted component. Because we cannot trust this capability, signals are not submitted by invoking cap directly but by using it as argument to our trusted PD-session interface. Otherwise, a potential signal receiver could supply a capability with a blocking interface to compromise the nonblocking behaviour of the signal submission.

Genode \rightarrow Pd_session \rightarrow **alloc_rpc_cap** pure virtual method

Allocate new RPC-object capability

Argument

ep **Native_capability**
Entry point that will use this capability

Exceptions

Out_of_ram If meta-data backing store is exhausted
Out_of_caps If cap_quota is exceeded

Return value

Native_capability New RPC capability

Genode \rightarrow Pd_session \rightarrow **free_rpc_cap** pure virtual method

Free RPC-object capability

Argument

cap **Native_capability**
Capability to free

Genode \rightarrow Pd_session \rightarrow **address_space** pure virtual method

Return value

Capability<Region_map> Region map of the PD's virtual address space

Genode \rightarrow Pd_session \rightarrow **stack_area** pure virtual method

Return value

Capability<Region_map> Region map of the PD's stack area

Genode \rightarrow Pd_session \rightarrow **linker_area** pure virtual method

Return value

Capability<Region_map> Region map of the PD's linker area

Genode	Pd_session	ref_account	
Define reference account for the PD session			pure virtual method
Argument			
- Capability <Pd_session>			
Exception			
Invalid_session			

Genode	Pd_session	transfer_quota	
Transfer capability quota to another PD session			pure virtual method
Arguments			
to	Capability <Pd_session>	Receiver of quota donation	
amount	Cap_quota	Amount of quota to donate	
Exceptions			
Out_of_caps			
Invalid_session			
Undefined_ref_account			

Quota can only be transferred if the specified PD session is either the reference account for this session or vice versa.

Genode	Pd_session	cap_quota	
Return value			pure virtual const method
Cap_quota	Current capability-quota limit		

Genode	Pd_session	used_caps	
Return value			pure virtual const method
Cap_quota	Number of capabilities allocated from the session		

Genode	Pd_session	avail_caps	
Return value			const method
Cap_quota	Amount of available capabilities		

Genode	Pd_session	transfer_quota	
Transfer quota to another RAM session			pure virtual method
Arguments			
to	Capability<Pd_session>	Receiver of quota donation	
amount	Ram_quota	Amount of quota to donate	
Exceptions			
Out_of_ram			
Invalid_session			
Undefined_ref_account			

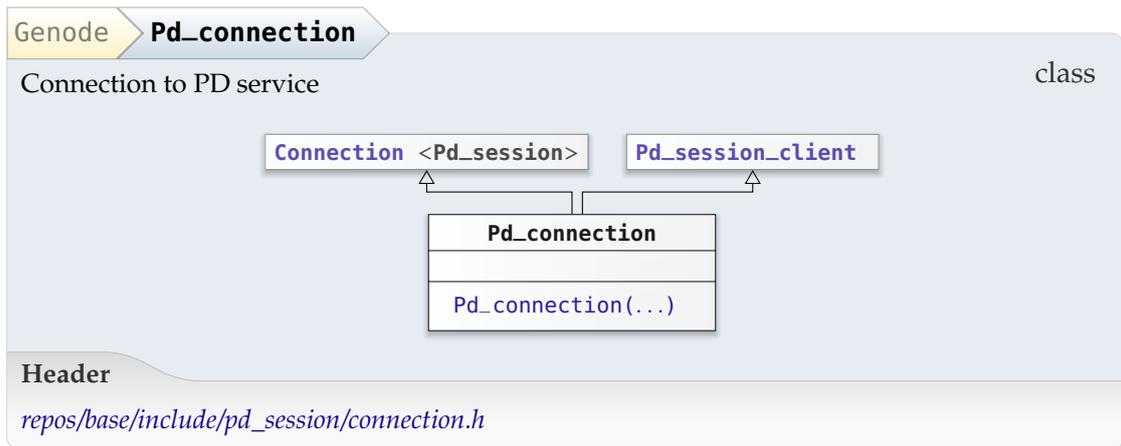
Quota can only be transferred if the specified PD session is either the reference account for this session or vice versa.

Genode	Pd_session	ram_quota	
Return value			pure virtual const method
Ram_quota	Current quota limit		

Genode	Pd_session	used_ram	
Return value			pure virtual const method
Ram_quota	Used quota		

Genode	Pd_session	avail_ram	
Return value			const method
Ram_quota	Amount of available quota		

Genode	Pd_session	native_pd	
Return value			pure virtual method
Capability<Native_pd>	Capability to kernel-specific PD operations		



Attached RAM dataspace The instantiation of an `Attached_ram_dataspace` object subsumes the tasks of allocating a dataspace from the component's PD session and attaching the dataspace to the component's region map. Furthermore, the reverse operations are performed during the destruction of an `Attached_ram_dataspace` object.

Genode **Attached_ram_dataspace** class

Utility to allocate and locally attach a RAM dataspace

Attached_ram_dataspace
<pre>Attached_ram_dataspace(...) ~Attached_ram_dataspace() cap() : Ram_dataspace_capability local_addr() : T * size() : size_t swap(...) realloc(...)</pre>

Header

[repos/base/include/base/attached_ram_dataspace.h](#)

Genode **Attached_ram_dataspace** **Attached_ram_dataspace** constructor

Arguments

ram	Ram_allocator &
rm	Region_map &
size	size_t
cached	Cache_attribute <i>Default is CACHED</i>

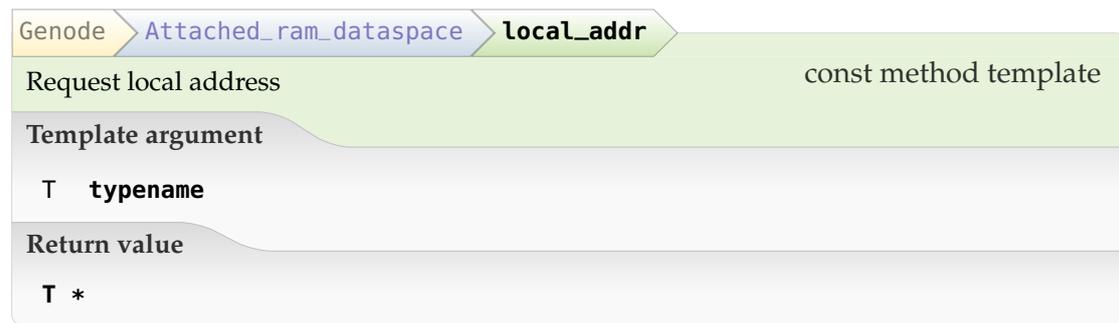
Exceptions

- Out_of_ram**
- Out_of_caps**
- Region_map::Region_conflict**
- Region_map::Invalid_dataspace**

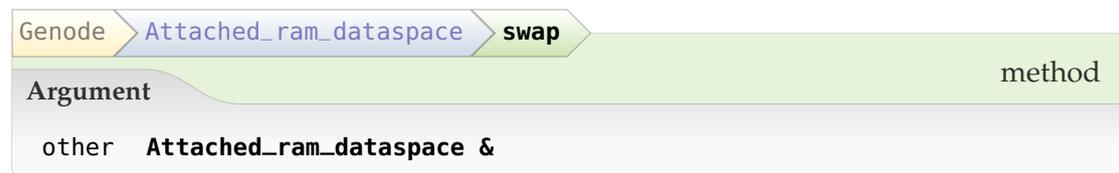
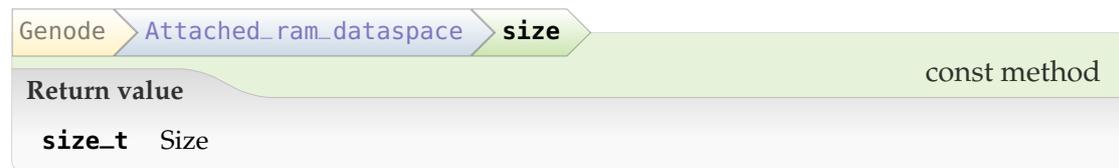
Genode **Attached_ram_dataspace** **cap** const method

Return value

Ram_dataspace_capability Capability of the used RAM dataspace



This is a template to avoid inconvenient casts at the caller. A newly allocated RAM dataspace is untyped memory anyway.



The content of the original dataspace is not retained.

8.5.2. ROM session interface

The ROM service (Section 4.5.1) provides access to ROM modules, e.g., binary data loaded by the boot loader (core’s ROM service described in Section 3.4.3). Each session refers to one ROM module. The module’s data is provided to the client in the form of a dataspace (Section 3.4.1).

Genode
namespace

ROM session interface

Types

Rom_dataspace is a subtype of Dataspace

Rom_dataspace_capability is defined as Capability<Rom_dataspace>

Header

repos/base/include/rom_session/rom_session.h

Genode
Rom_session
class

Session

↑

Rom_session

~Rom_session()
dataspace() : Rom_dataspace_capability
update() : bool
sigh(...)

RPC interface

Header

repos/base/include/rom_session/rom_session.h

Genode
Rom_session
dataspace

Request dataspace containing the ROM session data pure virtual method

Return value

Rom_dataspace_capability Capability to ROM dataspace

The capability may be invalid.
 Consecutive calls of this method are not guaranteed to return the same dataspace as dynamic ROM sessions may update the ROM data during the lifetime of the session.

When calling the method, the server may destroy the old dataspace and replace it with a new one containing the updated data. Hence, prior calling this method, the client should make sure to detach the previously requested dataspace from its local address space.

Genode	Rom_session	update	
Update ROM dataspace content			virtual method
Return value			
bool	True if the existing dataspace contains up-to-date content, or false if a new dataspace must be requested via the dataspace method		

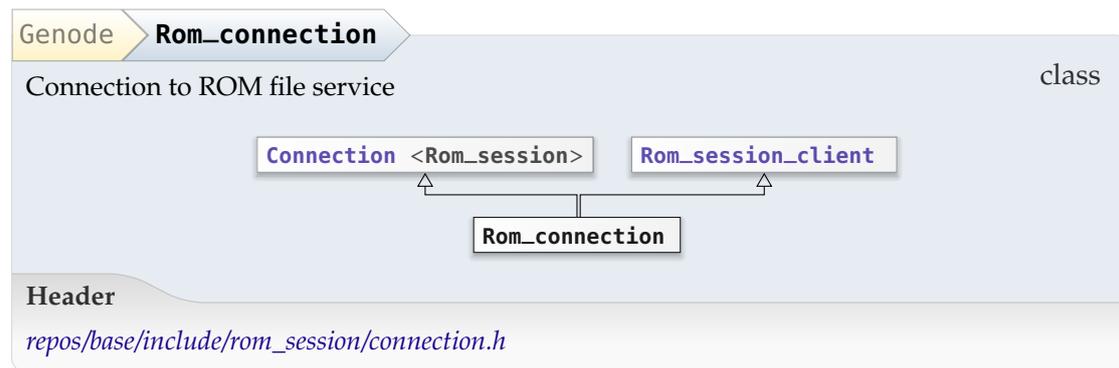
This method is an optimization for use cases where ROM dataspaces are updated at a high rate. In such cases, requesting a new dataspace for each update induces a large overhead because memory mappings must be revoked and updated (e.g., handling the page faults referring to the dataspace). If the updated content fits in the existing dataspace, those costly operations can be omitted.

When this method is called, the server may replace the dataspace content with new data.

Genode	Rom_session	sigh	
Register signal handler to be notified of ROM data changes			pure virtual method
Argument			
sigh	Signal_context_capability		

The ROM session interface allows for the implementation of ROM services that dynamically update the data exported as ROM dataspace during the lifetime of the session. This is useful in scenarios where this data is generated rather than originating from a static file, for example to update a program's configuration at runtime.

By installing a signal handler using the `sigh()` method, the client will receive a notification each time the data changes at the server. From the client's perspective, the original data contained in the currently used dataspace remains unchanged until the client calls `dataspace()` the next time.



Attached ROM dataspace By instantiating an `Attached_rom_dataspace` object, a ROM module is requested and made visible within the component's address space in a single step.

To accommodate the common use of a ROM session as provider of configuration data (Section 4.6) or an XML-formatted data model in a publisher-subscriber scenario 4.7.5, the `Attached_rom_dataspace` provides a convenient way to retrieve its content as an XML node via the `xml` method. The method always returns a valid `Xml_node` even in the event where the dataspace is invalid or contains no XML. In such cases, the returned XML node is `<empty/>`. This relieves the caller from handling exceptions that may occur during XML parsing.

Genode **Attached_rom_dataspace** class

Utility to open a ROM session and locally attach its content

Attached_rom_dataspace
<pre>Attached_rom_dataspace(...) cap() : Dataspace_capability local_addr() : T * local_addr() : T const * size() : size_t sigh(...) update() valid() : bool xml() : Xml_node</pre>

Accessor

size **size_t**

Header

repos/base/include/base/attached_rom_dataspace.h

Genode **Attached_rom_dataspace** **Attached_rom_dataspace** constructor

Arguments

env **Env &**

name **char const ***

Exceptions

Rom_connection::Rom_connection_failed

Region_map::Region_conflict

Region_map::Invalid_dataspace

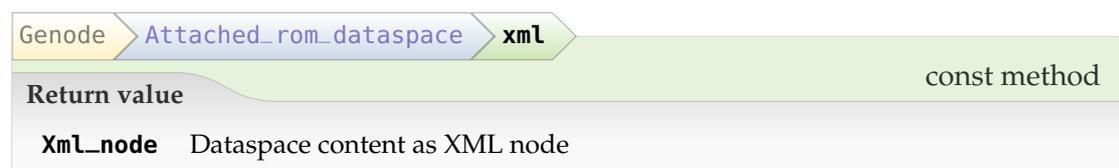
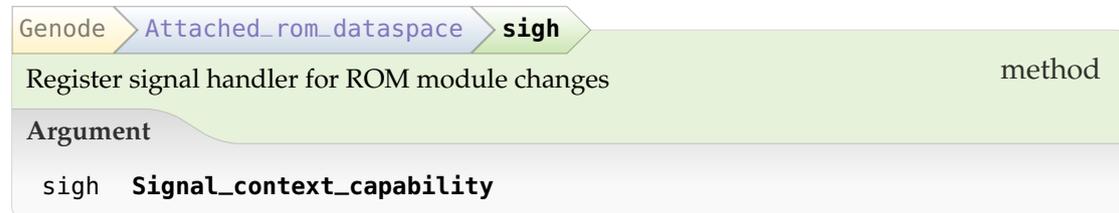
Out_of_ram

Out_of_caps

Genode **Attached_rom_dataspace** **cap** const method

Return value

Dataspace_capability Capability of the used dataspace

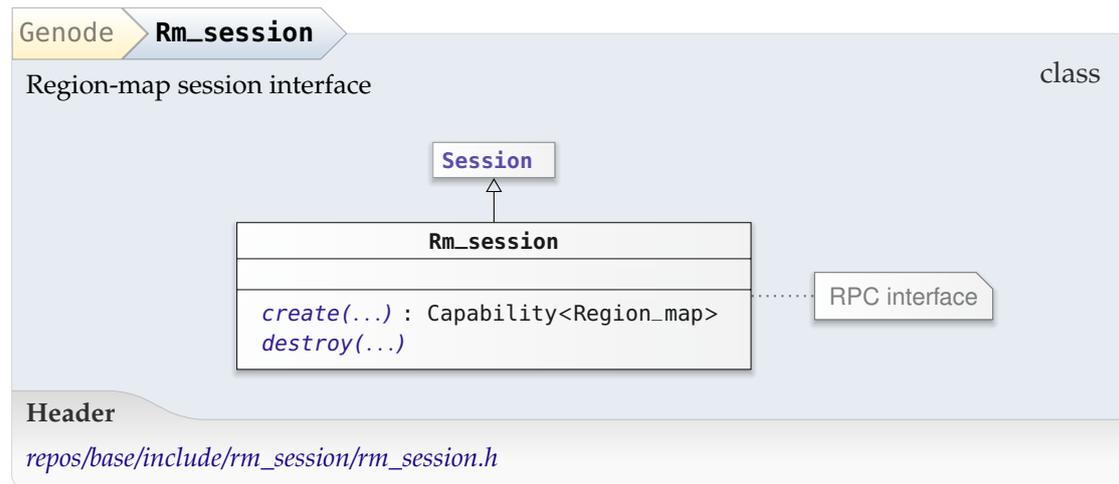


This method always returns a valid XML node. It never throws an exception. If the dataspace is invalid or does not contain properly formatted XML, the returned XML node has the form "<empty/>".

8.5.3. RM session interface

The region-map (RM) service (Section 3.4.5) allows for the manual creation of region maps that represent (portions of) virtual address spaces. Components can use this service to manage the virtual memory layout of so-called managed dataspace manually. For example, it allows a dataspace provider to populate the content of dataspace on demand, depending on the access patterns produced by the dataspace user.

Note that the RM service is not available on all base platforms. In particular, it is not supported on Linux.



Genode > Rm_session > **create**

Create region map pure virtual method

Argument

size **size_t**
Upper bound of region map

Exceptions

Out_of_ram
Out_of_caps

Return value

Capability<Region_map> Region-map capability

Genode > Rm_session > **destroy**

Destroy region map pure virtual method

Argument

- **Capability<Region_map>**

Genode > **Rm_connection** class

Connection to RM service

```

classDiagram
    class Connection["Connection <Rm_session>"]
    class Rm_session_client
    class Rm_connection
    Connection <|-- Rm_connection
    Rm_session_client <|-- Rm_connection
    
```

Rm_connection

Rm_connection(...)
create(...) : Capability<Region_map>

Header

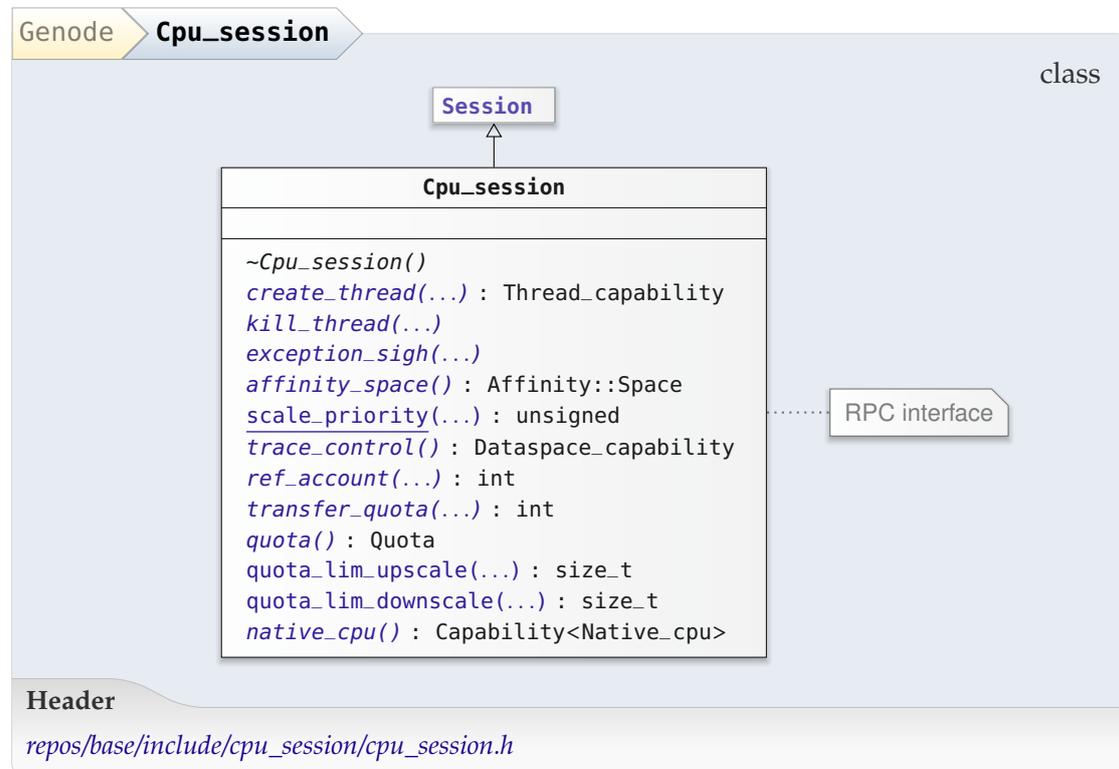
repos/base/include/rm_session/connection.h

Genode	Rm_connection	Rm_connection	
Argument			constructor
env	Env &		

Genode	Rm_connection	create	
Wrapper over create that handles resource requests from the server.			method
Argument			
size	size_t		
Return value			
Capability<Region_map>			

8.5.4. CPU session interface

The CPU service (Section 3.4.6) provides a facility for creating and managing threads. A CPU session corresponds to a CPU-time allocator, from which multiple threads can be allocated.



Genode > Cpu_session > **create_thread** pure virtual method

Create a new thread

Arguments

pd	Capability<Pd_session> Protection domain where the thread will be executed
name	Name const & Name for the thread
affinity	Location CPU affinity, referring to the session-local affinity space
weight	Weight CPU quota that shall be granted to the thread
utcb	addr_t Base of the UTCB that will be used by the thread <i>Default is 0</i>

Exceptions

- Thread_creation_failed**
- Out_of_ram**
- Out_of_caps**

Return value

Thread_capability Capability representing the new thread

Genode > Cpu_session > **kill_thread** pure virtual method

Kill an existing thread

Argument

thread	Thread_capability Capability of the thread to kill
--------	--

Genode > Cpu_session > **exception_sigh** pure virtual method

Register default signal handler for exceptions

Argument

- **Signal_context_capability**

This handler is used for all threads that have no explicitly installed exception handler. On Linux, this exception is delivered when the process triggers a SIGCHLD. On other platforms, this exception is delivered on the occurrence of CPU exceptions such as division by zero.

Genode	Cpu_session	affinity_space	pure virtual const method
Return value			
Affinity::Space			Affinity space of CPU nodes available to the CPU session

The dimension of the affinity space as returned by this method represent the physical CPUs that are available.

Genode	Cpu_session	scale_priority	class function
Translate generic priority value to kernel-specific priority levels			
Arguments			
pf_prio_limit	unsigned	Maximum priority used for the kernel, must be power of 2	
prio	unsigned	Generic priority value as used by the CPU session interface	
inverse	bool	Order of platform priorities, if true pf_prio_limit corresponds to the highest priority, otherwise it refers to the lowest priority. <i>Default is true</i>	
Return value			
unsigned	Platform-specific priority value		

Genode	Cpu_session	trace_control	pure virtual method
Request trace control dataspace			
Return value			
Dataspace_capability			

The trace-control dataspace is used to propagate tracing control information from core to the threads of a CPU session.

The trace-control dataspace is accounted to the CPU session.

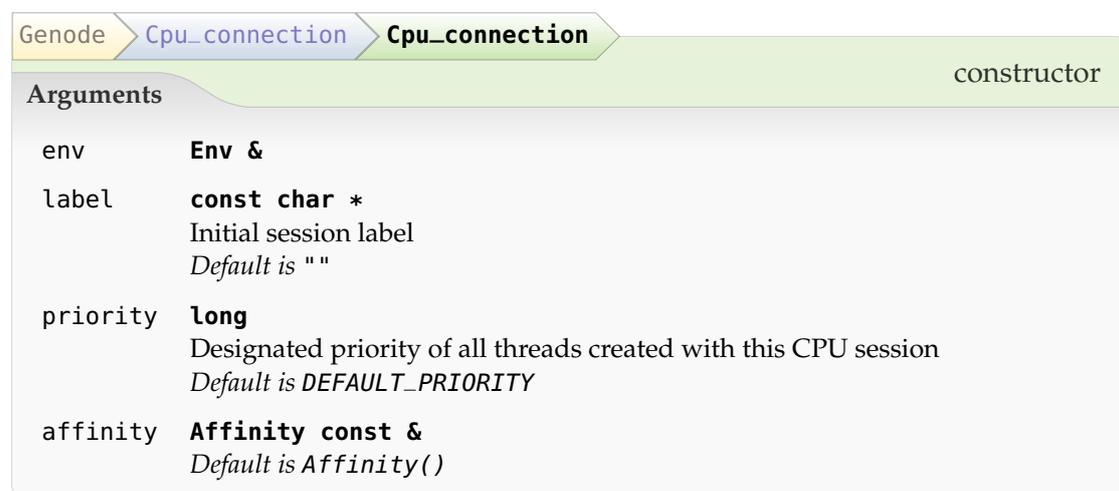
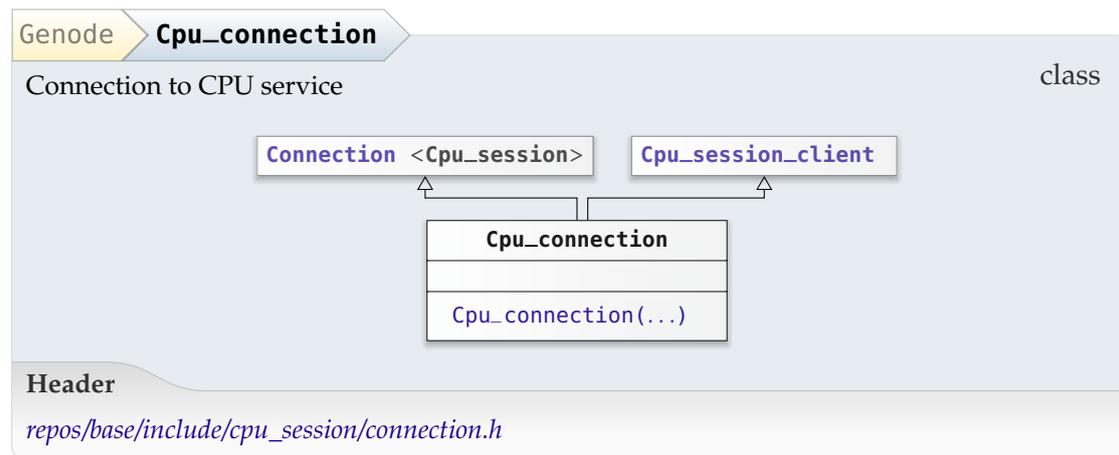
Genode	Cpu_session	ref_account	
Define reference account for the CPU session			pure virtual method
Argument			
cpu_session	Cpu_session_capability	Reference account	
Return value			
int	0 on success		

Each CPU session requires another CPU session as reference account to transfer quota to and from. The reference account can be defined only once.

Genode	Cpu_session	transfer_quota	
Transfer quota to another CPU session			pure virtual method
Arguments			
cpu_session	Cpu_session_capability	Receiver of quota donation	
amount	size_t	Percentage of the session quota scaled up to the QUOTA_LIMIT space	
Return value			
int	0 on success		

Quota can only be transferred if the specified CPU session is either the reference account for this session or vice versa.

Genode	Cpu_session	quota	
Return value			pure virtual method
Quota	Quota configuration of the session		
Genode	Cpu_session	quota_lim_upscale	
Scale up value from its space with <code>limit</code> to the <code>QUOTA_LIMIT</code> class function template space			
Template argument			
T	typename	<i>Default is <code>size_t</code></i>	
Arguments			
value	size_t	const	
limit	size_t	const	
Return value			size_t
Genode	Cpu_session	quota_lim_downscale	
Scale down value from the <code>QUOTA_LIMIT</code> space to a space with <code>limit</code> class function template			
Template argument			
T	typename	<i>Default is <code>size_t</code></i>	
Arguments			
value	size_t	const	
limit	size_t	const	
Return value			size_t
Genode	Cpu_session	native_cpu	
Return value			pure virtual method
Capability<Native_cpu>	Capability to kernel-specific CPU operations		



Genode **Affinity** Affinity to CPU nodes class

Affinity
<pre> Affinity(...) Affinity() space() : Space location() : Location scale_to(...) : Location </pre>

Accessors

space **Space**
location **Location**

Header

repos/base/include/base/affinity.h

The entity of CPU nodes is expected to form a grid where the Euclidean distance between nodes roughly correlate to the locality of their respective resources. Closely interacting processes are supposed to perform best when using nodes close to each other. To allow a relatively simple specification of such constraints, the affinity of a subsystem (e. g., a process) to CPU nodes is expressed as a rectangle within the grid of available CPU nodes. The dimensions of the grid are represented by `Affinity::Space`. The rectangle within the grid is represented by `Affinity::Location`.

Genode **Affinity** **Affinity** constructor

Arguments

space **Space const &**
location **Location const &**

Genode **Affinity** **scale_to** const method

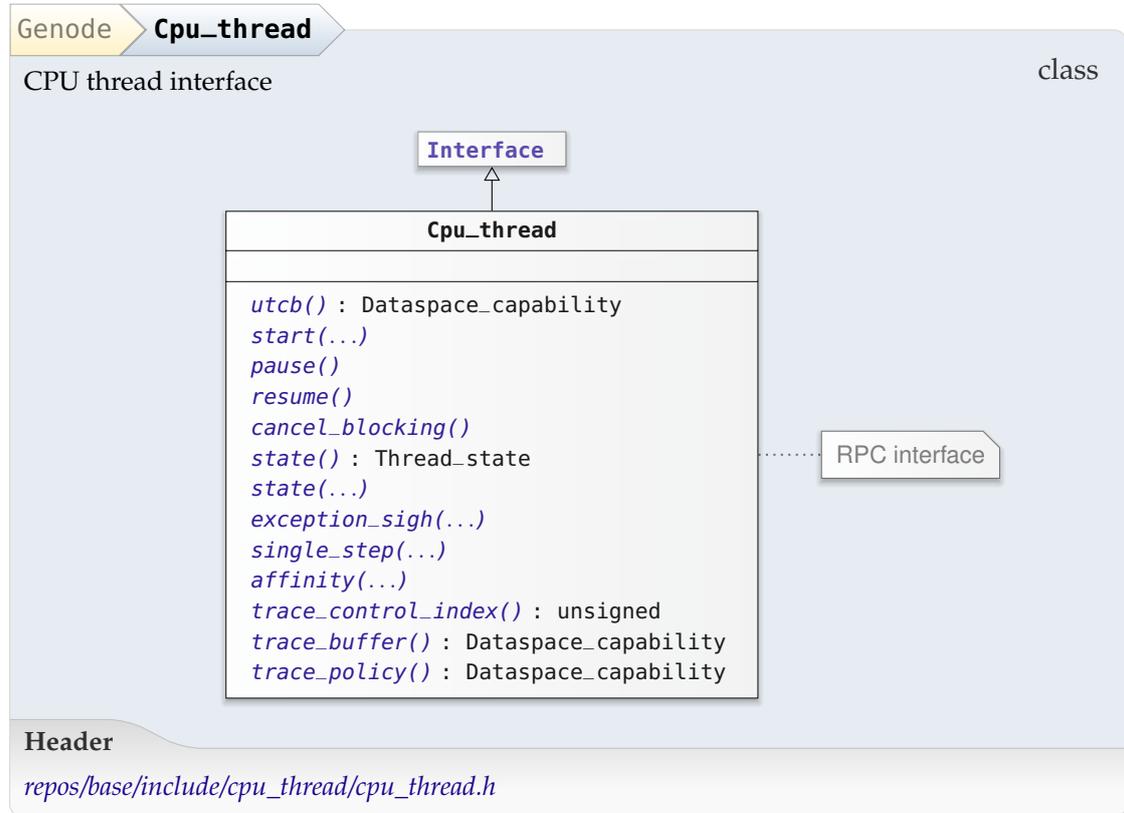
Argument

space **Space const &**

Return value

Location Location scaled to specified affinity space

Once created, a thread is referred to via a thread capability. This capability allows for the destruction of the thread via the CPU session, and provides the `Cpu_thread` RPC interface to operate on the thread.



Genode > Cpu_thread > **utcb**

Get dataspace of the thread's user-level thread-control block (UTCB) pure virtual method

Return value

Dataspace_capability

Genode > Cpu_thread > **start**

Modify instruction and stack pointer of thread - start the thread pure virtual method

Arguments

ip **addr_t**
Initial instruction pointer

sp **addr_t**
Initial stack pointer

Genode > Cpu_thread > **pause**

Pause the thread pure virtual method

After calling this method, the execution of the thread can be continued by calling **resume**.

Genode > Cpu_thread > **resume**

Resume the thread pure virtual method

Genode > Cpu_thread > **cancel_blocking**

Cancel a currently blocking operation pure virtual method

Genode > Cpu_thread > **state**

Get the current thread state pure virtual method

Exception

State_access_failed

Return value

Thread_state State of the targeted thread

Genode	Cpu_thread	state	
Override the current thread state			pure virtual method
Argument			
state	Thread_state const & State that shall be applied		
Exception			
State_access_failed			

Genode	Cpu_thread	exception_sigh	
Register signal handler for exceptions of the thread			pure virtual method
Argument			
handler	Signal_context_capability		

On Linux, this exception is delivered when the process triggers a SIGCHLD. On other platforms, this exception is delivered on the occurrence of CPU exceptions such as division by zero.

Genode	Cpu_thread	single_step	
Enable/disable single stepping			pure virtual method
Argument			
enabled	bool True = enable single-step mode; false = disable		

Since this method is currently supported by a small number of platforms, we provide a default implementation

Genode	Cpu_thread	affinity	
Define affinity of thread to one or multiple CPU nodes			pure virtual method
Argument			
location	Location Location within the affinity space of the thread's CPU session		

In the normal case, a thread is assigned to a single CPU. Specifying more than one CPU node is supposed to principally allow a CPU service to balance the load of threads among multiple CPUs.

Genode	Cpu_thread	trace_control_index	
Request index within the trace control block of the thread's CPU session			pure virtual method
Return value			
unsigned			

The trace control dataspace contains the control blocks for all threads of the CPU session. Each thread gets assigned a different index by the CPU service.

Genode	Cpu_thread	trace_buffer	
Request trace buffer for the thread			pure virtual method
Return value			
Dataspace_capability			

The trace buffer is not accounted to the CPU session. It is owned by a TRACE session.

Genode	Cpu_thread	trace_policy	
Request trace policy			pure virtual method
Return value			
Dataspace_capability			

The trace policy buffer is not accounted to the CPU session. It is owned by a TRACE session.

8.5.5. IO_MEM session interface

The IO_MEM service (Section 3.4.7) enables user-level device drivers to obtain memory-mapped device resources in the form of dataspace. Each IO_MEM session corresponds to the reservation of a physical address range, for which a dataspace is provided to the client. The user-level device driver can make the device resource visible in its address space by attaching the dataspace to the region map of its own PD session.

Genode Memory-mapped I/O session interface namespace

Types

- Io_mem_dataspace** is a subtype of Dataspace
- Io_mem_dataspace_capability** is defined as Capability<Io_mem_dataspace>

Header
[repos/base/include/io_mem_session/io_mem_session.h](#)

Genode **Io_mem_session** class

```

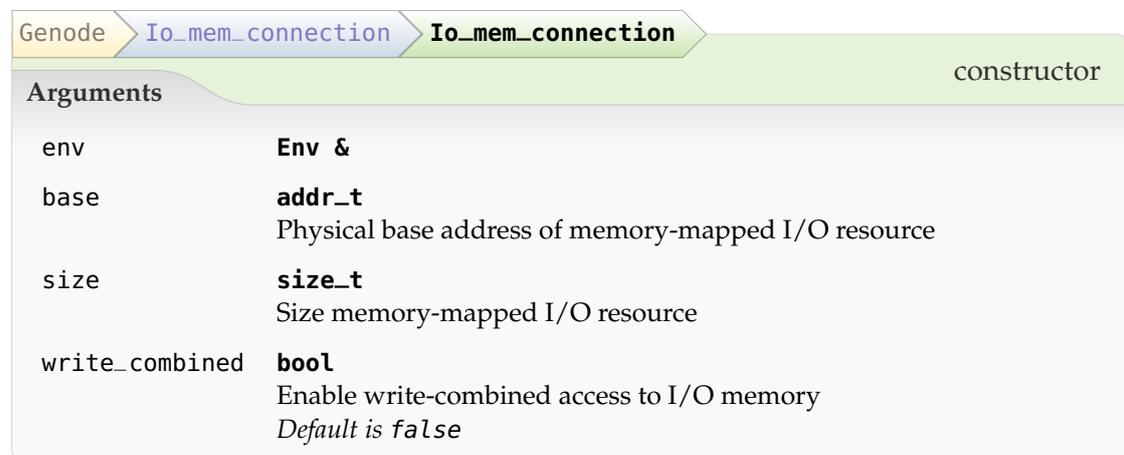
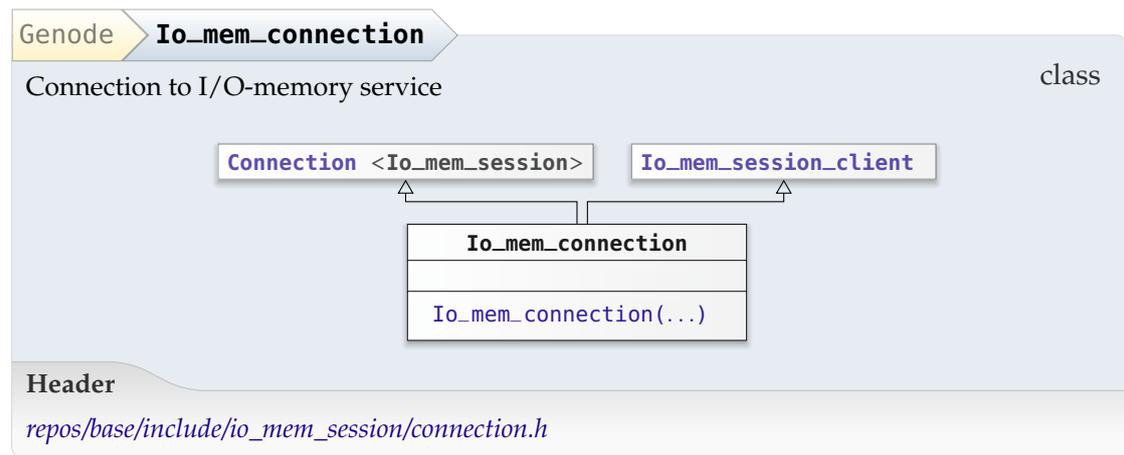
classDiagram
    class Session
    class Io_mem_session {
        ~Io_mem_session()
        dataspace() : Io_mem_dataspace_capability
    }
    Session <|-- Io_mem_session
    Io_mem_session ..|> RPC interface
    
```

Header
[repos/base/include/io_mem_session/io_mem_session.h](#)

Genode **Io_mem_session** **dataspace** pure virtual method

Request dataspace containing the IO_MEM session data

Return value
Io_mem_dataspace_capability Capability to IO_MEM dataspace (may be invalid)



Attached IO_MEM dataspace An instance of an `Attached_io_mem_dataspace` represents a locally mapped memory-mapped I/O range.

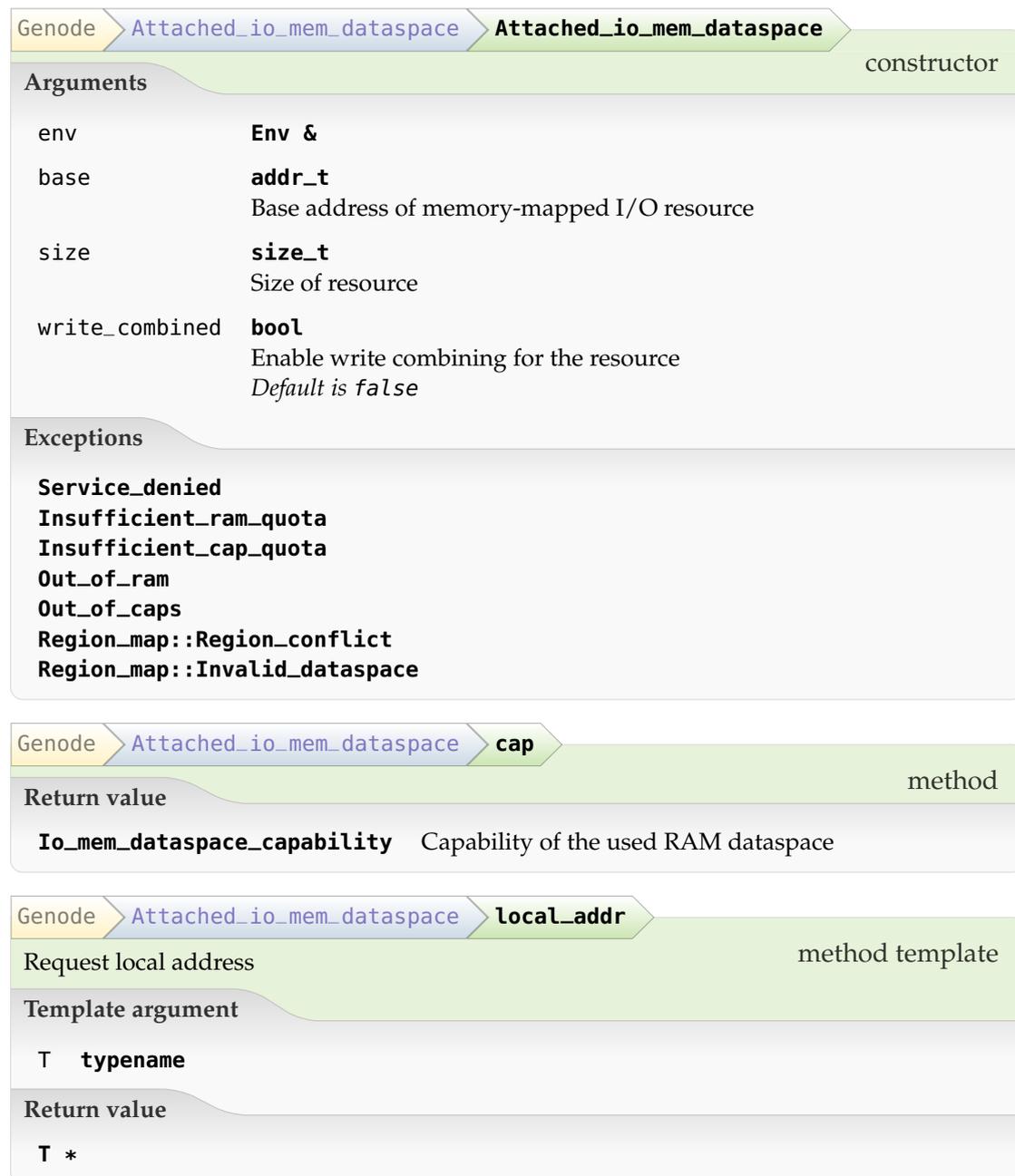
Genode **Attached_io_mem_dataspace** class

Request and locally attach a memory-mapped I/O resource

Attached_io_mem_dataspace
<code>Attached_io_mem_dataspace(...)</code> <code>~Attached_io_mem_dataspace()</code> <code>cap() : Io_mem_dataspace_capability</code> <code>local_addr() : T *</code>

Header
[repos/base/include/base/attached_io_mem_dataspace.h](#)

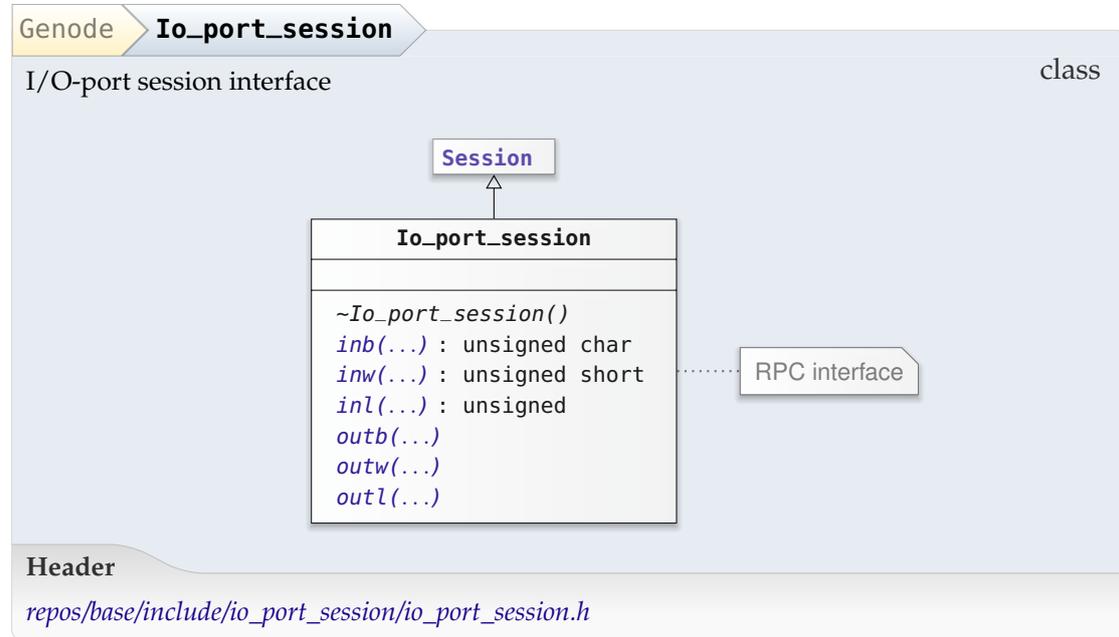
This class is a wrapper for a typical sequence of operations performed by device drivers to access memory-mapped device resources. Its sole purpose is to avoid duplicated code.



This is a template to avoid inconvenient casts at the caller. A newly allocated I/O MEM dataspace is untyped memory anyway.

8.5.6. IO_PORT session interface

On the x86 architecture, the IO_PORT service (Section 3.4.7) provides access to device I/O ports via an RPC interface. Each IO_PORT session corresponds to the access right to a port range.



