Thread Scheduling in Multi-core Operating Systems

How to Understand, Improve and Fix your Scheduler

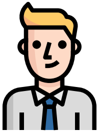
Redha Gouicem

Thesis defended on the 23rd of October 2020 before a jury composed of:

Mr. Pascal Felber, Full Professor, Université de Neuchâtel	*Reviewer*
Mr. Vivien Quéma, Full Professor, Grenoble INP (ENSIMAG)	*Reviewer*
Mr. Rachid Guerraoui, Full Professor, École Polytechnique Fédérale de Lausanne	*Examiner*
Ms. Karine Heydemann, Associate Professor (HDR), Sorbonne Université	*Examiner*
Mr. Etienne Rivière, Full Professor, Université Catholique de Louvain	*Examiner*
Mr. Gilles Muller, Senior Research Scientist, Inria	*Advisor*
Mr. Julien Sopena, Associate Professor, Sorbonne Université	*Advisor*

SORBONNE UNIVERSITÉ

Office worker



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Office worker
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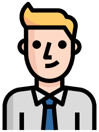

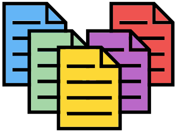

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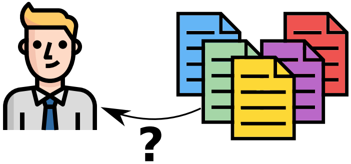

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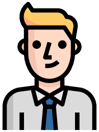

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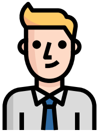

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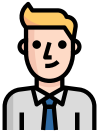

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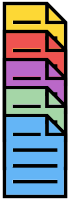

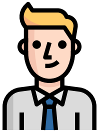

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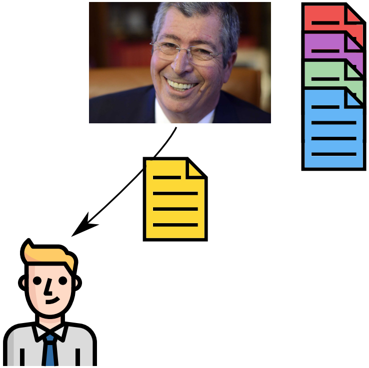

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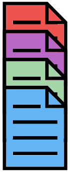

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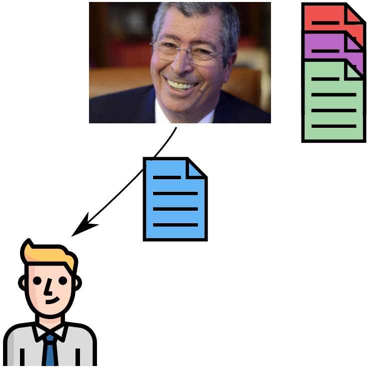

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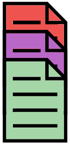

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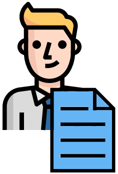

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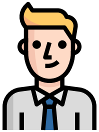

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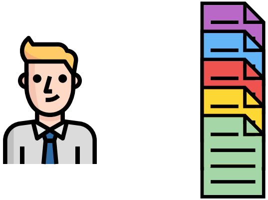

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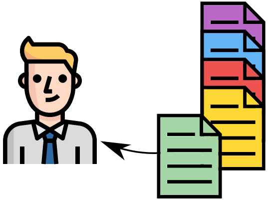

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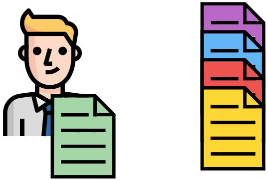

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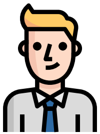

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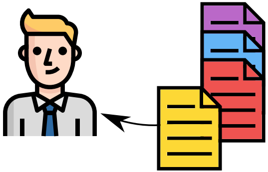

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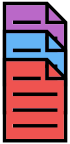

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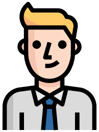

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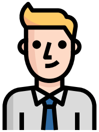

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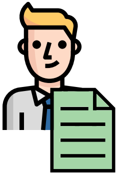

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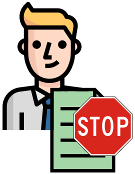

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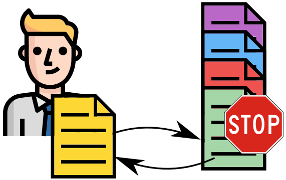

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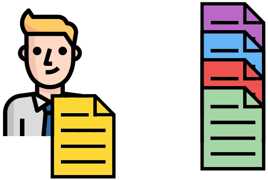

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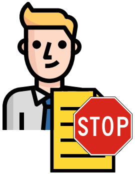

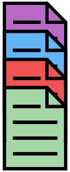

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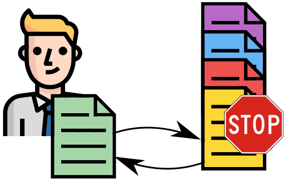

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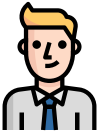

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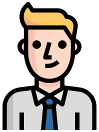

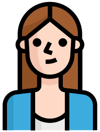

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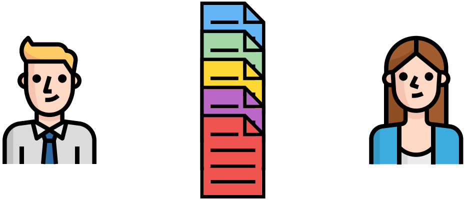

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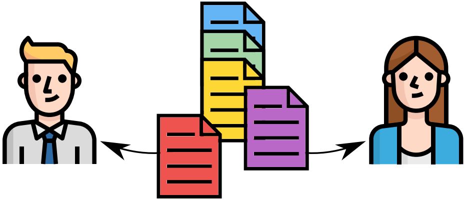

