Rethinking CPU scheduling for dynamic workloads on Sculpt OS

Johannes Schlatow and Stefan Kalkowski
<$firstname.$lastname@genode-labs.com>

Introduction

What is Sculpt OS?

- showcase for Genode OS Framework as Desktop OS
  - component-based OS framework
  - hierarchical distribution of resources
  - supports several microkernels
- official Sculpt OS image (`x86_64`) uses NOVA microhypervisor
- custom kernel (base-hw) primarily for ARM and test-driving new ideas

Sculpt OS: User perspective

Sculpt user assigns for each component:

- four scheduling groups with different latency expectations
  - **driver** – *latency-sensitive device drivers*
  - **multimedia** – *audio, video, latency-sensitive parts of UI*
  - **default** – *UI, desktop apps, computing*
  - **background** – *best effort*
- mapped to scheduling priorities of underlying microkernel
- rogue driver leads to starvation of lower-priority

→ **fixed-priority scheduling may lead to starvation**

Quota-based scheduling on custom kernel

Scheduling in Genode's custom kernel (base-hw) since 2014

- quota- and priority-based scheduling with radical degradation to round-robin
- mitigates rogue threads (e. g. broken device drivers)
- enables hierarchical distribution of CPU quota
- requires tuning for workload and target platform

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→ **no adequate solution for dynamic workloads**

Scheduling requirements for dynamic workloads

Take a step back: What do we need?

- fairness and adjustable latency
  - fair (proportional) share of CPU → prevents starvation
  - some threads prefer low latency
  - other threads do not care much about latency (best-effort and high-throughput)
- ease of configuration
- robustness against misconfiguration and workload changes

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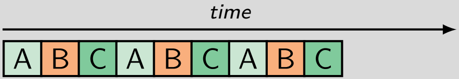
→ **revise scheduling for custom kernel**

Fair scheduling

Round-Robin

- each thread gets an equal share
- fixed time-slice length



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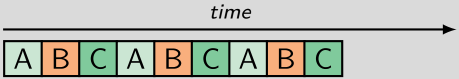

Weighted Round-Robin

- each thread is assigned a weight
- CPU share proportional to weight

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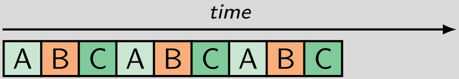
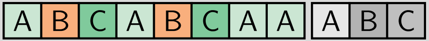


A	B	C	A	B	C	A	B	C

Weighted Round-Robin

- each thread is assigned a weight
- CPU share proportional to weight
- different interleaving schemes
  - weights: A=4, B=2, C=2



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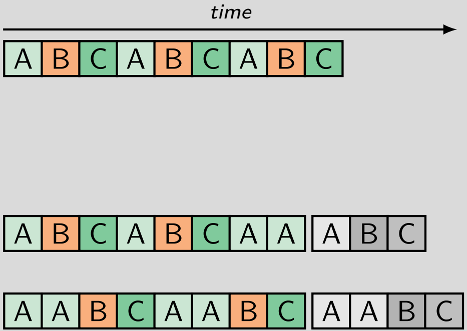

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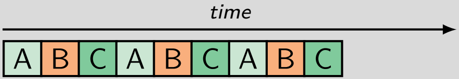
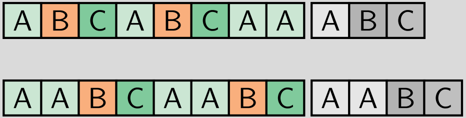


time

A B C A B C A B C

Weighted Round-Robin

- each thread is assigned a weight
- CPU share proportional to weight
- different interleaving schemes
  - weights: A=4, B=2, C=2
- round-based implementation
- not trivial for dynamic workloads



A B C A B C A A | A B C

A A B C A A B C | A A B C

Fair scheduling for dynamic workloads

Virtual-time scheduling

- each thread has a weight and a virtual time
- scheduler picks thread with minimum virtual time

$$\text{virtual time} += \frac{\Delta\text{real time}}{\text{weight}}$$

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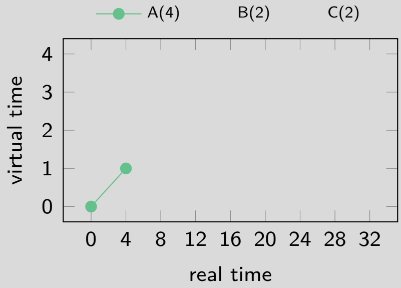
Example: run each thread for 4 units of real time