Genode **Io_port_session** **inb**

Read byte (8 bit) pure virtual method

Argument

address **unsigned short**
Physical I/O port address

Return value

unsigned char Value read from port

Genode **Io_port_session** **inw**

Read word (16 bit) pure virtual method

Argument

address **unsigned short**
Physical I/O port address

Return value

unsigned short Value read from port

Genode **Io_port_session** **inl**

Read double word (32 bit) pure virtual method

Argument

address **unsigned short**
Physical I/O port address

Return value

unsigned Value read from port

Genode **Io_port_session** **outb**

Write byte (8 bit) pure virtual method

Arguments

address **unsigned short**
Physical I/O port address

value **unsigned char**
Value to write to port

Genode **Io_port_session** **outw**

Write word (16 bit) pure virtual method

Arguments

address **unsigned short**
Physical I/O port address

value **unsigned short**
Value to write to port

Genode **Io_port_session** **outl**

Write double word (32 bit) pure virtual method

Arguments

address **unsigned short**
Physical I/O port address

value **unsigned**
Value to write to port

Genode **Io_port_connection** class

Connection to I/O-port service

```

classDiagram
    class Connection {
        <Io_port_session>
    }
    class Io_port_session_client
    class Io_port_connection {
        Io_port_connection(...)
    }
    Connection <|-- Io_port_connection
    Io_port_session_client <|-- Io_port_connection
    
```

Header

repos/base/include/io_port_session/connection.h

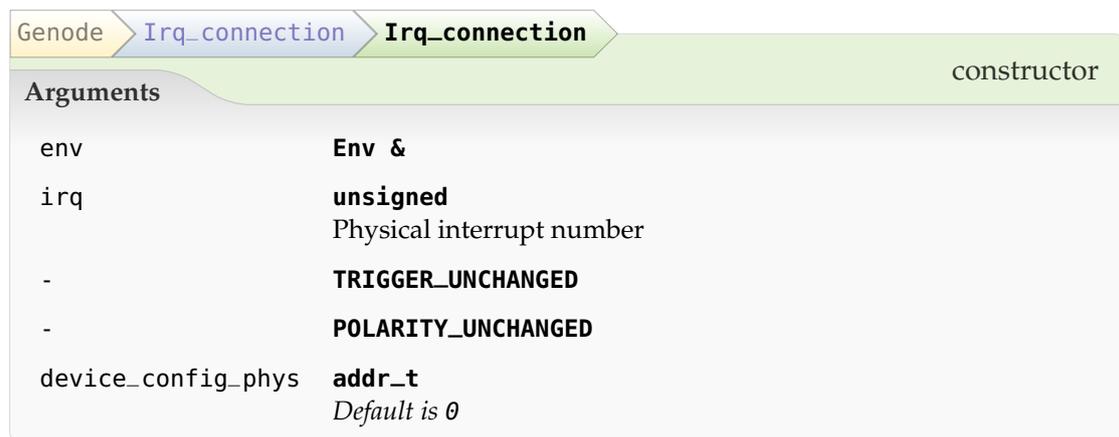
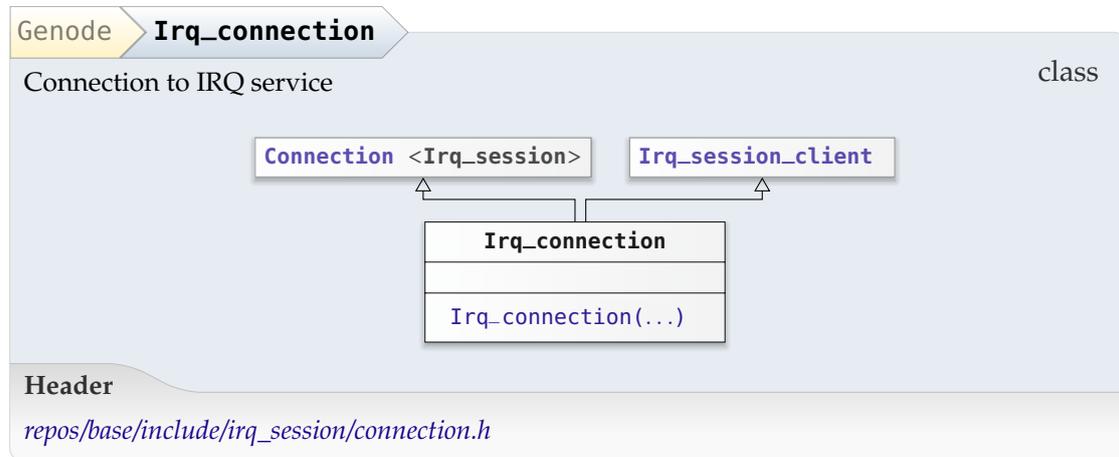
Genode **Io_port_connection** **Io_port_connection** constructor

Arguments

env	Env &
base	unsigned Base address of port range
size	unsigned Size of port range

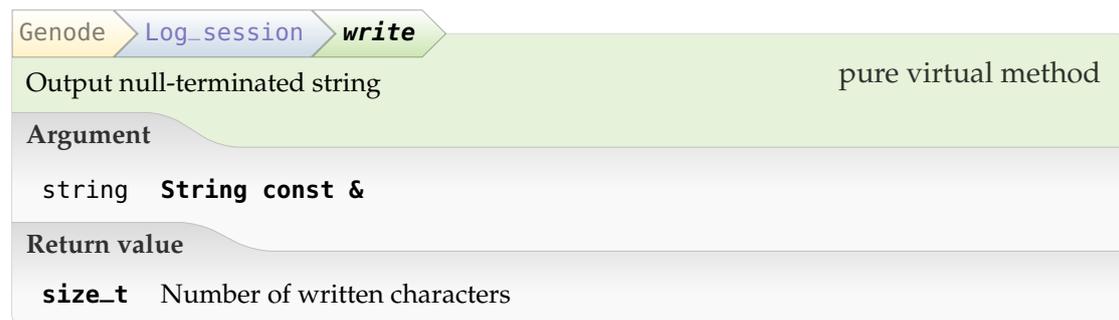
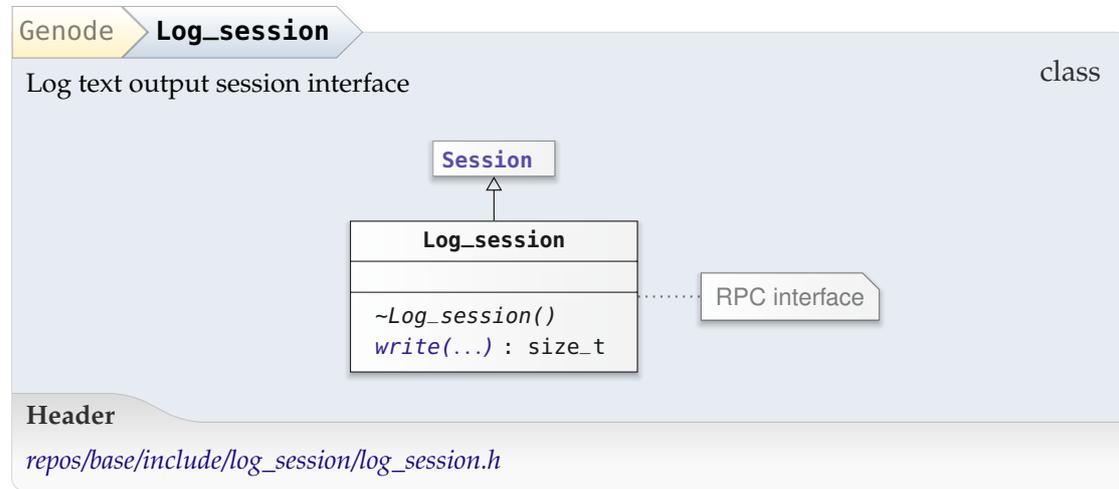
8.5.7. IRQ session interface

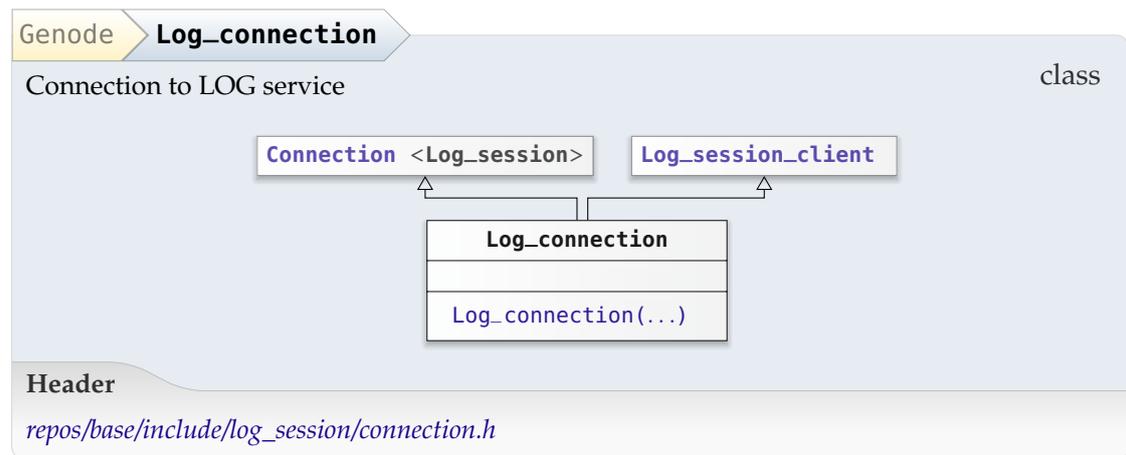
The IRQ service (Section 3.4.7) enables user-level device drivers to serve device interrupts. Each IRQ session corresponds to an associated interrupt line.



8.5.8. LOG session interface

For low-level debugging, core provides a simple LOG service (Section 3.4.8), which enables clients to print textual messages. In the LOG output, each message is tagged with the label of the corresponding client.

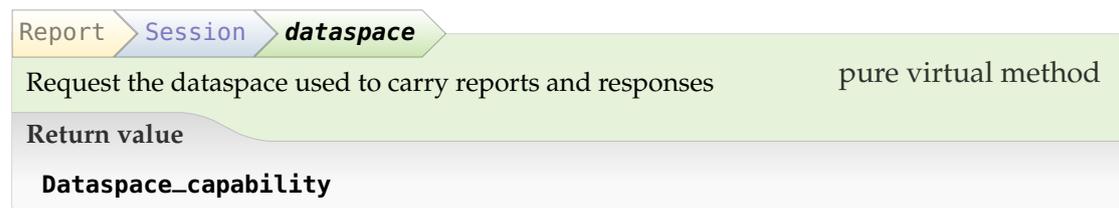
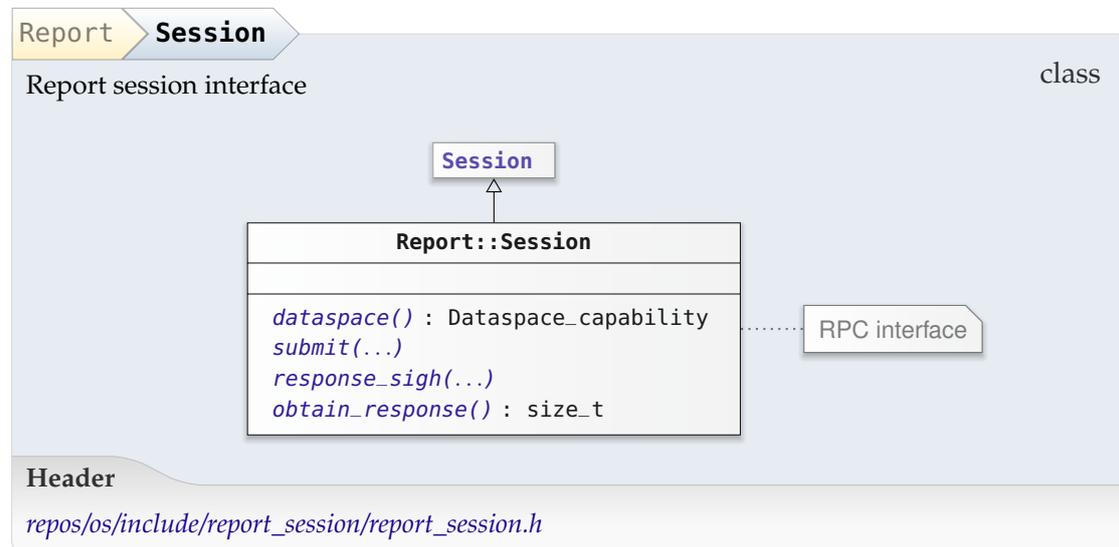




8.6. OS-level session interfaces

8.6.1. Report session interface

Report sessions (Section 4.5.2) allow a component to propagate internal state to the outside. The most prominent use case is the realization of publisher-subscriber communication schemes as discussed in Section 4.7.5.



While this method is called, the information in the dataspace must not be modified by the client.

Report > Session > **response_sigh** pure virtual method

Install signal handler for response notifications

Argument

- **Signal_context_capability**

Report > Session > **obtain_response** pure virtual method

Request a response from the recipient of reports

Return value

size_t Length of response in bytes

By calling this method, the client expects that the server will replace the content of the dataspace with new information.

Report > **Connection** class

Connection to Report service

```

classDiagram
    class Connection {
        <Session>
    }
    class Session_client
    class Report_Connection["Report::Connection"] {
        Connection(...)
    }
    Connection <|-- Report_Connection
    Session_client <|-- Report_Connection
    
```

Header

repos/os/include/report_session/connection.h

Report > Connection > **Connection** constructor

Arguments

env	Env &
label	char const *
buffer_size	size_t <i>Default is 4096</i>

The client-side Reporter is a convenient front end for the use of a report connection to propagate XML-formed data.

Genode Reporter class

```

Reporter
Reporter(...)
enabled(...)
enabled() : bool
name() : Name
clear()
report(...)
    
```

Accessor

name **Name**

Header

repos/os/include/os/reporter.h

Genode Reporter Reporter constructor

Arguments

env **Env &**

xml_name **char const ***

label **char const ***
Default is nullptr

buffer_size **size_t**
Default is 4096

Genode Reporter enabled method

Enable or disable reporting

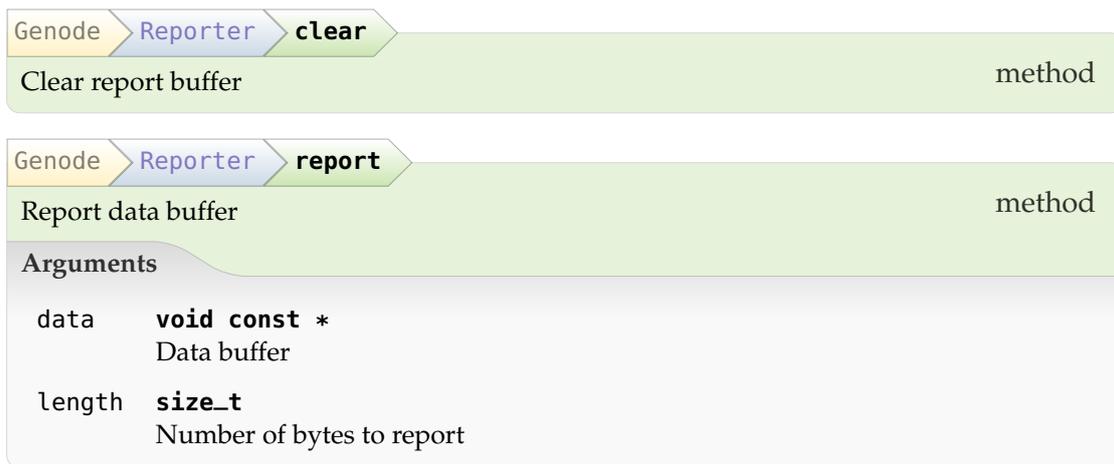
Argument

enabled **bool**

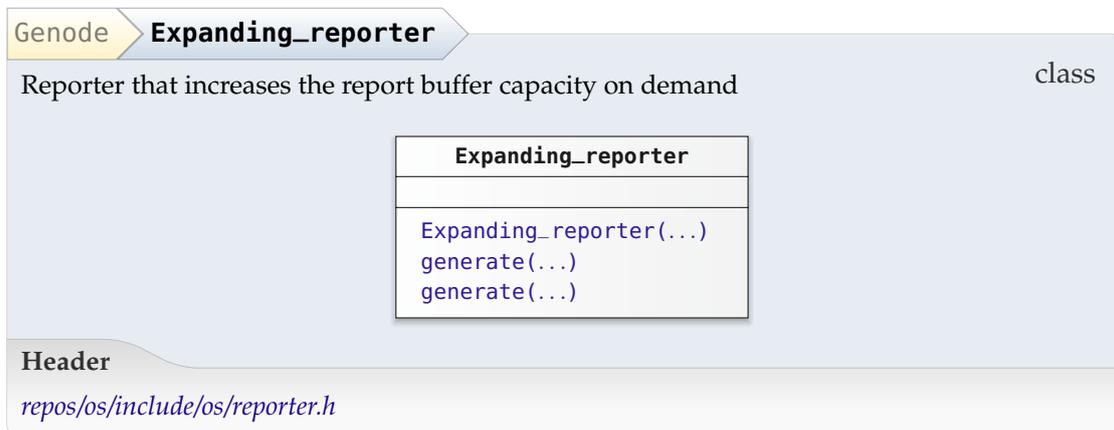
Genode Reporter enabled const method

Return value

bool True if reporter is enabled

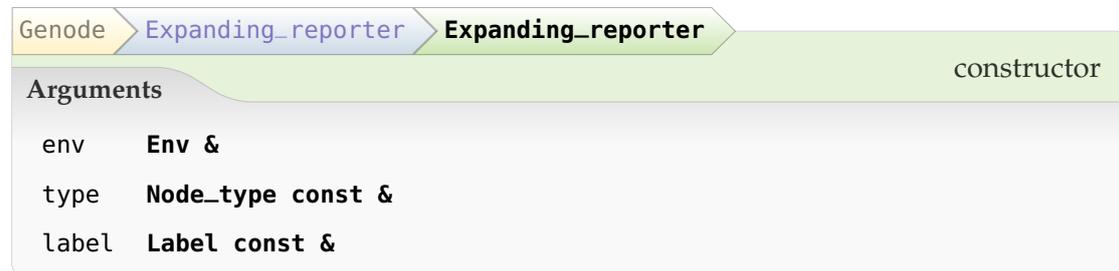


The `Expanding_reporter` further streamlines the generation of reports by eliminating the burden of handling `Buffer_exceeded` exceptions as thrown by the `Xml_generator` from components that generate reports. Such exceptions are easy to miss because reports are often small at testing time but become larger in complex scenarios. Whenever the report exceeds the current buffer size, the expanding reporter automatically upgrades the report session as needed. Note that such an upgrade consumes RAM quota. For components that strictly account RAM consumption to clients, the regular `Reporter` is preferable. However, in most cases - where reports are not accounted per client but to the component itself - the `Expanding_reporter` should better be used. Besides the builtin support for growing the report buffer, the expanding reporter alleviates the need to explicitly enable reports. In contrast to the `Reporter`, it is implicitly enabled at construction time.



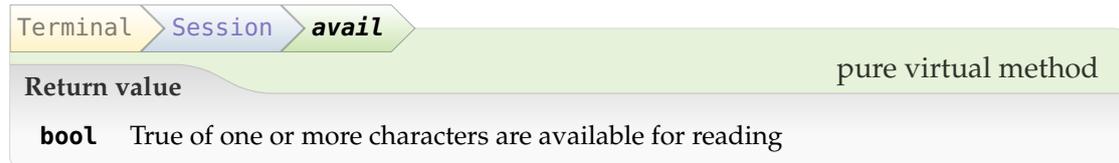
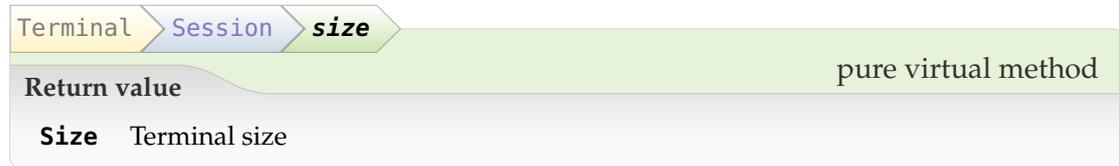
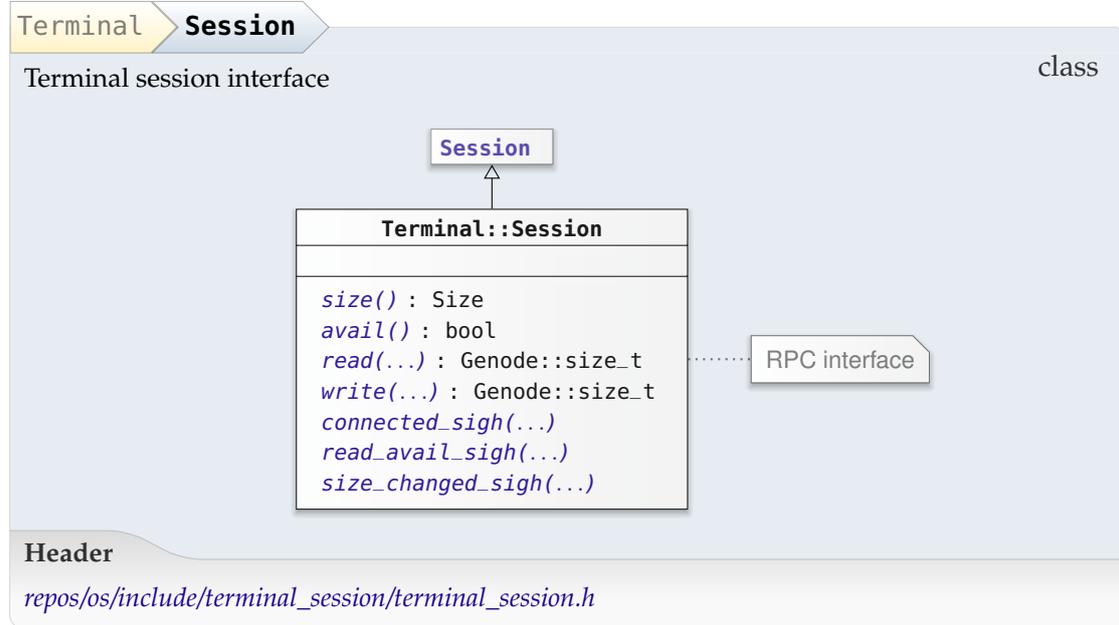
This convenience wrapper of the `Reporter` alleviates the need to handle `Xml_generator::Buffer_exceeded` exceptions manually. In most cases, the only reasonable way to handle such an excep-

tion is upgrading the report buffer as done by this class. Furthermore, in contrast to the regular Reporter, which needs to be enabled, the Expanding_reporter is implicitly enabled at construction time.



8.6.2. Terminal and UART session interfaces

A terminal session (Section 4.5.3) is a bi-directional communication channel. The UART session interface supplements the terminal session interface with a facility to parametrize UART configuration parameters



Terminal	Session	read	
Read characters from terminal			pure virtual method
Arguments			
buf		void *	
buf_size		size_t	
Return value			
Genode::size_t			

Terminal	Session	write	
Write characters to terminal			pure virtual method
Arguments			
buf		void const *	
num_bytes		size_t	
Return value			
Genode::size_t			

Terminal	Session	connected_sigh	
Register signal handler to be informed about the established connection			pure virtual method
Argument			
cap		Signal_context_capability	

This method is used for a simple startup protocol of terminal sessions. At session-creation time, the terminal session may not be ready to use. For example, a TCP terminal session needs an established TCP connection first. However, we do not want to let the session-creation block on the server side because this would render the servers entrypoint unavailable for all other clients until the TCP connection is ready. Instead, we deliver a `connected` signal to the client emitted when the session becomes ready to use. The `Terminal::Connection` waits for this signal at construction time.

Terminal > Session > **read_avail_sigh**

Register signal handler to be informed about ready-to-read characters pure virtual method

Argument

cap **Signal_context_capability**

Terminal > Session > **size_changed_sigh**

Register signal handler to be notified on terminal-size changes pure virtual method

Argument

cap **Signal_context_capability**

Terminal > **Connection**

Connection to Terminal service class

```

classDiagram
    class Connection {
        <Session>
    }
    class Session_client
    class Terminal_Connection["Terminal::Connection"] {
        Connection(...)
    }
    Connection <|-- Terminal_Connection
    Session_client <|-- Terminal_Connection
    
```

Header

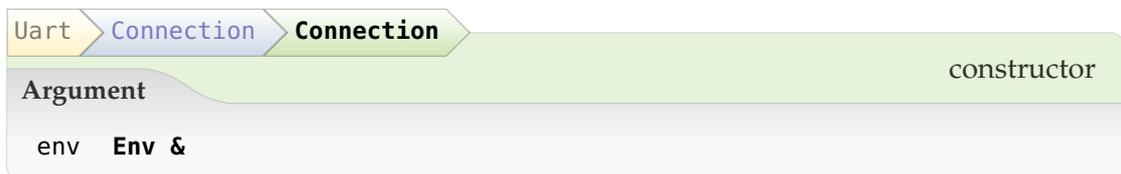
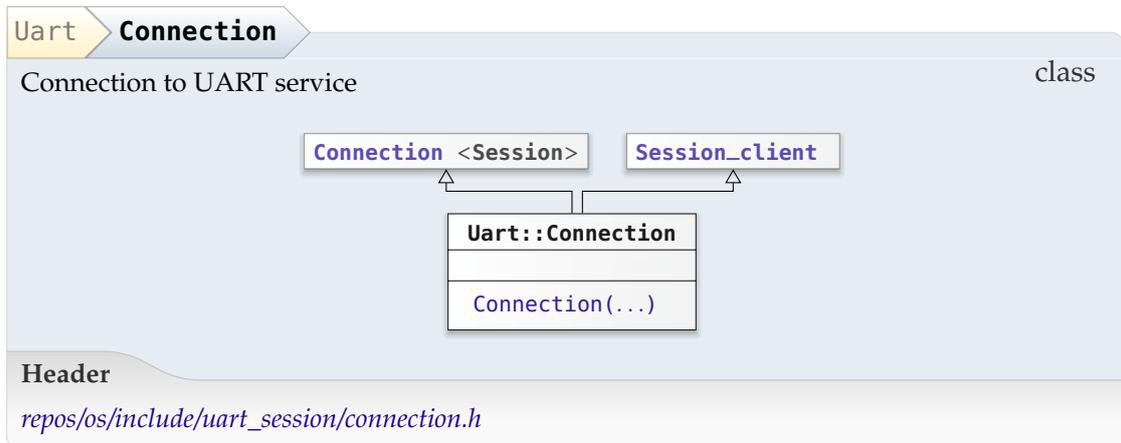
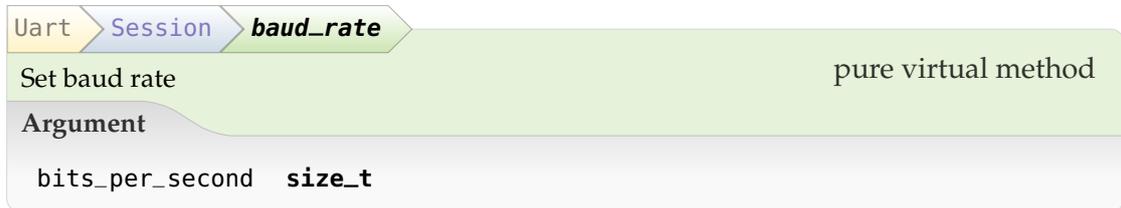
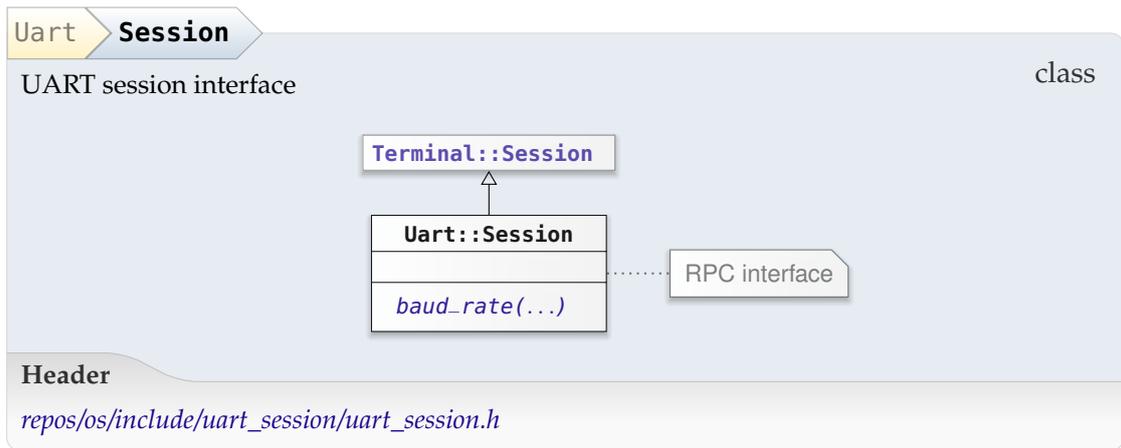
repos/os/include/terminal_session/connection.h

Terminal > Connection > **Connection**

Arguments constructor

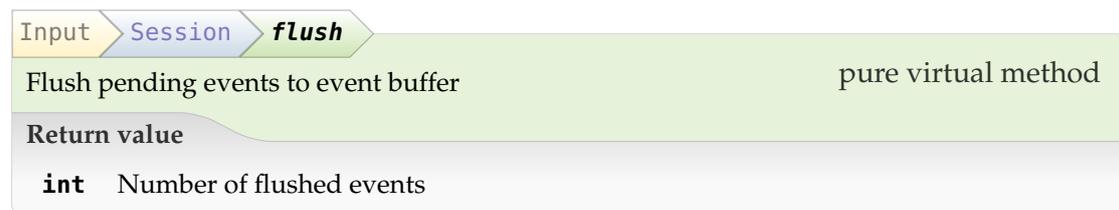
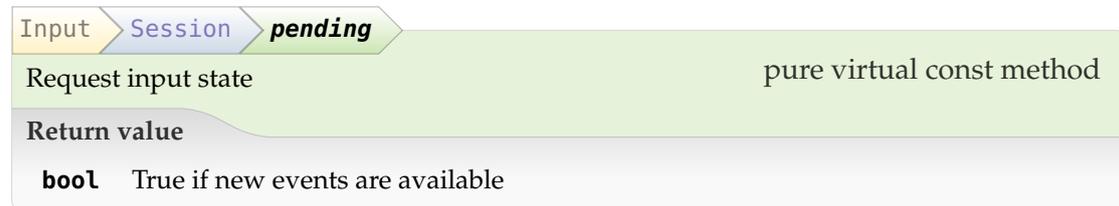
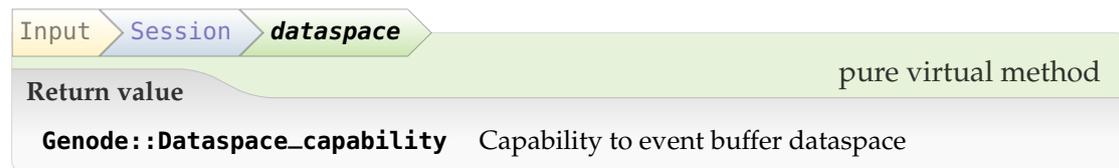
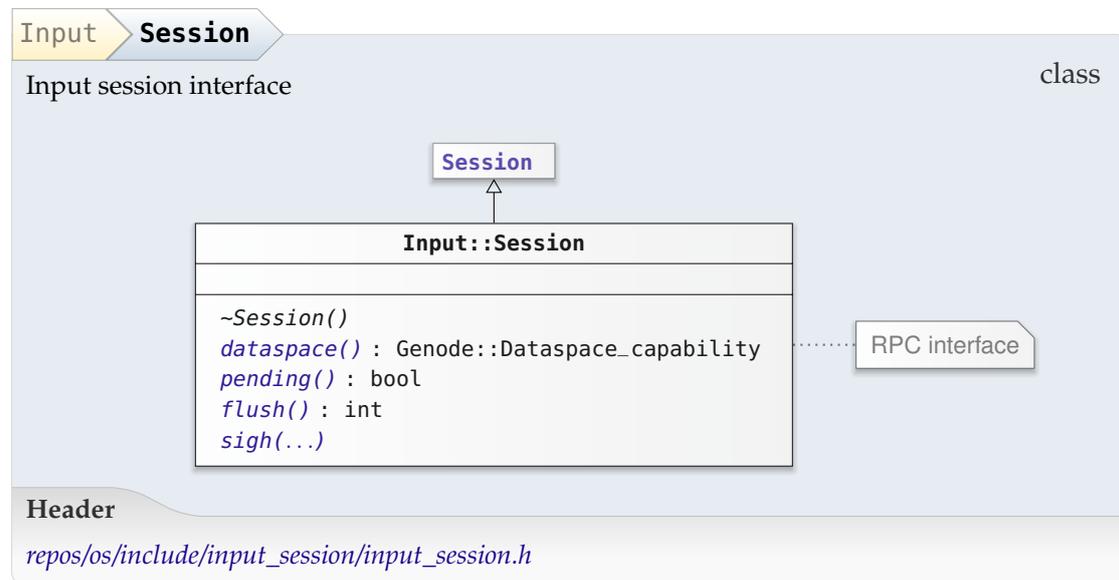
env **Env &**

label **char const ***
Default is ""



8.6.3. Input session interface

An input session (Section 4.5.4) represents a stream of user-input events.



Input → Session → **sigh**

Register signal handler to be notified on arrival of new input pure virtual method

Argument

- **Signal_context_capability**

Input → **Connection**

Connection to input service class

```

classDiagram
    class Connection {
        <Session>
    }
    class Session_client
    class Input_Connection["Input::Connection"] {
        Connection(...)
    }
    Connection <|-- Input_Connection
    Session_client <|-- Input_Connection
    
```

Header

[repos/os/include/input_session/connection.h](#)

Input → Connection → **Connection**

Arguments constructor

- env **Env &**
- label **char const ***
Default is ""

8.6.4. Framebuffer session interface

Framebuffer **Mode** class

Framebuffer mode info as returned by `Framebuffer::Session::mode()`

Framebuffer::Mode	
<code>bytes_per_pixel(...)</code>	<code>Genode::size_t</code>
<code>Mode()</code>	
<code>Mode(...)</code>	
<code>width()</code>	<code>int</code>
<code>height()</code>	<code>int</code>
<code>format()</code>	<code>Format</code>
<code>bytes_per_pixel()</code>	<code>Genode::size_t</code>
<code>print(...)</code>	

Accessors

`width` **int**
`height` **int**
`format` **Format**

Header

[repos/os/include/framebuffer_session/framebuffer_session.h](#)

Framebuffer **Mode** **bytes_per_pixel** class function

Argument

`format` **Format**

Return value

Genode::size_t

Framebuffer **Mode** **Mode** constructor

Arguments

`width` **int**
`height` **int**
`format` **Format**

Framebuffer > Mode > **bytes_per_pixel**

Return value const method

Genode::size_t Number of bytes per pixel

Framebuffer > Mode > **print**

Argument const method

out **Output &**

Framebuffer > **Session**

class

Session

↑

Framebuffer::Session

~Session()
dataspace() : Genode::Dataspace_capability
mode() : Mode
mode_sigh(...)
refresh(...)
sync_sigh(...)

RPC interface

Header

repos/os/include/framebuffer_session/framebuffer_session.h

Framebuffer > Session > **dataspace**

Request dataspace representing the logical frame buffer pure virtual method

Return value

Genode::Dataspace_capability

By calling this method, the framebuffer client enables the server to reallocate the framebuffer dataspace (e. g., on mode changes). Hence, prior calling this method, the client should make sure to have detached the previously requested dataspace from its local address space.

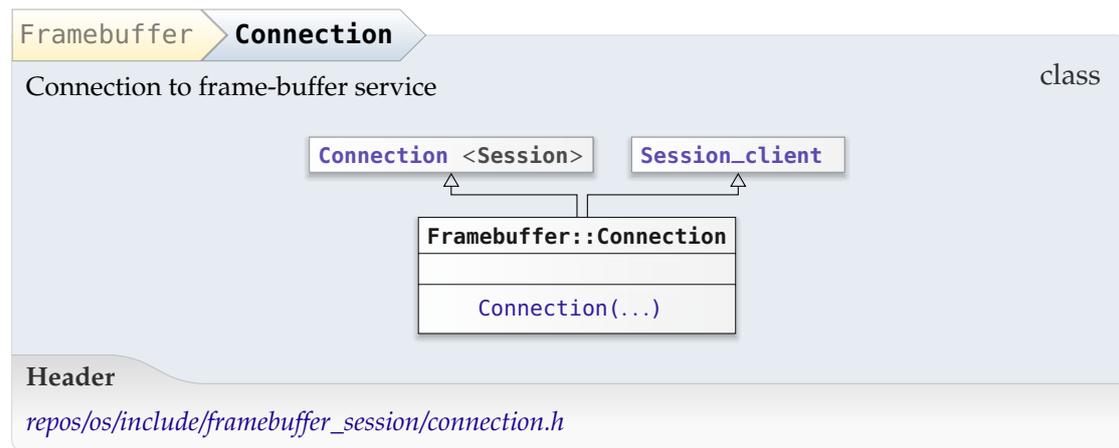
Framebuffer	Session	mode	
Request display-mode properties of the framebuffer ready to be obtained via the <code>dataspace()</code> method			pure virtual const method
Return value			
Mode			

Framebuffer	Session	mode_sigh	
Register signal handler to be notified on mode changes			pure virtual method
Argument			
sigh	Signal_context_capability		

The framebuffer server may support changing the display mode on the fly. For example, a virtual framebuffer presented in a window may get resized according to the window dimensions. By installing a signal handler for mode changes, the framebuffer client can respond to such changes. The new mode can be obtained using the `mode()` method. However, from the client's perspective, the original mode stays in effect until the it calls `dataspace()` again.

Framebuffer	Session	refresh	
Flush specified pixel region			pure virtual method
Arguments			
x	int		
y	int		
w	int		
h	int		

Framebuffer	Session	sync_sigh	
Register signal handler for refresh synchronization			pure virtual method
Argument			
-	Signal_context_capability		



The specified values are not enforced. After creating the session, you should validate the actual frame-buffer attributes by calling the `info` method of the frame-buffer interface.

8.6.5. Nitpicker session interface



Nitpicker	Session	create_view	
Create a new view at the buffer			pure virtual method
Argument			
parent	View_handle	Parent view <i>Default is View_handle()</i>	
Exception			
Invalid_handle			
Return value			
	View_handle	Handle for new view	

The parent argument allows the client to use the location of an existing view as the coordinate origin for the to-be-created view. If an invalid handle is specified (default), the view will be a top-level view.

Nitpicker	Session	destroy_view	
Destroy view			pure virtual method
Argument			
-	View_handle		

Nitpicker	Session	view_handle	
			pure virtual method
Arguments			
-	View_capability		
handle	View_handle	Designated view handle to be assigned to the imported view. By default, a new handle will be allocated. <i>Default is View_handle()</i>	
Exceptions			
Out_of_ram			
Out_of_caps			
Return value			
	View_handle	Session-local handle for the specified view	

The handle returned by this method can be used to issue commands via the execute method.

Nitpicker	Session	view_capability	
Request view capability for a given handle			pure virtual method
Argument			
- View_handle			
Return value			
View_capability			

The returned view capability can be used to share the view with another session.

Nitpicker	Session	release_view_handle	
Release session-local view handle			pure virtual method
Argument			
- View_handle			

Nitpicker	Session	command_dataspace	
Request dataspace used for issuing view commands to nitpicker			pure virtual method
Return value			
Genode::Dataspace_capability			

Nitpicker	Session	execute	
Execution batch of commands contained in the command dataspace			pure virtual method

Nitpicker	Session	mode	
Return value			pure virtual method
Framebuffer::Mode Physical screen mode			

Nitpicker	Session	mode_sigh	
Register signal handler to be notified about mode changes			pure virtual method
Argument			
- Signal_context_capability			

Nitpicker	Session	buffer	
Define dimensions of virtual framebuffer			pure virtual method
Arguments			
mode		Mode	
use_alpha		bool	
Exceptions			
Out_of_ram	Session quota does not suffice for specified buffer dimensions		
Out_of_caps			

Nitpicker	Session	focus	
Set focused session			pure virtual method
Argument			
focused		Capability<Session>	

Normally, the focused session is defined by the focus ROM, which is driven by an external policy component. However, in cases where one application consists of multiple nitpicker sessions, it is desirable to let the application manage the focus among its sessions by applying an application-local policy. The focus RPC function allows a client to specify another client that should receive the focus whenever the session becomes focused. As the designated receiver of the focus is referred to by its session capability, a common parent can manage the focus among its children. But unrelated sessions cannot interfere.

Nitpicker	Session	session_control	
Perform control operation on one or multiple sessions			virtual method
Arguments			
-		Label	
-		Session_control	

The label is used to select the sessions, on which the operation is performed. Nitpicker creates a selector string by concatenating the caller's session label with the supplied label argument. A session is selected if its label starts with the selector string. Thereby, the operation is limited to the caller session or any child session of the caller.

Nitpicker → Session → **ram_quota** class function

Arguments

mode **Mode**

use_alpha **bool**

Return value

size_t Number of bytes needed for virtual framebuffer of specified size

Nitpicker → **Connection** class

Connection to Nitpicker service

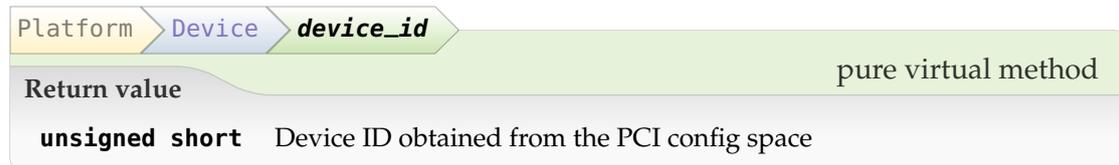
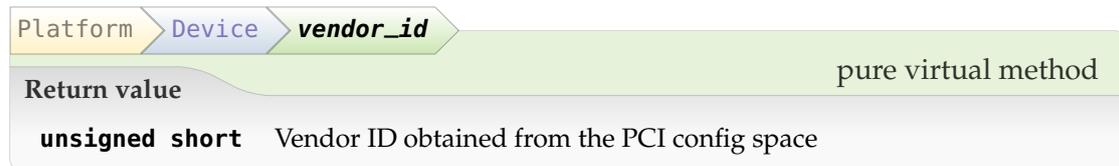
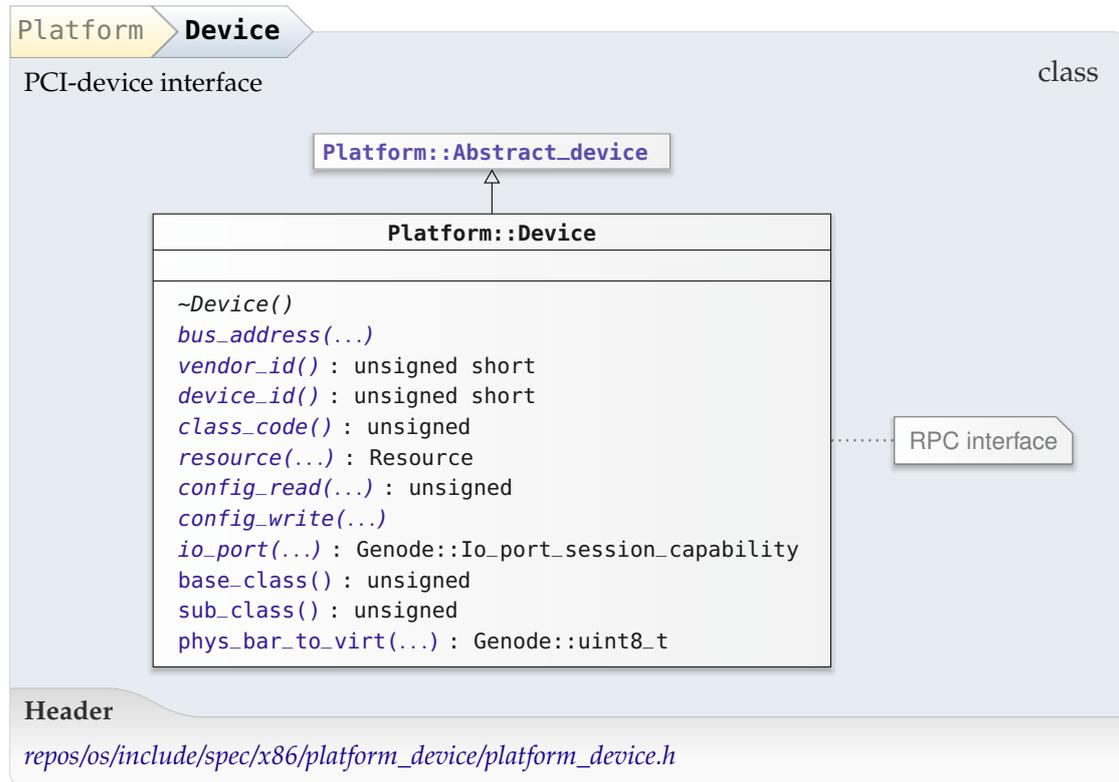
```

classDiagram
    class Connection {
        <Session>
    }
    class Session_client
    class Nitpicker_Connection["Nitpicker::Connection"]
    Connection <|-- Session_client
    Connection <|-- Nitpicker_Connection
    
```

Header

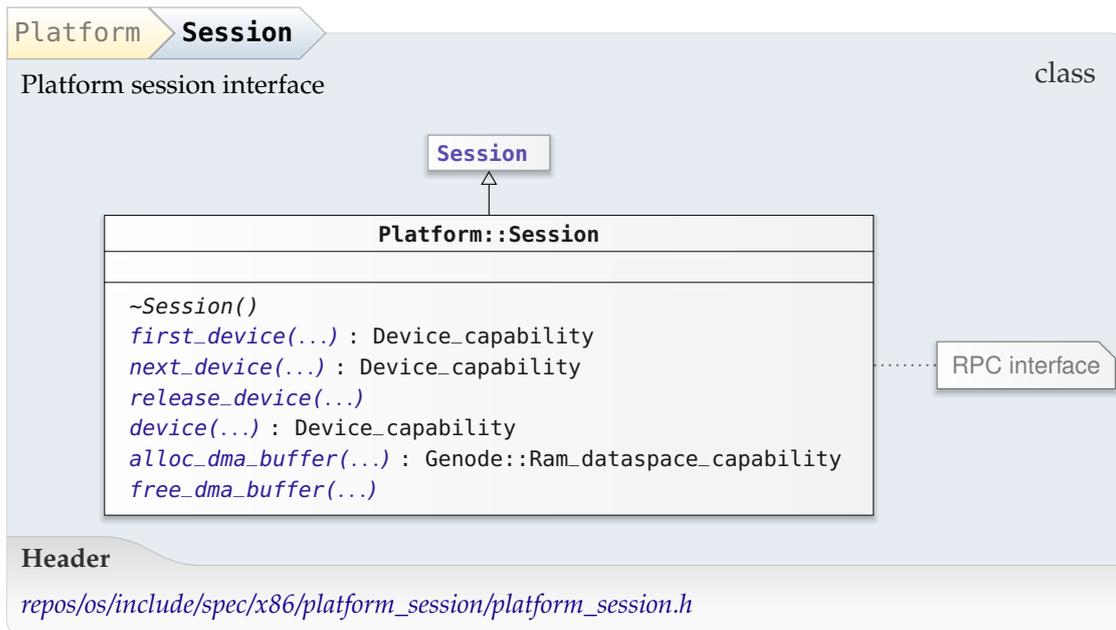
repos/os/include/nitpicker_session/connection.h

8.6.6. Platform session interface



Platform	Device	class_code	
Return value			pure virtual method
unsigned Device class code from the PCI config space			
Platform	Device	resource	
Query PCI-resource information			pure virtual method
Argument			
resource_id	int	Index of according PCI resource of the device	
Return value			
Resource Resource description			
Platform	Device	config_read	
Read configuration space			pure virtual method
Arguments			
address	unsigned char		
size	Access_size		
Return value			
unsigned			
Platform	Device	config_write	
Write configuration space			pure virtual method
Arguments			
address	unsigned char		
value	unsigned		
size	Access_size		
Exceptions			
Out_of_ram			
Out_of_caps			

Platform	Device	io_port	
Query Io_port of specified bar			pure virtual method
Argument			
id	uint8_t	Index of according PCI resource of the device	
Exceptions			
Out_of_ram			
Out_of_caps			
Return value			
Genode::Io_port_session_capability			
Platform	Device	base_class	
Return value			method
unsigned			
Platform	Device	sub_class	
Return value			method
unsigned			
Platform	Device	phys_bar_to_virt	
Convenience method to translate a PCI physical BAR id to a Genode virtual one usable with the io_port and io_mem methods. The virtual id is solely valid for the specific BAR type.			method
Argument			
phys_bar	uint8_t		
Return value			
Genode::uint8_t			



Platform **Session** **first_device** pure virtual method

Find first accessible device

Arguments

- **unsigned**
- **unsigned**

Return value

Device_capability

Platform **Session** **next_device** pure virtual method

Find next accessible device

Arguments

- prev_device **Device_capability**
Previous device
- **unsigned**
- **unsigned**

Return value

Device_capability

The `prev_device` argument is used to iterate through all devices.