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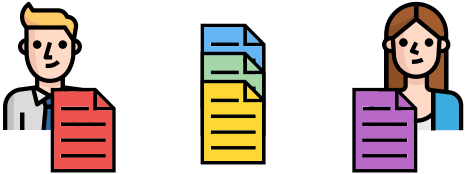

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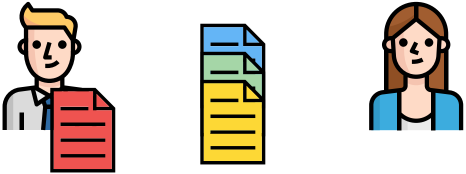

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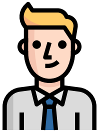

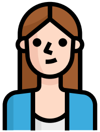

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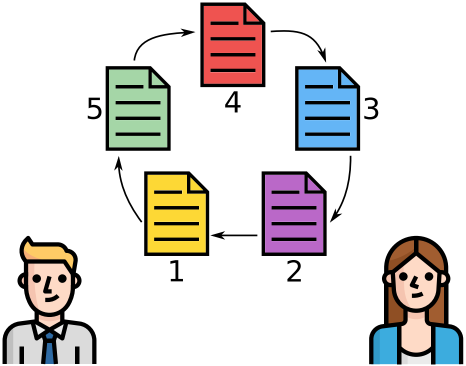

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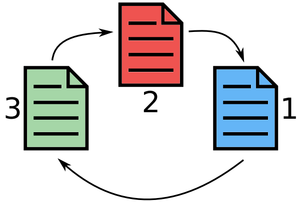

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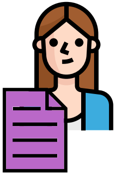

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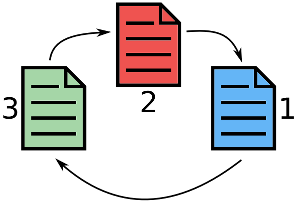

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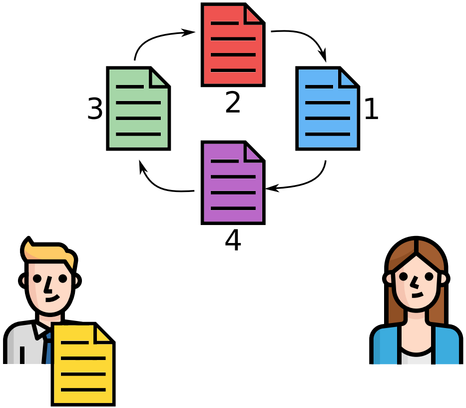

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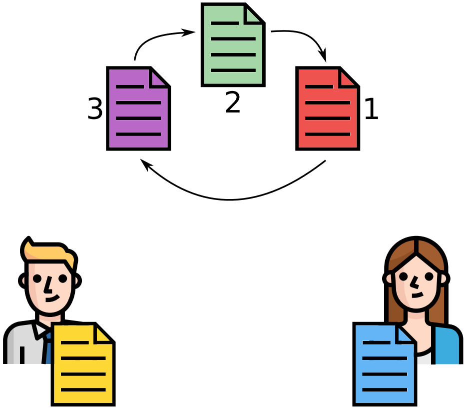

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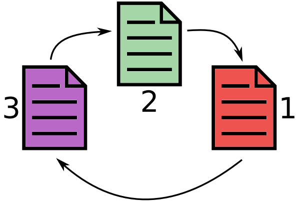

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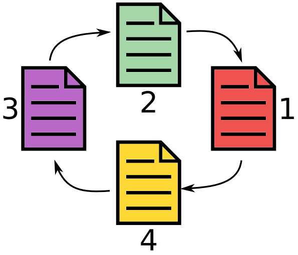

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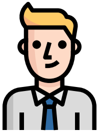

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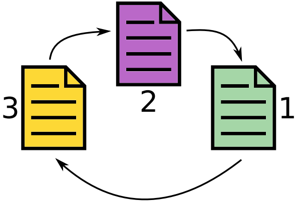

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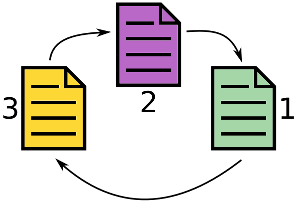

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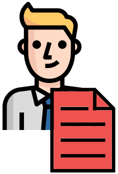

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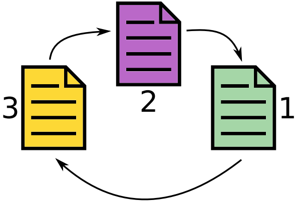

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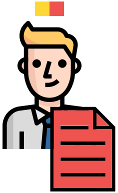

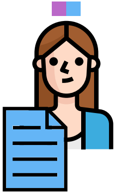

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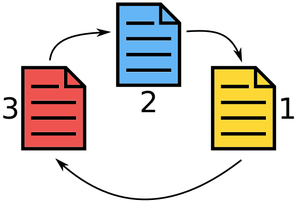

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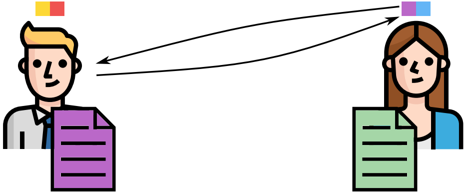

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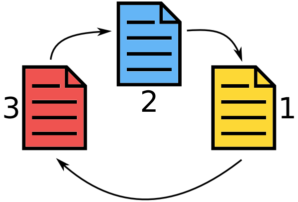

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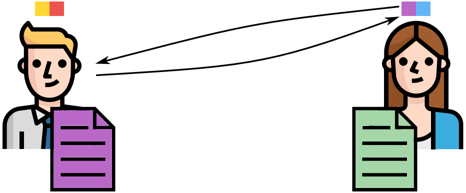

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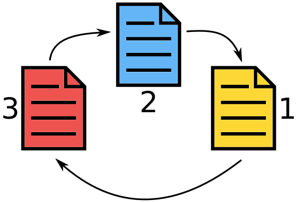
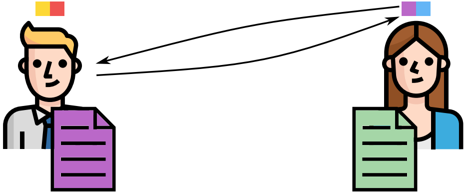
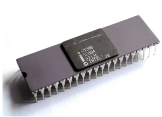
2000s: Heterogeneous architectures, SMT, frequency scaling, . . .