A

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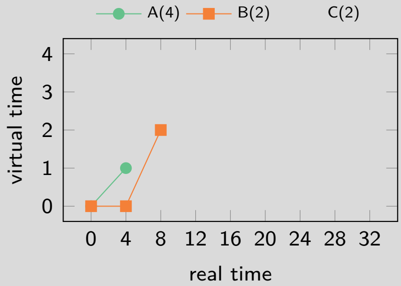

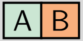

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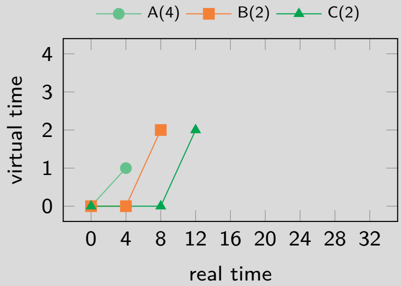

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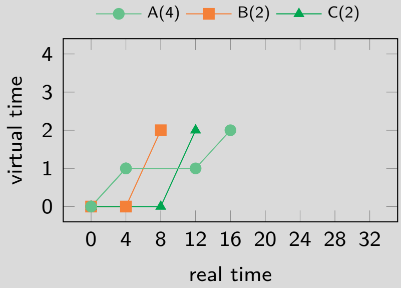

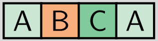

A B C A

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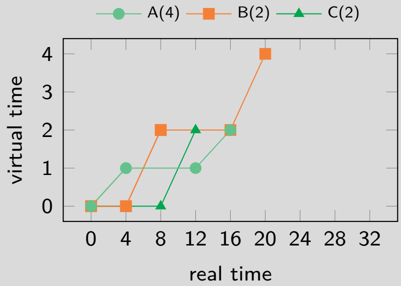

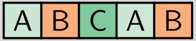

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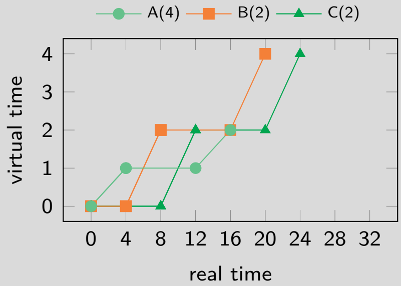

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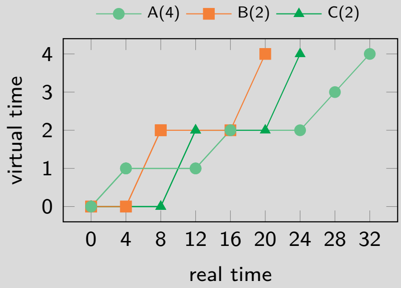

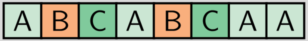
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Challenges with virtual-time scheduling

Open questions

- How to assign **weights** to threads?
- How to determine **time-slice** length?
- How to deal with **sleeping** threads?
- How to tune threads for low **latency**?

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Existing solutions

- EEVDF (Earliest Eligible Virtual Deadline First), new replacement for Linux' CFS
- BVT (Borrowed Virtual Time) ← **our basis for new scheduler**

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Approach

1. simulate basic scenarios to experiment with parameters and options
2. implement in custom kernel and evaluate

Adapting virtual-time scheduling for Sculpt OS

How to assign weights to threads?

$$\text{proportional share} = \frac{\text{sum of weights}}{\text{thread weight}}$$

- adding threads changes proportional share
  - e. g.: CPU share for **driver** threads shrinks with number of threads in **default**
- re-assigning weights of running threads complicates implementation

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Solution: hierarchical scheduling

- fixed proportional share for groups (hard-coded guesstimate)
- equal weights within each group
- relieves user from weight assignment

Dynamic time slices

How to determine time-slice length?

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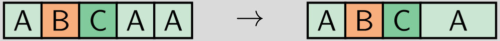

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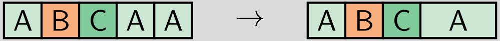

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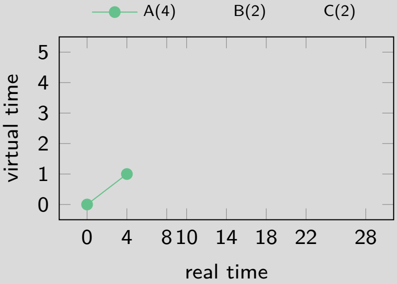
- catch up with lowest virtual time **plus** execute for a constant (real) time longer