Platform	Session	<i>release_device</i>	
Free server-internal data structures representing the device			pure virtual method
Argument			
device	Device_capability		

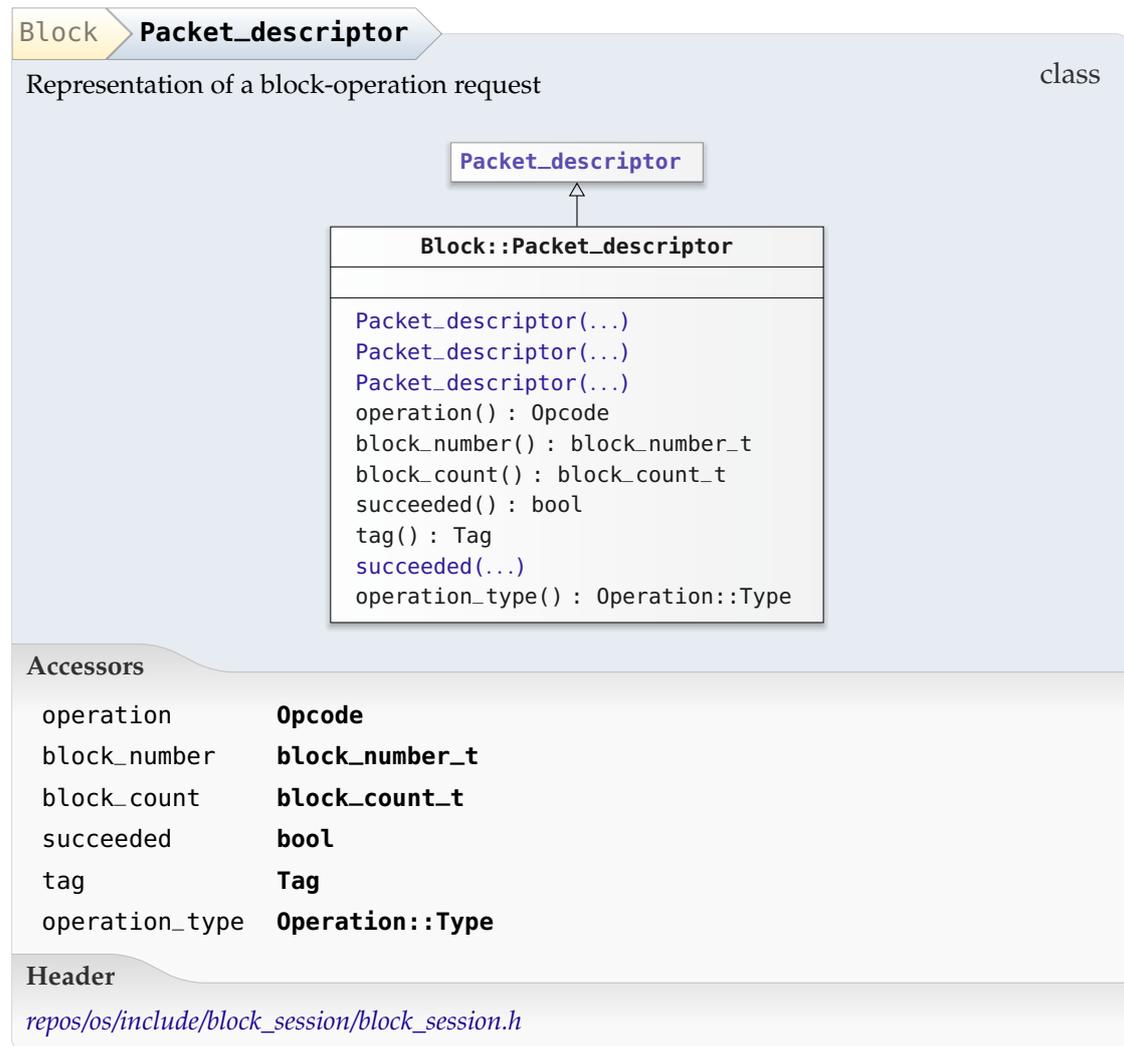
Use this method to relax the heap partition of your PCI session.

Platform	Session	<i>device</i>	
Provide non-PCI device known by unique name.			pure virtual method
Argument			
string	String const &		
Return value			
Device_capability			

Platform	Session	<i>alloc_dma_buffer</i>	
Allocate memory suitable for DMA.			pure virtual method
Argument			
-	size_t		
Return value			
Genode::Ram_dataspace_capability			

Platform	Session	<i>free_dma_buffer</i>	
Free previously allocated DMA memory			pure virtual method
Argument			
-	Ram_dataspace_capability		

8.6.7. Block session interface



The data associated with the `Packet_descriptor` is either the data read from or written to the block indicated by its number.

Block → Packet_descriptor → Packet_descriptor

constructor

Arguments

offset **off_t**
Default is 0

size **size_t**
Default is 0

Block → Packet_descriptor → Packet_descriptor

constructor

Arguments

p **Packet_descriptor**

op **Opcode**

block_number **block_number_t**

block_count **block_count_t**
Default is 1

Block → Packet_descriptor → Packet_descriptor

constructor

Arguments

operation **Operation**

payload **Payload**

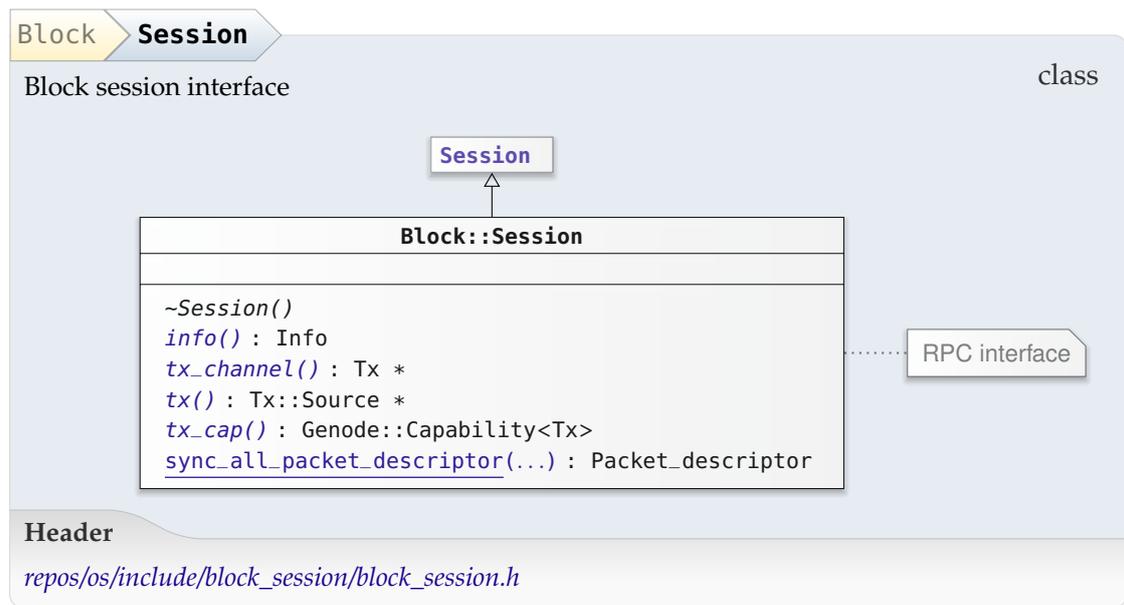
tag **Tag**

Block → Packet_descriptor → succeeded

method

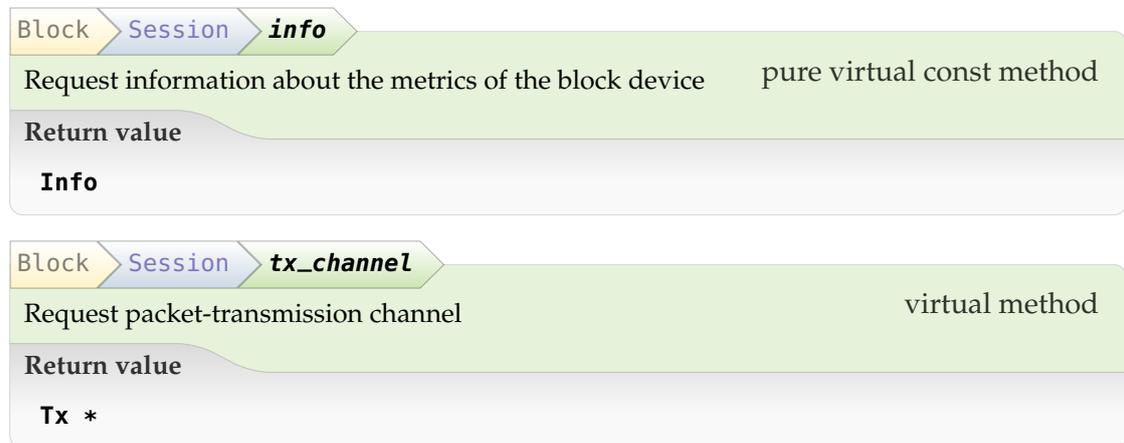
Argument

b **bool**



A block session corresponds to a block device that can be used to read or store data. Payload is communicated over the packet-stream interface set up between `Session_client` and `Session_server`.

Even though the methods `tx` and `tx_channel` are specific for the client side of the block session interface, they are part of the abstract `Session` class to enable the client-side use of the block interface via a pointer to the abstract `Session` class. This way, we can transparently co-locate the packet-stream server with the client in same program.



Block > Session > **tx** virtual method

Request client-side packet-stream interface of tx channel

Return value

Tx::Source *

Block > Session > **tx_cap** pure virtual method

Return value

Genode::Capability<Tx> Capability for packet-transmission channel

Block > Session > **sync_all_packet_descriptor** class function

Arguments

info **Info const &**

tag **Tag**

Return value

Packet_descriptor Packet descriptor for syncing the entire block session

Block > **Connection** class template

```

classDiagram
    class ConnectionTemplate["Connection <Session>"]
    class SessionClient["Session_client"]
    class BlockConnection["Block::Connection"]
    class Job["JOB"]

    ConnectionTemplate <|-- SessionClient
    ConnectionTemplate <|-- BlockConnection
    BlockConnection ..> Job : update_jobs(...)
    
```

Template argument

JOB **typename**
Default is void

Header

repos/os/include/block_session/connection.h

Block	Connection	Connection	constructor
Arguments			
env		Env &	
tx_block_alloc		Range_allocator *	
tx_buf_size		size_t Size of transmission buffer in bytes <i>Default is 128*1024</i>	
label		const char * <i>Default is ""</i>	

Block	Connection	sigh	method
Register handler for data-flow signals			
Argument			
sigh		Signal_context_capability	

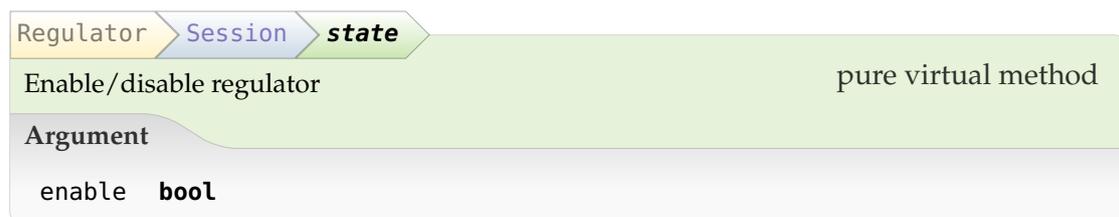
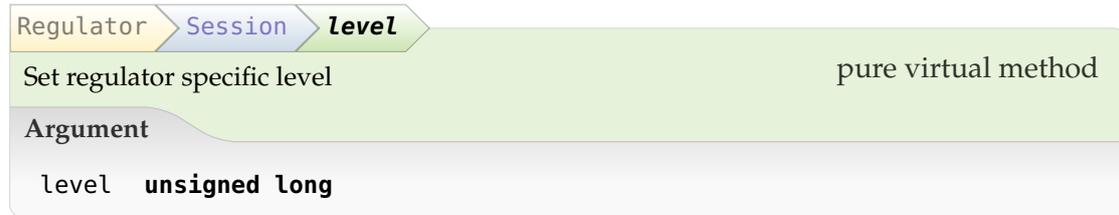
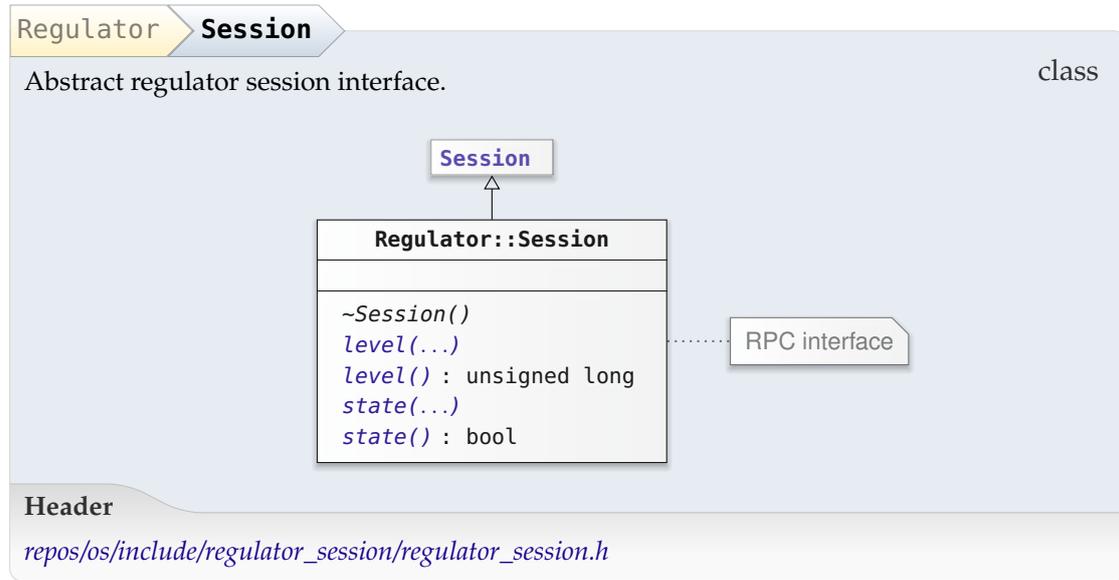
The handler is triggered on the arrival of new acknowledgements or when the server becomes ready for new requests. It is thereby able to execute `update_jobs` on these conditions.

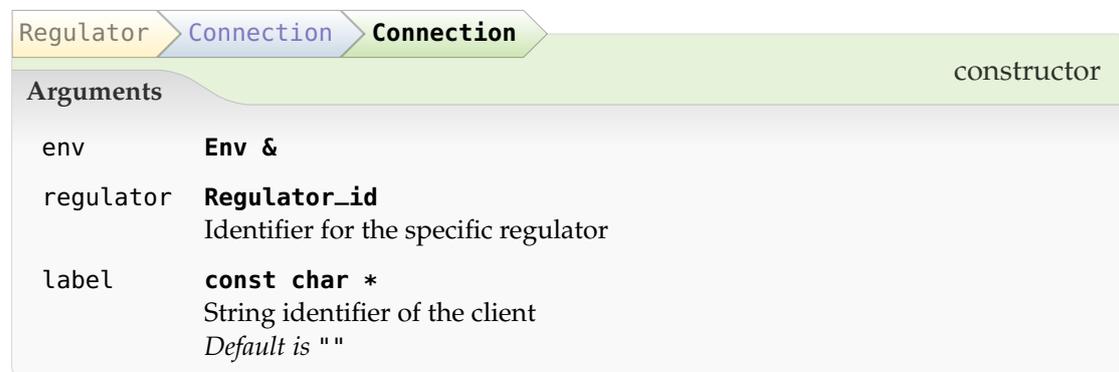
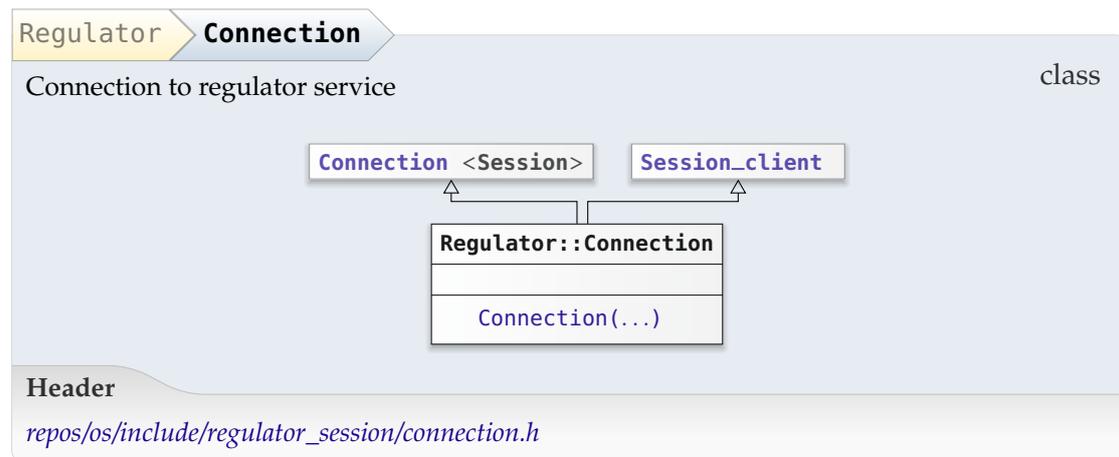
Block	Connection	update_jobs	
Handle the submission and completion of block-operation jobs			method template
Template argument			
POLICY typename			
Argument			
policy POLICY &			
Return value			
bool True if progress was made			

Block	Connection	dissolve_all_jobs	
Call fn with each job as argument			method template
Template argument			
FN typename			
Argument			
fn FN const &			

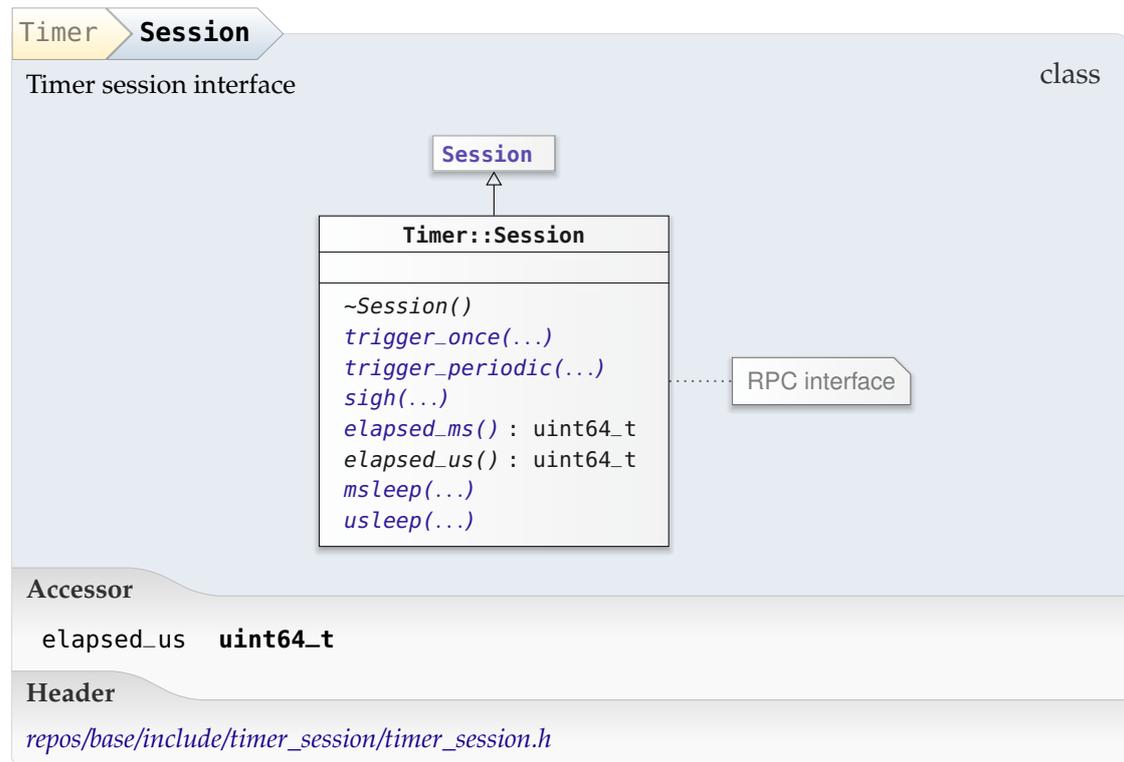
This method is intended for the destruction of the jobs associated with the connection before destructing the Connection object.

8.6.8. Regulator session interface



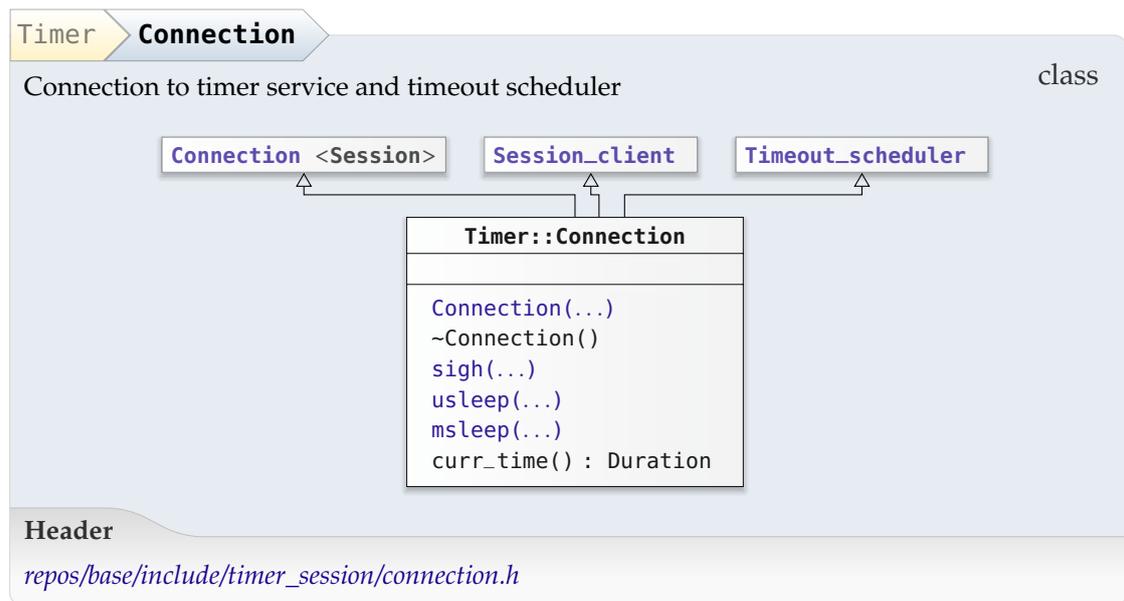


8.6.9. Timer session interface

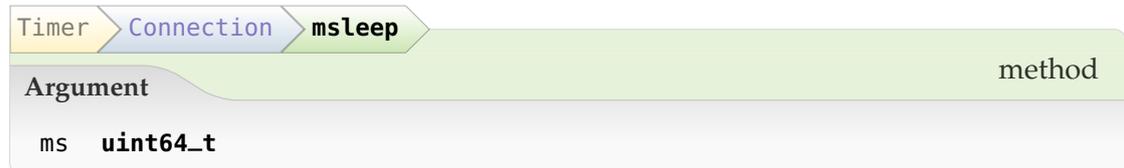
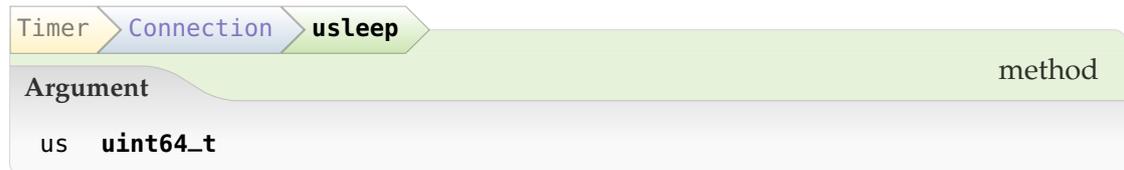
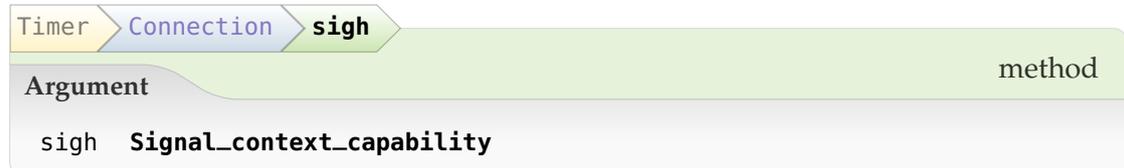
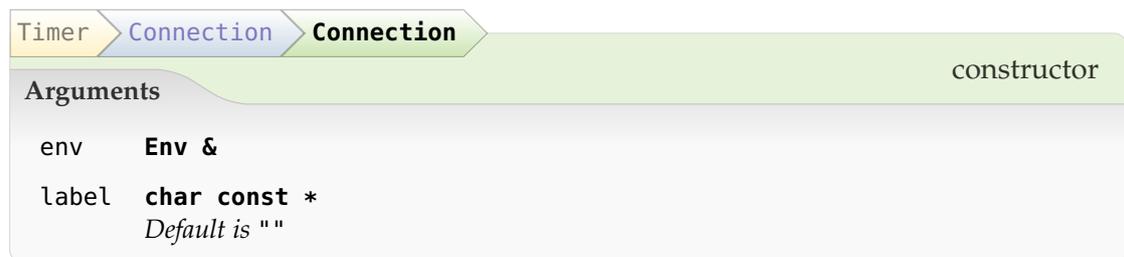


The first period will be triggered after us at the latest, but it might be triggered earlier as well.

Timer	Session	<i>sigh</i>		
Register timeout signal handler				pure virtual method
Argument				
	sigh	Signal_context_capability		
Timer	Session	<i>elapsed_ms</i>		
				pure virtual const method
Return value				
	uint64_t	Number of elapsed milliseconds since session creation		
Timer	Session	<i>msleep</i>		
Client-side convenience method for sleeping the specified number of milliseconds				pure virtual method
Argument				
	ms	uint64_t		
Timer	Session	<i>usleep</i>		
Client-side convenience method for sleeping the specified number of microseconds				pure virtual method
Argument				
	us	uint64_t		



Multiplexes a timer session amongst different timeouts.



The `Periodic_timeout` and `One_shot_timeout` classes provide a convenient API for implementing timeout handlers, following the same pattern as used for signal handlers (Section 8.14).

Timer > **Periodic_timeout** > class template

Periodic timeout that is linked to a custom handler, scheduled when constructed

```

class Timer::Periodic_timeout {
public:
    Periodic_timeout(...)
};
    
```

Template argument

HANDLER **typename**

Header

repos/base/include/timer_session/connection.h

Timer > Periodic_timeout > **Periodic_timeout** > constructor

Arguments

timeout_scheduler	Timeout_scheduler &
object	HANDLER &
method	Handler_method
duration	Microseconds

Timer → **One_shot_timeout** class template

One-shot timeout that is linked to a custom handler, scheduled manually

```

Timer::One_shot_timeout
    One_shot_timeout(...)
    schedule(...)
    discard()
    scheduled() : bool
    
```

Template argument
HANDLER **typename**

Header
repos/base/include/timer_session/connection.h

Timer → One_shot_timeout → **One_shot_timeout** constructor

Arguments

timeout_scheduler	Timeout_scheduler &
object	HANDLER &
method	Handler_method

Timer → One_shot_timeout → **schedule** method

Argument

duration	Microseconds
----------	---------------------

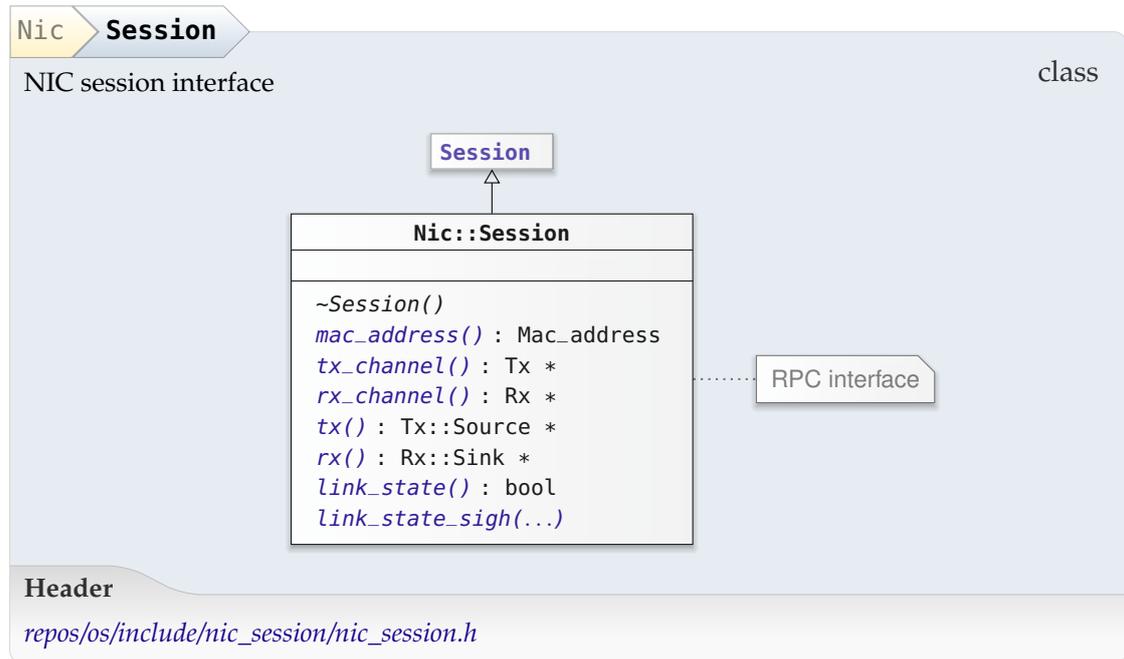
Timer → One_shot_timeout → **discard** method

Timer → One_shot_timeout → **scheduled** method

Return value

bool

8.6.10. NIC session interface



Nic > Session > **mac_address** pure virtual method

Request MAC address of network adapter

Return value
Mac_address

Nic > Session > **tx_channel** virtual method

Request packet-transmission channel

Return value
Tx *

Nic > Session > **rx_channel** virtual method

Request packet-reception channel

Return value
Rx *

Nic > Session > **tx**

Request client-side packet-stream interface of tx channel virtual method

Return value

Tx::Source *

Nic > Session > **rx**

Request client-side packet-stream interface of rx channel virtual method

Return value

Rx::Sink *

Nic > Session > **link_state**

Request current link state of network adapter (true means link detected) pure virtual method

Return value

bool

Nic > Session > **link_state_sigh**

Register signal handler for link state changes pure virtual method

Argument

sigh **Signal_context_capability**

Nic > **Connection** class

Connection to NIC service

```

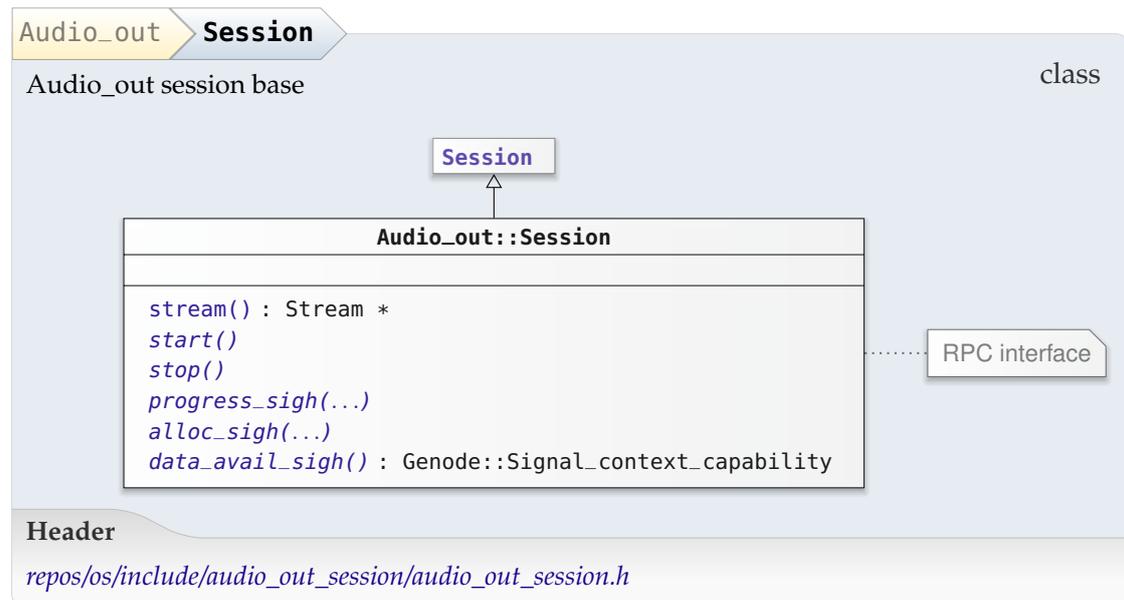
classDiagram
    class Connection {
        <Session>
    }
    class Session_client
    class Nic_Connection["Nic::Connection"] {
        Connection(...)
    }
    Connection <|-- Nic_Connection
    Session_client <|-- Nic_Connection
        
```

Header

[repos/os/include/nic_session/connection.h](#)

Nic		Connection	Connection	constructor
Arguments				
env		Env &		
tx_block_alloc		Range_allocator *		
tx_buf_size		size_t	Size of transmission buffer in bytes	
rx_buf_size		size_t	Size of reception buffer in bytes	
label		char const *	<i>Default is ""</i>	

8.6.11. Audio-out session interface



See: `client.h`, `connection.h`

Audio_out > Session > **alloc_sigh**

The alloc signal is sent from the server to the client when the stream queue leaves the full state. pure virtual method

Argument

sigh **Signal_context_capability**

See: client.h, connection.h

Audio_out > Session > **data_avail_sigh**

The data_avail signal is sent from the client to the server if the stream queue leaves the empty state. pure virtual method

Return value

Genode::Signal_context_capability

Audio_out > **Connection** class

Connection to audio service

```

classDiagram
    class Connection["Connection <Session>"]
    class Audio_out_Session_client["Audio_out::Session_client"]
    class Audio_out_Connection["Audio_out::Connection"]
    Connection <|-- Audio_out_Connection
    Audio_out_Session_client <|-- Audio_out_Connection
    class Audio_out_Connection {
        Connection(...)
    }
    
```

Header

repos/os/include/audio_out_session/connection.h

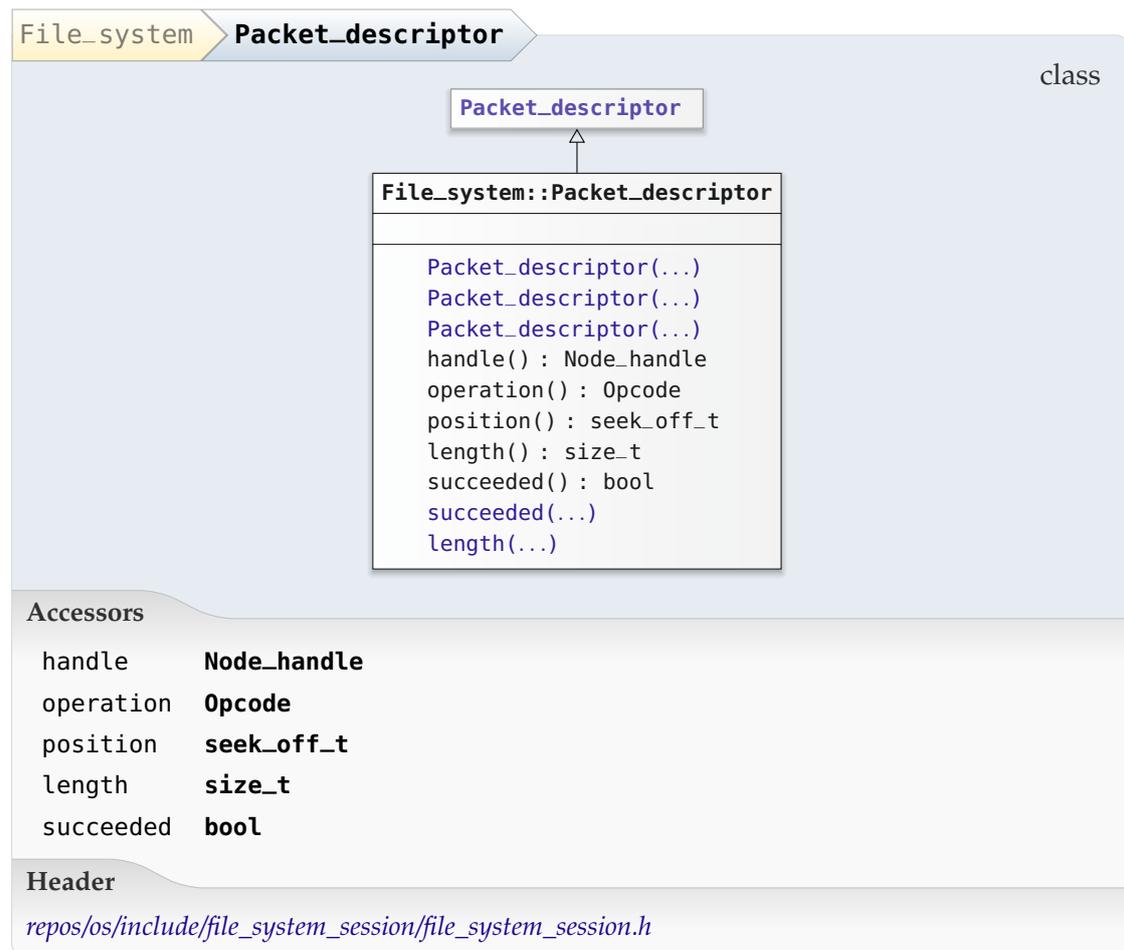
Audio_out	Connection	Connection	constructor
Arguments			
env	Env &		
channel	char const * Channel identifier (e. g., "front left")		
alloc_signal	bool Install alloc_signal, the client may then use wait_for_alloc when the stream is full <i>Default is true</i>		
progress_signal	bool Install progress signal, the client may then call wait_for_progress, which is sent when the server processed one or more packets <i>Default is false</i>		

8.6.12. File-system session interface

The file-system session (Section 4.5.13) interface provides to store and retrieve data in the form of files organized in a hierarchic directory structure. Directory operations are performed via a synchronous RPC interface whereas the actual read and write operations are performed asynchronously using a packet stream.

File_system		namespace
File-system session interface		
Types		
Node_handle	is defined as <code>Node::Id</code>	
File_handle	is defined as <code>File::Id</code>	
Dir_handle	is defined as <code>Directory::Id</code>	
Symlink_handle	is defined as <code>Symlink::Id</code>	
Watch_handle	is defined as <code>Watch::Id</code>	
seek_off_t	is defined as <code>Genode::uint64_t</code>	
file_size_t	is defined as <code>Genode::uint64_t</code>	
Out_of_ram	is defined as <code>Genode::Out_of_ram</code>	
Out_of_caps	is defined as <code>Genode::Out_of_caps</code>	
Mode	is an enumeration type Flags as supplied to file, dir, and symlink calls	
Name	is defined as <code>Genode::Rpc_in_buffer<MAX_NAME_LEN></code>	
Path	is defined as <code>Genode::Rpc_in_buffer<MAX_PATH_LEN></code>	
Exception	is a subtype of <code>Genode::Exception</code>	
Header		
<i>repos/os/include/file_system_session/file_system_session.h</i>		

A file-system client issues read or write requests by submitting packet descriptors to the file-system session's packet stream. Each packet descriptor contains all parameters of the transaction including the type of operation, the seek offset, and the length.

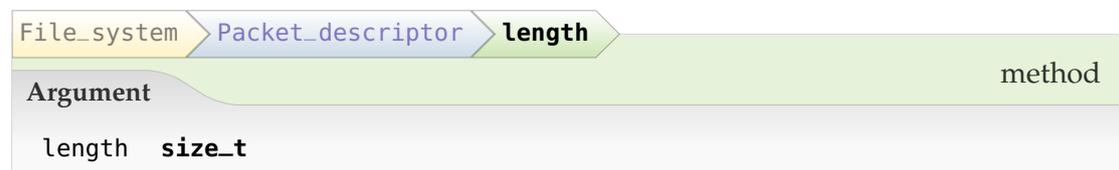


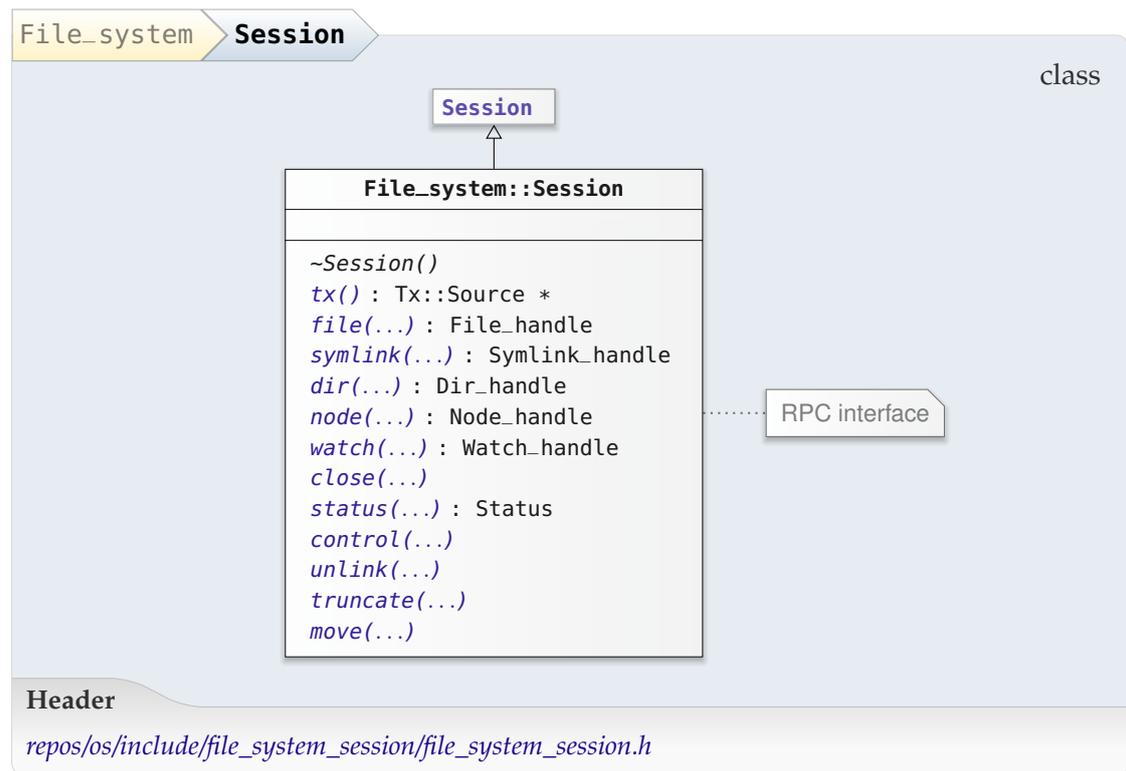


Note, if position is set to SEEK_TAIL read operations will read length bytes from the end of the file while write operations will append length bytes at the end of the file.