When Schedulers Answer to Hardware Evolution



Single core	Time management	batch processing preemption time sharing

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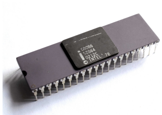

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Multi-processors
Multi-core
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Placement management { shared resources, contention, latency

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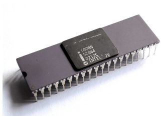

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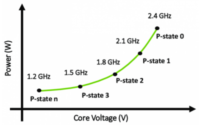

Dynamic frequency
Heterogeneity

Feature management
- perf/energy ratio
- different capabilities

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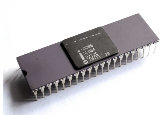

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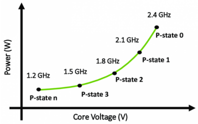

Dynamic frequency
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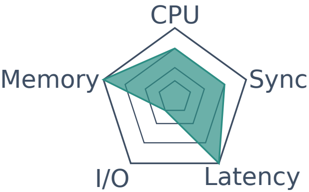
Resources are more and more complex to manage!

Application Requirements



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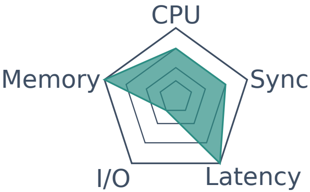

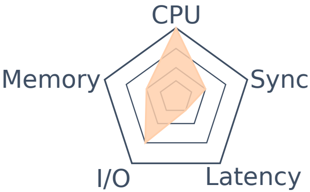

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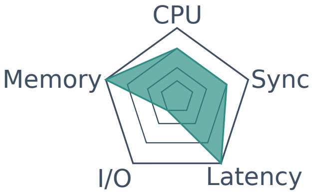

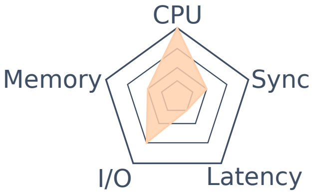

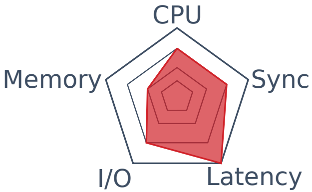

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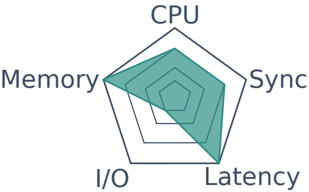

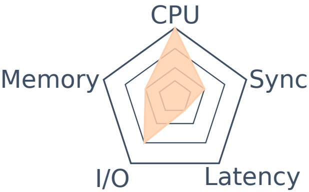

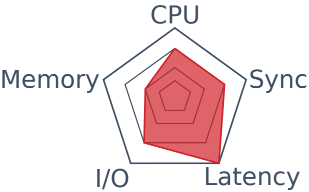

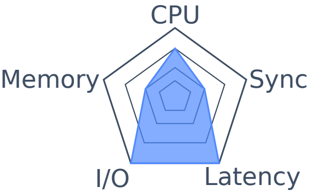

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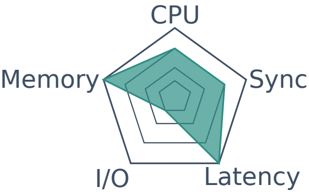
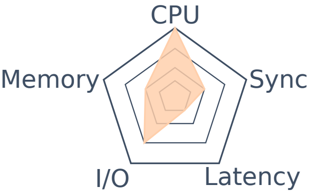
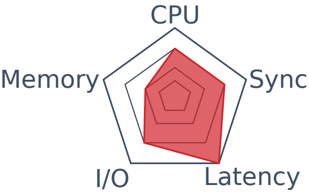
MEMCACHED

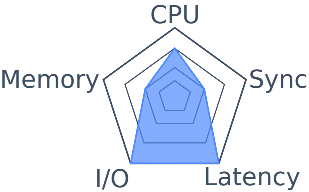




GCC

APACHE





NordVPN®

Requirements vary greatly from one application to another!

How do we satisfy these varying application requirements on all available hardware features?

Application-Specific	**General-Purpose**
✗ Impractical, requires lots of human power.	✔ Easier to maintain, ✗ but more and more complex.
We cannot make 1,000 schedulers for a 1,000 applications, but we can make 1 scheduler for a 1,000 applications. – S. Karamazov, probably	Most OSs implement a single scheduler (Linux, FreeBSD, Windows, OS X)

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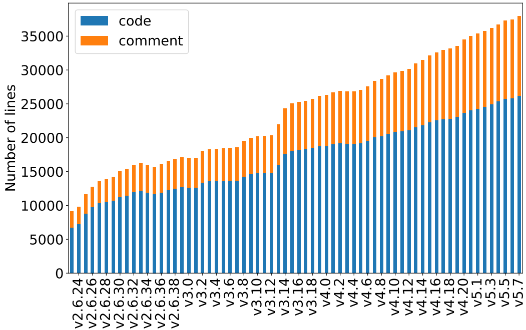