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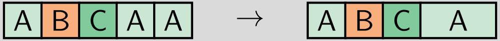

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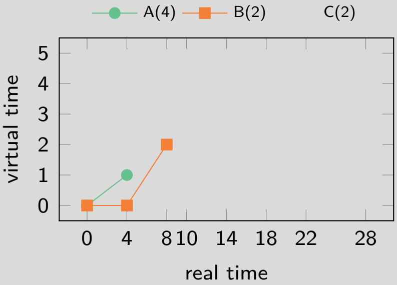

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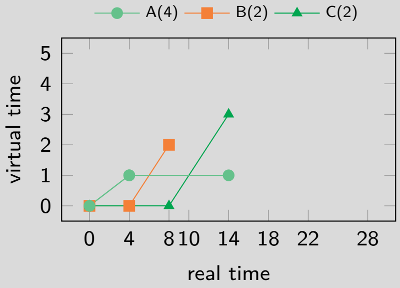

A	B	C

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A | B | C | A | A → A | B | C | A

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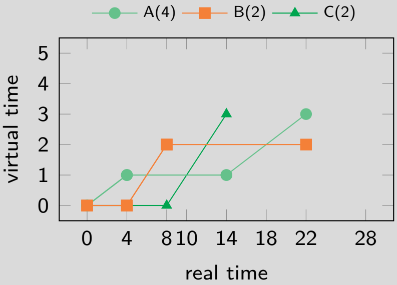

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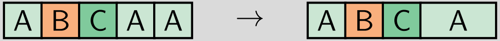

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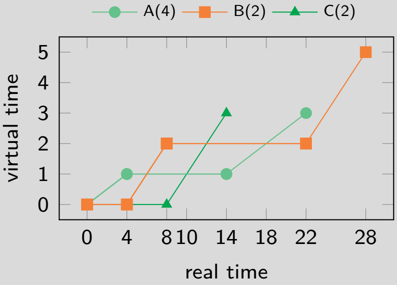
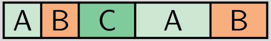
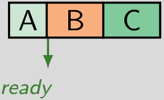




A B C A B

Sleeping policy

Let's take a nap!



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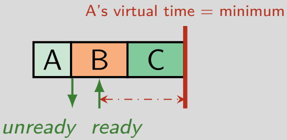

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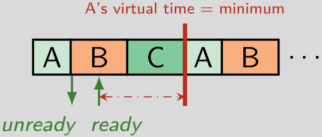

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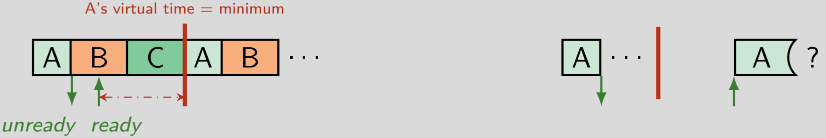

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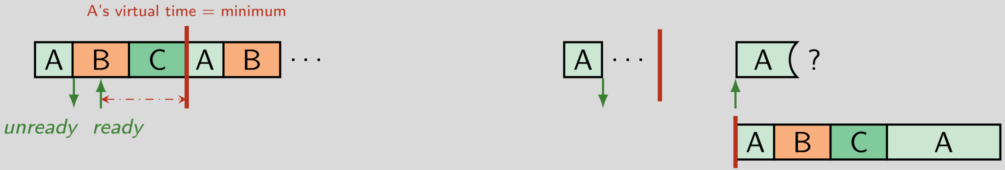
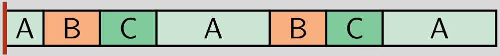


- sleeping time must not affect time-slice length
- **BVT**: increase virtual time to minimum virtual time when thread becomes ready
- proportional share is only maintained for active threads

Latency tuning

How to tune threads for low latency?