This constructor provided for sending server-side notification packets.





File_system > Session > **tx**

Request client-side packet-stream interface of tx channel virtual method

Return value

Tx::Source *

File_system > Session > **file**

Open or create file pure virtual method

Arguments

- **Dir_handle**
- name **Name const &**
- **Mode**
- create **bool**

Exceptions

Invalid_handle	Directory handle is invalid
Invalid_name	File name contains invalid characters
Lookup_failed	The name refers to a node other than a file
Node_already_exists	File cannot be created because a node with the same name already exists
No_space	Storage exhausted
Out_of_ram	Server cannot allocate metadata
Out_of_caps	
Permission_denied	
Unavailable	Directory vanished

Return value

File_handle

File_system	Session	<i>symlink</i>	
Open or create symlink			pure virtual method
Arguments			
-	Dir_handle		
name	Name const &		
create	bool		
Exceptions			
Invalid_handle		Directory handle is invalid	
Invalid_name		Symlink name contains invalid characters	
Lookup_failed		The name refers to a node other than a symlink	
Node_already_exists		Symlink cannot be created because a node with the same name already exists	
No_space		Storage exhausted	
Out_of_ram		Server cannot allocate metadata	
Out_of_caps			
Permission_denied			
Unavailable		Directory vanished	
Return value			
	Symlink_handle		

File_system	Session	<i>dir</i>
Open or create directory		pure virtual method
Arguments		
path	Path const &	
create	bool	
Exceptions		
Lookup_failed	Path lookup failed because one element of path does not exist	
Name_too_long	path is too long	
Node_already_exists	Directory cannot be created because a node with the same name already exists	
No_space	Storage exhausted	
Out_of_ram	Server cannot allocate metadata	
Out_of_caps		
Permission_denied		
Return value		
Dir_handle		

File_system	Session	<i>node</i>
Open existing node		pure virtual method
Argument		
path	Path const &	
Exceptions		
Lookup_failed	Path lookup failed because one element of path does not exist	
Out_of_ram	Server cannot allocate metadata	
Out_of_caps		
Return value		
Node_handle		

The returned node handle can be used merely as argument for status.

File_system	Session	watch	
Watch a node for for changes.			pure virtual method
Argument			
path Path const &			
Exceptions			
Lookup_failed	Path lookup failed because one element of path does not exist		
Out_of_ram	Server cannot allocate metadata		
Out_of_caps			
Unavailable	File-system is static or does not support notifications		
Return value			
Watch_handle			

When changes are made to the node at this path a CONTENT_CHANGED packet will be sent from the server to the client.

The returned node handle is used to identify notification packets.

File_system	Session	close	
Close file			pure virtual method
Argument			
- Node_handle			
Exception			
Invalid_handle	Node handle is invalid		

File_system	Session	status	
Request information about an open file or directory			pure virtual method
Argument			
- Node_handle			
Exceptions			
Invalid_handle	Node handle is invalid		
Unavailable	Node vanished		
Return value			
Status			

File_system > Session > **control**

Set information about an open file or directory pure virtual method

Arguments

- **Node_handle**
- **Control**

Exceptions

Invalid_handle	Node handle is invalid
Unavailable	Node vanished

File_system > Session > **unlink**

Delete file or directory pure virtual method

Arguments

dir	Dir_handle
name	Name const &

Exceptions

Invalid_handle	Directory handle is invalid
Invalid_name	name contains invalid characters
Lookup_failed	Lookup of name in dir failed
Not_empty	Argument is a non-empty directory and the backend does not support recursion
Permission_denied	
Unavailable	Directory vanished

File_system > Session > **truncate**

Truncate or grow file to specified size pure virtual method

Arguments

- **File_handle**

size	file_size_t
------	--------------------

Exceptions

Invalid_handle	Node handle is invalid
No_space	New size exceeds free space
Permission_denied	Node modification not allowed
Unavailable	Node vanished

File_system > Session > **move**

Move and rename directory entry pure virtual method

Arguments

- **Dir_handle**
from **Name const &**
- **Dir_handle**
to **Name const &**

Exceptions

Invalid_handle	A directory handle is invalid
Invalid_name	to contains invalid characters
Lookup_failed	from not found
Permission_denied	Node modification not allowed
Unavailable	A directory vanished

File_system > **Connection** class

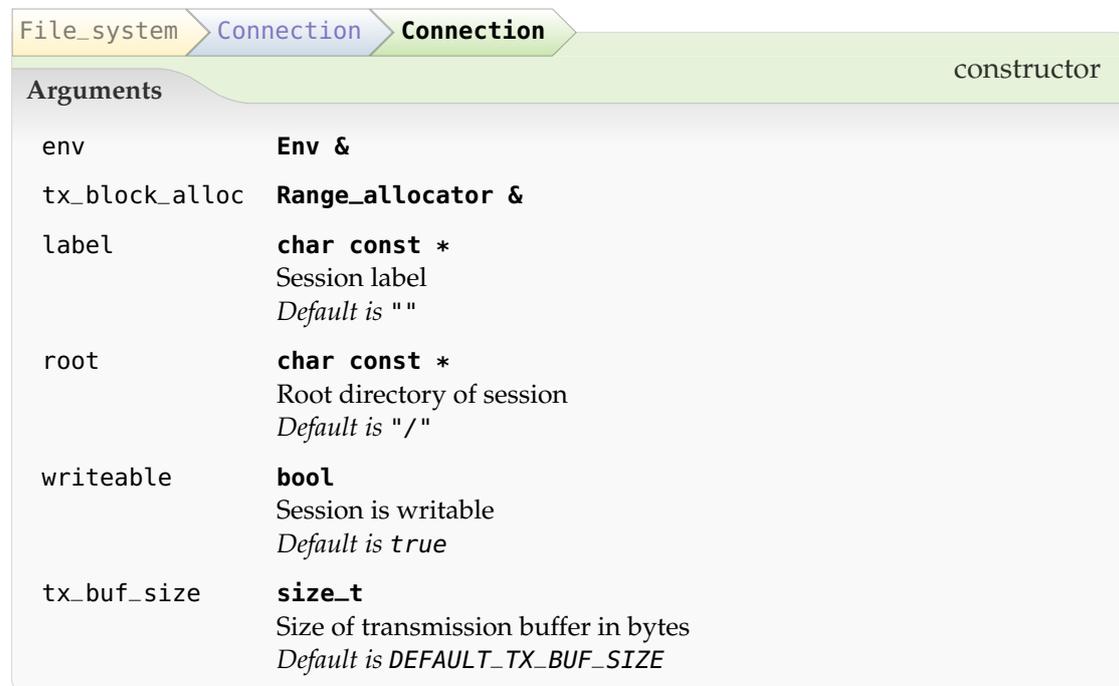
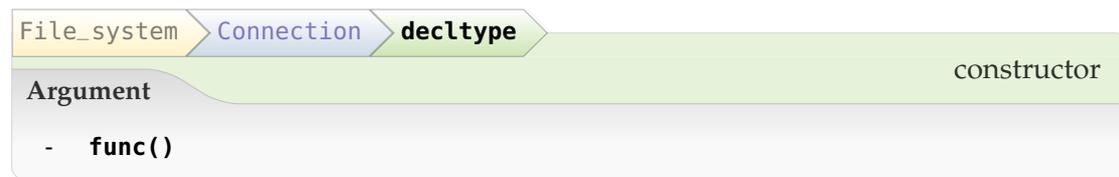
The base implementation of a File_system connection

```

classDiagram
    class Connection["Connection <Session>"]
    class Session_client
    class File_system_Connection["File_system::Connection"]
    Connection <|-- File_system_Connection
    Session_client <|-- File_system_Connection
    class File_system_Connection {
        decltype(...)
        Connection(...)
        dir(...) : Dir_handle
        file(...) : File_handle
        symlink(...) : Symlink_handle
        node(...) : Node_handle
        watch(...) : Watch_handle
    }
    
```

Header

repos/os/include/file_system_session/connection.h



The file-system session's status and control operations use the compound structures `Status` and `Control` as arguments. The format of the data retrieved by reading a directory node is defined by the `Directory_entry`.

File_system > **Status** class

File_system::Status
directory() : bool
symlink() : bool

Header
repos/os/include/file_system_session/file_system_session.h

File_system > Status > **directory** const method

Return value
bool True if node is a directory

File_system > Status > **symlink** const method

Return value
bool True if node is a symbolic link

File_system > **Control** class

File_system::Control

Header
repos/os/include/file_system_session/file_system_session.h

File_system **Directory_entry**

Data structure returned when reading from a directory node class

`File_system::Directory_entry`

Header

repos/os/include/file_system_session/file_system_session.h

8.7. Fundamental types

8.7.1. Integer types

Genode provides common integer types in its namespace. Integer types that can be derived from built-in compiler types are defined in *base/stdint.h* and *base/fixed_stdint.h*. Whereas the former is independent from the machine type, the latter differs between 32-bit and 64-bit architectures.

Genode		namespace
Integer types		
Types		
size_t	is defined as unsigned long Integer type for non-negative size values	
addr_t	is defined as unsigned long Integer type for memory addresses	
off_t	is defined as long Integer type for memory offset values	
umword_t	is defined as unsigned long Integer type corresponding to a machine register	
Header		
repos/base/include/base/stdint.h		

The fixed-width integer types for 32-bit architectures are defined as follows.

Fixed-width integer types for 32-bit architectures		root namespace
Types		
genode_int8_t	is defined as signed char	
genode_uint8_t	is defined as unsigned char	
genode_int16_t	is defined as signed short	
genode_uint16_t	is defined as unsigned short	
genode_int32_t	is defined as signed	
genode_uint32_t	is defined as unsigned	
genode_int64_t	is defined as signed long long	
genode_uint64_t	is defined as unsigned long long	
Header		
repos/base/include/spec/32bit/base/fixed_stdint.h		

Genode		namespace
Fixed-width integer types for 32-bit architectures		
Types		
int8_t	is defined as genode_int8_t	
uint8_t	is defined as genode_uint8_t	
int16_t	is defined as genode_int16_t	
uint16_t	is defined as genode_uint16_t	
int32_t	is defined as genode_int32_t	
uint32_t	is defined as genode_uint32_t	
int64_t	is defined as genode_int64_t	
uint64_t	is defined as genode_uint64_t	
Header		
repos/base/include/spec/32bit/base/fixed_stdint.h		

The fixed-width integer types for 64-bit architectures are defined as follows.

Fixed-width integer types for 64-bit architectures		root namespace
Types		
genode_int8_t	is defined as signed char	
genode_uint8_t	is defined as unsigned char	
genode_int16_t	is defined as signed short	
genode_uint16_t	is defined as unsigned short	
genode_int32_t	is defined as signed	
genode_uint32_t	is defined as unsigned	
genode_int64_t	is defined as signed long long	
genode_uint64_t	is defined as unsigned long long	
Header		
repos/base/include/spec/64bit/base/fixed_stdint.h		

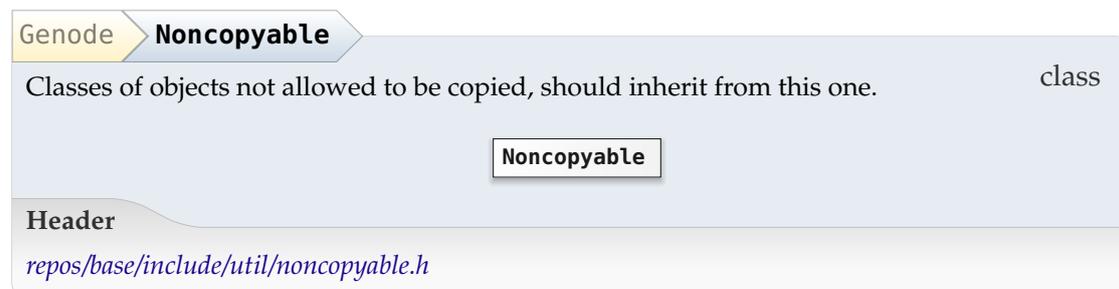
Genode		namespace
Fixed-width integer types for 64-bit architectures		
Types		
int8_t	is defined as genode_int8_t	
uint8_t	is defined as genode_uint8_t	
int16_t	is defined as genode_int16_t	
uint16_t	is defined as genode_uint16_t	
int32_t	is defined as genode_int32_t	
uint32_t	is defined as genode_uint32_t	
int64_t	is defined as genode_int64_t	
uint64_t	is defined as genode_uint64_t	
Header		
repos/base/include/spec/64bit/base/fixed_stdint.h		

8.7.2. Exception types

Genode facilitates the use of exceptions to signal errors but it uses exception types only as textual expression of error code and for grouping errors. Normally, exceptions do not carry payload. For code consistency, exception types should inherit from the `Exception` base class. By convention, exceptions carry no payload.



8.7.3. C++ supplements



This class declares a private copy-constructor and assignment-operator. It's sufficient to inherit private from this class, and let the compiler detect any copy violations.

8.8. Data structures

The framework API features a small library of data structures that are solely exist to support the framework implementation. They have been designed under the following considerations:

- They should be **as simple as possible** to make them easy to evaluate for correctness. Low complexity takes precedence over performance.
- Each data structure provides a **rigid interface** that is targeted at a specific use case and does not attempt to be a power tool. For example, the `Fifo` deliberately provides no way to randomly access elements, the `List` merely provides the functionality to remember elements but lacks list-manipulation operations.
- Data structures perform no hidden anonymous memory allocations by **storing meta data intrusively**. This is precondition for allowing resources multiplexers and runtime environments to properly account their local memory allocations. Section 3.3.3 provides the rationale behind the need for full control over memory allocations.

8.8.1. List and registry

Most book-keeping tasks in Genode rely on single-connected lists, which use the `List` template.

Genode **List** class template

Single-connected list

```

class List
{
    List()
    first() : LT *
    first() : LT const *
    insert(...)
    remove(...)
}
  
```

Template argument

`LT` **typename**
List element type

Accessor

`first` **LT const ***

Header

[repos/base/include/util/list.h](#)

Genode **List** **first** method

Return value

`LT *` First list element

Genode **List** **insert** method

Insert element after specified element into list

Arguments

`le` **LT const ***
List element to insert

`at` **LT const ***
Target position (preceding list element)
Default is 0

Genode	List	remove	
Remove element from list			method
Argument			
le LT const *			

Genode	List_element	
Helper for using member variables as list elements		class template
<pre> classDiagram class List_element { List_element(...) object(): T * } class List { <List_element<T> > } List_element < -- List </pre>		
Template argument		
T typename Type of compound object to be organized in a list		
Accessor		
object T *		
Header		
repos/base/include/util/list.h		

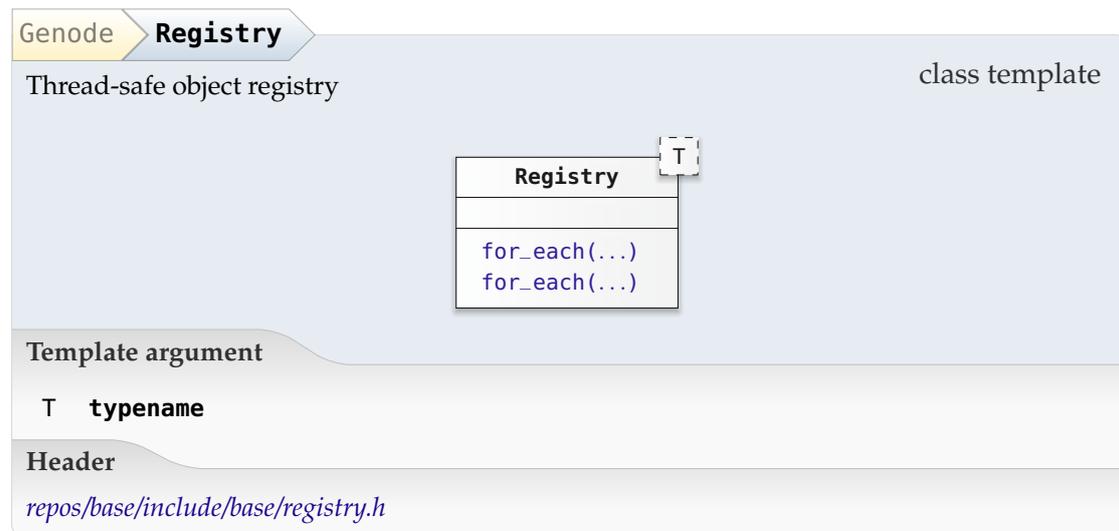
This helper allow the creation of lists that use member variables to connect their elements. This way, the organized type does not need to publicly inherit `List<LT>::Element`. Furthermore objects can easily be organized in multiple lists by embedding multiple `List_element` member variables.

Genode	List_element	List_element	
			constructor
Argument			
object T *			

Registry Most commonly, lists are used as containers that solely remember dynamically created objects. In this use case, the lifetime of the remembered object is tightly

coupled with its presence in the list. The `Registry` class template represents a safe wrapper around the raw list that ensures this presumption and thereby eliminates classes of list-related bugs by design, e. g., double insertion, missing removal.

An object type to be remembered in a `Registry` inherits the `Registry::Element` base class, which takes its registry and a reference to the object itself as arguments. Thereby, the relationship of the object with its corresponding registry is fixed at the object's construction time. Once constructed, it is implicitly part of the registry. The registry provides a `for_each` method to iterate over its elements. Unlike the traversal of a raw list, this `for_each` operation is thread safe. It also supports the safe destruction of the currently visited object.



Genode	Registry	for_each	method template
Template argument			
FUNC typename			
Argument			
fn FUNC const &			

Genode	Registry	for_each	const method template
Template argument			
FUNC typename			
Argument			
fn FUNC const &			

As an alternative to the use of the `Registry::Element` base class, the `Registered` and `Registered_no_delete` helper templates supplement arbitrary object types with the ability to become registry elements. They wrap a given object type in a new type whereby the original type remains untainted by the fact that its objects are kept in a registry.

Genode	Registered	class template
Convenience helper to equip a type <code>T</code> with a <code>Registry::Element</code>		
<pre> classDiagram class T class Registered { Registered(...) } T < -- Registered </pre>		
Template argument		
T typename		
Header		
<i>repos/base/include/base/registry.h</i>		

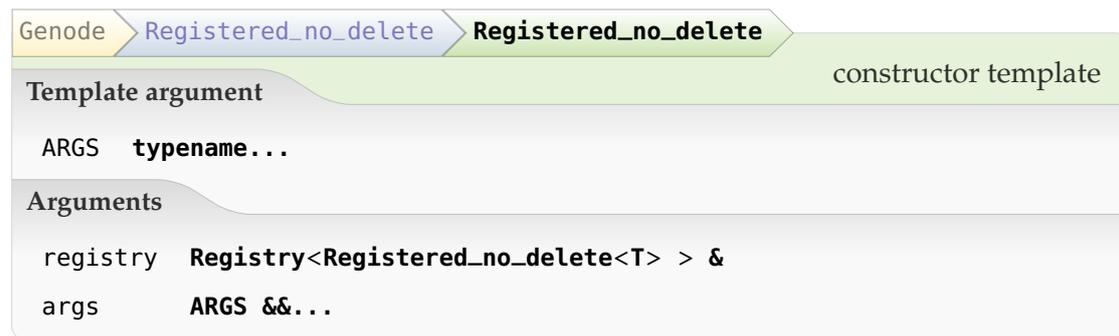
Using this helper, an arbitrary type can be turned into a registry element type. E.g., in order to keep `Child_service` objects in a registry, a new registry-compatible type

can be created via `Registered<Child_service>`. Objects of this type can be kept in a `Registry<Registered<Child_service> >`. The constructor of such “registered” objects expect the registry as the first argument. The other arguments are forwarded to the constructor of the enclosed type.

Genode	Registered	Registered	constructor template
Template argument			
ARGS	typename...		
Arguments			
registry	Registry<Registered<T> > &		
args	ARGS &&...		

Genode	Registered_no_delete	class template
Variant of Registered that does not require a vtable in the base class		
<pre> classDiagram class T class Registered_no_delete { Registered_no_delete(...) } T < -- Registered_no_delete </pre>		
Template argument		
T	typename	
Header		
<i>repos/base/include/base/registry.h</i>		

The generic `Registered` convenience class requires the base class to provide a vtable resp. a virtual destructor for safe deletion of a base class pointer. By using `Registered_no_delete`, this requirement can be lifted.



8.8.2. Fifo queue

Because the `List` inserts new list elements at the list head, it cannot be used for implementing wait queues requiring first-in-first-out semantics. For such use cases, there exists a dedicated `Fifo` template.

Genode **Fifo** class template

First-in first-out (FIFO) queue

Fifo QT

```

empty() : bool
Fifo()
head(...)
remove(...)
enqueue(...)
for_each(...)
dequeue(...)
dequeue_all(...)

```

Template argument

QT **typename**
Queue element type

Header

[repos/base/include/util/fifo.h](#)

Genode **Fifo** **empty** method

Return value

bool True if queue is empty

Genode **Fifo** **head** const method template

Call func of type void (QT&) the head element

Template argument

FUNC **typename**

Argument

func **FUNC const &**

Genode	Fifo	remove	
Remove element explicitly from queue			method
Argument			
qe QT &			
Genode	Fifo	enqueue	
Attach element at the end of the queue			method
Argument			
e QT &			
Genode	Fifo	for_each	
Call func of type void (QT&) for each element in order			const method template
Template argument			
FUNC typename			
Argument			
func FUNC const &			
Genode	Fifo	dequeue	
Remove head and call func of type void (QT&)			method template
Template argument			
FUNC typename			
Argument			
func FUNC const &			
Genode	Fifo	dequeue_all	
Remove all fifo elements			method template
Template argument			
FUNC typename			
Argument			
func FUNC const &			

This method removes all elements in order and calls the lambda func of type void

(QT&) for each element. It is intended to be used prior the destruction of the FIFO.

Genode **Fifo_element** class template

Helper for using member variables as FIFO elements

```

Fifo <Fifo_element<T> >
    ↑
    Fifo_element
    ~~~~~
    Fifo_element(...)
    object() : T &
    object() : T const &
        
```

Template argument

T typename
Type of compound object to be organized in a FIFO

Accessor

object **T const &**

Header

[repos/base/include/util/fifo.h](#)

This helper allows the creation of FIFOs that use member variables to connect their elements. This way, the organized type does not need to publicly inherit `Fifo<QT>::Element`. Furthermore, objects can easily be organized in multiple FIFOs by embedding multiple `Fifo_element` member variables.

Genode **Fifo_element** **Fifo_element** constructor

Argument

object **T &**

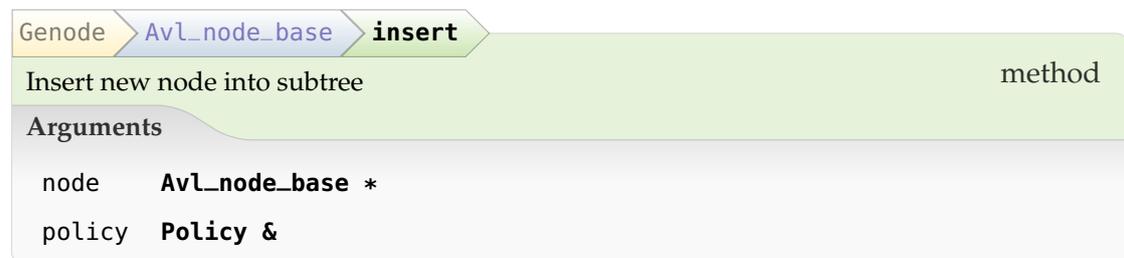
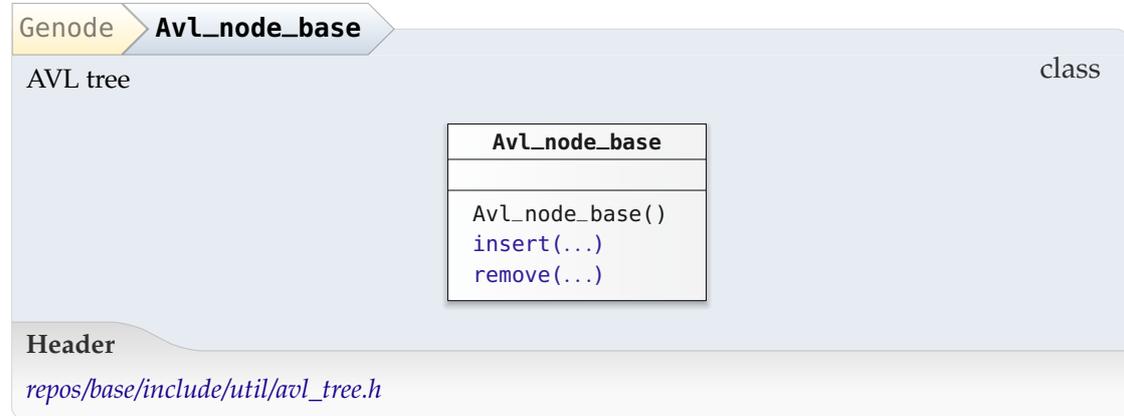
Genode **Fifo_element** **object** method

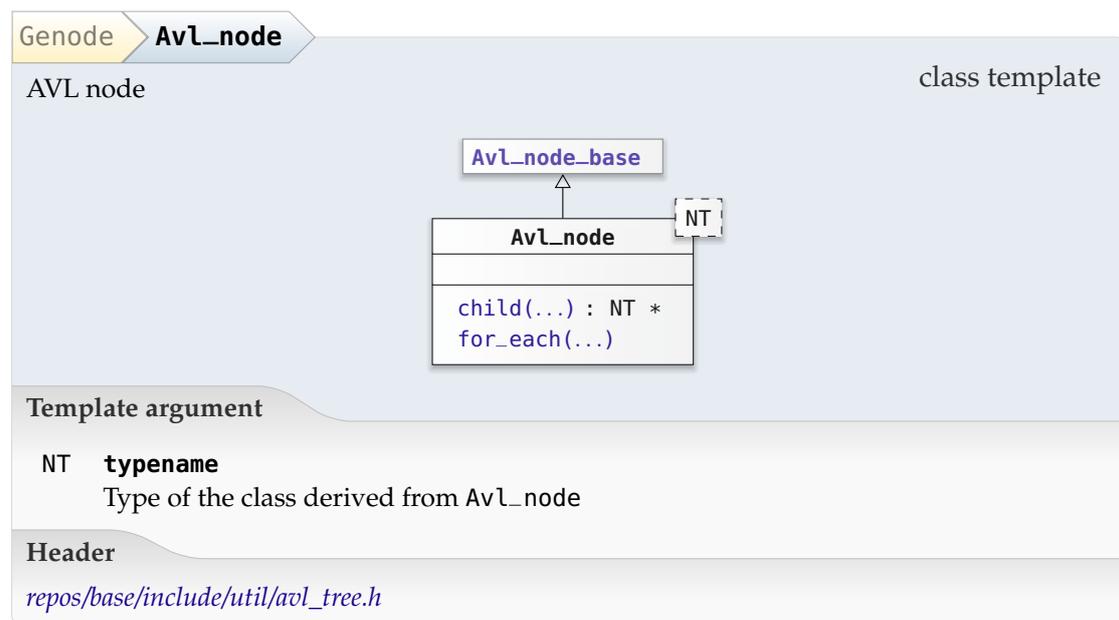
Return value

T &

8.8.3. AVL tree

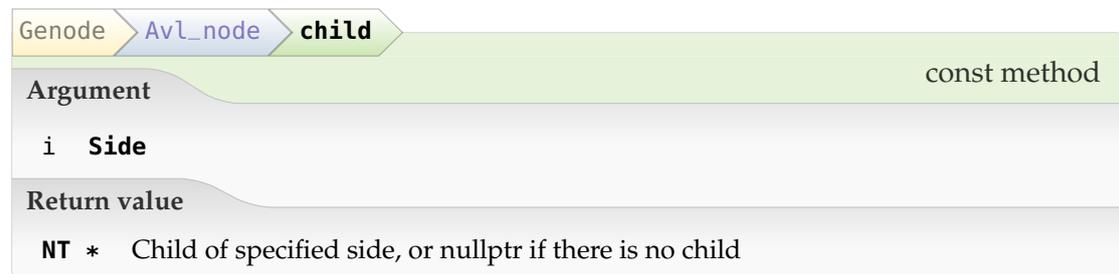
For use cases where associative arrays are needed such as allocators, there is class template for creating AVL trees. The tree-balancing mechanism is implemented in the `Avl_node_base` class. The actual `Avl_node` and `Avl_tree` classes are tagged with the element type, which ensures that each AVL tree hosts only one type of elements.





Each object to be stored in the AVL tree must be derived from AvL_node. The type of the derived class is to be specified as template argument to enable AvL_node to call virtual methods specific for the derived class.

The NT class must implement a method called higher that takes a pointer to another NT object as argument and returns a bool value. The bool value is true if the specified node is higher or equal in the tree order.



This method can be called by the NT objects to traverse the tree.

Genode > **Avl_node** > **for_each**

Apply a functor (read-only) to every node within this subtree const method template

Template argument

FUNC **typename**

Argument

functor **FUNC &&**
Function that takes a const NT reference

Genode > **Avl_tree**

Root node of the AVL tree class template

Avl_tree NT

insert(...)
remove(...)
first() : NT *
for_each(...)

Template argument

NT **typename**

Header

repos/base/include/util/avl_tree.h

The real nodes are always attached at the left branch of this root node.

Genode > **Avl_tree** > **insert**

Insert node into AVL tree method

Argument

node **Avl_node<NT> ***

Genode > **Avl_tree** > **remove**

Remove node from AVL tree method

Argument

node **Avl_node<NT> ***

Genode > Avl_tree > **first**

Request first node of the tree const method

Return value

NT * First node, or nullptr if the tree is empty

Genode > Avl_tree > **for_each**

Apply a functor (read-only) to every node within the tree const method template

Template argument

FUNC typename

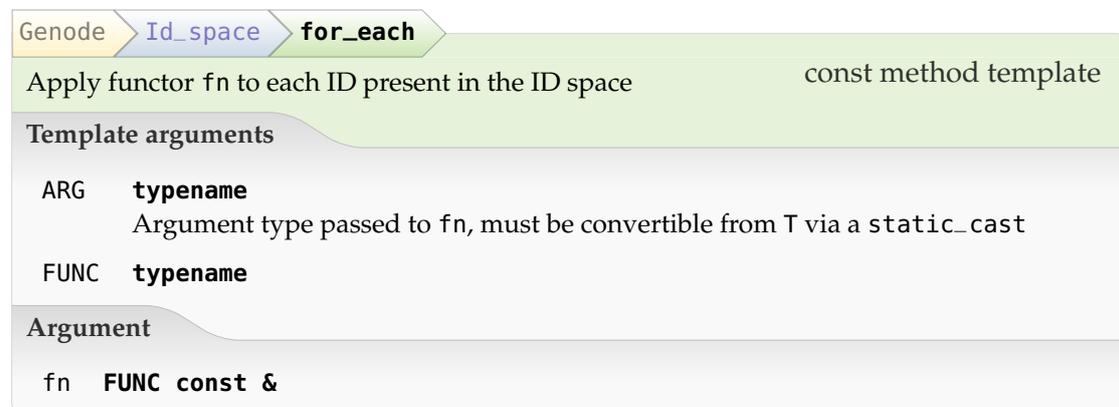
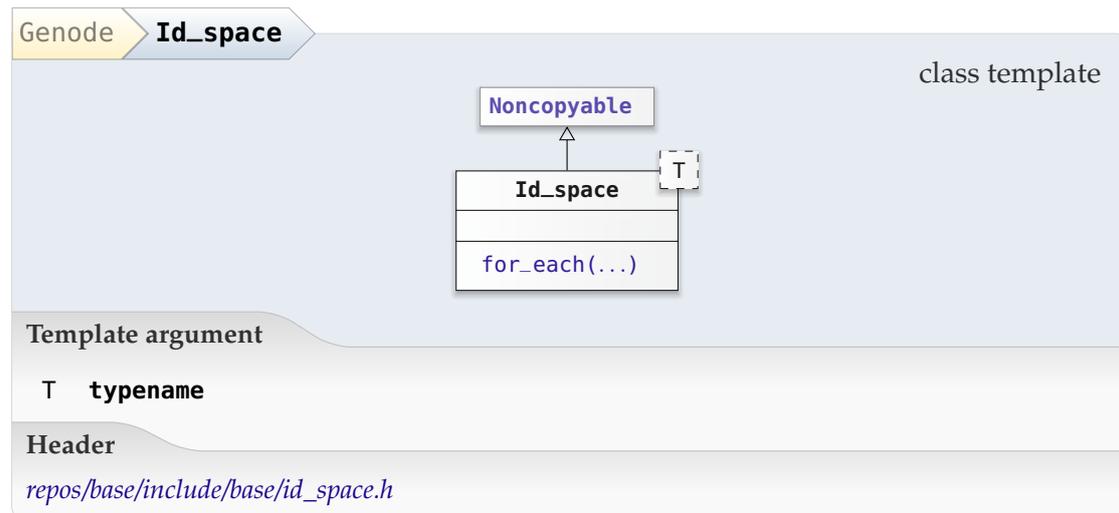
Argument

functor **FUNC &&**
Function that takes a const NT reference

The iteration order corresponds to the order of the keys

8.8.4. ID space

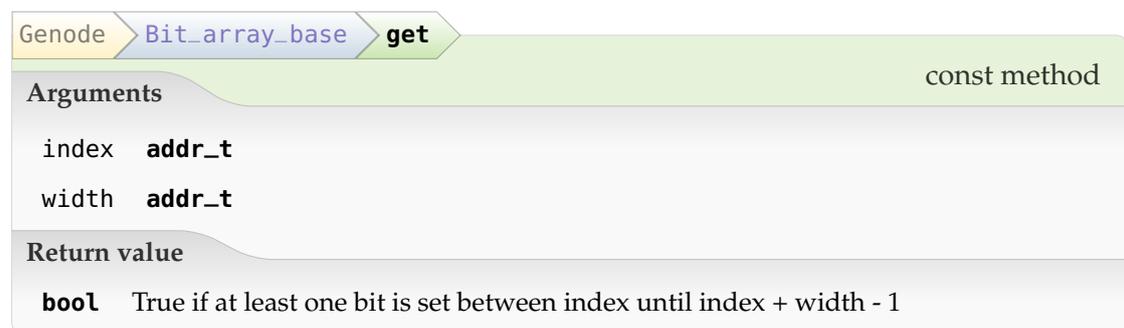
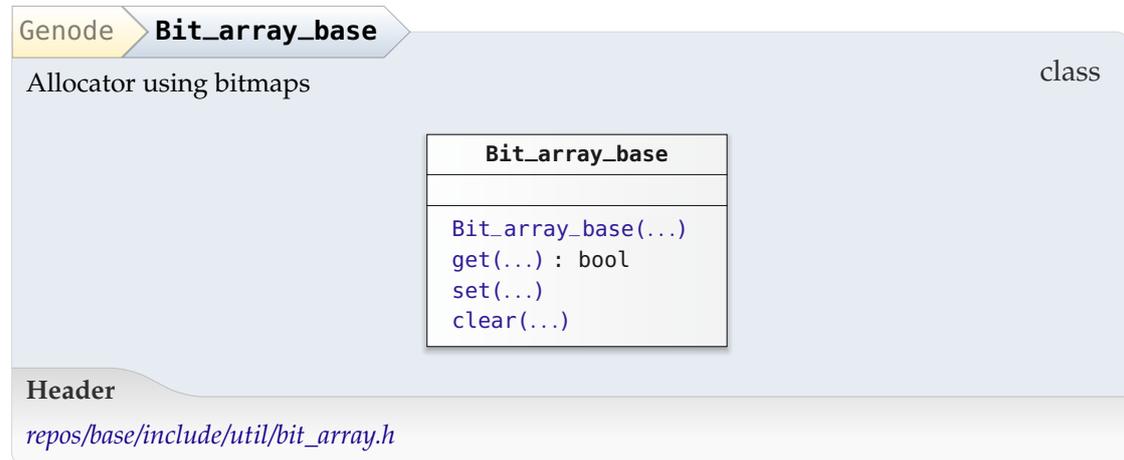
Similar to how the Registry provides a safe wrapper around list's most common use case, the Id_space covers a prominent use case for AVL trees in a safeguarded fashion, namely the association of objects with IDs. Internally, IDs are kept in an AVL tree but that implementation detail remains hidden from the API. In contrast to a bit allocator, the ID space can be sparsely populated and does not need to be dimensioned. The lifetime of an ID is bound to an Element object, which relieves the programmer from manually allocating/deallocating IDs for objects.



This function is called with the ID space locked. Hence, it is not possible to modify the ID space from within fn.

8.8.5. Bit array

Bit arrays are typically used for the allocation of IDs. The `Bit_array_base` class operates on a memory buffer specified to its constructor. The `Bit_array` class template addresses the common case where the ID space is dimensioned at compile time. It takes the number of bits as arguments and hosts the memory buffer for storing the bits within the object.



Genode > Bit_array_base > **set** method

Arguments

index **addr_t const**
width **addr_t const**

Genode > Bit_array_base > **clear** method

Arguments

index **addr_t const**
width **addr_t const**

Genode > **Bit_array** class template

Allocator using bitmaps

```

classDiagram
    class Bit_array_base
    class Bit_array {
        <template> BITS
        Bit_array()
        Bit_array(...)
    }
    Bit_array_base <|-- Bit_array
            
```

Template argument

BITS unsigned

Header

repos/base/include/util/bit_array.h

Genode > Bit_array > **Bit_array** constructor

Argument

o **const Bit_array &**

8.9. Object lifetime management

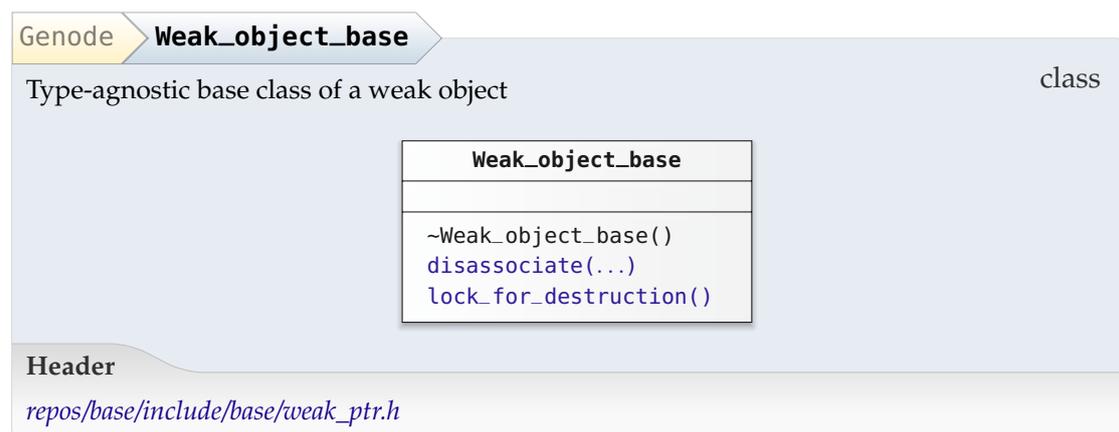
8.9.1. Thread-safe weak pointers

Dangling pointers represent one of the most common cause for instabilities of software written in C or C++. Such a situation happens when an object disappears while pointers to the object are still in use. One way to solve this problem is to explicitly notify the holders of those pointers about the disappearance of the object. But this would require the object to keep references to those pointer holders, which, in turn, might disappear as well. Consequently, this approach tends to become a complex solution, which is prone to deadlocks or race conditions when multiple threads are involved.

The utilities provided by *base/weak_ptr.h* implement a more elegant pattern called “weak pointers” to deal with such situations. An object that might disappear at any time is represented by the `Weak_object` class template. It keeps track of a list of so-called weak pointers pointing to the object. A weak pointer, in turn, holds privately the pointer to the object alongside a validity flag. It cannot be used to dereference the object. For accessing the actual object, a locked pointer must be created from a weak pointer. If this creation succeeds, the object is guaranteed to be locked (not destroyed) until the locked pointer gets destroyed. If the object no longer exists, the locked pointer will become invalid. This condition can (and should) be detected via the `Locked_ptr::is_valid()` function prior dereferencing the pointer.

In the event a weak object gets destructed, all weak pointers that point to the object are automatically invalidated. So a subsequent conversion into a locked pointer will yield an invalid pointer, which can be detected (in contrast to a dangling pointer).

To use this mechanism, the destruction of a weak object must be deferred until no locked pointer points to the object anymore. This is done by calling the function `Weak_object::lock_for_destruction()` at the beginning of the destructor of the to-be-destructed object. When this function returns, all weak pointers to the object will have been invalidated. So it is safe to destruct and free the object.



Genode **Weak_object_base** **disassociate** method

Argument

ptr **Weak_ptr_base ***

Genode **Weak_object_base** **lock_for_destruction** method

Mark object as safe to be destructed

This method must be called by the destructor of a weak object to defer the destruction until no Locked_ptr is held to the object.

Genode **Weak_object** class template

Weak object

```

classDiagram
    class Weak_object_base
    class Weak_object["Weak_object<T>"]
    Weak_object_base <|-- Weak_object
    class Weak_ptr["Weak_ptr<T>"]
    class Weak_ptr_const["Weak_ptr<T const> const"]
    Weak_object --> Weak_ptr
    Weak_object --> Weak_ptr_const
  
```

Template argument

T **typename**
Type of the derived class

Header

repos/base/include/base/weak_ptr.h

This class template must be inherited in order to equip an object with the weak-pointer mechanism.

Genode > Weak_object > **weak_ptr**

Obtain a weak pointer referring to the weak object method

Return value

Weak_ptr<T>

Genode > Weak_object > **weak_ptr_const**

Const version of weak_ptr const method

Return value

Weak_ptr<T const> const

This function is useful in cases where the returned weak pointer is merely used for comparison operations.

Genode > **Weak_ptr_base**

Type-agnostic base class of a weak pointer class

```

classDiagram
    class Weak_ptr_base {
        Weak_ptr_base()
        ~Weak_ptr_base()
        operator =(...) : Weak_ptr_base &
        operator ==(...) : bool
    }
    class List {
        <Weak_ptr_base>
    }
    Weak_ptr_base <|-- List
  
```

Header

repos/base/include/base/weak_ptr.h

This class implements the mechanics of the the Weak_ptr class template. It is not used directly.

Genode > Weak_ptr_base > Weak_ptr_base

Default constructor, produces invalid pointer constructor

Genode > Weak_ptr_base > operator =

Assignment operator method

Argument

other Weak_ptr_base const &

Return value

Weak_ptr_base &

Genode > Weak_ptr_base > operator ==

Test for equality const method

Argument

other Weak_ptr_base const &

Return value

bool

Genode > Weak_ptr

Weak pointer to a given type class template

```

classDiagram
    class Weak_ptr_base
    class Weak_ptr {
        Weak_ptr()
        Weak_ptr(...)
        operator =(...) : Weak_ptr &
    }
    Weak_ptr_base <|-- Weak_ptr
    Weak_ptr -- T
        
```

Template argument

T typename

Header

repos/base/include/base/weak_ptr.h

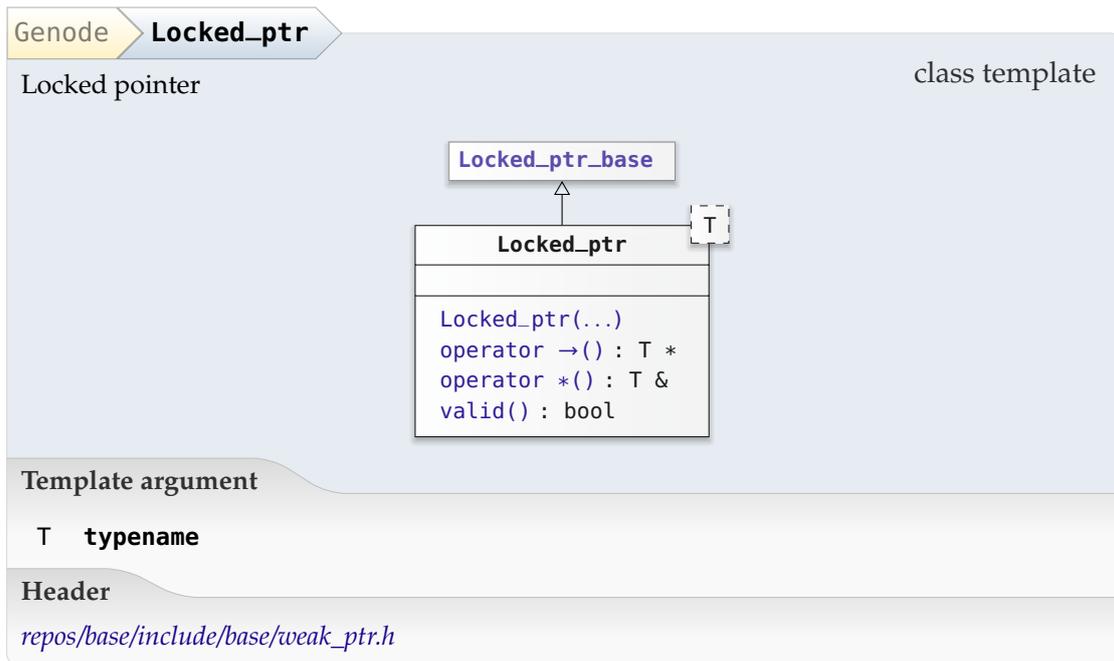
A weak pointer can be obtained from a weak object (an object that inherits the `Weak_object` class template) and safely survives the lifetime of the associated weak object. If the weak object disappears, all weak pointers referring to the object are automatically invalidated. To avoid race conditions between the destruction and use of a weak object, a weak pointer cannot be de-reference directly. To access the object, a weak pointer must be turned into a locked pointer (`Locked_ptr`).