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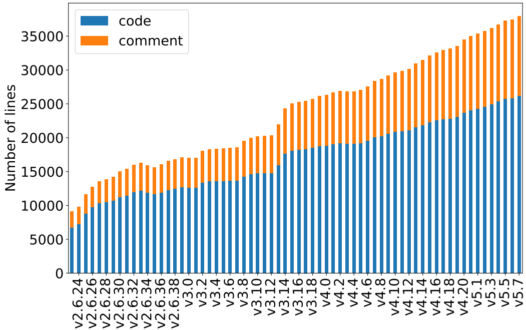

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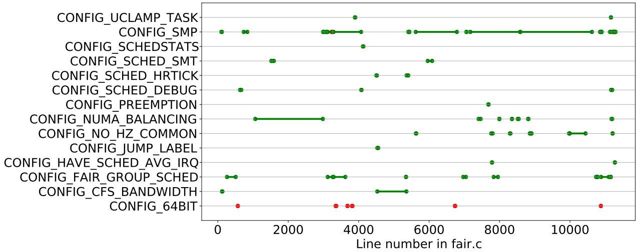

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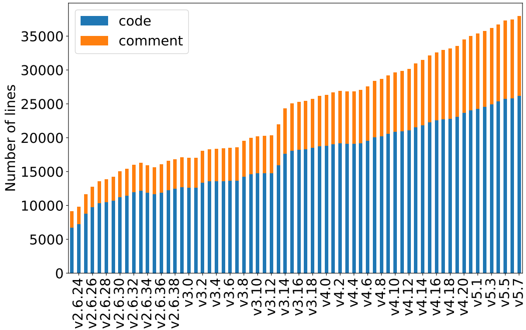

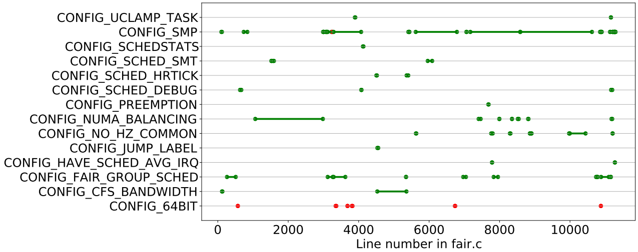

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Maintenance and configuration are hard and impractical

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How can we help **developers** implement **efficient** schedulers in a **safe** and **easy** way?

How can we help **users** get the best **performance** for their applications?

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Axis 1

Scheduler Development

Writing Schedulers

Developing an efficient scheduler is a **daunting** task, with various skills needed:

- Knowledge of scheduling
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- Low-level programming skills

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We propose **Ipanema**, a **Domain Specific Language** for multi-core schedulers.

The **compiler** takes **Ipanema source code** and outputs two targets:

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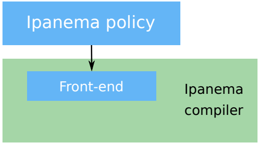

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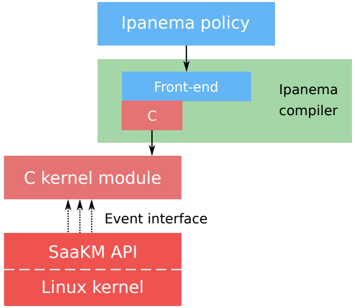

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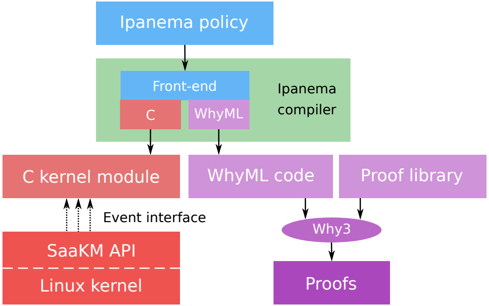

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The **Ipanema DSL** abstracts **multi-core scheduling** for developers.

Two main features:

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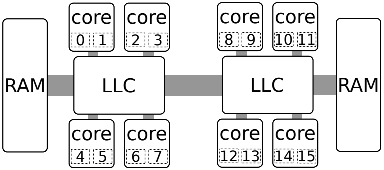

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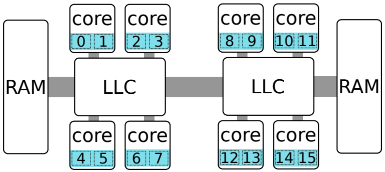

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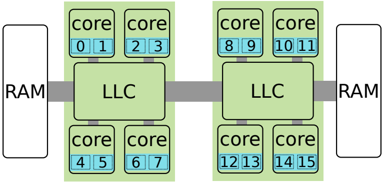

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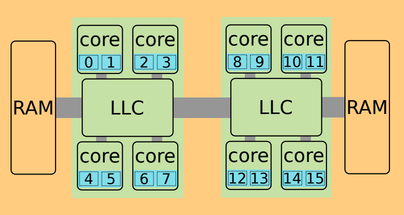

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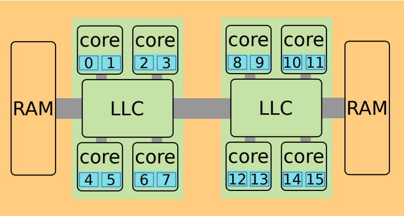

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We need a hierarchical load balancer!

Load Balancing in Ipanema

Balancing is abstracted into **3 phases**, most of the code is **generated** by the compiler.

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steal_for(dst):
    stealable_cores = {}
    foreach c in all_cores
        if can_steal_core(c, dst)
            stealable_cores.add(c)
```
PHASE 1

Phase 1: Finding stealable cores (lockless).
can_steal_core() is user-defined

Phase 2: Selecting the target core (lockless)
select_core() and **stop_steal** are user-defined

Phase 3: Stealing threads from target (**with locks**)
steal_thread() and **stop_steal_core** are user-defined

Minimal locking for performance and
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        src = select_core(stealable_cores)
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        foreach t in src.runqueue                  ┐        PHASE 3
            if steal_thread(t, src, dst)           │
                src.runqueue.del(t)                │ src
                tmp_rq.add(t)                      │
            if stop_steal_core                     │
                break                              ┘
        foreach t in tmp_rq                        ┐ dst
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The Ipanema Language

Easy to learn **C-like syntax**, **7 handlers** to write (thread transitions) + balancing.