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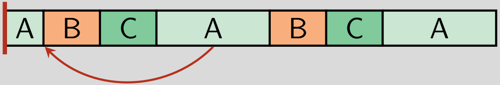

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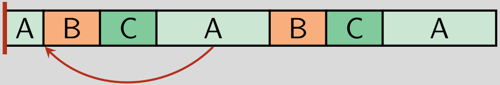

From BVT:

- each thread is assigned a *warp value*
- virtual time of a warping thread is reduced by its warp value
  - thread is preferred in scheduling decision
  - thread's time slice increases by *warp value * weight*

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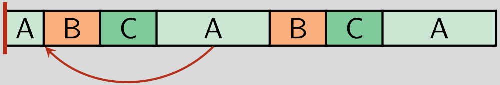

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In Sculpt:

- per-group warp value (hard-coded guesstimate)
- warp state of group derived from thread with lowest virtual time
- fixed time limit for each thread to run with warp enabled without sleeping

Configuration

Configuration

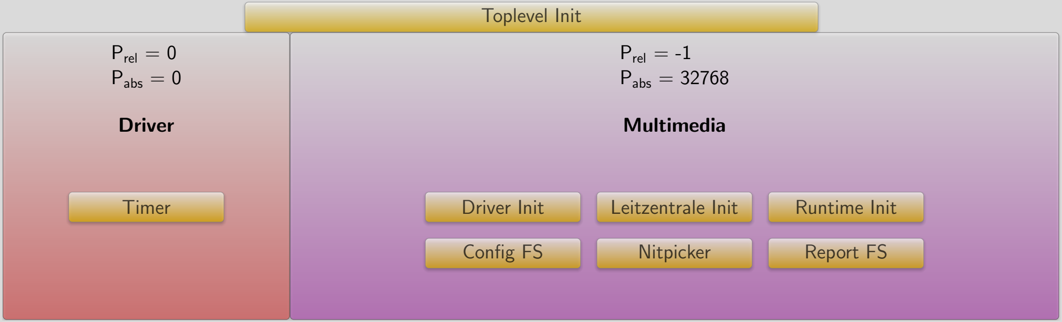
Hard-coded scheduling configuration

- four hard-coded scheduling groups

Group	Weight	Warp
driver	10	4.5ms
multimedia	5	4ms
default	5	2ms
background	1	0ms

- Sculpt's two-level priority hierarchy mapped to groups

Mapping Sculpt's component priorities to scheduling groups



Toplevel Init

P_{rel} = 0
P_{abs} = 0

Driver

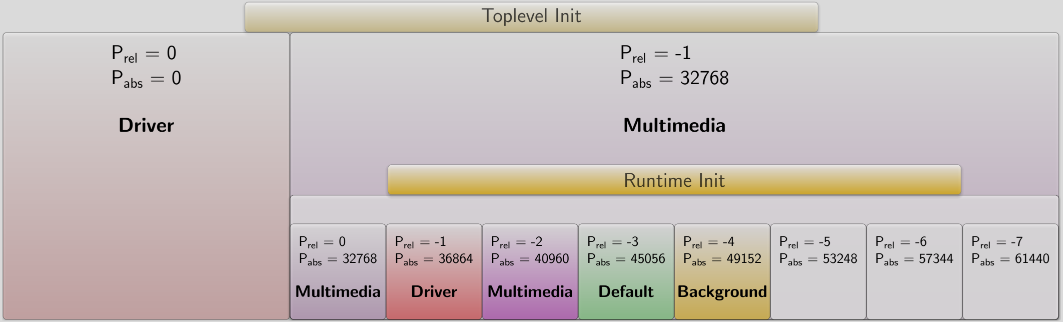
Timer

P_{rel} = -1
P_{abs} = 32768

Multimedia

Driver Init
Leitzentrale Init
Runtime Init
Config FS
Nitpicker
Report FS

Mapping Sculpt's component priorities to scheduling groups



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Runtime Init

$P_{rel} = 0$
$P_{abs} = 32768$
Multimedia

$P_{rel} = -1$
$P_{abs} = 36864$
Driver

$P_{rel} = -2$
$P_{abs} = 40960$
Multimedia

$P_{rel} = -3$
$P_{abs} = 45056$
Default

$P_{rel} = -4$
$P_{abs} = 49152$
Background

$P_{rel} = -5$
$P_{abs} = 53248$

$P_{rel} = -6$
$P_{abs} = 57344$

$P_{rel} = -7$
$P_{abs} = 61440$

Demo

Live demo

Summary

- implementation matches expectations
  - in benchmarks
  - in user experience on Sculpt
- side-effect: reworked base-hw internals
- minimal configuration burden for Sculpt OS users
- groups and group-parameters hard-coded but configurable in framework

Sculpt OS 25.10 image with base-hw for x86_64

`https://depot.genode.org/skalk/image/sculpt-pc-2026-01-29.img.xz`

References

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https://github.com/genodelabs/genode/issues/5117

GitHub Issue #5604 (Evaluation)
https://github.com/genodelabs/genode/issues/5604

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FOSDEM 2017 talk on base-hw
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