Genode **Weak_ptr** **Weak_ptr** constructor
 Default constructor creates invalid pointer

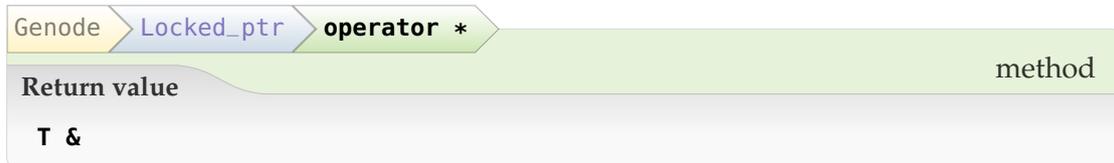
Genode **Weak_ptr** **Weak_ptr** constructor
 Copy constructor
Argument
 other **Weak_ptr<T> const &**

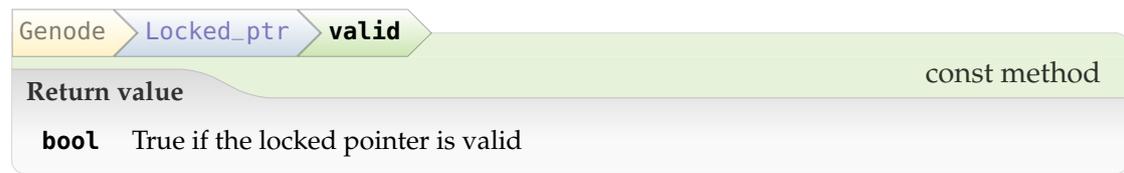
Genode **Weak_ptr** **operator =** method
 Assignment operator
Argument
 other **Weak_ptr<T> const &**
Return value
Weak_ptr &

Genode **Locked_ptr_base** class
Locked_ptr_base
Header
repos/base/include/base/weak_ptr.h



A locked pointer is constructed from a weak pointer. After construction, its validity can (and should) be checked by calling the `valid` method. If the locked pointer is valid, the pointed-to object is known to be locked until the locked pointer is destroyed. During this time, the locked pointer can safely be de-referenced. The typical pattern of using a locked pointer is to declare it as a local variable. Once the execution leaves the scope of the variable, the locked pointer is destroyed, which unlocks the pointed-to weak object. It effectively serves as a lock guard.





Only if `valid`, the locked pointer can be de-referenced. Otherwise, the attempt will result in a null-pointer access.

8.9.2. Late and repeated object construction

The `construct_at` utility allows for the manual placement of objects without the need to have a global placement new operation nor the need for type-specific new operators.

Genode		namespace
Utility for the manual placement of objects		
Function		
<ul style="list-style-type: none"> • <code>Genode::construct_at(...)</code> : T * 		
Header		
repos/base/include/util/construct_at.h		
Genode	Genode::construct_at	function template
Construct object of given type at a specific location		
Template arguments		
T	typename	Object type
ARGS	typename...	
Arguments		
at	void *	Desired object location
args	ARGS &&...	List of arguments for the object constructor
Return value		
T *		Typed object pointer

We use move semantics (ARGS &&) because otherwise the compiler would create a temporary copy of all arguments that have a reference type and use a reference to this copy instead of the original within this function.

There is a slight difference between the object that is constructed by this function and a common object of the given type. If the destructor of the given type or of any base of the given type is virtual, the vtable of the returned object references an empty `delete(void *)` operator for that destructor. However, this shouldn't be a problem as an object constructed by this function should never get destructed implicitly or through a `delete` expression.

The Genode framework promotes a programming style that largely avoids dynamic memory allocations. For the most part, higher-level objects aggregate lower-level objects as class members. This functional programming style leads to robust programs

but it poses a problem for programs that are expected to adopt their behaviour at run-time. A way to selectively replace an aggregated object by a new version with updated constructor arguments is desired. The `Reconstructible` utility solves this problem by wrapping an object of the type specified as template argument. In contrast of a regular object, a `Reconstructible` object can be re-constructed any number of times by calling `construct` with the constructor arguments. It is accompanied with a so-called `Constructible` utility, which leaves the wrapped object unconstructed until `construct` is called the first time.



This class template acts as a smart pointer that refers to an object contained within the smart pointer itself. The contained object may be repeatedly constructed and destructed while staying in the same place. This is useful for replacing aggregated members during the lifetime of a compound object.

Genode	Reconstructible	Reconstructible	
Constructor that omits the initial construction of the object			constructor
Argument			
- Lazy *			

Genode	Reconstructible	Reconstructible	
Template argument			constructor template
ARGS typename...			
Argument			
args ARGS &&...			

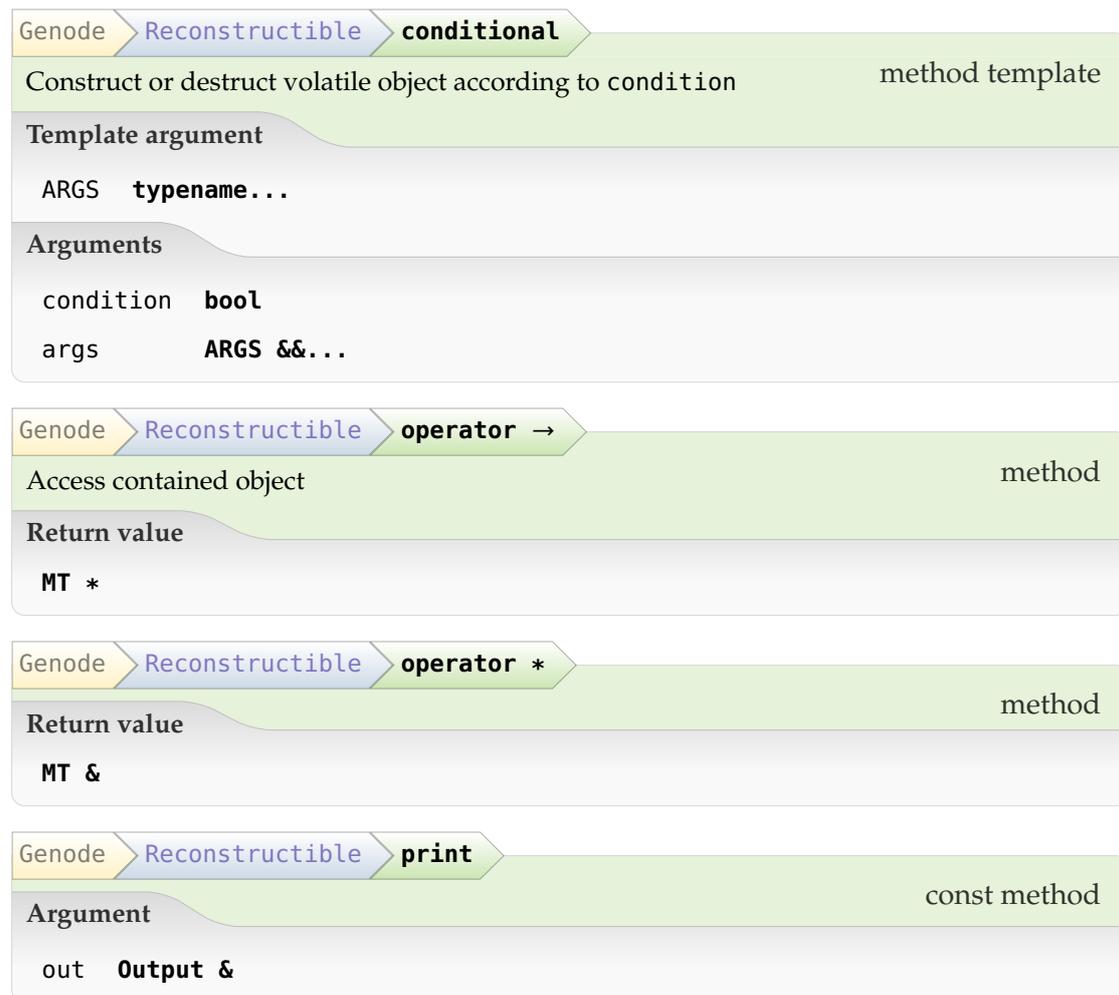
The arguments are forwarded to the constructor of the embedded object.

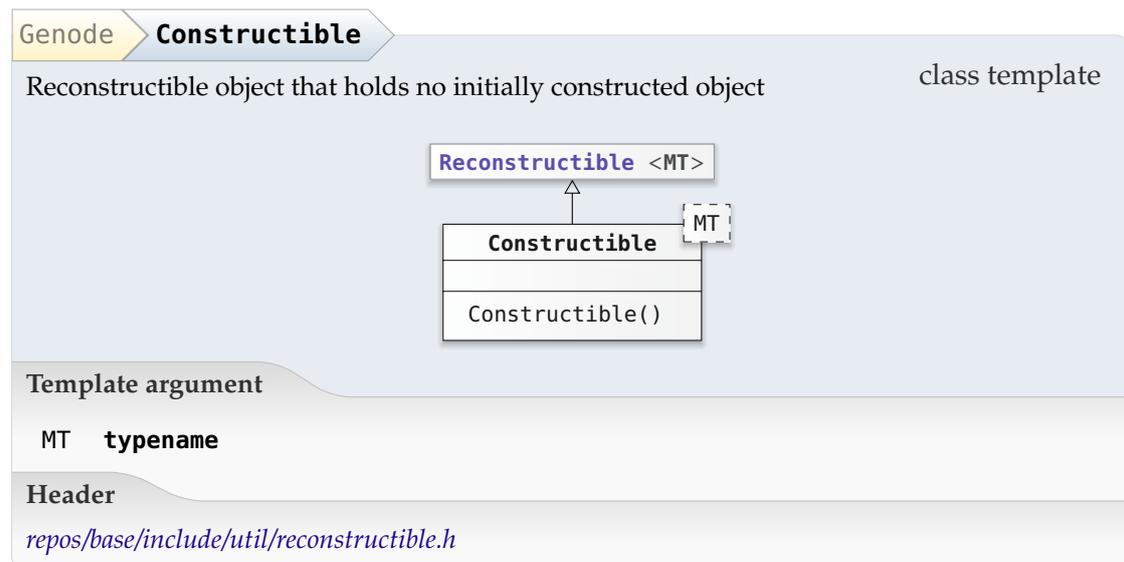
Genode	Reconstructible	construct	
Construct new object in place			method template
Template argument			
ARGS typename...			
Argument			
args ARGS &&...			

If the Reconstructible already hosts a constructed object, the old object will be destructed first.

Genode	Reconstructible	destruct	
Destruct object			method

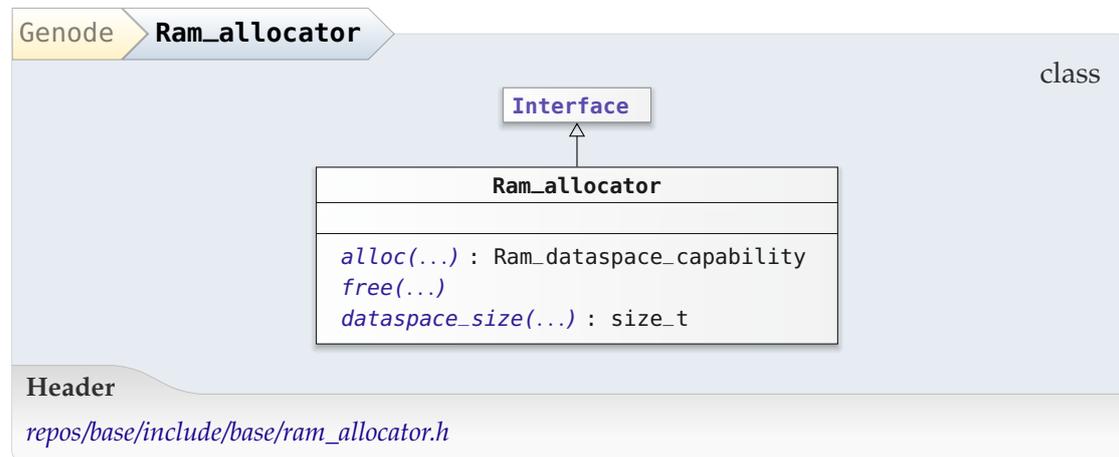
Genode	Reconstructible	constructed	
Return value			const method
bool True of volatile object contains a constructed object			





8.10. Physical memory allocation

Throughout Genode, physical memory is allocated in the form of RAM dataspaces by using the `Ram_allocator` interface. This interface is implemented by the PD session and thereby allows a component to use its RAM budget. The RAM dataspaces allocated from the `Ram_allocator` interface may serve as backing store for fine-grained component-local allocators such as the Heap (Section 8.11).

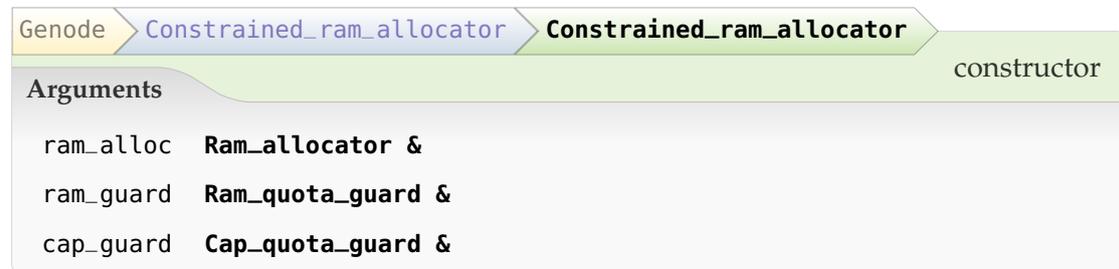
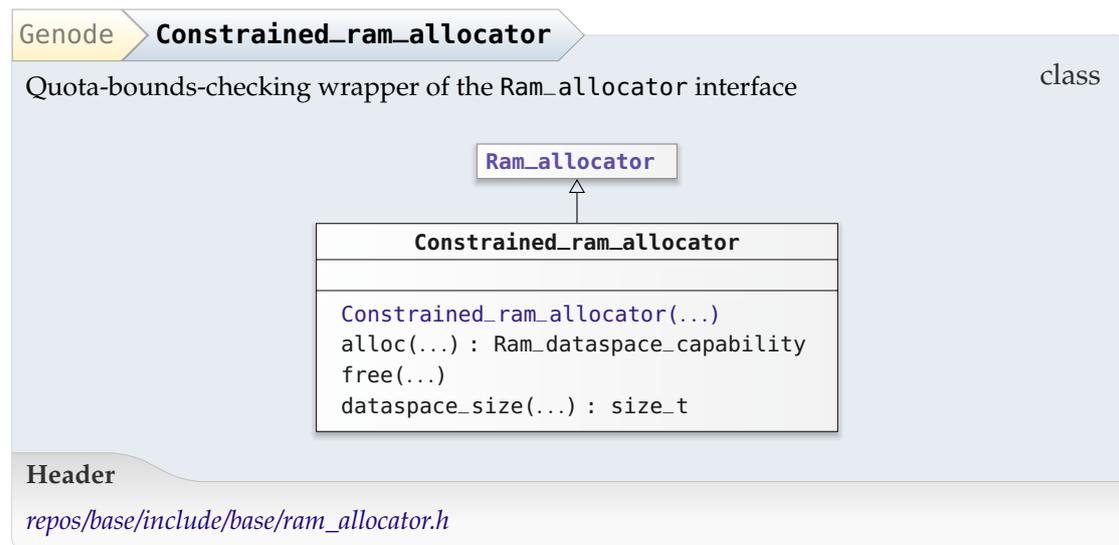


Genode	Ram_allocator	alloc	
Allocate RAM dataspace			pure virtual method
Arguments			
size	size_t	Size of RAM dataspace	
cached	Cache_attribute	Selects cacheability attributes of the memory, uncached memory, i. e., for DMA buffers <i>Default is CACHED</i>	
Exceptions			
Out_of_ram			
Out_of_caps			
Return value			
Ram_dataspace_capability	Capability to new RAM dataspace		

Genode	Ram_allocator	free	
Free RAM dataspace			pure virtual method
Argument			
ds	Ram_dataspace_capability	Dataspace capability as returned by alloc	

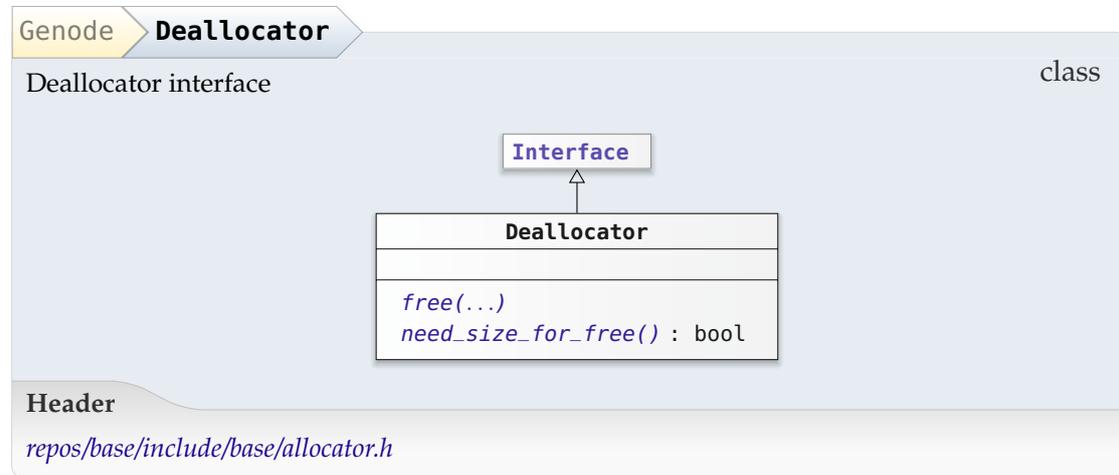
Genode	Ram_allocator	dataspace_size	
			pure virtual const method
Argument			
ds	Ram_dataspace_capability		
Return value			
size_t	Size of dataspace in bytes		

Constraining RAM allocations The operations of the `Ram_allocator` interface are the basis for Genode's RAM accounting. In cases where a server needs to allocate RAM on behalf of its clients, the interface provides a natural hook to track and constrain the client-specific RAM usage. The `Constrained_ram_allocator` implements the interface by forwarding all operations to another `Ram_allocator` instance while restricting allocations to a quota limit. Exceeding the limit results in an `Out_of_ram` exception.



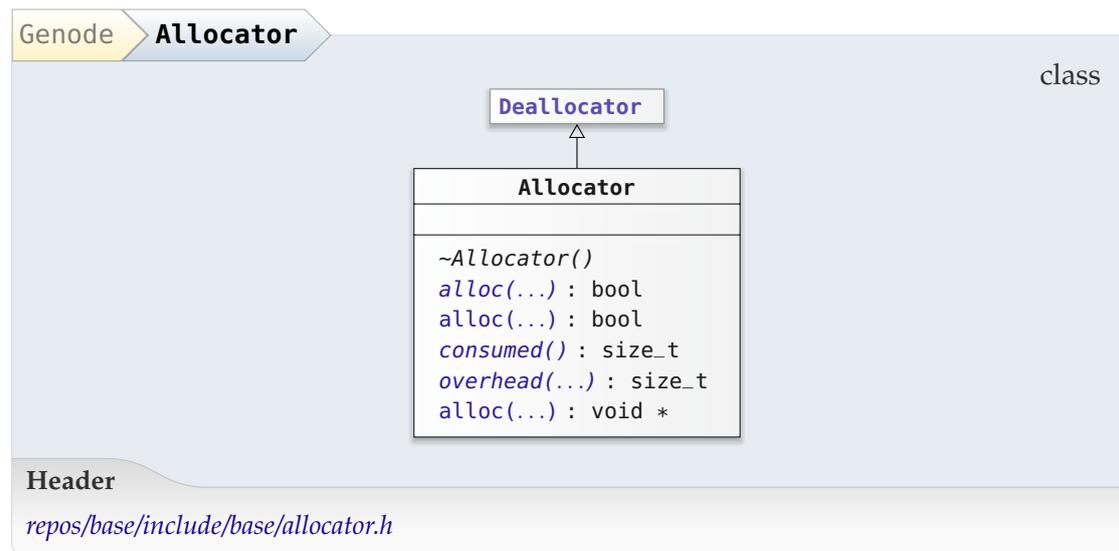
8.11. Component-local allocators

Component-local allocators implement the generic Deallocator and Allocator interfaces. Allocators that operate on address ranges supplement the plain Allocator by implementing the more specific Range_allocator interface.



The generic Allocator interface requires the caller of free to supply a valid size argument but not all implementations make use of this argument. If this method returns false, it is safe to call free with an invalid size.

Allocators that rely on the size argument must not be used for constructing objects whose constructors may throw exceptions. See the documentation of operator delete(void *, Allocator *) below for more details.



Genode	Allocator	alloc	
Allocate block			pure virtual method
Arguments			
size	size_t	Block size to allocate	
out_addr	void **	Resulting pointer to the new block, undefined in the error case	
Exceptions			
Out_of_ram			
Out_of_caps			
Return value			
bool	True on success		

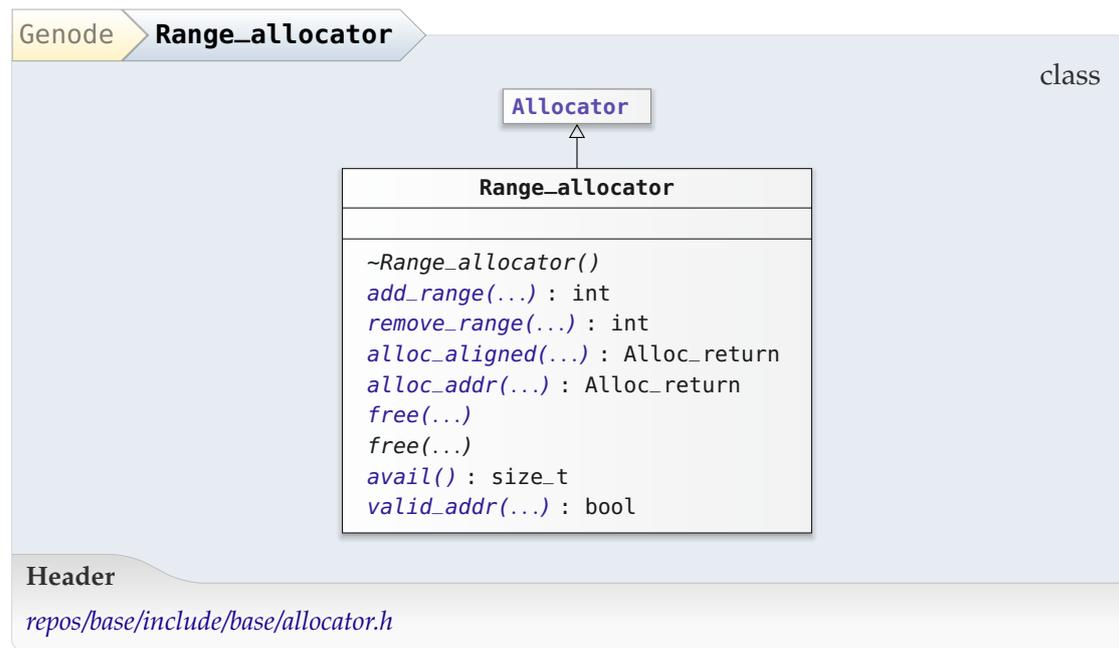
Genode	Allocator	alloc	
Allocate typed block			method template
Template argument			
T	typename		
Arguments			
size	size_t		
out_addr	T **		
Exceptions			
Out_of_ram			
Out_of_caps			
Return value			
bool			

This template allocates a typed block returned as a pointer to a non-void type. By providing this method, we prevent the compiler from warning us about “dereferencing type-punned pointer will break strict-aliasing rules”.

Genode	Allocator	consumed	
			virtual const method
Return value			
size_t	Total amount of backing store consumed by the allocator		

Genode	Allocator	overhead	
			pure virtual const method
Argument			
size	size_t		
Return value			
size_t	Meta-data overhead per block		

Genode	Allocator	alloc	
Allocate block and signal error as an exception			method
Argument			
size	size_t	Block size to allocate	
Exceptions			
Out_of_ram			
Out_of_caps			
Return value			
void *	Pointer to the new block		



Genode > **Range_allocator** > **add_range** pure virtual method

Add free address range to allocator

Arguments

base **addr_t**
 size **size_t**

Return value

int

Genode > **Range_allocator** > **remove_range** pure virtual method

Remove address range from allocator

Arguments

base **addr_t**
 size **size_t**

Return value

int

Genode	Range_allocator	alloc_aligned	
Allocate block			pure virtual method
Arguments			
size	size_t	Size of new block	
out_addr	void **	Start address of new block, undefined in the error case	
align	int	Alignment of new block specified as the power of two	
from	addr_t	Default is 0	
to	addr_t	Default is ~0UL	
Return value			
Alloc_return			

Genode	Range_allocator	alloc_addr	
Allocate block at address			pure virtual method
Arguments			
size	size_t	Size of new block	
addr	addr_t	Desired address of block	
Return value			
Alloc_return	ALLOC_OK on success, or OUT_OF_METADATA if meta-data allocation failed, or RANGE_CONFLICT if specified range is occupied		

Genode	Range_allocator	free	
Free a previously allocated block			pure virtual method
Argument			
addr	void *		

NOTE: We have to declare the `Allocator::free(void *)` method here as well to make the compiler happy. Otherwise the C++ overload resolution would not find `Allocator::free(void *)`.

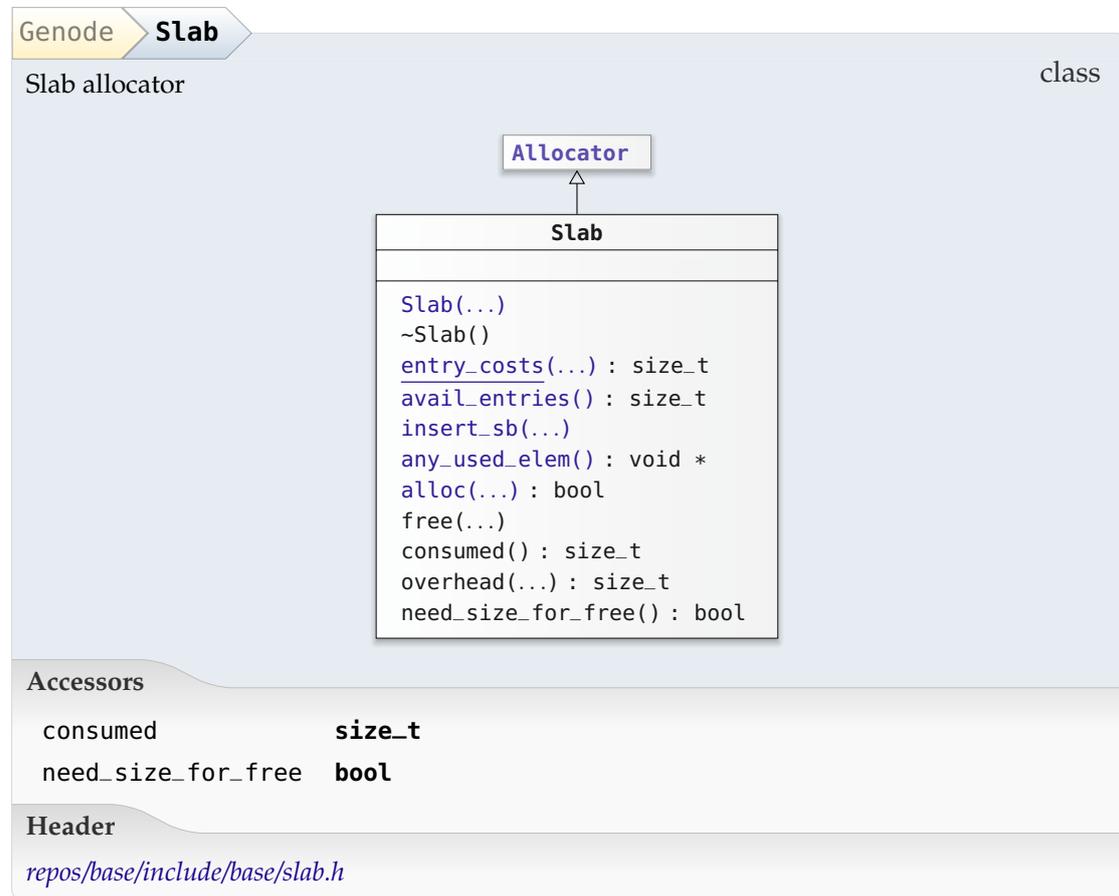
Genode	Range_allocator	avail	
Return value			pure virtual const method
size_t	The sum of available memory		

Note that the returned value is not necessarily allocatable because the memory may be fragmented.

Genode	Range_allocator	valid_addr	
Check if address is inside an allocated block			pure virtual const method
Argument			
addr	addr_t	Address to check	
Return value			
bool	True if address is inside an allocated block, false otherwise		

8.11.1. Slab allocator

The Slab allocator is tailored for allocating small fixed-size memory blocks from a big chunk of memory. For the common use case of using a slab allocator for a certain type rather than for a known byte size, there exists a typed slab allocator as a front end of Slab.



At construction time, there exists one initial slab block that is used for the first couple

of allocations, especially for the allocation of the second slab block.

Genode		Slab	entry_costs	
				class function
Arguments				
slab_size		size_t		
block_size		size_t		
Return value				
size_t	Number of bytes consumed per slab entry			

The function takes the slab-internal meta-data needs and the actual slab entry into account.

Genode		Slab	avail_entries	
				const method
Return value				
size_t	Number of unused slab entries			

Genode		Slab	insert_sb	
Add new slab block as backing store				method
Argument				
ptr	void *			

The specified `ptr` has to point to a buffer with the size of one slab block.

Genode		Slab	any_used_elem	
				method
Return value				
void *	A used slab element, or <code>nullptr</code> if empty			

Genode		Slab	alloc	
Allocate slab entry				method
Arguments				
size	size_t			
addr	void **			
Return value				
bool				

The `size` parameter is ignored as only slab entries with preconfigured slab-entry size

are allocated.

Genode **Tslab** class template

```

classDiagram
    class Slab
    class Tslab {
        Tslab(...)
        Tslab(...)
        first_object() T *
    }
    Slab <|-- Tslab
    
```

Template arguments

T **typename**

BLOCK_SIZE **size_t**

Header

repos/base/include/base/tslab.h

Genode **Tslab** **Tslab** constructor

Arguments

backing_store **Allocator ***

initial_sb **void ***
Default is 0

Genode **Tslab** **Tslab** constructor

Arguments

backing_store **Allocator &**

initial_sb **void ***
Default is 0

Genode **Tslab** **first_object** method

Return value

T *

8.11.2. AVL-tree-based best-fit allocator

In contrast to the rather limited slab allocators, `Allocator_avl` allows for arbitrary allocations from a list of address regions. It implements a best-fit allocation strategy, supports arbitrary alignments, and allocations at specified addresses.



Genode	Allocator_avl_base	_revert_allocations_and_ranges	method
Clean up the allocator and detect dangling allocations			

This method is called at the destruction time of the allocator. It makes sure that the allocator instance releases all memory obtained from the meta-data allocator.

Genode	Allocator_avl_base	_find_by_address	const method
Find block by specified address			
Arguments			
addr	addr_t		
size	size_t	<i>Default is 0</i>	
check_overlap	bool	<i>Default is 0</i>	
Return value			
Block *			

Genode	Allocator_avl_base	Allocator_avl_base	constructor
Arguments			
md_alloc	Allocator *		
md_entry_size	size_t		

This constructor can only be called from a derived class that provides an allocator for block meta-data entries. This way, we can attach custom information to block meta data.

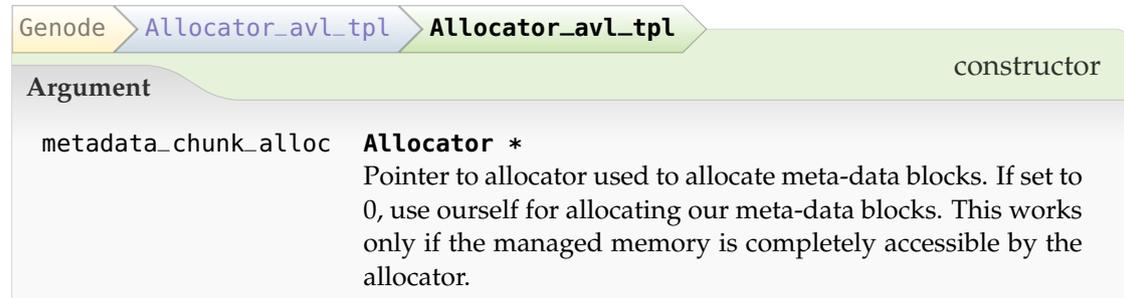
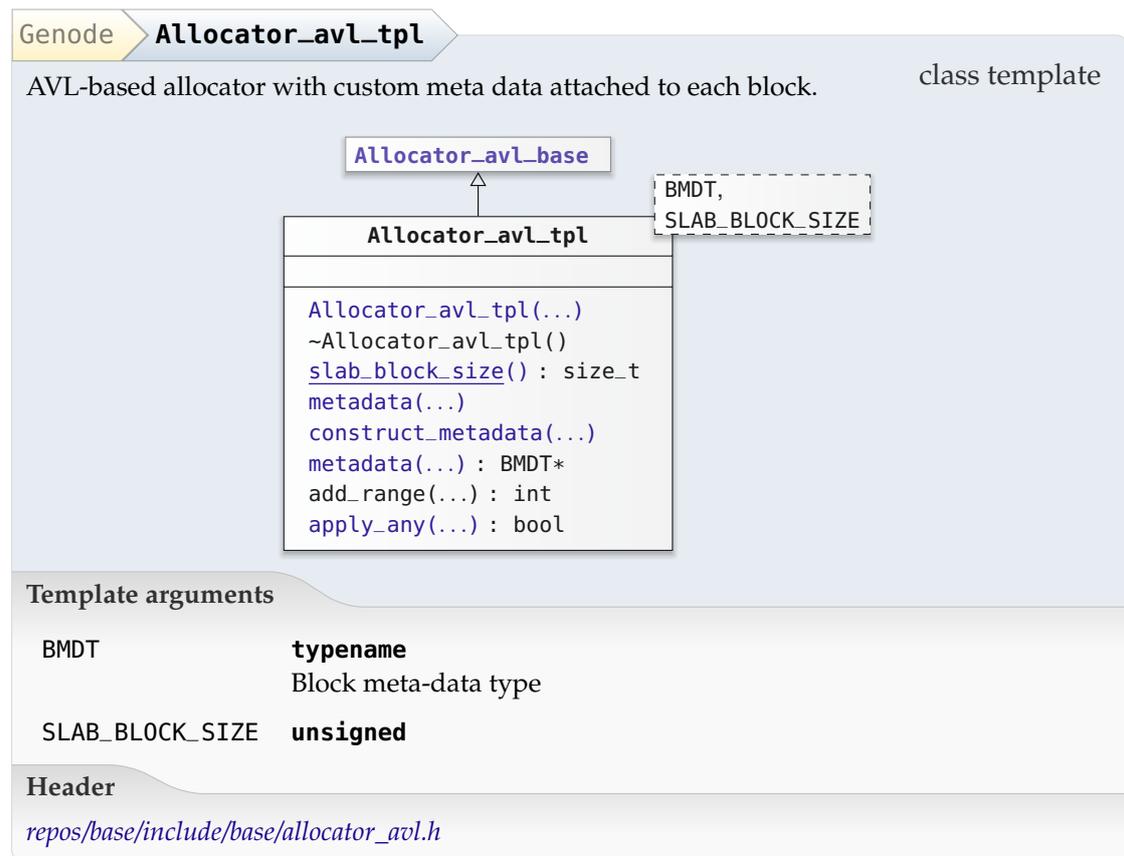
Genode	Allocator_avl_base	any_block_addr	method
Argument			
out_addr	addr_t *	Result that contains address of block	
Return value			
bool True if block was found or false if there is no block available			

If no block was found, out_addr is set to zero.



The overhead is a rough estimation. If a block is somewhere in the middle of a free area, we could consider the meta data for the two free subareas when calculating the overhead.

The `sizeof(umword_t)` represents the overhead of the meta-data slab allocator.



Genode > Allocator_avl_tpl > metadata

Assign custom meta data to block at specified address const method

Arguments

addr **void ***
 bmd **BMDT**

Exception

Assign_metadata_failed

Genode > Allocator_avl_tpl > construct_metadata

Construct meta-data object in place method template

Template argument

ARGS **typename...**
 Arguments passed to the meta-data constructor

Arguments

addr **void ***
 args **ARGS &&...**

Genode > Allocator_avl_tpl > metadata

Argument const method

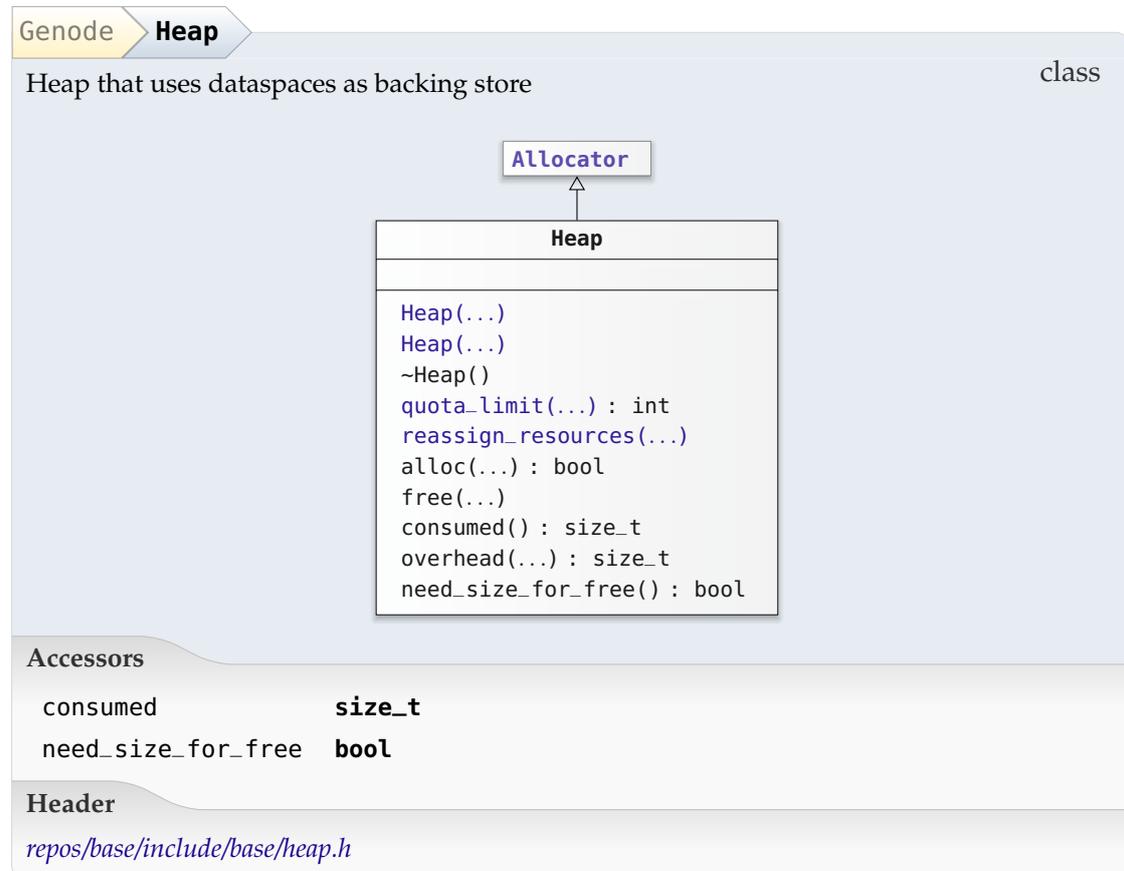
addr **void ***

Return value

BMDT* Meta data that was attached to block at specified address

Genode	Allocator_avl_tpl	apply_any	method template
<p>Apply functor <code>fn</code> to the metadata of an arbitrary member of the allocator. This method is provided for destructing each member of the allocator. Calling the method repeatedly without removing or inserting members will produce the same member.</p>			
Template argument			
<code>FUNC typename</code>			
Argument			
<code>fn FUNC const &</code>			
Return value			
<code>bool</code>			

8.11.3. Heap and sliced heap



The heap class provides an allocator that uses a list of dataspace of a RAM allocator as backing store. One dataspace may be used for holding multiple blocks.

Genode > Heap > Heap

constructor

Arguments

ram_allocator	Ram_allocator *
region_map	Region_map *
quota_limit	size_t <i>Default is UNLIMITED</i>
static_addr	void * <i>Default is 0</i>
static_size	size_t <i>Default is 0</i>

Genode > Heap > Heap

constructor

Arguments

ram	Ram_allocator &
rm	Region_map &

Genode > Heap > quota_limit

Reconfigure quota limit

method

Argument

new_quota_limit	size_t
-----------------	---------------

Return value

int Negative error code if new quota limit is higher than currently used quota.

Genode > Heap > reassign_resources

Re-assign RAM allocator and region map

method

Arguments

ram	Ram_allocator *
rm	Region_map *

Genode **Sliced_heap** class

Heap that allocates each block at a separate dataspace

```

class Allocator
    ^
class Sliced_heap
    meta_data_size() : size_t
    Sliced_heap(...)
    ~Sliced_heap()
    alloc(...) : bool
    free(...)
    consumed() : size_t
    overhead(...) : size_t
    need_size_for_free() : bool
    
```

Accessors

consumed **size_t**
 need_size_for_free **bool**

Header

repos/base/include/base/heap.h

Genode **Sliced_heap** **meta_data_size** class function

Return value

size_t Size of header prepended to each allocated block in bytes

Genode **Sliced_heap** **Sliced_heap** constructor

Arguments

ram_alloc **Ram_allocator &**
 region_map **Region_map &**

8.11.4. Bit allocator

Genode **Bit_allocator** class template

Bit_allocator
<pre> Bit_allocator() Bit_allocator(...) alloc(...) : addr_t alloc_addr(...) free(...) </pre>

Template argument
BITS unsigned

Header
repos/base/include/util/bit_allocator.h

Genode **Bit_allocator** **Bit_allocator** constructor

Argument
 o **const Bit_allocator &**

Genode **Bit_allocator** **alloc** method

Argument
 num_log2 **size_t const**
Default is 0

Return value
addr_t

Genode	Bit_allocator	alloc_addr	
Allocate specific block of bits			method
Arguments			
bit_start	addr_t const		
num_log2	size_t const	2-based logarithm of size of block	
		<i>Default is 0</i>	
Exceptions			
Range_conflict			
Array::Invalid_index_access			

Genode	Bit_allocator	free	
			method
Arguments			
bit_start	addr_t const		
num_log2	size_t const		
		<i>Default is 0</i>	

8.12. String processing

8.12.1. Basic string operations

There exists a small set of string-manipulation operations as global functions in the Genode namespace.

Genode	namespace
String utilities	
Functions	
<ul style="list-style-type: none"> • <code>strlen(...)</code> : <code>size_t</code> • <code>strcmp(...)</code> : <code>int</code> • <code>memmove(...)</code> : <code>void *</code> • <code>memcpy(...)</code> : <code>void *</code> • <code>strncpy(...)</code> : <code>char *</code> • <code>memcmp(...)</code> : <code>int</code> • <code>memset(...)</code> : <code>void *</code> • <code>digit(...)</code> : <code>int</code> • <code>is_letter(...)</code> : <code>bool</code> • <code>is_digit(...)</code> : <code>bool</code> • <code>is_whitespace(...)</code> : <code>bool</code> • <code>ascii_to_unsigned(...)</code> : <code>size_t</code> • <code>ascii_to(...)</code> : <code>size_t</code> • <code>end_of_quote(...)</code> : <code>bool</code> • <code>unpack_string(...)</code> : <code>int</code> 	
Header	
<i>repos/base/include/util/string.h</i>	

Genode	strlen	global function
Argument		
<code>s</code>	<code>const char *</code>	
Return value		
<code>size_t</code>	Length of null-terminated string in bytes	

Genode **strcmp** global function

Compare two strings

Arguments

s1 **const char ***

s2 **const char ***

len **size_t**
Maximum number of characters to compare, default is unlimited
Default is ~0UL

Return value

int 0 if both strings are equal, or a positive number if s1 is higher than s2, or a negative number if s1 is lower than s2

Genode **memmove** global function

Copy memory buffer to a potentially overlapping destination buffer

Arguments

dst **void ***
Destination memory block

src **const void ***
Source memory block

size **size_t**
Number of bytes to move

Return value

void * Pointer to destination memory block

Genode	memcpy	global function
Copy memory buffer to a non-overlapping destination buffer		
Arguments		
dst	void * Destination memory block	
src	const void * Source memory block	
size	size_t Number of bytes to copy	
Return value		
	void * Pointer to destination memory block	

Genode	strncpy	global function
Copy string		
Arguments		
dst	char * Destination buffer	
src	const char * Buffer holding the null-terminated source string	
size	size_t Maximum number of characters to copy	
Return value		
	char * Pointer to destination string	

Note that this function is not fully compatible to the C standard, in particular there is no zero-padding if the length of `src` is smaller than `size`. Furthermore, in contrast to the `libc` version, this function always produces a null-terminated string in the `dst` buffer if the `size` argument is greater than 0.