```
On unblock {
    core c = first(active_cores order = { lowest nr_tasks } );
    e.target => c.ready;
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Ipanema policies are:

- **small** in Ipanema
- **smaller than CFS** in generated C code
- **standard library** with data structures and helpers (SaaKM: 1,527 lines of code)

Policy	Ipanema	C
CFS (vanilla, baseline)		5,712
CFS-CWC	360	1,006
CFS-CWC-FLAT	242	791
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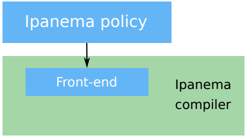
This module is inserted in a modified Linux kernel featuring **SaaKM**, the Scheduler as a Kernel Module interface.



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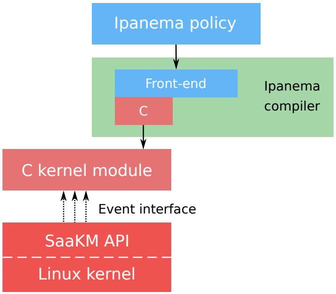

Scheduling Class VS SaaKM

Linux scheduling class API

- ✗ Designed with CFS in mind
  → **no genericity**
- ✗ Schedulers are **built-in** the kernel binary
  → hard to distribute 1,000s of schedulers
  → statically enabled
- ✗ **Poorly documented and specified**
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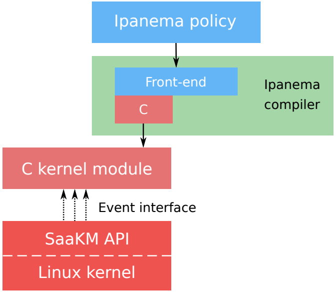

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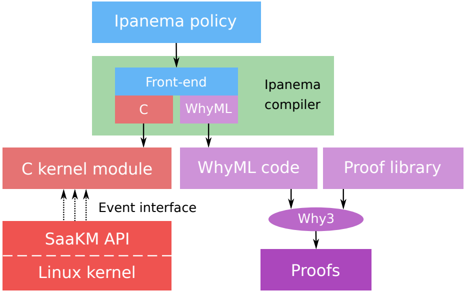

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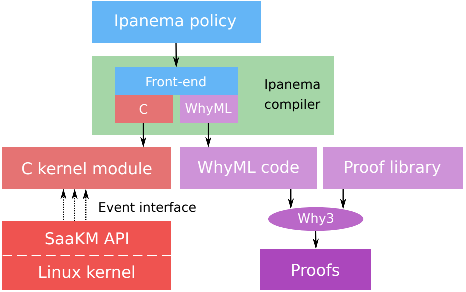

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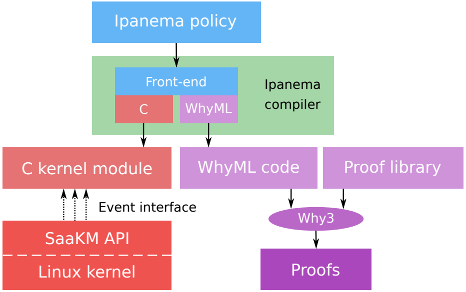

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Evaluating the Ipanema System

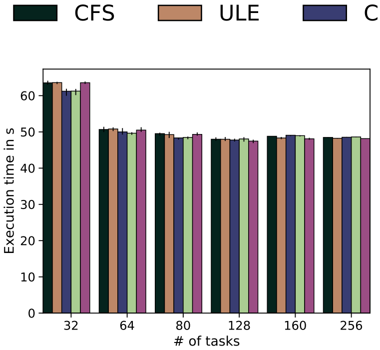
Experimental setup:

- Intel Xeon E7-8870 v4 (4 sockets, 160 cores with SMT enabled)
- 512 GiB of RAM
- OS: Debian Buster
- Kernel: Linux 4.19 with the SaaKM interface
- Applications: NAS benchmark, kernel build, OLTP with MySQL and MongoDB

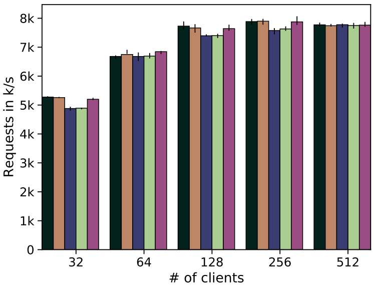
Scheduling policies:

- `CFS`: vanilla 4.19 scheduler, used as a baseline
- `CFS-CWC`: simplified and work-conserving version of CFS written in Ipanema
- `CFS-CWC-FLAT`: same as `CFS-CWC` with a flat topology
- `ULE` and `ULE-CWC`: simplified versions of the FreeBSD scheduler written in Ipanema

Evaluating the Ipanema System: Kernel Build and Database



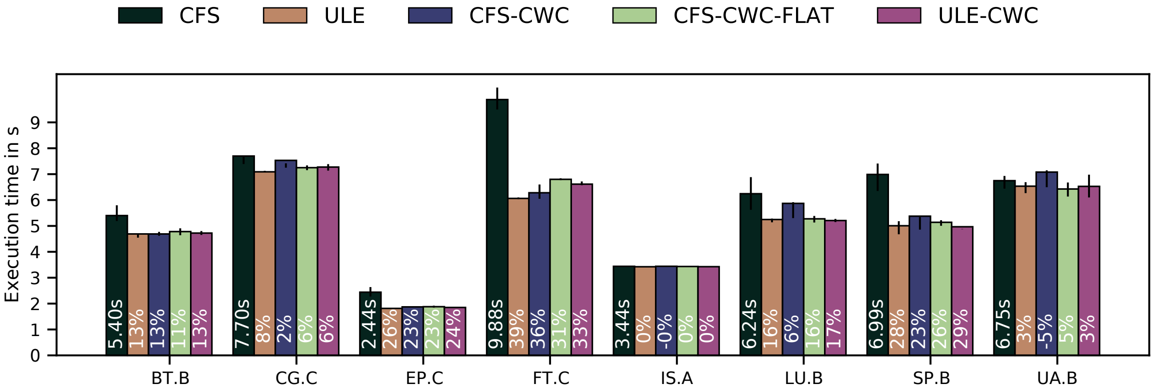
Kernel build



sysbench OLTP with MongoDB (throughput)

Ipanema policies are on par with CFS on these applications.

Evaluating the Ipanema System: the NAS Benchmark



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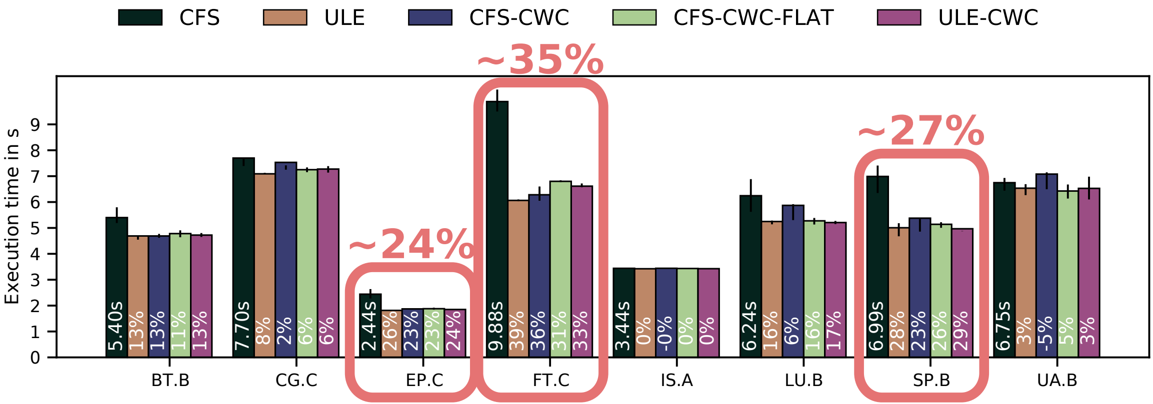

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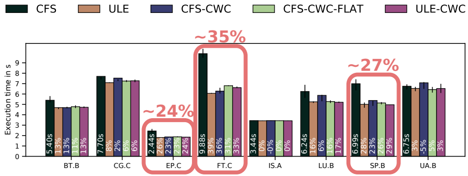

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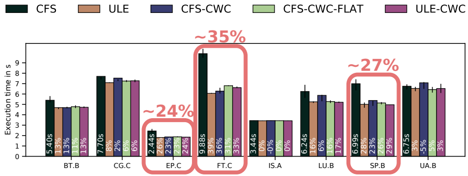
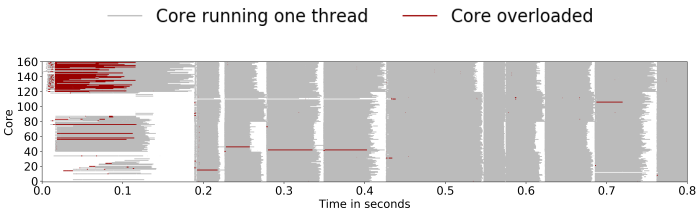
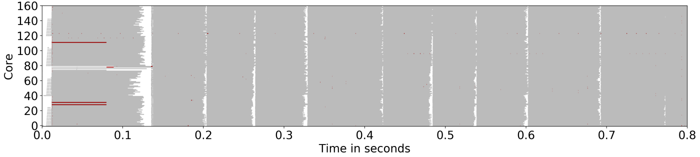




CFS



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Scheduler Development

1. **Ipanema DSL**
    - Abstracts scheduling concepts
    - Easy development, no low-level C code skills required
    - Allows the production of small efficient schedulers
2. **SaaKM interface**
    - Easy to use event-based interface
    - Scheduler hot plugging
    - Syscall and cgroup user interfaces
3. **Property verification** (collaboration)
    - The Ipanema DSL is tailored to help produce WhyML proofs
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Perspectives

- Extend the standard library (new data structures)
- Enable the development of meta-schedulers

Axis 1: Contributions

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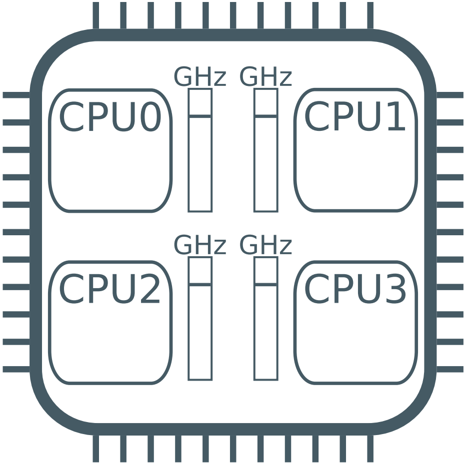
Axis 2

Performance Enhancement

Dynamic Frequency Scaling



The frequency of a CPU:

- depends on the load
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  $\Rightarrow$ the load of **one** core impacts the frequency of **all** cores on the chip

When all CPUs are fully loaded, **nominal frequency** is guaranteed.