Genode **memcmp** global function

Compare memory blocks

Arguments

p0 **const void ***
p1 **const void ***
size **size_t**

Return value

int 0 if both memory blocks are equal, or a negative number if p0 is less than p1, or a positive number if p0 is greater than p1

Genode **memset** global function

Fill destination buffer with given value

Arguments

dst **void ***
Destination buffer

i **int**
Byte value

size **size_t**
Buffer size in bytes

Return value

void *

Genode **digit** global function

Convert ASCII character to digit

Arguments

c **char**

hex **bool**
Consider hexadecimals
Default is false

Return value

int Digit or -1 on error

Genode **is_letter** global function

Argument

c **char**

Return value

bool True if character is a letter

Genode **is_digit** global function

Arguments

c **char**

hex **bool**
Default is false

Return value

bool True if character is a digit

Genode **is_whitespace** global function

Argument

c **char**

Return value

bool True if character is whitespace

Genode	ascii_to_unsigned	function template
Read unsigned long value from string		
Template argument		
T	typename	
Arguments		
s	const char * Source string	
result	T & Destination variable	
base	unsigned Integer base	
Return value		
size_t	Number of consumed characters	

If the base argument is 0, the integer base is detected based on the characters in front of the number. If the number is prefixed with “0x”, a base of 16 is used, otherwise a base of 10.

Genode	ascii_to	global function
Read boolean value from string		
Arguments		
s	char const *	
result	bool &	
Return value		
size_t	Number of consumed characters	

Genode	ascii_to	global function
Read unsigned char value from string		
Arguments		
s	const char *	
result	unsigned char &	
Return value		
size_t	Number of consumed characters	

Genode **ascii_to** global function

Read unsigned short value from string

Arguments

s **const char ***
result **unsigned short &**

Return value

size_t Number of consumed characters

Genode **ascii_to** global function

Read unsigned long value from string

Arguments

s **const char ***
result **unsigned long &**

Return value

size_t Number of consumed characters

Genode **ascii_to** global function

Read unsigned long long value from string

Arguments

s **const char ***
result **unsigned long**

Return value

size_t Number of consumed characters

Genode **ascii_to** global function

Read unsigned int value from string

Arguments

s **const char ***
result **unsigned int &**

Return value

size_t Number of consumed characters

Genode	ascii_to	
Read signed long value from string		global function
Arguments		
s	const char *	
result	long &	
Return value		
size_t	Number of consumed characters	

Genode	ascii_to	
Read <code>Number_of_bytes</code> value from string and handle the size suffixes		global function
Arguments		
s	const char *	
result	Number_of_bytes &	
Return value		
size_t	Number of consumed characters	

This function scales the resulting size value according to the suffixes for G (2^{30}), M (2^{20}), and K (2^{10}) if present.

Genode	ascii_to	
Read double float value from string		global function
Arguments		
s	const char *	
result	double &	
Return value		
size_t	Number of consumed characters	

Genode	end_of_quote	
Check for end of quotation		global function
Argument		
s	const char *	
Return value		
bool		

Checks if next character is non-backslashed quotation mark.

Genode	unpack_string	
Unpack quoted string		global function
Arguments		
src	const char *	Source string including the quotation marks ("...")
dst	char *	Destination buffer
dst_len	int	
Return value		
int	Number of characters or negative error code	

To cover the common case of embedding a string buffer as a member variable in a class, there exists the `String` class template, which alleviates the need for C-style arrays in such situations.

The `String` constructor takes any number of arguments, which will appear concatenated in the constructed `String`. Each argument must be printable as explained in Section 8.12.3.

Genode
String
class template

Buffer that contains a null-terminated string

CAPACITY

String

```

size() : size_t
String()
String(...)
String(...)
String(...)
length() : size_t
capacity() : size_t
valid() : bool
string() : char const *
operator ==(...) : bool
operator !=(...) : bool
operator ==(...) : bool
operator !=(...) : bool
print(...)

```

Template argument

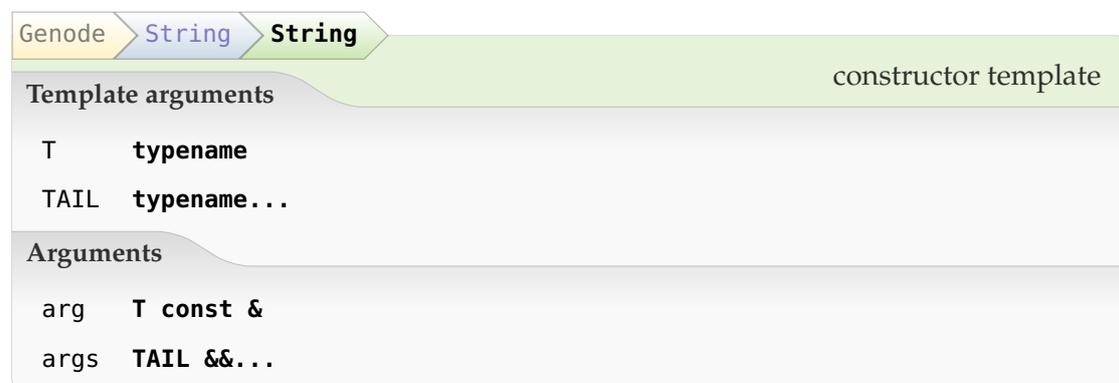
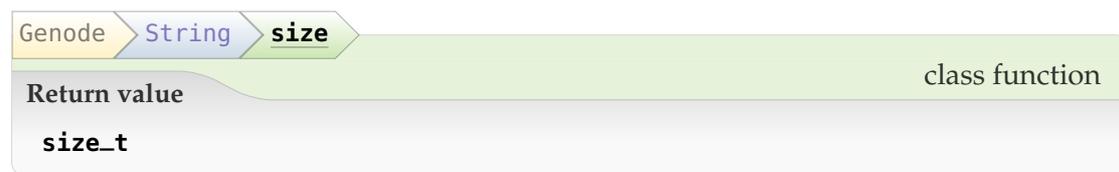
CAPACITY **size_t**
Buffer size including the terminating zero, must be higher than zero

Accessors

valid **bool**
string **char const ***

Header

repos/base/include/util/string.h



The constructor accepts a non-zero number of arguments, which are concatenated in the resulting `String` object. In order to generate the textual representation of the arguments, the argument types must support the `Output` interface, e. g., by providing `print` method.

If the textual representation of the supplied arguments exceeds `CAPACITY`, the resulting string gets truncated. The caller may check for this condition by evaluating the `length` of the constructed `String`. If `length` equals `CAPACITY`, the string may fit perfectly into the buffer or may have been truncated. In general, it would be safe to assume the latter.



Overload for the common case of constructing a `String` from a string literal.

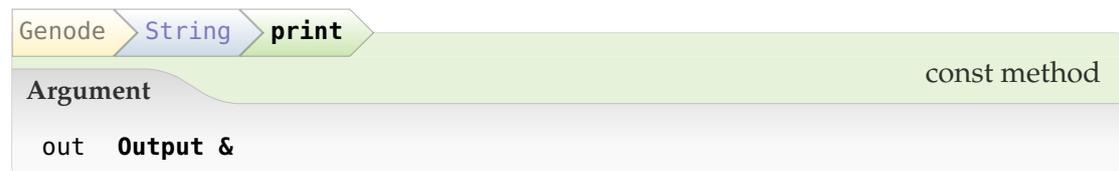
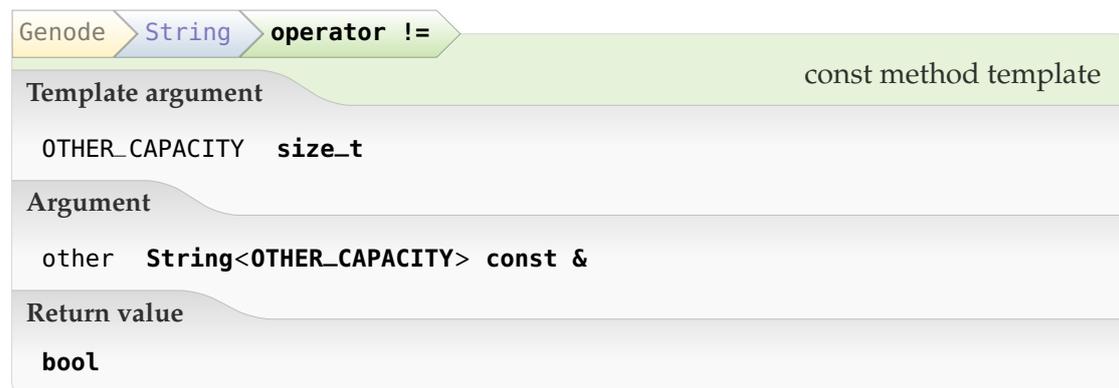
Genode	String	String	
Copy constructor			constructor template
Template argument			
N unsigned			
Argument			
other String<N> const &			

Genode	String	length	
Return value			const method
size_t Length of string, including the terminating null character			

Genode	String	capacity	
Return value			class function
size_t			

Genode	String	operator ==	
Argument			const method
other char const *			
Return value			
bool			

Genode	String	operator !=	
Argument			const method
other char const *			
Return value			
bool			



There exist a number of printable helper classes that cover typical use cases for producing formatted text output.

Number_of_bytes wraps an integer value and produces an output suffixed with K, M, or G whenever the value is a multiple of a kilobyte, megabyte, or gigabyte.

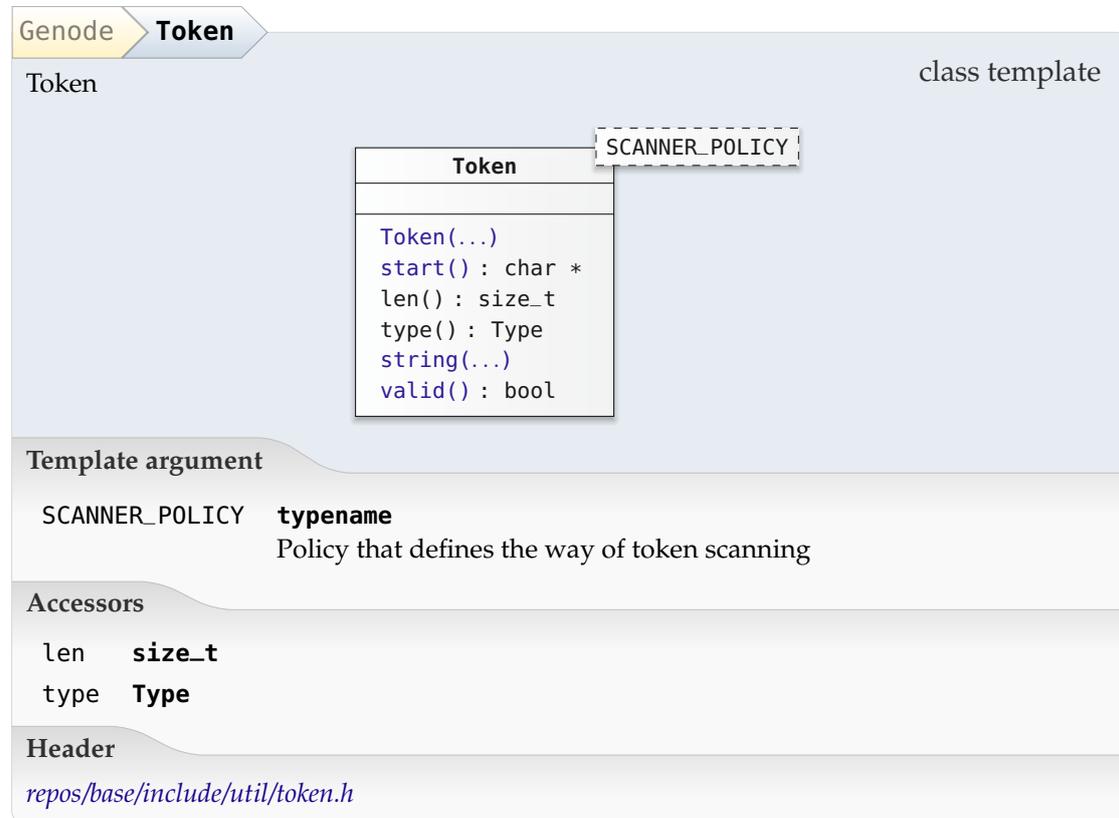
Cstring wraps a plain C character array to make it printable. There exist two constructors. The constructor with one argument expects a null-terminated character array. The other constructor takes the number of to-be-printed characters as arguments.

Hex wraps an integer value and produces hexadecimal output.

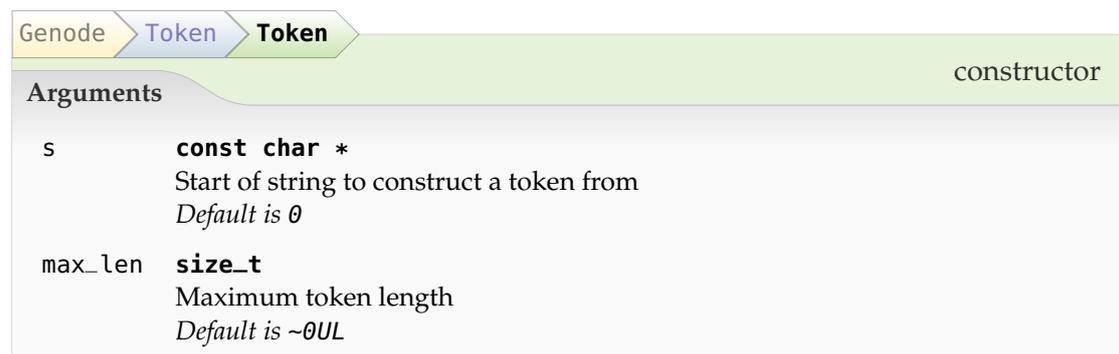
Char produces a character corresponding to the ASCII value the wrapped integer argument.

8.12.2. Tokenizing

For parsing structured text such as argument strings or XML, simple tokenizing support is provided via the Token class.



This class is used to group characters of a string which belong to one syntactical token types number, identifier, string, whitespace or another single character. See `Scanner_policy_identifier_with_underline` for an example scanner policy.



The `max_len` argument is useful for processing character arrays that are not null-

terminated.

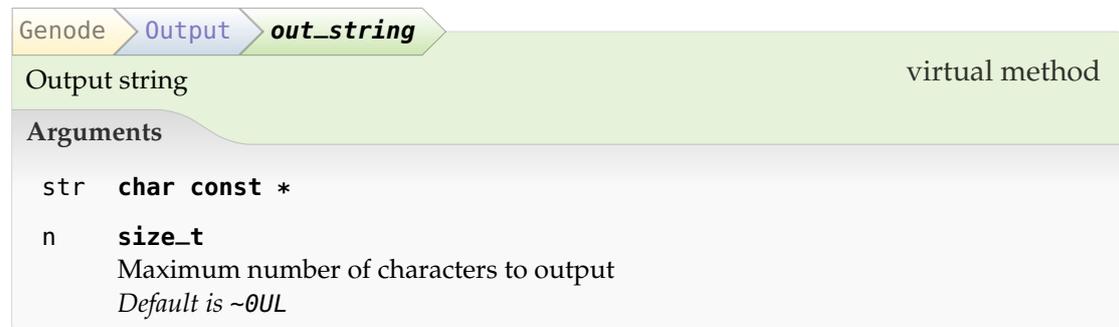
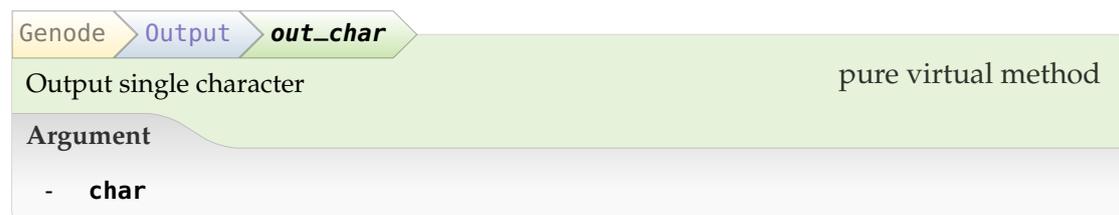
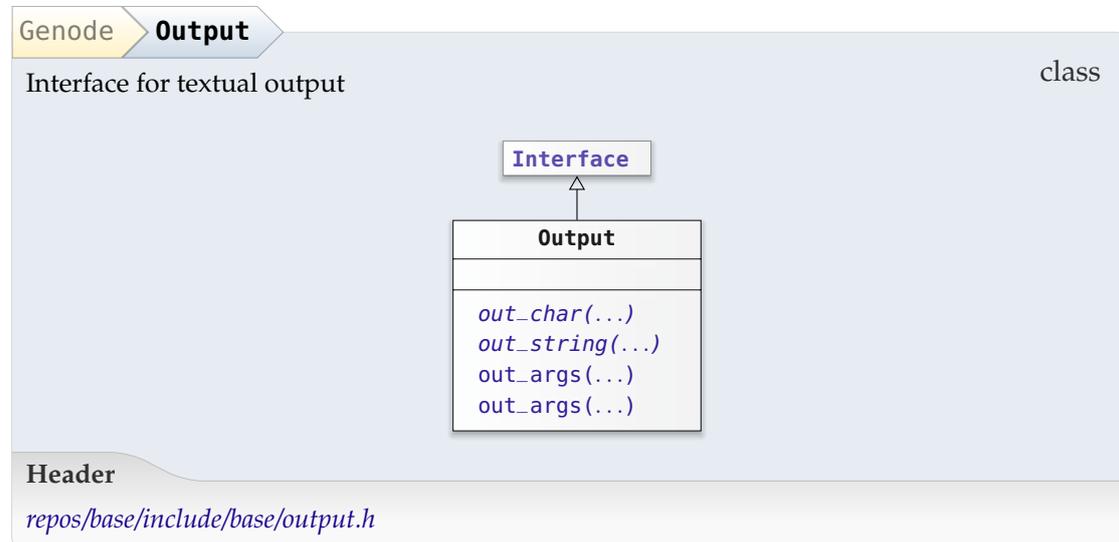
Genode	Token	start	
Accessors			const method
Return value			
char *			

Genode	Token	string	
Arguments			const method
dst			char *
max_len			size_t

Genode	Token	valid	
Return value			const method
bool			True if token is valid

8.12.3. Diagnostic output

To enable components to produce diagnostic output like errors, warnings, and log messages, Genode offers a simple `Output` interface for sequentially writing single characters or character sequences.



The output stops on the first occurrence of a null character in the string or after `n` characters.

The default implementation uses `out_char`. This method may be overridden by the backend for improving efficiency.

Genode	Output	out_args	
Helper for the sequential output of a variable list of arguments			class function template
Template arguments			
HEAD	typename		
TAIL	typename...		
Arguments			
output	Output	&	
head	HEAD	&&	
tail	TAIL	&&...	

Genode	Output	out_args	
			class function template
Template argument			
LAST	typename		
Arguments			
output	Output	&	
last	LAST	&&	

Functions for generating output for different types are named `print` and take an `Output &` as first argument. The second argument is a `const &` to the value to print. Overloads of the `print` function for commonly used basic types are provided. Furthermore, there is a function template that is used if none of the type-specific overloads match. This function template expects the argument to be an object with a `print` method. In contrast to a plain `print` function overload, such a method is able to incorporate private state into the output.

Genode namespace

Interface for textual output

Functions

- `print(...)`

Header

repos/base/include/base/output.h

Genode **print** global function

Print null-terminated string

Arguments

output **Output &**

- **char const ***

Genode **print** global function

Disallow printing non-const character buffers

Arguments

- **Output &**

- **char ***

For `char *` types, it is unclear whether the argument should be printed as a pointer or a string. The call must resolve this ambiguity by either casting the argument to `void *` or wrapping it in a `Cstring` object.

Genode	print	
Print pointer value		global function
Arguments		
output	Output &	
-	void const *	

Genode	print	
Print arbitrary pointer types		function template
Template argument		
T	typename	
Arguments		
output	Output &	
ptr	T *	

This function template takes precedence over the one that takes a constant object reference as argument.

Genode	print	
Print unsigned long value		global function
Arguments		
output	Output &	
long	unsigned	

Genode	print	
Print unsigned long long value		global function
Arguments		
output	Output &	
long	unsigned long	

Genode	print	global function
Arguments		
o	Output &	
v	unsigned char	

Genode	print	global function
Arguments		
o	Output &	
v	unsigned short	

Genode	print	global function
Arguments		
o	Output &	
v	unsigned int	

Genode	print	global function
Print signed long value		
Arguments		
output	Output &	
-	long	

Genode	print	global function
Print signed long long value		
Arguments		
output	Output &	
long	long	

Genode	print	global function
Arguments		
o	Output &	
v	char	

Genode **print** global function

Arguments

- o **Output &**
- v **short**

Genode **print** global function

Arguments

- o **Output &**
- v **int**

Genode **print** global function

Print bool value

Arguments

- output **Output &**
- value **bool**

Genode **print** global function

Print single-precision float

Arguments

- output **Output &**
- **float**

Genode **print** global function

Print double-precision float

Arguments

- output **Output &**
- **double**

Genode print		function template
Print information about object obj		
Template argument		
T	typename	
Arguments		
output	Output &	
obj	T const &	

The object type must provide a `const print(Output &)` method that produces the textual representation of the object.

In contrast to overloads of the `Genode::print` function, the `T::print` method is able to access object-internal state, which can thereby be incorporated into the textual output.

Genode print		function template
Print a variable number of arguments		
Template arguments		
HEAD	typename	
TAIL	typename...	
Arguments		
output	Output &	
head	HEAD const &	
tail	TAIL &&...	

The component's execution environment provides an implementation of the `Output` interface that targets a LOG session. This output back end is offered to the component in the form of the `log`, `warning`, and `error` functions that accept an arbitrary number of arguments that are printed in a concatenated fashion. Each messages is implicitly finalized with a newline character.

Genode	LOG output functions	namespace
Functions		
<ul style="list-style-type: none"> • <code>log(...)</code> • <code>warning(...)</code> • <code>error(...)</code> • <code>raw(...)</code> 		
Header		
<code>repos/base/include/base/log.h</code>		

Genode	log	
Write args as a regular message to the log		function template
Template argument		
ARGS	typename...	
Argument		
args	ARGS &&...	

Genode	warning	
Write args as a warning message to the log		function template
Template argument		
ARGS	typename...	
Argument		
args	ARGS &&...	

The message is automatically prefixed with “Warning: ”. Please refer to the description of the error function regarding the convention of formatting error/warning messages.

Genode	error	
Write args as an error message to the log		function template
Template argument		
ARGS	typename...	
Argument		
args	ARGS &&...	

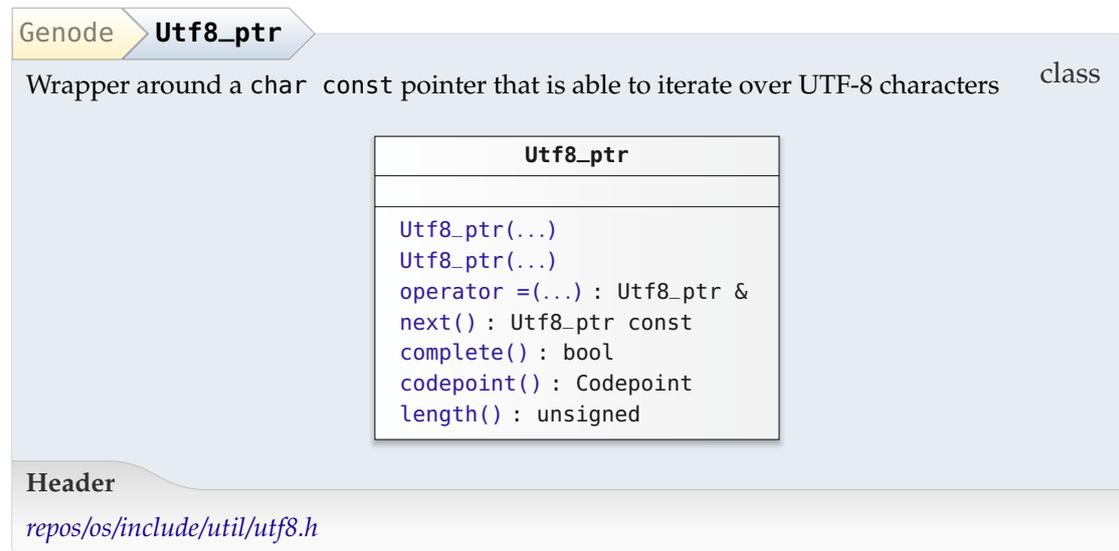
The message is automatically prefixed with "Error: ". Hence, the message argument does not need to additionally state that it is an error message. By convention, the actual message should be brief, starting with a lower-case character.

Genode	raw	
Write args directly via the kernel (i. e., kernel debugger)		function template
Template argument		
ARGS	typename...	
Argument		
args	ARGS &&...	

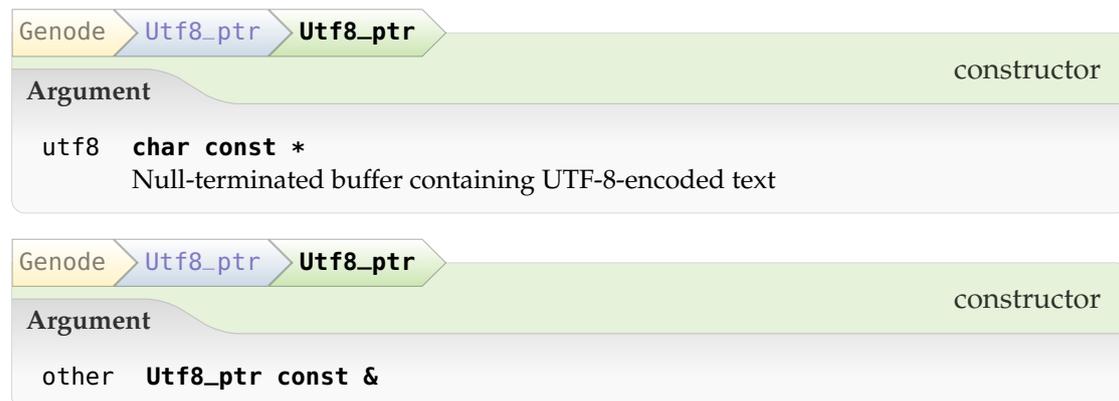
This function is intended for temporarily debugging purposes only.

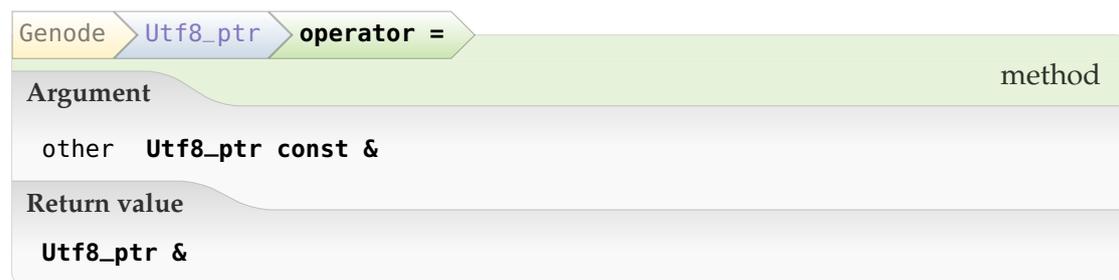
8.12.4. Unicode handling

The string-handling utilities described in Section 8.12.1 operate on ASCII-encoded character strings where each character is encoded as one byte. It goes without saying that ASCII is unsuitable for user-facing components that are ultimately expected to support the display of international characters. The `Utf8_ptr` utility accommodates such components with an easy way to extract a sequence of Unicode codepoints from an UTF-8-encoded string.



Note that this class is not a smart pointer. It is suffixed with `_ptr` to highlight the fact that it stores a pointer while being copyable. Hence, objects of this type must be handled with the same caution as pointers.





This method solely checks for a premature truncation of the string. It does not check the validity of the UTF-8 sequence. The success of `complete` method is a precondition for the correct operation of the `next` or `codepoint` methods. A complete sequence may still yield an invalid Codepoint.



8.13. Multi-threading and synchronization

8.13.1. Threads

A thread is created by constructing an object of a class inherited from `Thread`. The new thread starts its execution at the entry member function. Thereby, each thread runs in the context of its object and can access context-specific information by accessing its member variables. This largely alleviates the need for a thread-local storage (TLS) mechanism. Threads use a statically allocated stack, which is dimensioned according to the corresponding constructor argument.

Genode
Thread
class

Concurrent flow of control

Thread

```

Thread(...)
Thread(...)
~Thread()
entry()
start()
name() : Name
alloc_secondary_stack(...) : void*
free_secondary_stack(...)
cap() : Thread_capability
cancel_blocking()
native_thread() : Native_thread &
stack_top() : void *
stack_base() : void *
stack_virtual_size() : size_t
stack_area_virtual_base() : addr_t
stack_area_virtual_size() : size_t
myself() : Thread *
mystack() : Stack_info
stack_size(...)
utcb() : Native_utcb *
join()
trace(...)
trace(...)
trace(...)
affinity() : Affinity::Location

```

Header

repos/base/include/base/thread.h

A `Thread` object corresponds to a physical thread. The execution starts at the `entry()` method as soon as `start()` is called.

Genode		Thread	Thread	constructor
Arguments				
env	Env &	Component environment		
name	Name const &	Thread name, used for debugging		
stack_size	size_t	Stack size		
location	Location	CPU affinity relative to the CPU-session's affinity space		
weight	Weight	Scheduling weight relative to the other threads sharing the same CPU session		
cpu	Cpu_session &			
Exceptions				
Stack_too_large				
Stack_alloc_failed				
Out_of_stack_space				

The env argument is needed because the thread creation procedure needs to interact with the environment for attaching the thread's stack, the trace-control dataspace, and the thread's trace buffer and policy.

Genode		Thread	Thread	constructor
Arguments				
env	Env &			
name	Name const &			
stack_size	size_t			

This is a shortcut for the common case of creating a thread via the environment's CPU session, at the default affinity location, and with the default weight.

Genode > Thread > **entry**
 Entry method of the thread pure virtual method

Genode > Thread > **start**
 Start execution of the thread virtual method

This method is virtual to enable the customization of threads used as server activation.

Genode > Thread > **name**
 Request name of thread const method

Return value
Name

Genode > Thread > **alloc_secondary_stack** method

Add an additional stack to the thread

Arguments

name **char const ***
 stack_size **size_t**

Exceptions

Stack_too_large
Stack_alloc_failed
Out_of_stack_space

Return value
void* Pointer to the new stack's top

The stack for the new thread will be allocated from the RAM session of the component environment. A small portion of the stack size is internally used by the framework for storing thread-specific information such as the thread's name.

Genode	Thread	free_secondary_stack	
Remove a secondary stack from the thread			method
Argument			
stack_addr			void*
Genode	Thread	cap	
Request capability of thread			const method
Return value			
Thread_capability			
Genode	Thread	cancel_blocking	
Cancel currently blocking operation			method
Genode	Thread	native_thread	
Return value			method
Native_thread &			Kernel-specific thread meta data
Genode	Thread	stack_top	
Return value			const method
void *			Pointer just after first stack element
Genode	Thread	stack_base	
Return value			const method
void *			Pointer to last stack element
Genode	Thread	stack_virtual_size	
Return value			class function
size_t			Virtual size reserved for each stack within the stack area
Genode	Thread	stack_area_virtual_base	
Return value			class function
addr_t			The local base address of the stack area

Genode	Thread	stack_area_virtual_size	
Return value			class function
size_t Total size of the stack area			

Genode	Thread	myself	
Return value			class function
Thread * Pointer to caller's Thread object			

Genode	Thread	mystack	
Return value			class function
Stack_info Information about the current stack			

Genode	Thread	stack_size	
Ensure that the stack has a given size at the minimum			method
Argument			
size	size_t const	Minimum stack size	
Exceptions			
Stack_too_large			
Stack_alloc_failed			

Genode	Thread	utcb	
Return value			method
Native_utcb * User-level thread control block			

Note that it is safe to call this method on the result of the `myself` class function. It handles the special case of `myself` being 0 when called by the main thread during the component initialization phase.

Genode	Thread	join	
Block until the thread leaves the entry method			method

Join must not be called more than once. Subsequent calls have undefined behaviour.

Genode Thread **trace**

Log null-terminated string as trace event class function

Argument

cstring **char const ***

Genode Thread **trace**

Log binary data as trace event class function

Arguments

data **char const ***
len **size_t**

Genode Thread **trace**

Log trace event as defined in base/trace.h class function template

Template argument

EVENT **typename**

Argument

event **EVENT const ***

Genode Thread **affinity**

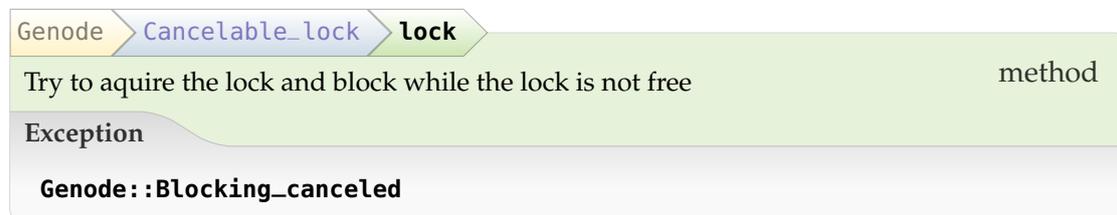
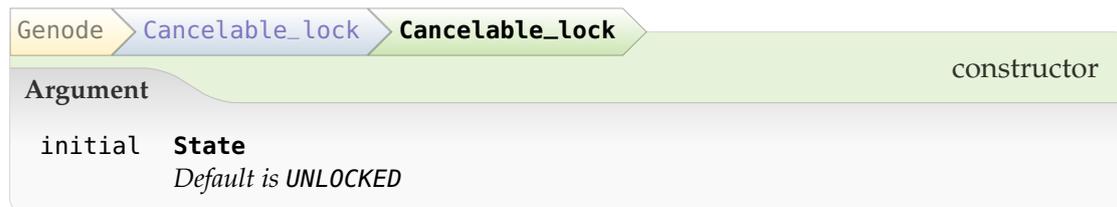
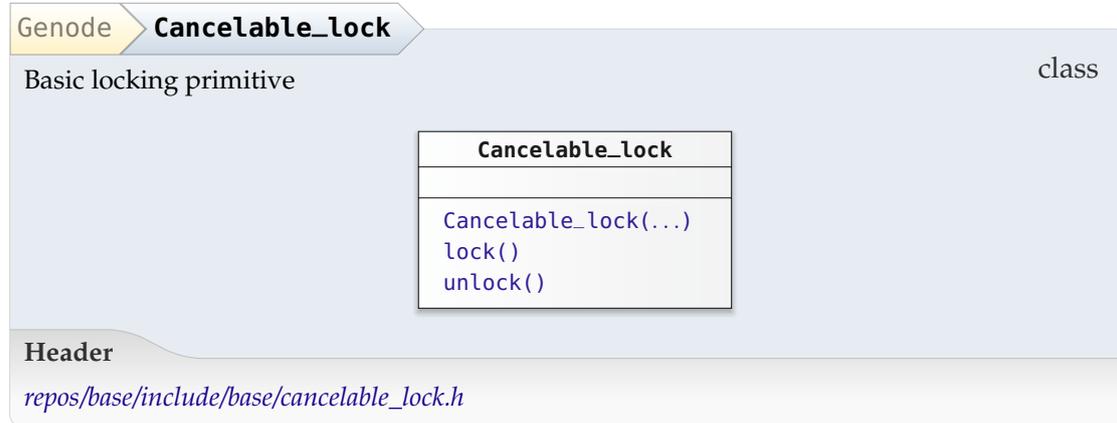
Thread affinity const method

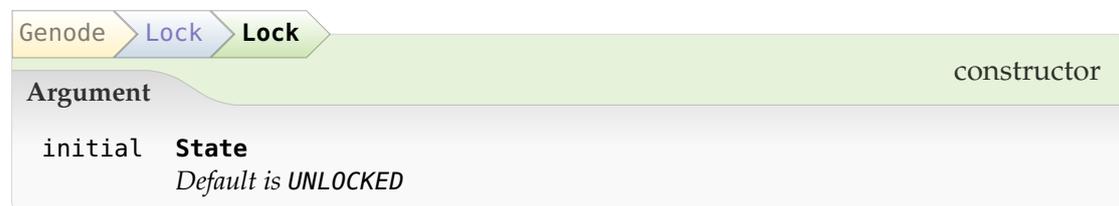
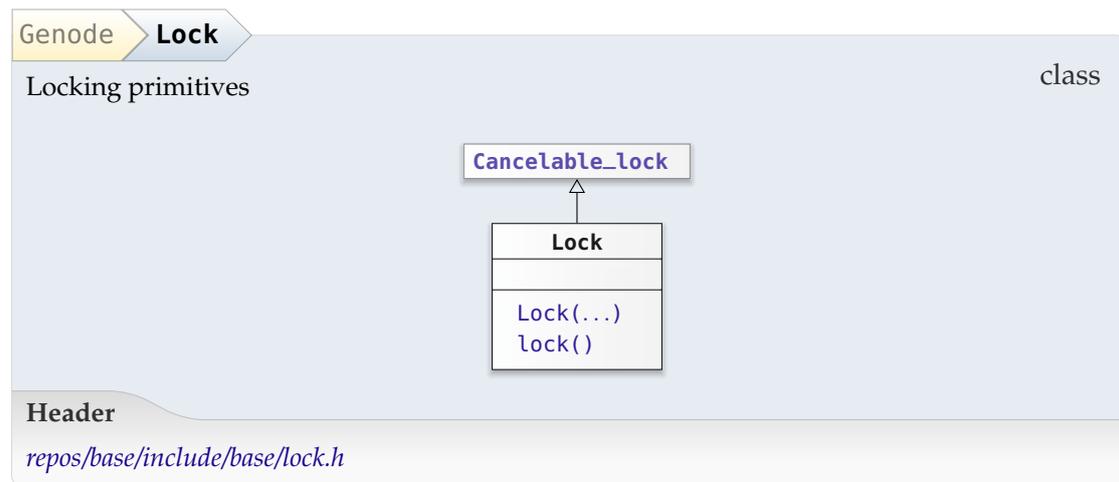
Return value

Affinity::Location

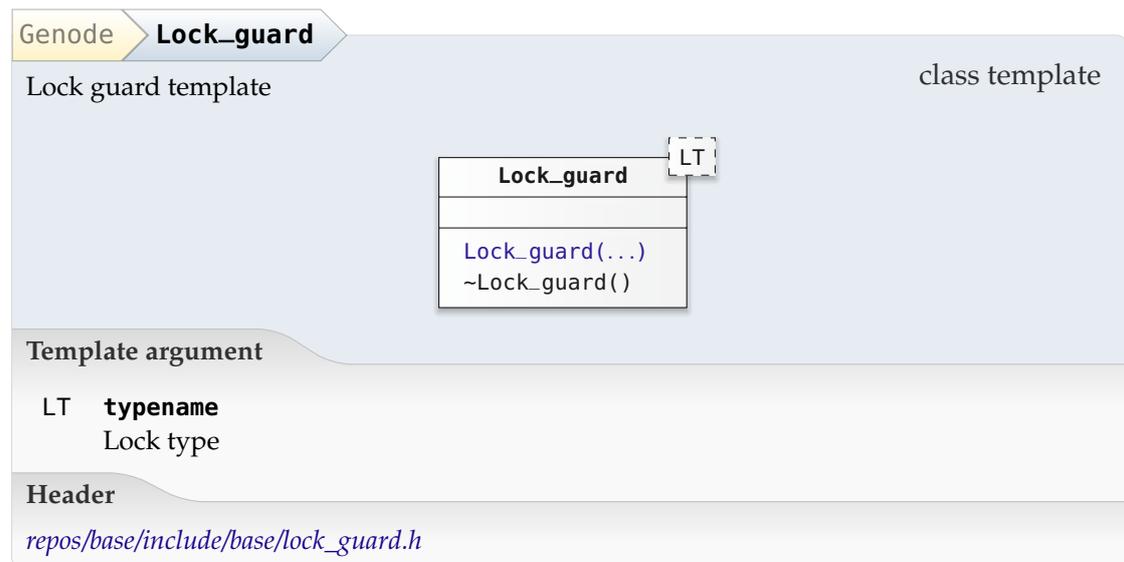
8.13.2. Locks and semaphores

For mutual exclusive execution of critical sections, there exists a simple lock interface providing lock and unlock semantics. The lock comes in two flavours. Cancelable locks can be unblocked by force via core's cancel-blocking mechanism. In contrast, a non-cancelable lock (`Lock`) does not reflect the cancellation of its blocking operation at the API level but transparently re-enters its blocking state after a cancellation.





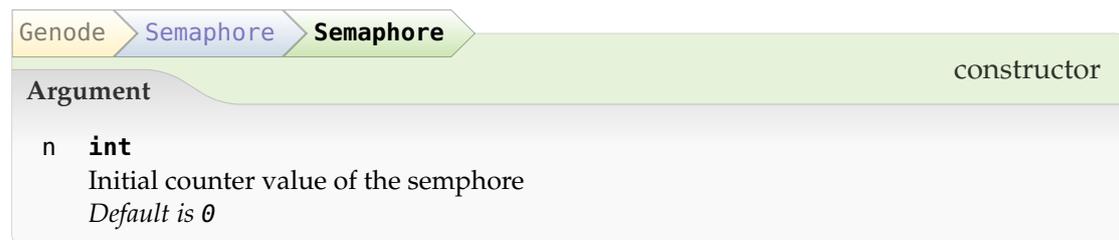
For the use case of using locks for protecting critical sections, the `Lock_guard` provides a convenient mechanism for the automated unlocking of a lock when leaving a variable scope.



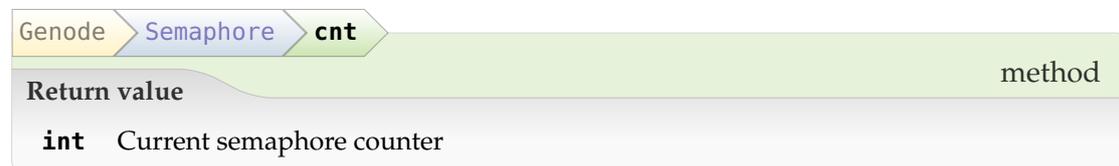
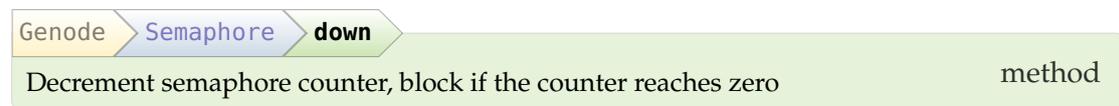
A lock guard is instantiated as a local variable. When a lock guard is constructed, it acquires the lock that is specified as constructor argument. When the control flow leaves the scope of the lock-guard variable via a return statement or an exception, the lock guard's destructor gets called, freeing the lock.



Alongside lock-based mutual exclusion of entering critical sections, organizing threads in a producer-consumer relationship is a common design pattern for thread synchronization. The Semaphore interface enables the implementation of this synchronization scheme.



This method may wake up another thread that currently blocks on a down call at the same semaphore.



To synchronize method calls of an object, the Synced_interface can be used to equip the class of the called object with thread safety.