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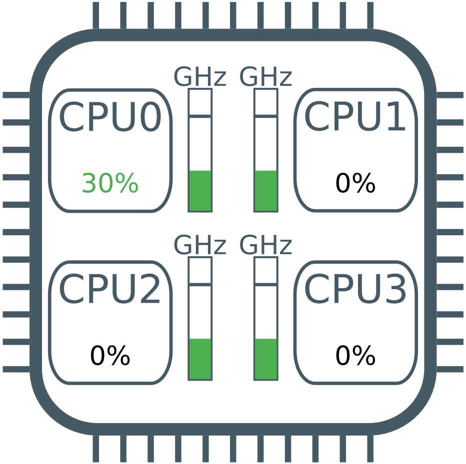

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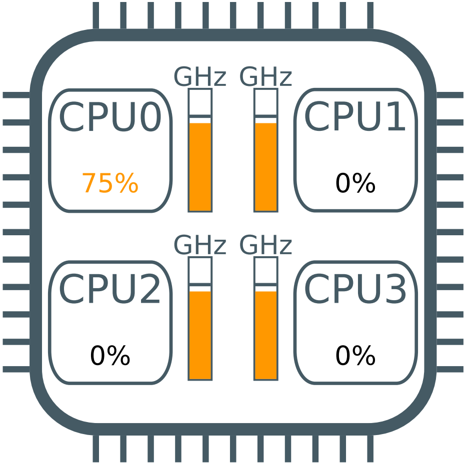

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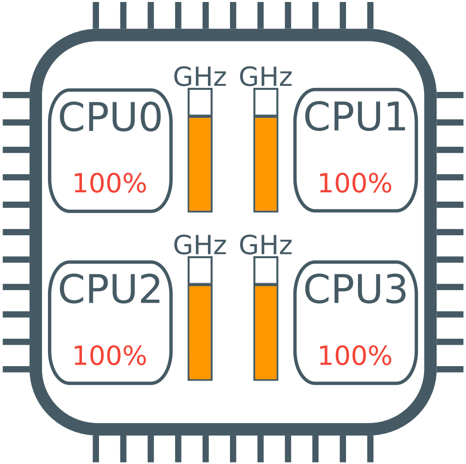

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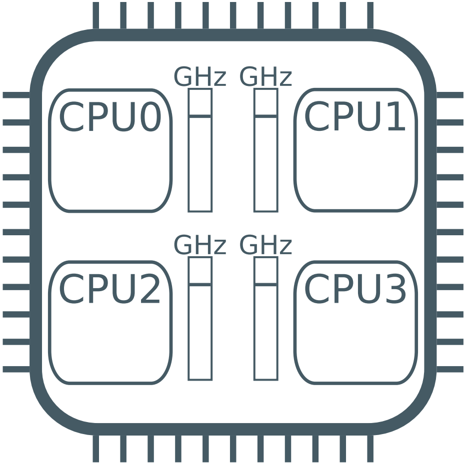
Dynamic Frequency Scaling on Modern Processors



On modern chips, frequency is managed **per core**:

- Intel Cascade Lake (2019)
- AMD Ryzen (2019)

Each core sets **its** frequency to match **its** load. **Idle cores** run at the **minimal frequency** while busy cores use higher frequencies.

⇒ Energy savings

Turbo mode: when some cores not active, busy cores can use even higher frequencies

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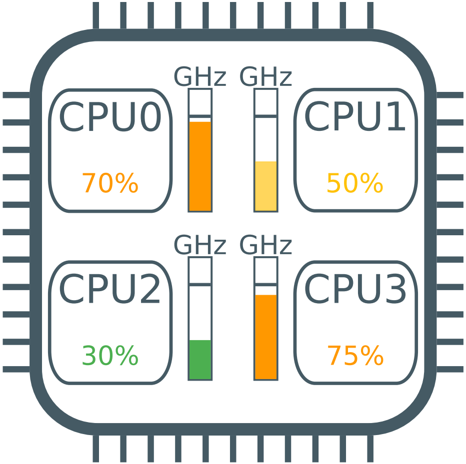

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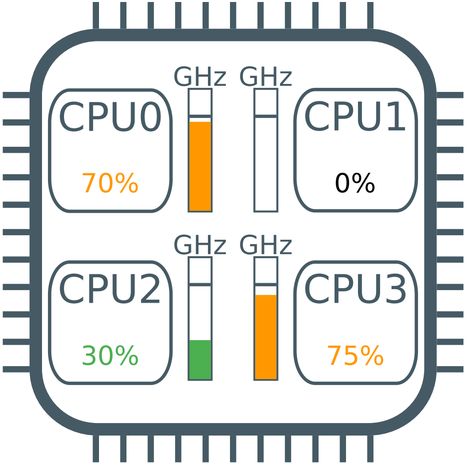

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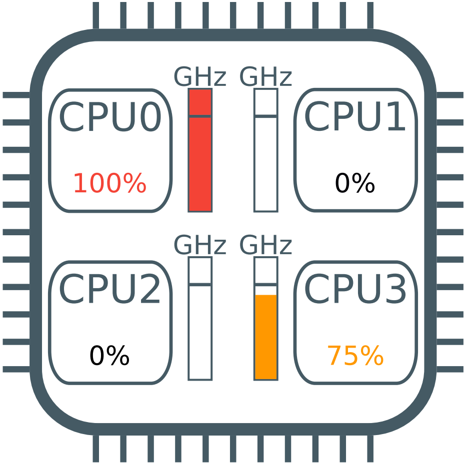

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- Linux *scaling governors* (ondemand, schedutil)
- hardware frequency scaling (e.g. Intel HWP)