Genode > Synced_interface > Synced_interface class template

```

Synced_interface
Synced_interface(...)
operator ()() : Guard
operator ()() : Guard
    
```

IF, LOCK

Template arguments

IF **typename**

LOCK **typename**

Accessor

operator () **Guard**

Header

repos/base/include/base/synced_interface.h

Genode > Synced_interface > Synced_interface constructor

Arguments

lock **LOCK &**

interface **IF ***

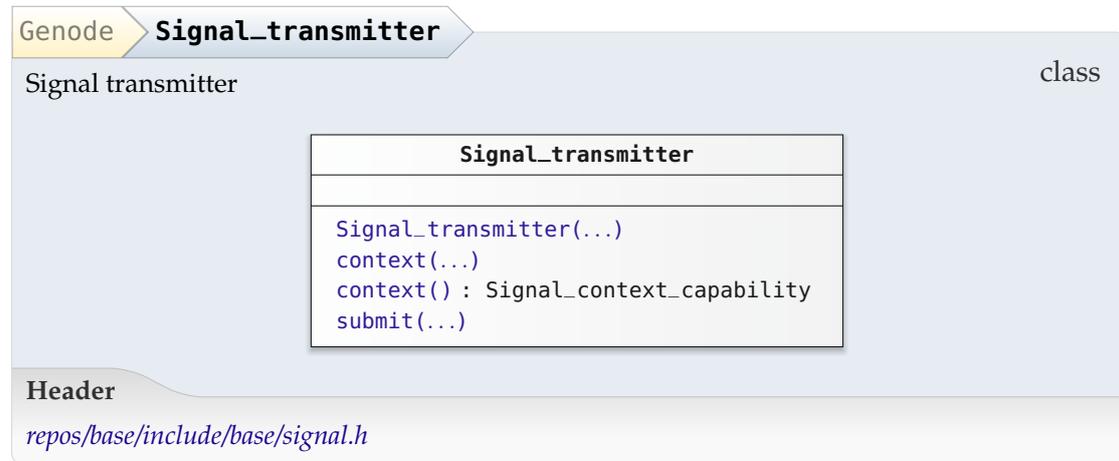
Genode > Synced_interface > operator () method

Return value

Guard

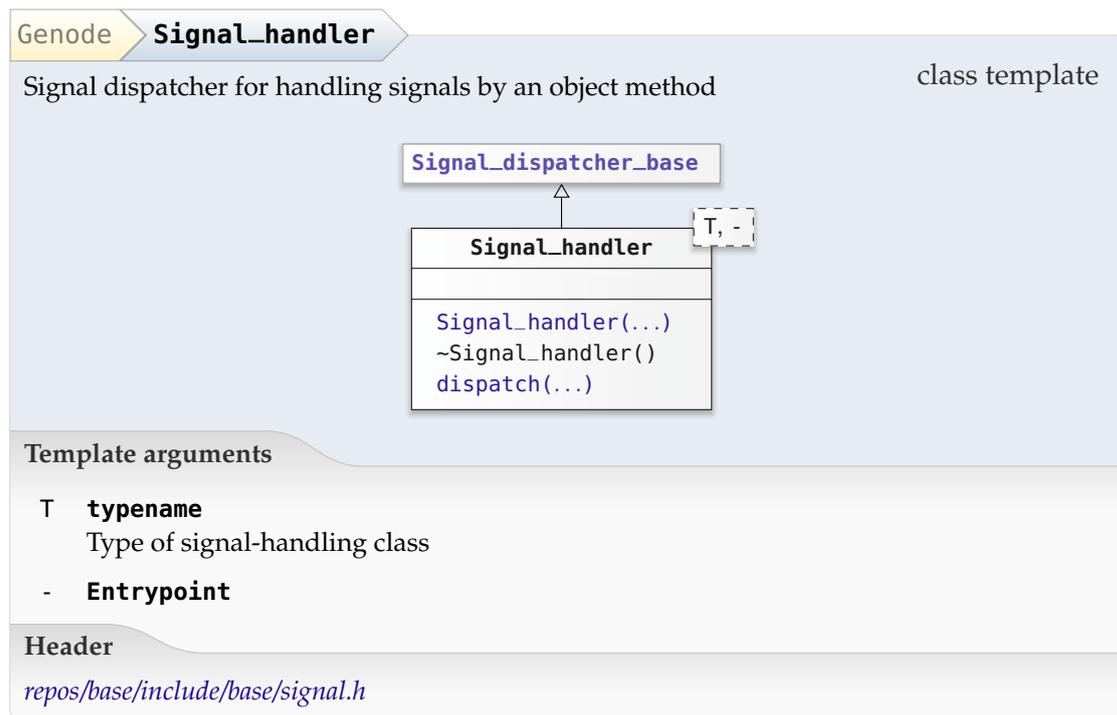
8.14. Signalling

Section 3.6.2 provides the high-level description of the mechanism for the delivery of asynchronous notifications (signals). The API defines interfaces for signal transmitters and for the association of signal handlers with entrypoints. An entrypoint can be associated with many signal handlers where each handler usually corresponds to a different signal source. Each signal handler is addressable via a distinct capability. Those so-called signal-context capabilities can be delegated across component boundaries in the same way as RPC-object capabilities. If a component is in possession of a signal-context capability, it can trigger the corresponding signal handler by using a so-called signal transmitter. The signal transmitter provides fire-and-forget semantics for signal submission. Signals serve as mere notifications and cannot carry any payload.



Each signal-transmitter instance acts on behalf the context specified as constructor argument. Therefore, the resources needed for the transmitter such as the consumed memory `sizeof(Signal_transmitter)` should be accounted to the owner of the context.

Genode	Signal_transmitter	Signal_transmitter	constructor
Argument			
context	Signal_context_capability	Capability to signal context that is going to receive signals produced by the transmitter <i>Default is Signal_context_capability()</i>	
Genode	Signal_transmitter	context	method
Set signal context			
Argument			
context	Signal_context_capability		
Genode	Signal_transmitter	context	method
Return value			
	Signal_context_capability	Signal context	
Genode	Signal_transmitter	submit	method
Trigger signal submission to context			
Argument			
cnt	unsigned	Number of signals to submit at once <i>Default is 1</i>	



This utility associates an object method with signals. It is intended to be used as a member variable of the class that handles incoming signals of a certain type. The constructor takes a pointer-to-member to the signal-handling method as argument.



A `Signal_handler` object is meant to be hosted as a member of the class that also contains a member function to be executed upon the arrival of a signal. Its constructor takes the entrypoint, the signal-handling object, and a pointer to the handling func-

tion as arguments. The following example illustrates the common pattern of using a `Signal_handler`.

```
class Main
{
    ...
    Entrypoint &_ep;
    ...
    void _handle_config();

    Signal_handler<Main> _config_handler =
        { _ep, *this, &Main::_handle_config };
    ...
};
```

In the example above, the `_config_handler` creates a signal-context capability for the `_handle_config` method. In fact, the `_config_handler` is a capability since the `Signal_handler` is derived from `Signal_context_capability`. Therefore, the `_config_handler` can be directly passed as argument to an RPC call for registering a signal handler at a server.

8.15. Remote procedure calls

Section 3.6.1 provides the high-level description of synchronous remote procedure calls (RPC).

8.15.1. RPC mechanism

The RPC mechanism consists of the following header files:

base/rpc.h Contains the basic type definitions and utility macros to declare RPC interfaces.

base/rpc_args.h Contains definitions of non-trivial argument types used for transferring strings and binary buffers. Its use by RPC interfaces is optional.

base/rpc_server.h Contains the interfaces of the server-side RPC API. In particular, this part of the API consists of the `Rpc_object` class template.

base/rpc_client.h Contains the API support for invoking RPC functions. It is complemented by the definitions in *base/capability.h*. The most important elements of the client-side RPC API are the `Capability` class template and `Rpc_client`, which is a convenience wrapper around `Capability`.

Each RPC interface is an abstract C++ interface, supplemented by a few annotations. For example:

```
#include <session/session.h>
#include <base/rpc.h>

namespace Hello { struct Session; }

struct Hello::Session : Genode::Session
{
    static const char *service_name() { return "Hello"; }

    virtual void say_hello() = 0;
    virtual int add(int a, int b) = 0;

    GENODE_RPC(Rpc_say_hello, void, say_hello);
    GENODE_RPC(Rpc_add, int, add, int, int);
    GENODE_RPC_INTERFACE(Rpc_say_hello, Rpc_add);
};
```

The macros `GENODE_RPC` and `GENODE_RPC_INTERFACE` are defined in *base/rpc.h* and enrich the interface with type information. They are only used at compile time and

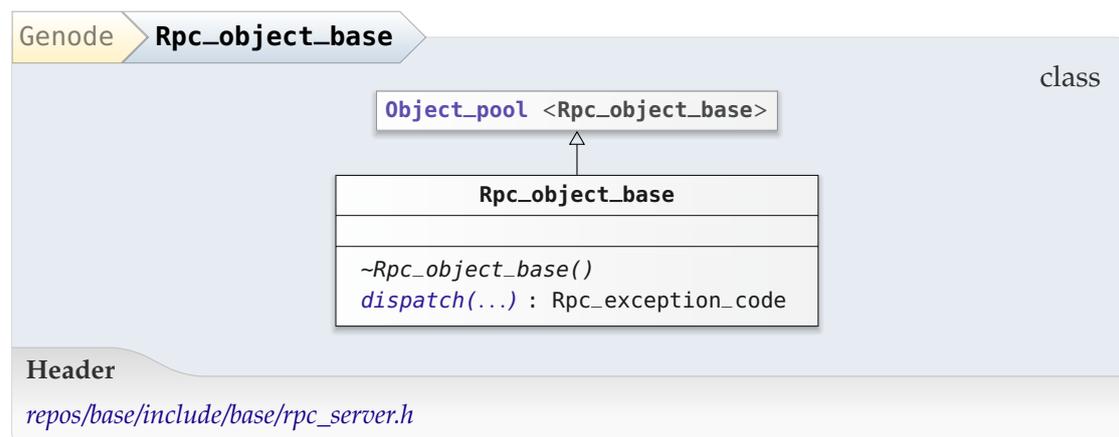
have no effect on the run time or the size of the class. Each RPC function is represented as a type. In the example, the type meta data of the `say_hello` function is attached to the `Rpc_say_hello` type within the scope of `Session`. The macro arguments are:

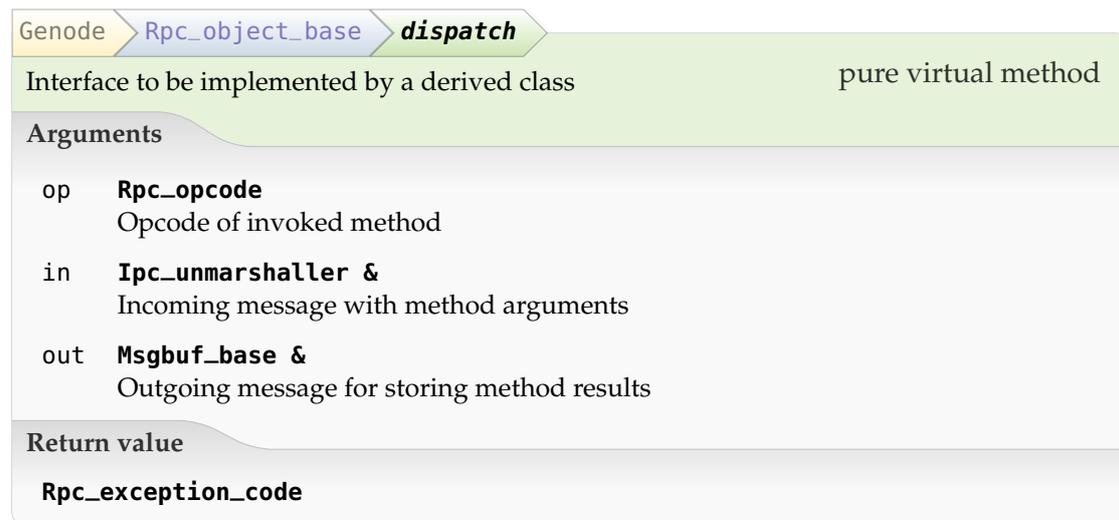
```
GENODE_RPC(func_type, ret_type, func_name, arg_type ...)
```

The `func_type` argument is an arbitrary type name (except for the type name `Rpc_functions`) used to refer to the RPC function, `ret_type` is the return type or `void`, `func_name` is the name of the server-side function that implements the RPC function, and the list of `arg_type` arguments comprises the RPC function argument types. The `GENODE_RPC_INTERFACE` macro defines a type called `Rpc_functions` that contains the list of the RPC functions provided by the RPC interface.

Server side The implementation of the RPC interface inherits the `Rpc_object` class template with the interface type as argument and implements the abstract RPC interface class.

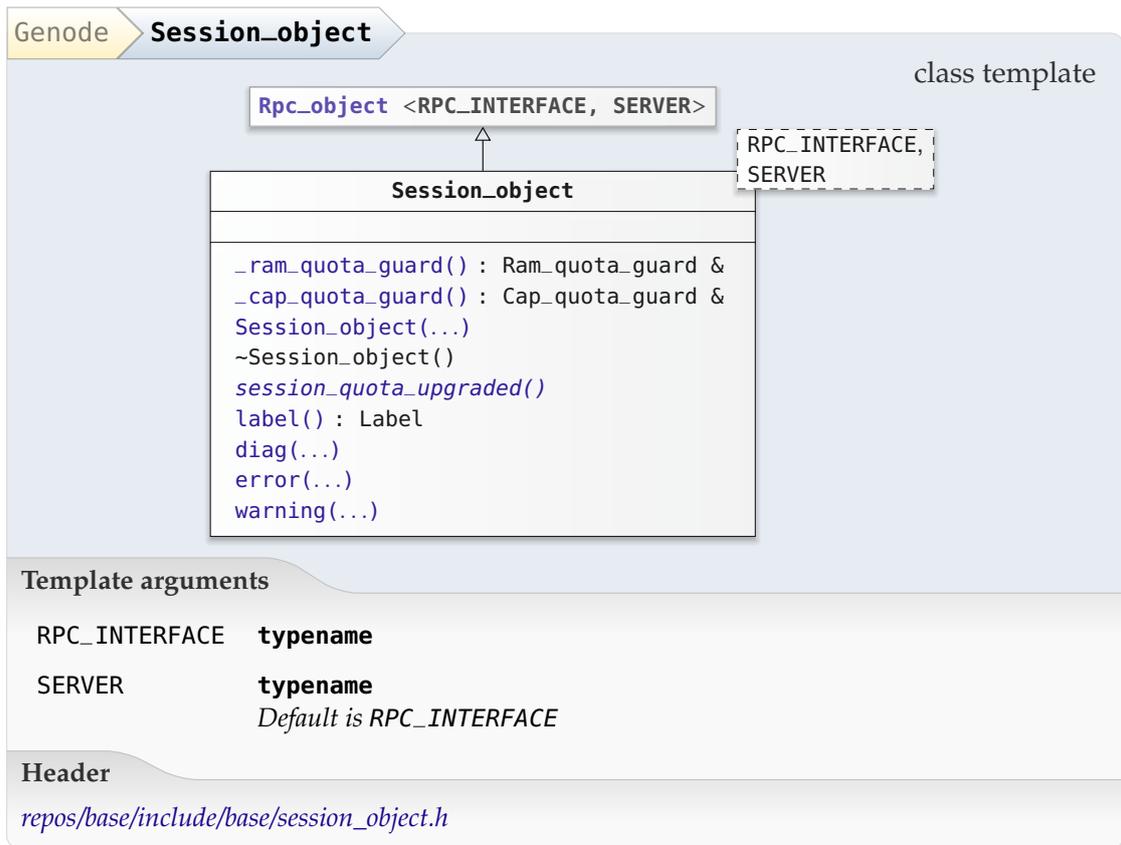
The server-side RPC dispatching is performed by the compile-time-generated `dispatch` method of the `Rpc_object` class template, according to the type information found in the annotations of the `Session` interface.





To make an instance of an RPC object invocable via RPC, it must be associated with an RPC entrypoint. By passing an RPC object to the `Entrypoint::manage` method, a new capability for the RPC object is created. The capability is tagged with the type of the RPC object.

Most server-side RPC interfaces are session interfaces. In contrast to plain RPC objects (like a `Region_map`), all sessions carry a client-provided budget of RAM and capabilities, and are associated with a client-specific label. The `Session_object` class template captures commonalities of this kind of RPC objects.



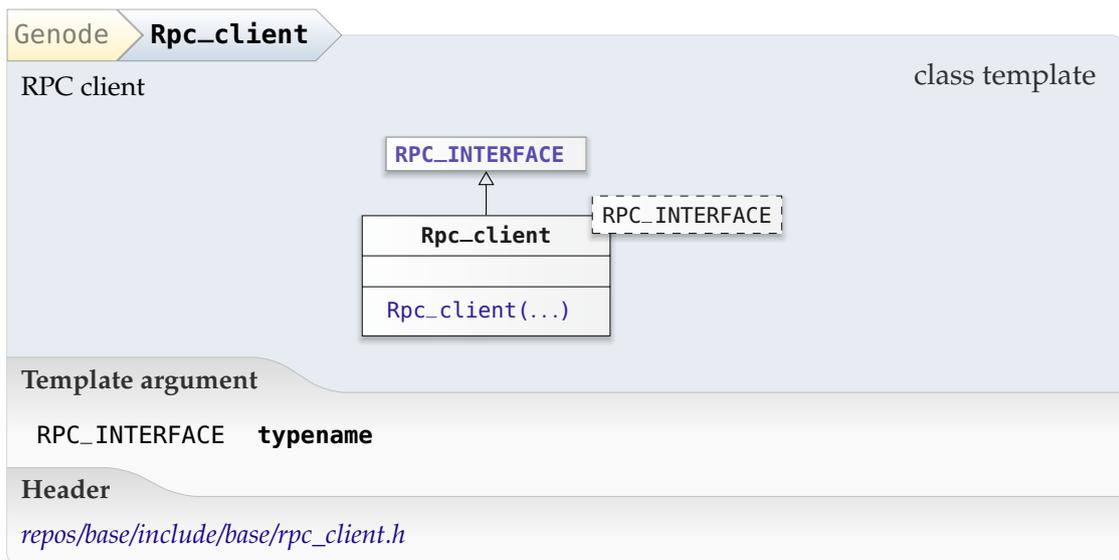
Genode	Session_object	Session_object	constructor
Arguments			
ep	Entrypoint &		
resources	Resources const &		
label	Label const &		
diag	Diag		
Genode	Session_object	session_quota_upgraded	virtual method
Hook called whenever the session quota was upgraded by the client			
Genode	Session_object	Label	const method
Return value			
Label	Client-specific session label		
Genode	Session_object	diag	method template
Output label-prefixed diagnostic message conditionally			
Template argument			
ARGS	typename...		
Argument			
args	ARGS &&...		

The method produces output only if the session is in diagnostic mode (defined via the `diag` session argument).

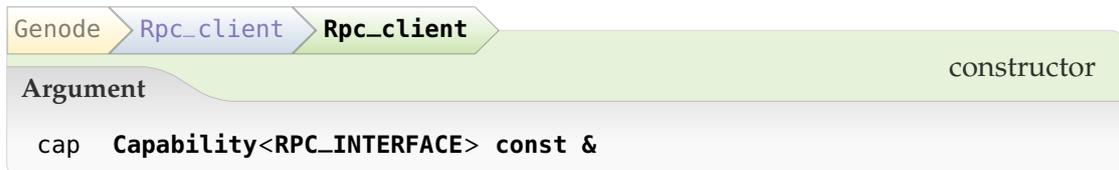


Client side At the client side, a capability can be invoked by the capability's `call` method template with the `RPC functions` type as template argument. The method arguments correspond to the RPC function arguments.

By convention, the `Capability::call` method is rarely used directly. Instead, each RPC interface is accompanied with a client-side implementation of the abstract interface where each RPC function is implemented by calling the `Capability::call` method. This convention is facilitated by the `Rpc_client` class template.



This class template is the base class of the client-side implementation of the specified `RPC_INTERFACE`. Usually, it inherits the pure virtual functions declared in `RPC_INTERFACE` and has the built-in facility to perform RPC calls to this particular interface. Hence, the client-side implementation of each pure virtual interface function comes down to a simple wrapper in the line of `return call<Rpc_function>(arguments...)`.



Using this template, the client-side implementation of the example RPC interface looks as follows.

```
#include <hello_session/hello_session.h>
#include <base/rpc_client.h>

namespace Hello { struct Session_client; }

struct Hello::Session_client : Genode::Rpc_client<Session>
{
    Session_client(Genode::Capability<Session> cap)
    : Genode::Rpc_client<Session>(cap) { }

    void say_hello()
    {
        call<Rpc_say_hello>();
    }

    int add(int a, int b)
    {
        return call<Rpc_add>(a, b);
    }
};
```

For passing RPC arguments and results, the regular C++ type-conversion rules are in effect. If there is no valid type conversion, or if the number of arguments is wrong, or if the RPC type annotations are not consistent with the abstract interface, the error is detected at compile time.

8.15.2. Transferable argument types

The arguments specified to `GENODE_RPC` behave mostly as expected for a normal function call. But there are some notable differences:

Value types Value types are supported for basic types and plain-old-data types (self-sufficient structs or classes). The object data is transferred as such. If the type is not self-sufficient (it contains pointers or references), the pointers and references are transferred as plain data, most likely pointing to the wrong thing in the callee's address space.

Const references Const references behave like value types. The referenced object is transferred to the server and a reference to the server-local copy is passed to the server-side function. Note that in contrast to a normal function call that takes a reference argument, the size of the referenced object is accounted for allocating the message buffer on the client side.

Non-const references Non-const references are handled similar to const references. In addition the server-local copy gets transferred back to the caller so that server-side modifications of the object become visible to the client.

Capabilities Capabilities can be transferred as values, const references, or non-const references.

Variable-length buffers There exists special support for passing binary buffers to RPC functions using the `Rpc_in_buffer` class template provided by `base/rpc_args.h`. The maximum size of the buffer must be specified as template argument. An `Rpc_in_buffer` object does not contain a copy of the data passed to the constructor, only a pointer to the data. In contrast to a fixed-sized object containing a copy of the payload, the RPC framework does not transfer the whole object but only the actually used payload.

Pointers Pointers and const pointers are handled similar to references. The pointed-to argument gets transferred and the server-side function is called with a pointer to the local copy.

By default, all RPC arguments are input arguments, which are transferred to the server. The return type of the RPC function, if present, is an output-only value. To avoid a reference argument from acting as both input- and output argument, a const reference should be used.

8.15.3. Throwing C++ exceptions across RPC boundaries

The propagation of C++ exceptions from the server to the client is supported by a special variant of the `GENODE_RPC` macro:

```
GENODE_RPC_THROW(func_type, ret_type, func_name,  
                 exc_type_list, arg_type ...)
```

This macro accepts an additional `exc_type_list` argument, which is a type list of exception types. Exception objects are not transferred as payload. The RPC mechanism propagates solely the information that the specific exception was raised. Hence, information provided with the thrown object will be lost when crossing an RPC boundary.

8.15.4. RPC interface inheritance

It is possible to extend existing RPC interfaces with additional RPC functions. Internally, such an RPC interface inheritance is realized by concatenation of the `Rpc_functions` type lists of both the base interface and the derived interface. This use case is supported by a special version of the `GENODE_RPC_INTERFACE` macro:

```
GENODE_RPC_INTERFACE_INHERIT(base_interface,  
                               rpc_func ...)
```

8.15.5. Casting capability types

For typed capabilities, the same type conversion rules apply as for pointers. In fact, a typed capability pretty much resembles a typed pointer, pointing to a remote object. Hence, assigning a specialized capability (e. g., `Capability<Input::Session>`) to a base-typed capability (e. g., `Capability<Session>`) is always valid. For the opposite case, a static cast is needed. For capabilities, this cast is supported by

```
static_cap_cast<INTERFACE>(cap)
```

In rare circumstances, mostly in platform-specific base code, a reinterpret cast for capabilities is required. It allows to convert any capability to another type:

```
reinterpret_cap_cast<INTERFACE>(cap)
```

8.15.6. Non-virtual RPC interface functions

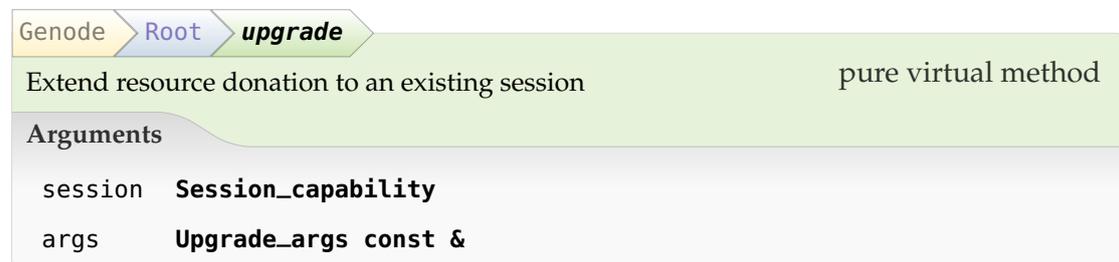
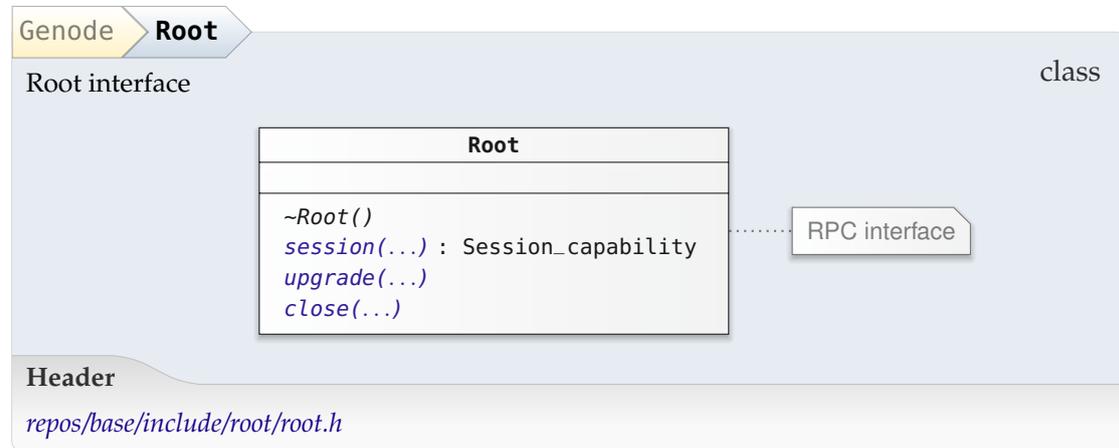
It is possible to declare RPC functions using `GENODE_RPC`, which do not exist as virtual functions in the abstract interface class. In this case, the function name specified as third argument to `GENODE_RPC` is of course not valid for the interface class but an alternative class can be specified as second argument to the server-side `Rpc_object`. This way, a server-side implementation may specify its own class to direct the RPC function to a local (possibly non-virtual) implementation.

8.15.7. Limitations of the RPC mechanism

The maximum **number of RPC function arguments** is limited to 7. If a function requires more arguments, it may be worthwhile to consider grouping some of them in a compound struct.

8.15.8. Root interface

Each service type is represented as an RPC object implementing the root interface. The server announces its service type by providing the service name and the capability of the service's root interface (announce function of the parent interface). Given the capability to the root interface, the parent is then able to create and destroy sessions.



Genode > **Root** > **close**

Close session pure virtual method

Argument

session **Session_capability**

Genode > **Typed_root**

Root interface supplemented with information about the managed session type class template

```

classDiagram
    class Root
    class Typed_root {
        <del>Root</del>
        SESSION_TYPE
    }
    Root <|-- Typed_root
  
```

Template argument

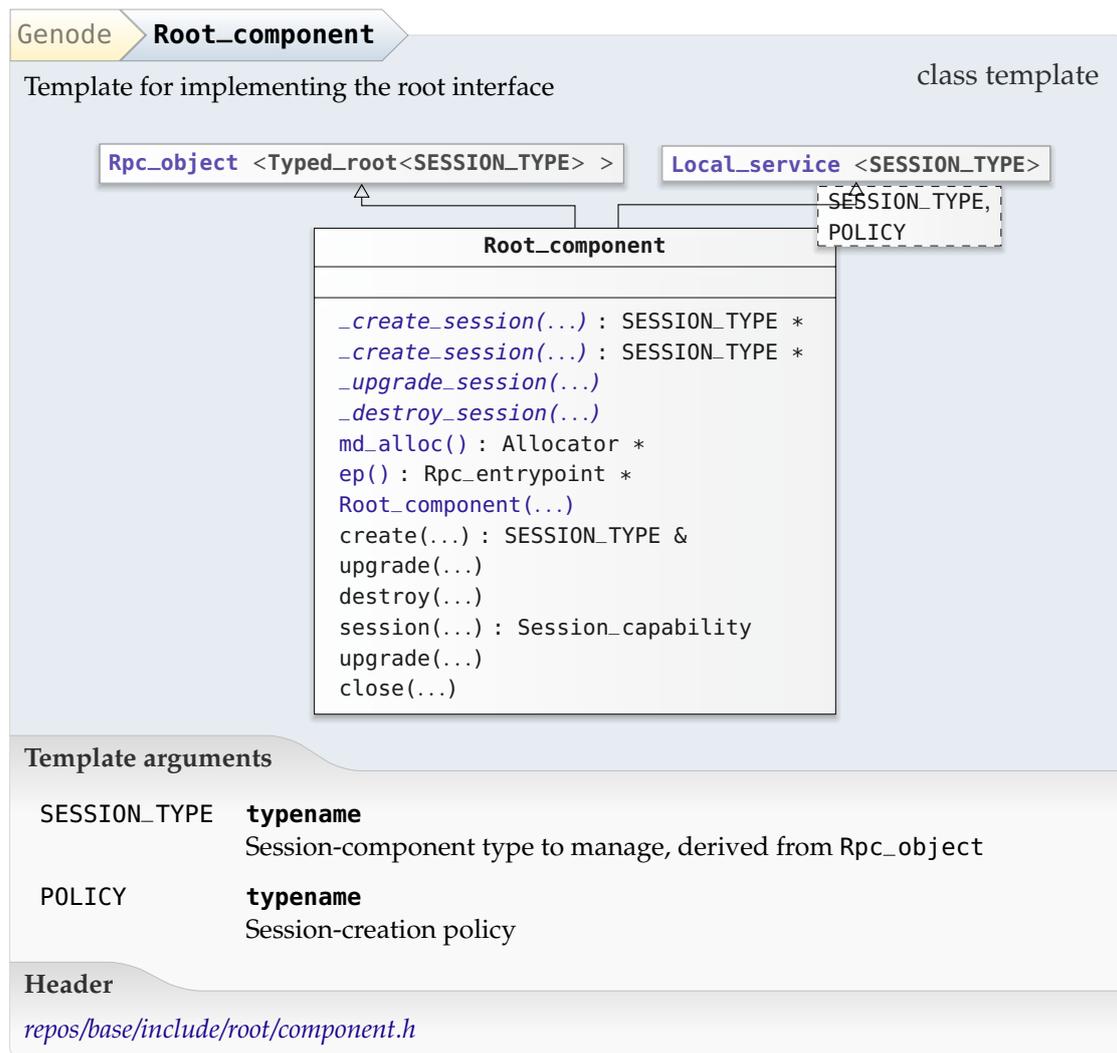
SESSION_TYPE **typename**

Header

[repos/base/include/root/root.h](#)

This class template is used to automatically propagate the correct session type to `Parent::announce()` when announcing a service.

Because defining root interfaces for services follows a recurring pattern, there exists default template classes that implement the standard behaviour of the root interface for services with multiple clients (`Root_component`) and services with a single client (`Static_root`).



The POLICY template parameter allows for constraining the session creation to only one instance at a time (using the `Single_session` policy) or multiple instances (using the `Multiple_sessions` policy).

The POLICY class must provide the following two methods:

'`acquire(const char *args)`' is called with the session arguments at creation time of each new session. It can therefore implement a session-creation policy taking session arguments into account. If the policy denies the creation of a new session, it throws one of the exceptions defined in the Root interface.

'`release`' is called at the destruction time of a session. It enables the policy to keep track of and impose restrictions on the number of existing sessions.

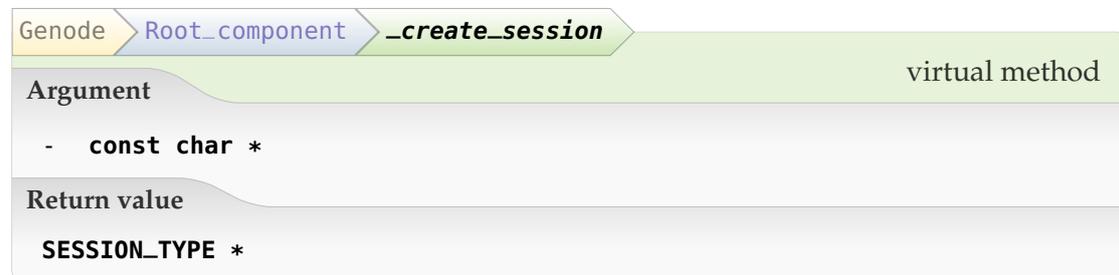
The default policy `Multiple_clients` imposes no restrictions on the creation of new sessions.



Only a derived class knows the constructor arguments of a specific session. Therefore, we cannot unify the call of its new operator and must implement the session creation at a place, where the required knowledge exist.

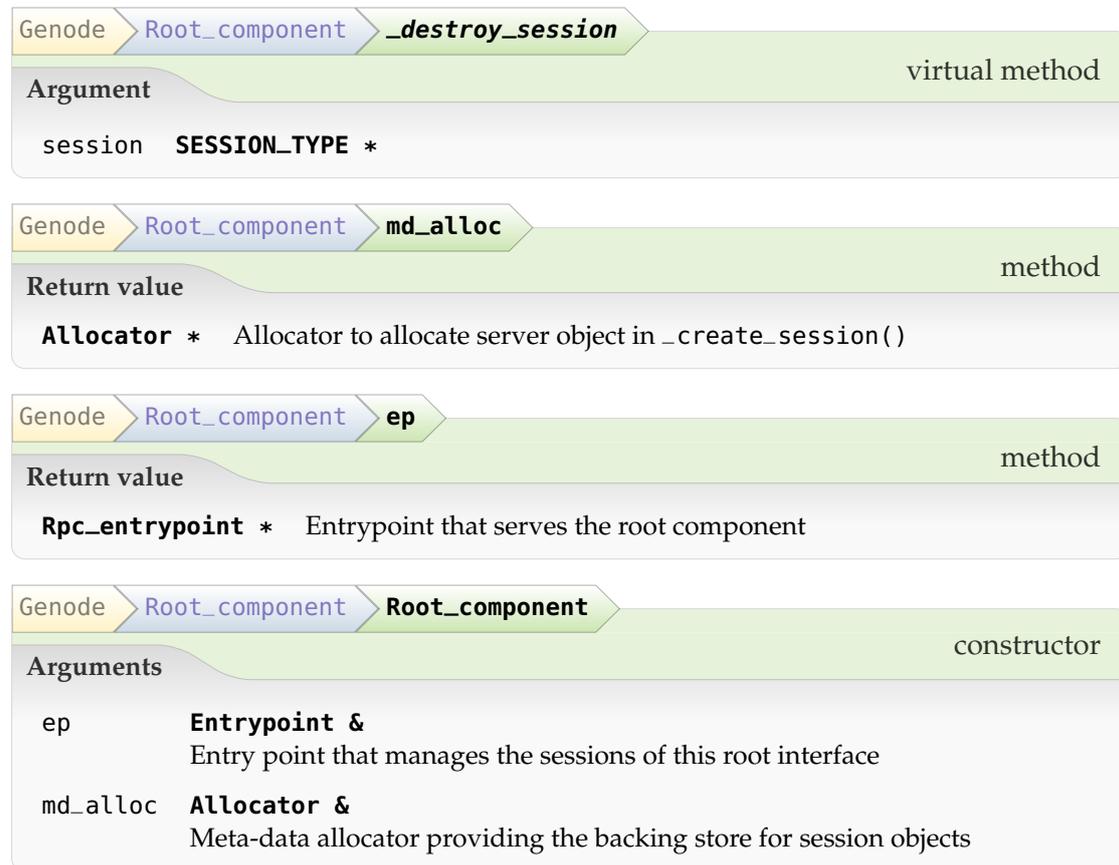
In the implementation of this method, the heap, provided by Root_component must be used for allocating the session object.

If the server implementation does not evaluate the session affinity, it suffices to override the overload without the affinity argument.



Once a session is created, its client can successively extend its quota donation via the Parent::transfer_quota operation. This will result in the invocation of Root::upgrade

at the root interface the session was created with. The root interface, in turn, informs the session about the new resources via the `_upgrade_session` method. The default implementation is suited for sessions that use a static amount of resources accounted for at session-creation time. For such sessions, an upgrade is not useful. However, sessions that dynamically allocate resources on behalf of its client, should respond to quota upgrades by implementing this method.

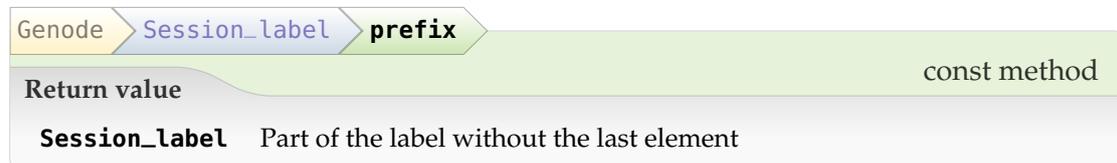


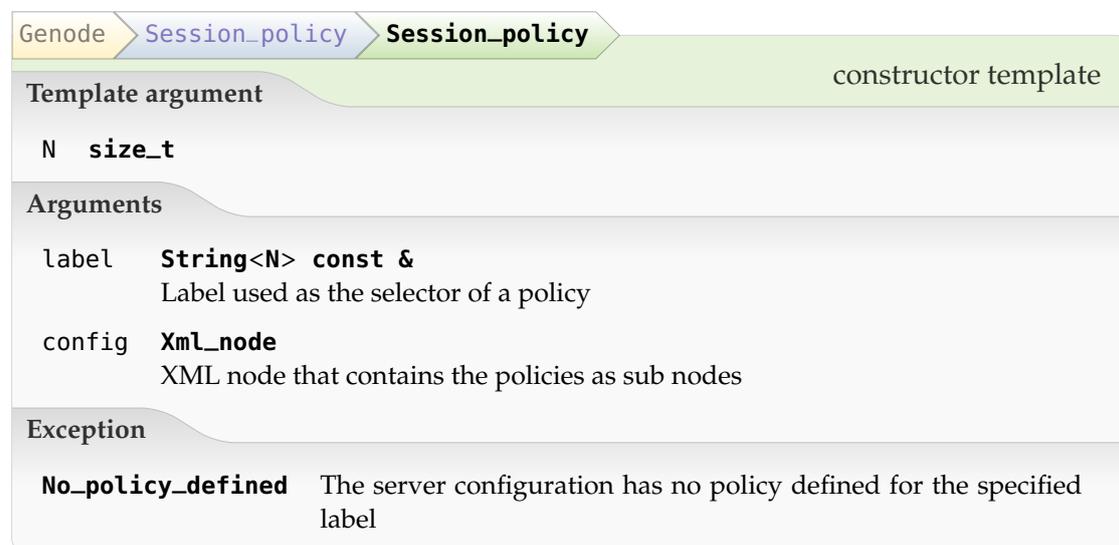
8.15.9. Server-side policy handling

The `Session_label` and `Session_policy` utilities aid the implementation of the server-side policy-selection mechanism described in Section 4.6.2.



This constructor is needed because GCC 8 disregards derived copy constructors as candidate.



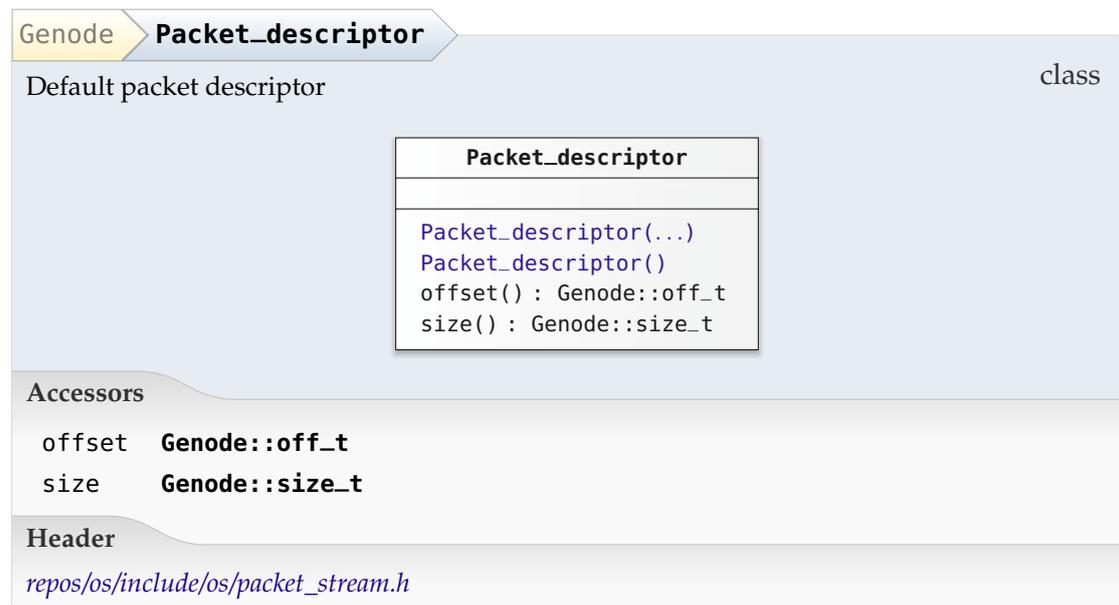


On construction, the `Session_policy` looks up the policy XML node that matches the label provided as argument. The server-side policies are defined in one or more policy subnodes of the server's config node. Each policy node has a label attribute. If the policy label matches the first part of the label as delivered as session argument, the policy matches. If multiple policies match, the one with the longest label is selected.

8.15.10. Packet stream

The `Packet_stream` is the building block of the asynchronous transfer of bulk data (Section 3.6.6). The public interface consists of the two class templates `Packet_stream_source`, and `Packet_stream_sink`. Both communication parties agree on a policy with regard to the organization of the communication buffer by specifying the same `Packet_stream_policy` as template argument.

The communication buffer consists of three parts, a submit queue, an acknowledgement queue, and a bulk buffer. The submit queue contains packets generated by the source to be processed by the sink. The acknowledgement queue contains packets that are processed and acknowledged by the sink. The bulk buffer contains the actual payload. The assignment of packets to bulk-buffer regions is performed by the source.



A class used as `PACKET_DESCRIPTOR` arguments to the `Packet_stream_policy` template must implement the interface of this class.

Genode **Packet_descriptor** **Packet_descriptor** constructor

Arguments

offset **off_t**

size **size_t**

Genode **Packet_descriptor** **Packet_descriptor** constructor

Default constructor used for instantiating arrays of packet-descriptors used as submit and ack queues.

Genode **Packet_stream_base** class

Common base of Packet_stream_source and Packet_stream_sink

Packet_stream_base

Header

repos/os/include/os/packet_stream.h

Genode **Packet_stream_source** class template

Originator of a packet stream

Packet_stream_source POLICY

Template argument

POLICY **typename**

Header

repos/os/include/os/packet_stream.h

Genode **Packet_stream_sink** class template

Receiver of a packet stream

Packet_stream_sink POLICY

Template argument

POLICY **typename**

Header

[repos/os/include/os/packet_stream.h](#)

Genode **Packet_stream_policy** class template

Policy used by both sides source and sink

Packet_stream_policy PACKET_DESCRIPTOR, SUBMIT_QUEUE_SIZE, ACK_QUEUE_SIZE, CONTENT_TYPE

Template arguments

PACKET_DESCRIPTOR **typename**

SUBMIT_QUEUE_SIZE **unsigned**

ACK_QUEUE_SIZE **unsigned**

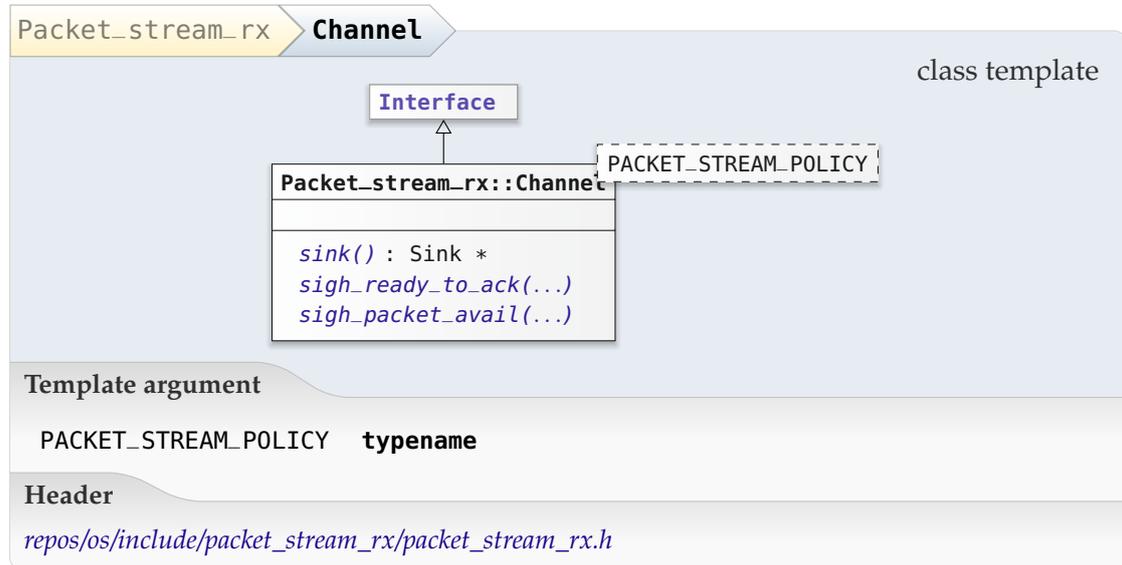
CONTENT_TYPE **typename**

Header

[repos/os/include/os/packet_stream.h](#)

In client-server scenarios, each client and server can play the role of either a source or a sink of packets. To ease the use of packet streams in such scenarios, the classes within the `Packet_stream_rx` and `Packet_stream_tx` namespaces provide ready-to-use building blocks to be aggregated in session interfaces.

Data transfer from server to client

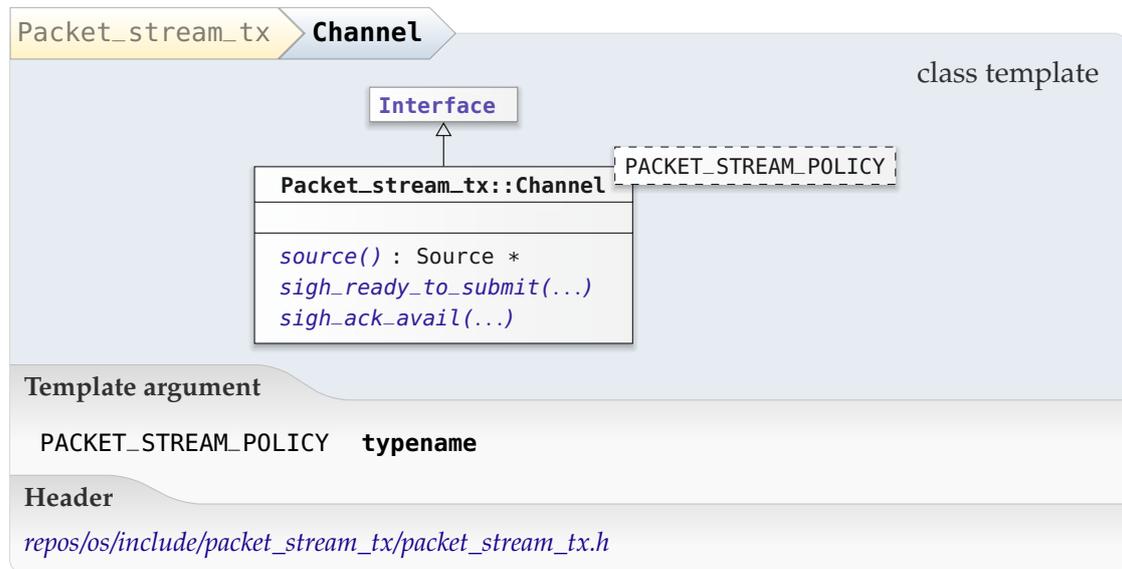


See documentation of `Packet_stream_tx::Cannel::source`.

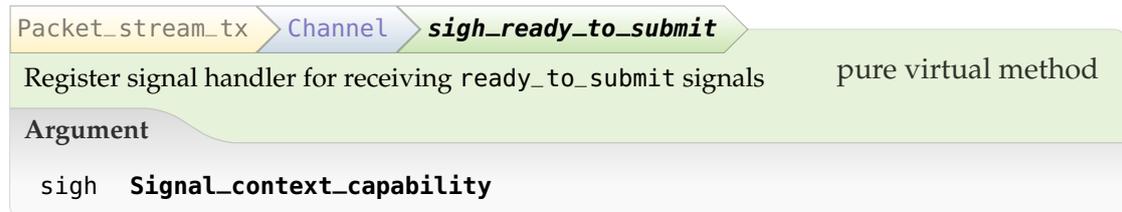




Data transfer from client to server



This method enables the client-side use of the Channel using the abstract Channel interface only. This is useful in cases where both source and sink of the Channel are co-located in one program. At the server side of the Channel, this method has no meaning.



8.16. XML processing

The configuration concept (Chapter 6 and Section 4.6) of the framework relies on XML syntax. Hence, there is the need to process XML-formed data. For parsing XML data, the `Xml_node` and the accompanying `Xml_attribute` utilities are provided. Those utilities operate directly on a text buffer that contains XML data. There is no conversion step into an internal representation. This approach alleviates the need for allocating any meta data while extracting information from XML data. The XML parser is stateless.

Vice versa, the `Xml_generator` serves as a utility for generating XML formatted data. The scope of an XML node is represented by a lambda function. Hence, nested XML nodes can be created by nested lambda functions, which makes the structure of the XML data immediately apparent in the C++ source code. As for the `Xml_node` the `Xml_generator` does not use any internal intermediate representation of the XML data. No dynamic memory allocations are needed while generating XML-formatted output.

A typical component imports parts of its internal state from XML input, most prominently its configuration. This import is not a one-off operation but may occur multiple times during the lifetime of the component. Hence, the component is faced with the challenge of updating its internal data model from potentially changing XML input. The `List_model` provides a convenient and robust formalism to implement such partial model updates.

8.16.1. XML parsing

Genode's XML parser consists of the two classes `Xml_node` and `Xml_attribute`. Its primary use case is the provisioning of configuration information to low-level components. Consequently, it takes the following considerations into account:

Low complexity Because the parser is implicitly used in most components, it must not be complex to keep its footprint on the trusted computing base as small as possible.

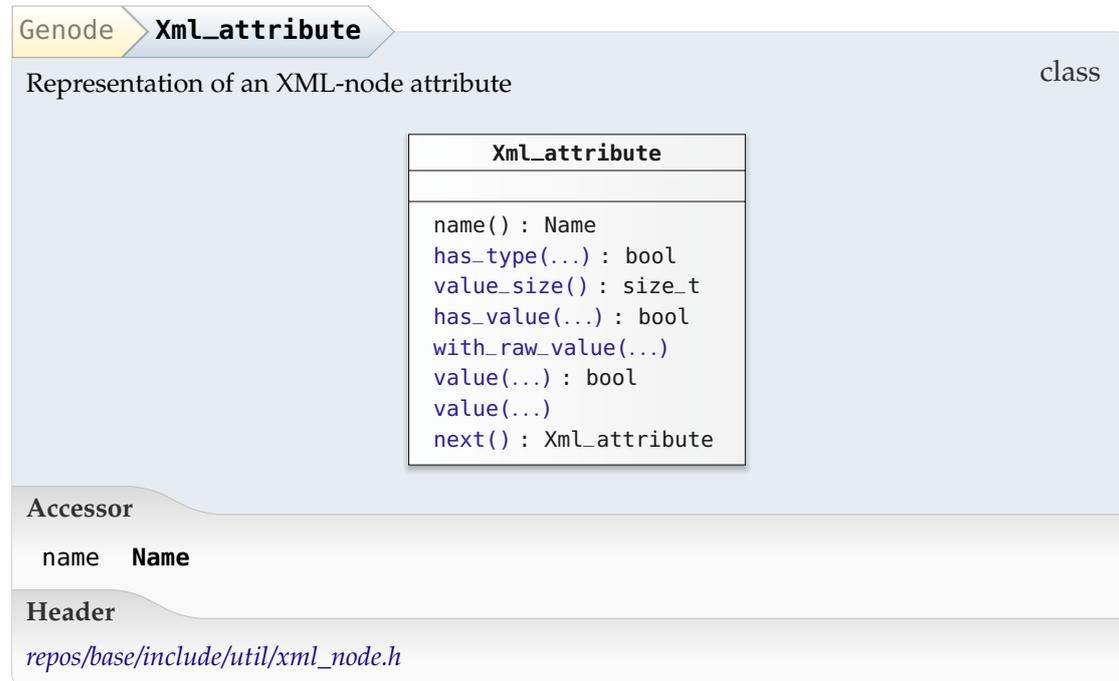
Free-standing The parser must be able to operate without external dependencies such as a C runtime. Otherwise, each Genode-based system would inherit such dependencies.

No dynamic memory allocations The parser should not dynamically allocate memory to be usable in resource multiplexers and runtime environments where no anonymous memory allocations are allowed (Section 3.3.3).

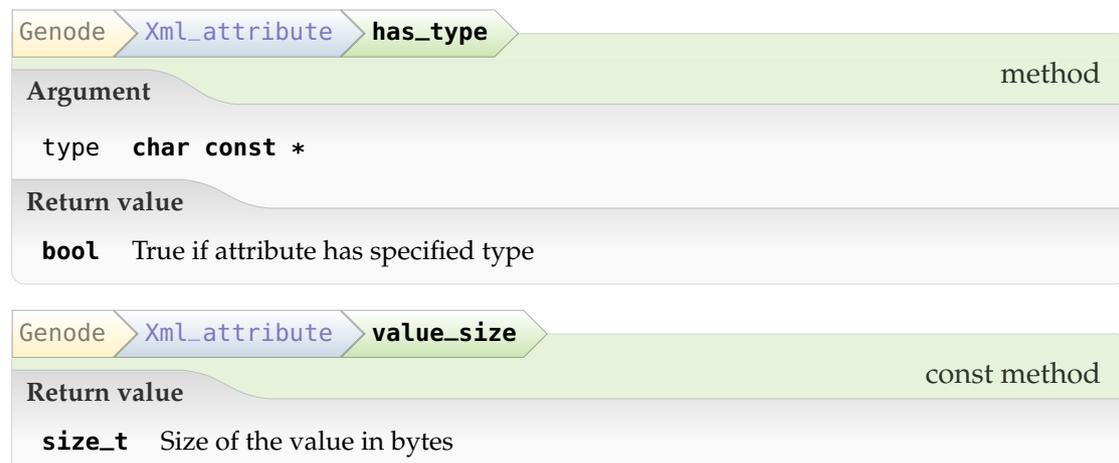
Robustness The parser must be robust in the sense that it must not contain buffer overflows, infinite loops, memory corruptions, or any other defect that may make the program crash.

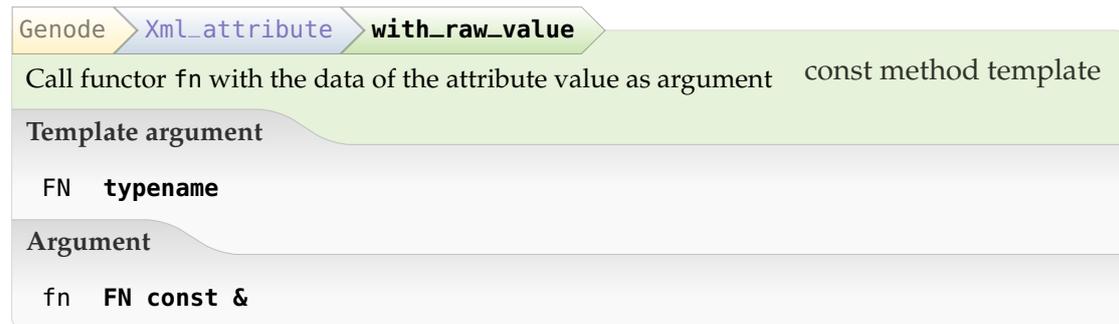
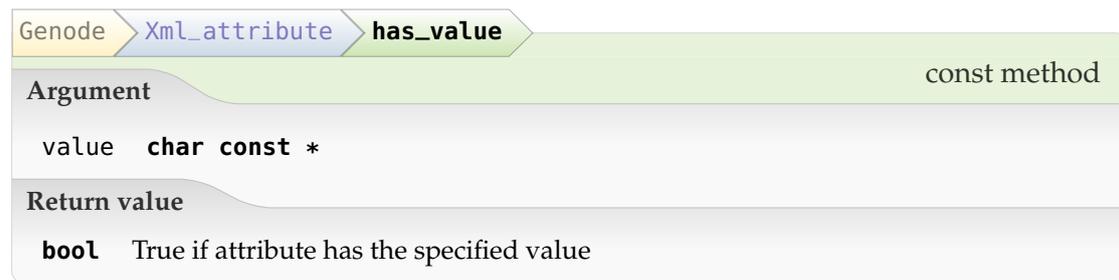
Other possible goals like expressive error messages, the support for more general use cases, and even the adherence to standards are deliberately subordinated. Given its low

complexity, the XML parser cannot satisfy components that need advanced XML processing such as validating XML data against a DTD or schema, mutating XML nodes, or using different character encodings. In such cases, component developers may consider the use of ported 3rd-party XML parser.



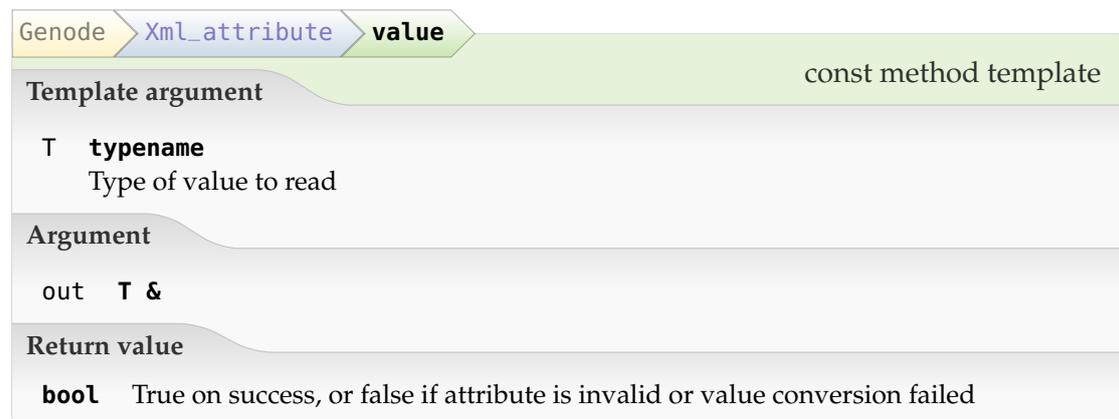
An attribute has the form name="value".





The functor is called with the start pointer (`char const *`) and size (`size_t`) of the attribute value as arguments.

Note that the content of the buffer is not null-terminated but delimited by the size argument.



Genode **Xml_attribute** **next**

Return value const method

Xml_attribute Next attribute in attribute list

Genode **Xml_node**

Representation of an XML node class

Xml_node
<pre> Xml_node(...) size() : size_t content_size() : size_t type() : Type has_type(...) : bool with_raw_node(...) with_raw_content(...) decoded_content(...) : size_t decoded_content() : STRING num_sub_nodes() : size_t next() : Xml_node next(...) : Xml_node last(...) : bool sub_node(...) : Xml_node sub_node(...) : Xml_node with_sub_node(...) for_each_sub_node(...) for_each_sub_node(...) attribute(...) : Xml_attribute attribute(...) : Xml_attribute attribute_value(...) : T has_attribute(...) : bool has_sub_node(...) : bool print(...) differs_from(...) : bool </pre>

Accessor

type **Type**

Header

repos/base/include/util/xml_node.h

Genode	Xml_node	Xml_node	constructor
Arguments			
addr	char const *		
max_len	size_t	<i>Default is ~0UL</i>	
Exception			
Invalid_syntax			

The constructor validates if the start tag has a matching end tag of the same depth and counts the number of immediate sub nodes.

Genode	Xml_node	size	const method
Return value			
size_t	Size of node including start and end tags in bytes		

Genode	Xml_node	content_size	const method
Return value			
size_t	Size of node content		

Genode	Xml_node	has_type	const method
Argument			
type	char const *		
Return value			
bool	True if tag is of specified type		

Genode	Xml_node	with_raw_node	const method template
Call functor fn with the node data (char const *, size_t)			
Template argument			
FN	typename		
Argument			
fn	FN const &		

Genode	Xml_node	with_raw_content	
Call functor <code>fn</code> with <code>content</code> (<code>char const *</code> , <code>size_t</code>) as <code>const</code> method template argument			
Template argument			
FN typename			
Argument			
fn FN const &			

Note that the `content` is not null-terminated. It points directly into a sub range of the unmodified `Xml_node` data.

If the node has no content, the functor `fn` is not called.

Genode	Xml_node	decoded_content	
Export decoded node content from XML node			<code>const</code> method
Arguments			
dst	char *	Destination buffer	
dst_len	size_t	Size of destination buffer in bytes	
Return value			
size_t	Number of bytes written to the destination buffer		

This function transforms XML character entities into their respective characters.

Genode	Xml_node	decoded_content	
Read decoded node content as <code>Genode::String</code>			<code>const</code> method template
Template argument			
STRING	typename		
Return value			
STRING			

Genode	Xml_node	num_sub_nodes	
Return value			<code>const</code> method
size_t	The number of the XML node's immediate sub nodes		

Genode	Xml_node	next	
			const method
Exception			
Nonexistent_sub_node Subsequent node does not exist			
Return value			
Xml_node XML node following the current one			

Genode	Xml_node	next	
			const method
Argument			
type	char const * Type of XML node, or nullptr for matching any type		
Exception			
Nonexistent_sub_node Subsequent node does not exist			
Return value			
Xml_node Next XML node of specified type			

Genode	Xml_node	last	
			const method
Argument			
type	char const * <i>Default is 0</i>		
Return value			
bool True if node is the last of a node sequence			

Genode	Xml_node	sub_node	
			const method
Argument			
idx	unsigned Index of sub node, default is the first node <i>Default is 0U</i>		
Exception			
Nonexistent_sub_node No such sub node exists			
Return value			
Xml_node Sub node with specified index			

Genode	Xml_node	sub_node	
			const method
Argument			
type char const *			
Exception			
Nonexistent_sub_node No such sub node exists			
Return value			
Xml_node First sub node that matches the specified type			

Genode	Xml_node	with_sub_node	
Apply functor fn to first sub node of specified type			const method template
Template argument			
FN typename			
Arguments			
type char const *			
fn FN const &			

The functor is called with the sub node as argument. If no matching sub node exists, the functor is not called.

Genode	Xml_node	for_each_sub_node	
Execute functor fn for each sub node of specified type			const method template
Template argument			
FN	typename		
Arguments			
type	char const *		
fn	FN const &		

Genode	Xml_node	for_each_sub_node	
Execute functor fn for each sub node			const method template
Template argument			
FN	typename		
Argument			
fn	FN const &		

Genode	Xml_node	attribute	
			const method
Argument			
idx	unsigned Attribute index, first attribute has index 0		
Exception			
Nonexistent_attribute	No such attribute exists		
Return value			
Xml_attribute	XML attribute		

Genode	Xml_node	attribute	
			const method
Argument			
type	char const *		Name of attribute type
Exception			
	Nonexistent_attribute	No such attribute exists	
Return value			
	Xml_attribute	XML attribute	

Genode	Xml_node	attribute_value	
Read attribute value from XML node			const method template
Template argument			
T	typename		
Arguments			
type	char const *	Attribute name	
default_value	T const	Value returned if no attribute with the name type is present.	
Return value			
T	Attribute value or specified default value		

The type of the return value corresponds to the type of the default value.

Genode	Xml_node	has_attribute	const method
Argument			
type	char const *		
Return value			
bool	True if attribute of specified type exists		

Genode	Xml_node	has_sub_node	const method
Argument			
type	char const *		
Return value			
bool	True if sub node of specified type exists		

Genode	Xml_node	print	const method
Argument			
output	Output &		

Genode	Xml_node	differs_from	const method
Argument			
another	Xml_node const &		
Return value			
bool	True if this node differs from another		

8.16.2. XML generation





Genode	Xml_generator	attribute	method
Arguments			
name	char const *		
value	bool		

Genode	Xml_generator	attribute	method
Arguments			
name	char const *		
value	long		

Genode	Xml_generator	attribute	method
Arguments			
name	char const *		
value	long		

Genode	Xml_generator	attribute	method
Arguments			
name	char const *		
value	int		

Genode	Xml_generator	attribute	method
Arguments			
name	char const *		
value	unsigned long		

Genode	Xml_generator	attribute	method
Arguments			
name	char const *		
value	unsigned long		

Genode	Xml_generator	attribute	
Arguments			method
name	char const *		
value	unsigned		

Genode	Xml_generator	attribute	
Arguments			method
name	char const *		
value	double		

Genode	Xml_generator	append	
Append content to XML node			method
Arguments			
str	char const *		
str_len	size_t	<i>Default is ~0UL</i>	

This method must not be followed by calls of attribute.

Genode	Xml_generator	append_sanitized	
Append sanitized content to XML node			method
Arguments			
str	char const *		
str_len	size_t	<i>Default is ~0UL</i>	

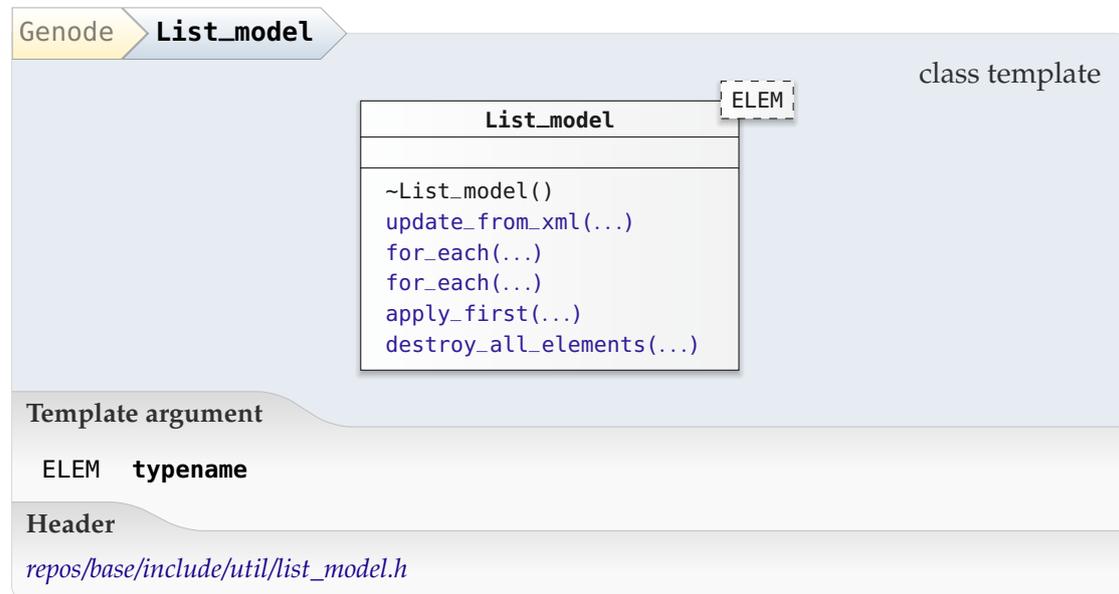
This method must not be followed by calls of attribute.

Genode	Xml_generator	append_content	
Append printable objects to XML node as sanitized content			method template
Template argument			
ARGS	typename...		
Argument			
args	ARGS &&...		

This method must not be followed by calls of attribute.

8.16.3. XML-based data models

The `List_model` utility eases the implementation of component-internal data models created and updated from XML. The transformation is defined by the implementation of the `Update_policy` interface. As a low-level mechanism, the list model is not thread safe.



Genode	List_model	update_from_xml	
Update data model according to XML structure node			method template
Template argument			
POLICY typename			
Arguments			
policy POLICY &			
node Xml_node			
Exception			
Unknown_element_type			

Genode	List_model	for_each	
Call functor fn for each const element			const method template
Template argument			
FN typename			
Argument			
fn FN const &			

Genode	List_model	for_each	
Call functor fn for each non-const element			method template
Template argument			
FN typename			
Argument			
fn FN const &			

Genode	List_model	apply_first	
Apply functor fn to the first element of the list model			const method template
Template argument			
FN typename			
Argument			
fn FN const &			

Using this method combined with the `Element::next` method, the list model can be

traversed manually. This is handy in situations where the list-model elements are visited via recursive function calls instead of a `for_each` loop.

Genode	List_model	destroy_all_elements	method template
Remove all elements from the data model			
Template argument			
POLICY	typename		
Argument			
policy	POLICY &		

This method should be called at the destruction time of the `List_model`. List-model elements are not implicitly destroyed by the destructor because the `policy` needed to destruct elements is not kept as member of the list model (multiple policies may applied to the same list model).

Genode::List_model	Update_policy	class template				
Policy interface to be supplied to <code>List_model::update_from_xml</code>						
<table border="1"> <tr> <td>List_model::Update_policy</td> <td>ELEM</td> </tr> <tr> <td colspan="2"> <pre> destroy_element(...) create_element(...) : ELEM & update_element(...) element_matches_xml_node(...) : bool node_is_element(...) : bool </pre> </td> </tr> </table>			List_model::Update_policy	ELEM	<pre> destroy_element(...) create_element(...) : ELEM & update_element(...) element_matches_xml_node(...) : bool node_is_element(...) : bool </pre>	
List_model::Update_policy	ELEM					
<pre> destroy_element(...) create_element(...) : ELEM & update_element(...) element_matches_xml_node(...) : bool node_is_element(...) : bool </pre>						
Template argument						
ELEM	typename Element type, must be a list element					
Header						
<i>repos/base/include/util/list_model.h</i>						

This class template is merely a blue print of a policy to document the interface.

Genode::List_model	Update_policy	destroy_element	
Destroy element			method
Argument			
elem	ELEM &		

When this function is called, the element is no longer contained in the model's list.

Genode::List_model	Update_policy	create_element	
Create element of the type given in the elem_node			method
Argument			
elem_node	Xml_node		
Exception			
List_model::Unknown_element_type			
Return value			
ELEM &			

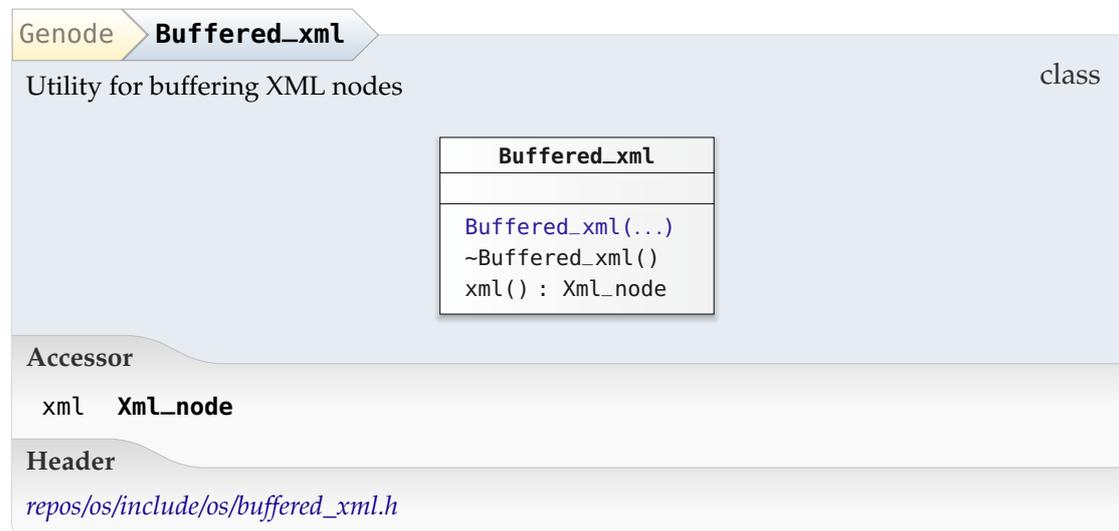
Genode::List_model	Update_policy	update_element	
Import element properties from XML node			method
Arguments			
elem	ELEM &		
elem_node	Xml_node		

Genode::List_model	Update_policy	element_matches_xml_node	
			class function
Arguments			
-	Element const &		
-	Xml_node		
Return value			
bool	True if element corresponds to XML node		



This method allows the policy to disregard certain XML node types from building the data model.

In some situations, it is convenient to keep a verbatim copy of XML input as part of the internal data model. As the `Xml_node` is merely a light-weight pointer into XML data, it cannot be stored when the underlying XML data is updated dynamically. Instead, the XML input must be copied into the internal data model. The `Buffered_xml` utility takes care of the backing-store allocation and copying of an existing `Xml_node`.



8.17. Component management

8.17.1. Shared objects

Genode > Shared_object > Shared_object class

Shared_object
Shared_object(...) ~Shared_object() lookup(...) : T

Header
repos/base/include/base/shared_object.h

Genode > Shared_object > Shared_object constructor

Load shared object and dependencies

Arguments

- **Env &**
- md_alloc **Allocator &**
Backing store for the linker's dynamically allocated meta data
- name **char const ***
ROM module name of shared object to load
- bind **Bind**
Bind functions immediately (BIND_NOW) or on demand (BIND_LAZY)
- keep **Keep**
Unload ELF object if no longer needed (DONT_KEEP), or keep ELF object loaded at all times (KEEP)

Exception

Invalid_rom_module

Genode > Shared_object > ~Shared_object destructor

Close and unload shared object

Genode Shared_object Lookup

Lookup a symbol in shared object and it's dependencies const method template

Template argument

T **typename**
*Default is void **

Argument

symbol **const char ***
 Symbol name

Exception

Invalid_symbol

Return value

T Symbol address

Genode Address_info

Address_info

Address_info(...)

class

Header

repos/base/include/base/shared_object.h

Genode Address_info Address_info

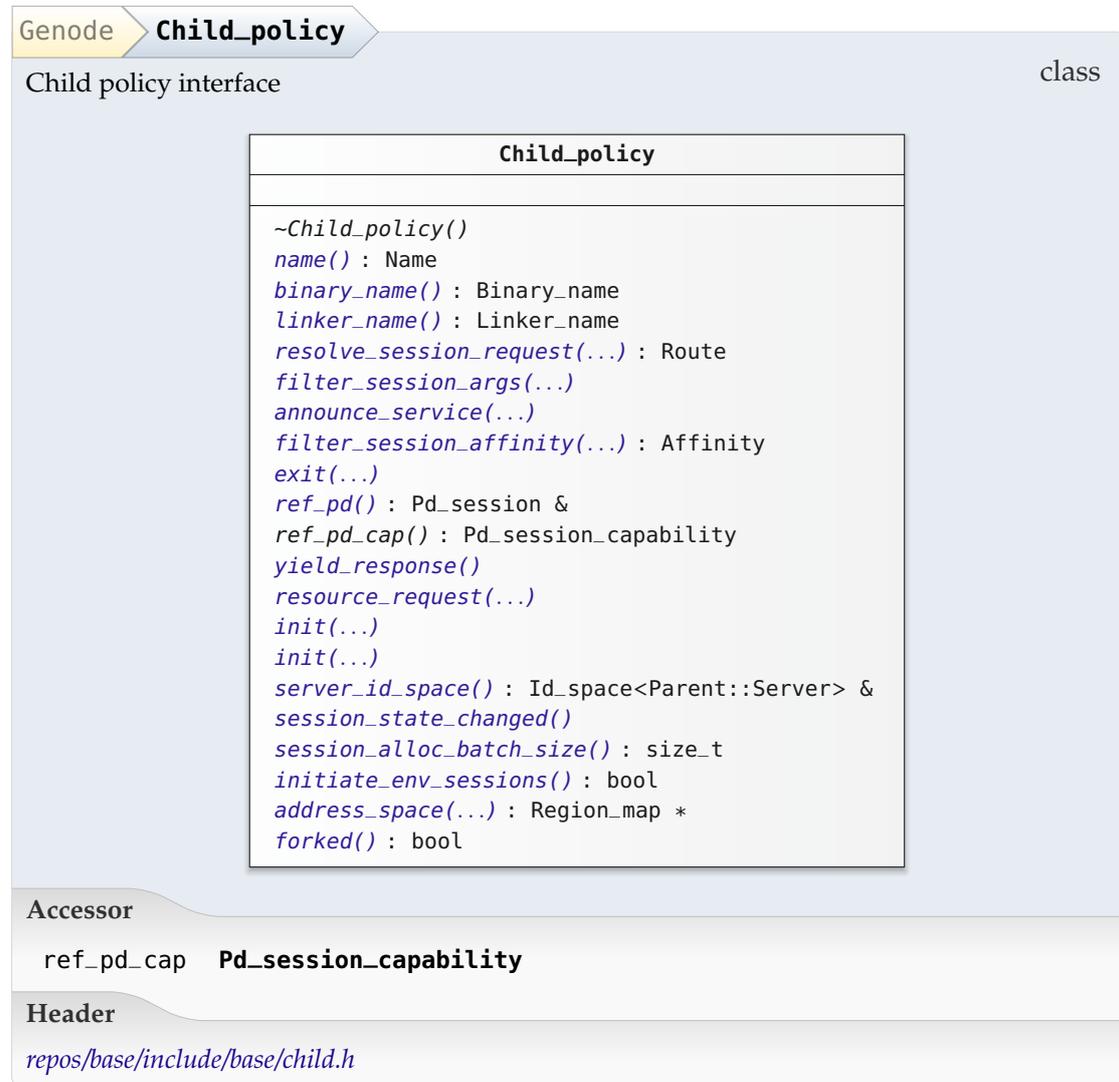
constructor

Argument

addr **addr_t**

8.17.2. Child management

For components that manage a number of child components, each child is represented by an instance of the `Child` class. This instance contains the policy to be applied to the child (for example, how session requests are routed to services) and contains the child's execution environment including the PD session holding the child's RAM and capability quota.



A child-policy object is an argument to a `Child`. It is responsible for taking policy decisions regarding the parent interface. Most importantly, it defines how session requests are resolved and how session arguments are passed to servers when creating sessions.

Genode	Child_policy	name	
		Name of the child used as the child's label prefix	pure virtual const method
		Return value	
		Name	
Genode	Child_policy	binary_name	
		ROM module name of the binary to start	virtual const method
		Return value	
		Binary_name	
Genode	Child_policy	linker_name	
		ROM module name of the dynamic linker	virtual const method
		Return value	
		Linker_name	
Genode	Child_policy	resolve_session_request	
		Determine service and server-side label for a given session request	pure virtual method
		Arguments	
		- Name const &	
		- Session_label const &	
		Exception	
		Service_denied	
		Return value	
		Route Routing and policy-selection information for the session	
Genode	Child_policy	filter_session_args	
		Apply transformations to session arguments	virtual method
		Argument	
		- Name const &	

Genode	Child_policy	announce_service	virtual method
Register a service provided by the child			
Argument			
- Name const &			

Genode	Child_policy	filter_session_affinity	virtual method
Apply session affinity policy			
Argument			
affinity	Affinity const &		Affinity passed along with a session request
Return value			
Affinity	Affinity subordinated to the child policy		

Genode	Child_policy	exit	virtual method
Exit child			
Argument			
exit_value	int		

Genode	Child_policy	ref_pd	pure virtual method
Reference PD session			
Return value			
Pd_session &			

The PD session returned by this method is used for session cap-quota and RAM-quota transfers.

Genode	Child_policy	yield_response	virtual method
Respond to the release of resources by the child			

This method is called when the child confirms the release of resources in response to a yield request.

Genode	Child_policy	resource_request	
Take action on additional resource needs by the child			virtual method
Argument			
- Resource_args const &			

Genode	Child_policy	init	
Initialize the child's CPU session			virtual method
Arguments			
- Cpu_session &			
- Capability<Cpu_session>			

The function may install an exception signal handler or assign CPU quota to the child.

Genode	Child_policy	init	
Initialize the child's PD session			virtual method
Arguments			
- Pd_session &			
- Capability<Pd_session>			

The function must define the child's reference account and transfer the child's initial RAM and capability quotas. It may also install a region-map fault handler for the child's address space (`Pd_session::address_space`);.

Genode	Child_policy	server_id_space	
ID space for sessions provided by the child			virtual method
Exception			
Nonexistent_id_space			
Return value			
Id_space<Parent::Server> &			

Genode	Child_policy	session_state_changed	
Notification hook invoked each time a session state is modified			virtual method

Genode	Child_policy	session_alloc_batch_size	virtual const method
Granularity of allocating the backing store for session meta data			
Return value			
size_t			

Session meta data is allocated from `ref_pd`. The first batch of session-state objects is allocated at child-construction time.

Genode	Child_policy	initiate_env_sessions	virtual const method
Return value			
bool True to create the environment sessions at child construction			

By returning `false`, it is possible to create `Child` objects without routing of their environment sessions at construction time. Once the routing information is available, the child's environment sessions must be manually initiated by calling `Child::initiate_env_sessions()`.

Genode	Child_policy	address_space	virtual method
Argument			
- Pd_session &			
Return value			
Region_map * Region map for the child's address space			

By default, the function returns a `nullptr`. In this case, the `Child` interacts with the address space of the child's PD session via RPC calls to the `Pd_session::address_space`. By overriding the default, those RPC calls can be omitted, which is useful if the child's PD session (including the PD's address space) is virtualized by the parent. If the virtual PD session is served by the same entrypoint as the child's parent interface, an RPC call to `pd` would otherwise produce a deadlock.

Genode	Child_policy	forked	virtual const method
Return value			
bool True if ELF loading should be inhibited			

Genode **Child**

Implementation of the parent interface that supports resource trading

class

```

Child
Child(...)
~Child()
active() : bool
initiate_env_pd_session()
initiate_env_sessions()
env_sessions_closed() : bool
env_ram_quota() : Ram_quota
env_cap_quota() : Cap_quota
close_all_sessions()
for_each_session(...)
effective_quota(...) : Ram_quota
effective_quota(...) : Cap_quota
pd_session_cap() : Pd_session_capability
parent_cap() : Parent_capability
ram() : Ram_allocator &
ram() : Ram_allocator const &
cpu() : Cpu_session &
pd() : Pd_session &
pd() : Pd_session const &
session_factory() : Session_state::Factory &
yield(...)
notify_resource_avail()
heartbeat()
skipped_heartbeats() : unsigned
announce(...)
session_sigh(...)
session(...) : Session_capability
session_cap(...) : Session_capability
upgrade(...) : Upgrade_result
close(...) : Close_result
exit(...)
session_response(...)
deliver_session_cap(...)
main_thread_cap() : Thread_capability
resource_avail_sigh(...)
resource_request(...)
yield_sigh(...)
yield_request() : Resource_args
yield_response()
heartbeat_sigh(...)
heartbeat_response()

```

Accessors

pd_session_cap	Pd_session_capability
parent_cap	Parent_capability
ram	Ram_allocator const &
pd	Pd_session const &
main_thread_cap	Thread_capability

Header

GENODE  LABS[repos/base/include/base/child.h](https://github.com/genode/genode/blob/master/repos/base/include/base/child.h)

There are three possible cases of how a session can be provided to a child: The service is implemented locally, the session was obtained by asking our parent, or the session is provided by one of our children.

These types must be differentiated for the quota management when a child issues the closing of a session or transfers quota via our parent interface.

If we close a session to a local service, we transfer the session quota from our own account to the client.

If we close a parent session, we receive the session quota on our own account and must transfer this amount to the session-closing child.

If we close a session provided by a server child, we close the session at the server, transfer the session quota from the server's RAM session to our account, and subsequently transfer the same amount from our account to the client.

Genode		Child	Child	constructor
Arguments				
rm	Region_map &	Local address space, usually <code>env.rm()</code>		
entrypoint	Rpc_entrypoint &	Entrypoint used to serve the parent interface of the child		
policy	Child_policy &	Policy for the child		
Exception				
Service_denied	The initial sessions for the child's environment could not be established			

Genode		Child	~Child	virtual destructor

On destruction of a child, we close all sessions of the child to other services.

Genode		Child	active	const method
Return value				
bool	True if the child has been started			

After the child's construction, the child is not always able to run immediately. In particular, a session of the child's environment may still be pending. This method returns true only if the child's environment is completely initialized at the time of calling.

If all environment sessions are immediately available (as is the case for local services or parent services), the return value is expected to be true. If this is not the case, one of child's environment sessions could not be established, e. g., the ROM session of the

binary could not be obtained.

Genode **Child** **initiate_env_pd_session** method
 Initialize the child's PD session

Genode **Child** **initiate_env_sessions** method
 Trigger the routing and creation of the child's environment session

See the description of `Child_policy::initiate_env_sessions`.

Genode **Child** **env_sessions_closed** const method
Return value
bool True if the child is safe to be destroyed

The child must not be destroyed until all environment sessions are closed at the respective servers. Otherwise, the session state, which is kept as part of the child object may be gone before the close request reaches the server.

Genode **Child** **env_ram_quota** class function
 Quota unconditionally consumed by the child's environment
Return value
Ram_quota

Genode **Child** **env_cap_quota** class function
Return value
Cap_quota

Genode **Child** **close_all_sessions** method

Genode **Child** **for_each_session** const method template
Template argument
 FN **typename**
Argument
 fn **FN const &**

Genode > Child > **effective_quota**

Deduce env session costs from usable RAM quota class function

Argument

quota **Ram_quota**

Return value

Ram_quota

Genode > Child > **effective_quota**

Deduce env session costs from usable cap quota class function

Argument

quota **Cap_quota**

Return value

Cap_quota

Genode > Child > **ram**

Return value method

Ram_allocator &

Genode > Child > **cpu**

Return value method

Cpu_session &

Genode > Child > **pd**

Return value method

Pd_session &

Genode > Child > **session_factory**

Request factory for creating session-state objects method

Return value

Session_state::Factory &

Genode	Child	yield	
Instruct the child to yield resources			method
Argument			
args	Resource_args const &		

By calling this method, the child will be notified about the need to release the specified amount of resources. For more details about the protocol between a child and its parent, refer to the description given in `parent/parent.h`.

Genode	Child	notify_resource_avail	
Notify the child about newly available resources			const method

Genode	Child	heartbeat	
Notify the child to give a lifesign			method

Genode	Child	skipped_heartbeats	
			const method
Return value			
unsigned	Number of missing heartbeats since the last response from the child		

8.18. Utilities for user-level device drivers

To avoid common implementation bugs in device drivers, the framework facilitates the declaration of hardware register and bit layouts in the form of C++ types. By subjecting the device driver's interaction with the hardware to the C++ type system, the consistency of register accesses with the hardware specifications can be maintained automatically. Such hardware specifications are declarative and can be cleanly separated from the program logic of the driver. The actual driver program is relieved from any intrinsics in the form of bit-masking operations.

The MMIO access utilities comes in the form of two header files located at *util/register.h* and *util/mmio.h*.

8.18.1. Register declarations

The class templates found in *util/register.h* provide a means to express register layouts using C++ types. In a way, these templates make up for C++'s missing facility to define accurate bitfields. The following example uses the `Register` class template to define a register as well as a bitfield within the register:

```
struct Vaporizer : Register<16>
{
    struct Enable : Bitfield<2,1> { };
    struct State  : Bitfield<3,3> {
        enum{ SOLID = 1, LIQUID = 2, GASSY = 3 };
    };

    static void    write (access_t value);
    static access_t read  ();
};
```

In the example, `Vaporizer` is a 16-bit register, which is expressed via the `Register` template argument. The `Register` class template allows for accessing register content at a finer granularity than the whole register width. To give a specific part of the register a name, the `Register::Bitfield` class template is used. It describes a bit region within the range of the compound register. The bit 2 corresponds to true if the device is enabled and bits 3 to 5 encode the `State`. To access the actual register, the methods `read()` and `write()` must be provided as back end, which performs the access of the whole register. Once defined, the `Vaporizer` offers a handy way to access the individual parts of the register, for example:

```
/* read the whole register content */
Vaporizer::access_t r = Vaporizer::read();

/* clear a bit field */
Vaporizer::Enable::clear(r);

/* read a bit field value */
unsigned old_state = Vaporizer::State::get(r);

/* assign new bit field value */
Vaporizer::State::set(r, Vaporizer::State::LIQUID);

/* write whole register */
Vaporizer::write(r);
```

Bitfields that span multiple registers The register interface of hardware devices may be designed such that bitfields are not always consecutive in a single register. For example, values of the HDMI configuration of the Exynos-5 SoC are scattered over multiple hardware registers. The problem is best illustrated by the following example of a hypothetical timer device. The bits of the clock count value are scattered across two hardware registers, the lower 6 bits of the 16-bit-wide register 0x2, and two portions of the 32-bit-wide register 0x4. A declaration of those registers would look like this:

```
struct Clock_2 : Register<0x2, 16>
{
    struct Value : Bitfield<0, 6> { };
};

struct Clock_1 : Register<0x4, 32>
{
    struct Value_2 : Bitfield<2, 13> { };
    struct Value_1 : Bitfield<18, 7> { };
};
```

Writing a clock value needs consecutive write accesses to both registers with bit shift operations applied to the value:

```
write<Clock_1::Value_1>(clk);
write<Clock_1::Value_2>(clk >> 7);
write<Clock_2::Value>(clk >> 20);
```

The new `Bitset_2` and `Bitset_3` class templates contained in `util/register.h` allow the user to compose a logical bit field from 2 or 3 physical bit fields. The order of

the template arguments expresses the order of physical bits in the logical bit set. Each argument can be a register, a bit field, or another bit set. The declaration of such a composed bit set for the example above looks as follows:

```
struct Clock : Bitset_3<Clock_1::Value_1,  
                      Clock_1::Value_2,  
                      Clock_2::Value> { };
```

With this declaration in place, the driver code becomes as simple as:

```
write<Clock>(clk);
```

Under the hood, the framework performs all needed consecutive write operations on the registers 0x2 and 0x4.

8.18.2. Memory-mapped I/O

The utilities provided by *util/mmio.h* use the Register template class as a building block to provide easy-to-use access to memory-mapped I/O registers. The Mmio class represents a memory-mapped I/O region taking its local base address as constructor argument. The following example illustrates its use:

```
class Timer : Mmio  
{  
    struct Value    : Register<0x0, 32> { };  
    struct Control  : Register<0x4, 8> {  
        struct Enable : Bitfield<0,1> { };  
        struct Irq    : Bitfield<3,1> { };  
        struct Method : Bitfield<1,2>  
        {  
            enum { ONCE = 1, RELOAD = 2, CYCLE = 3 };  
        };  
    };  
};  
  
public:  
  
    Timer(addr_t base) : Mmio(base) { }  
  
    void enable();  
    void set_timeout(Value::access_t duration);  
    bool irq_raised();  
};
```

The memory-mapped timer device consists of two registers: The 32-bit `Value` register and the 8-bit `Control` register. They are located at the MMIO offsets `0x0` and `0x4`, respectively. Some parts of the `Control` register have specific meanings as expressed by the `Bitfield` definitions within the `Control` struct.

Using these declarations, accessing the individual bits becomes almost a verbatim description of how the device is used. For example:

```
void enable()
{
    /* access an individual bitfield */
    write<Control::Enable>(true);
}

void set_timeout(Value::access_t duration)
{
    /* write complete content of a register */
    write<Value>(duration);

    /* write all bitfields as one transaction */
    write<Control>(Control::Enable::bits(1) |
                  Control::Method::bits(Control::Method::ONCE) |
                  Control::Irq::bits(0));
}

bool irq_raised()
{
    return read<Control::Irq>();
}
```