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- maximize the instructions per joule metric (Weiser'94 [2])
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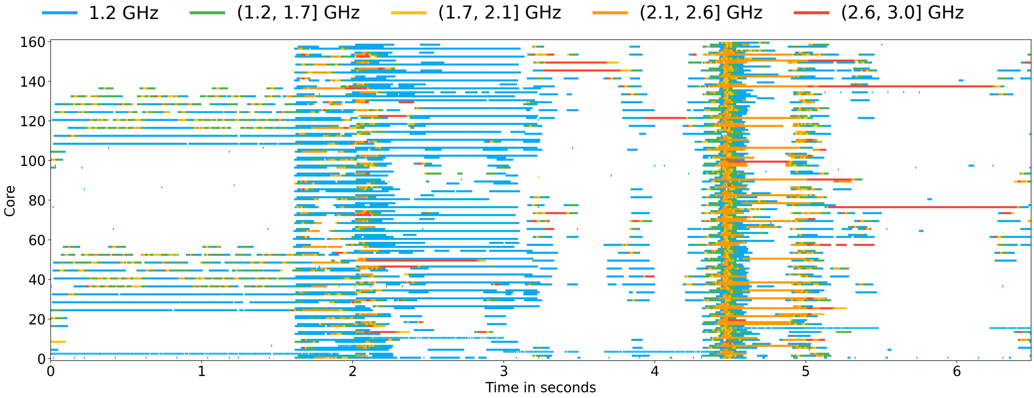

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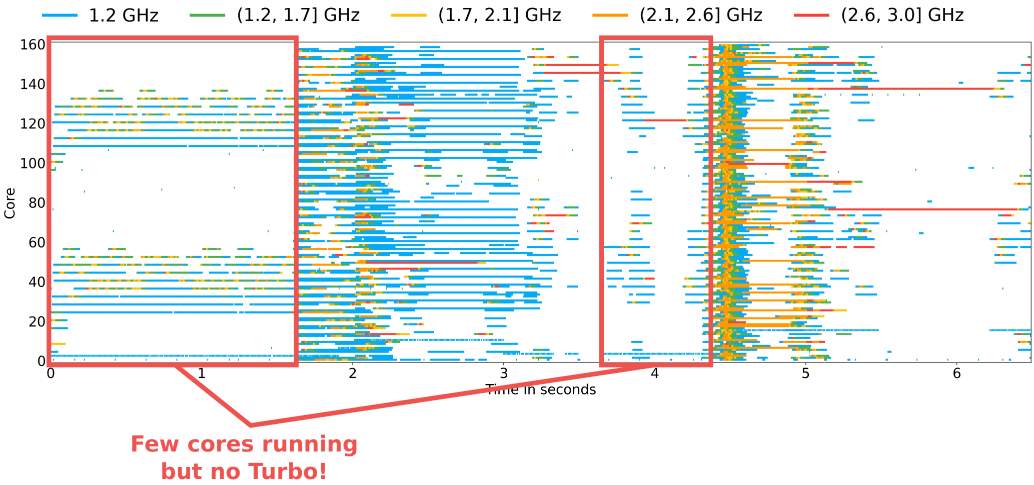

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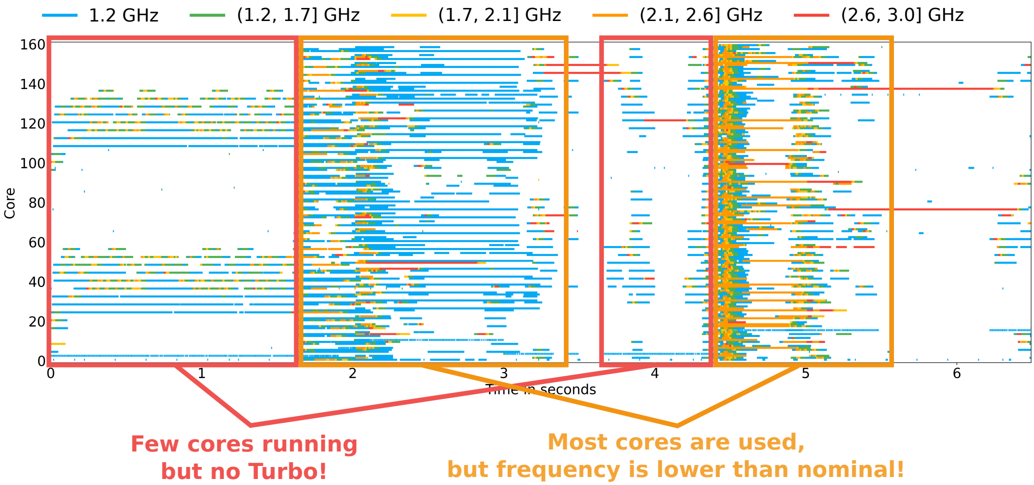

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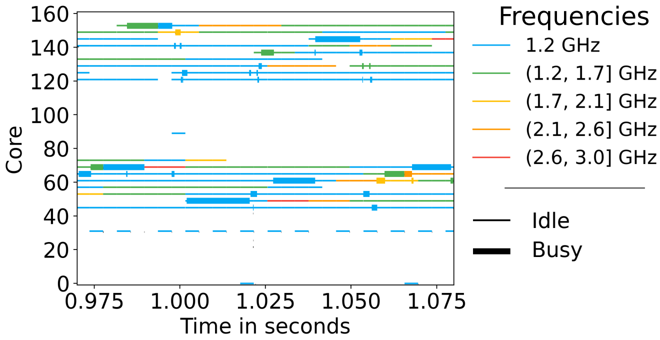

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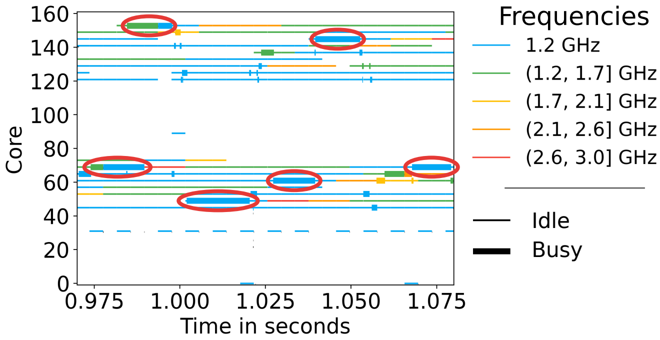

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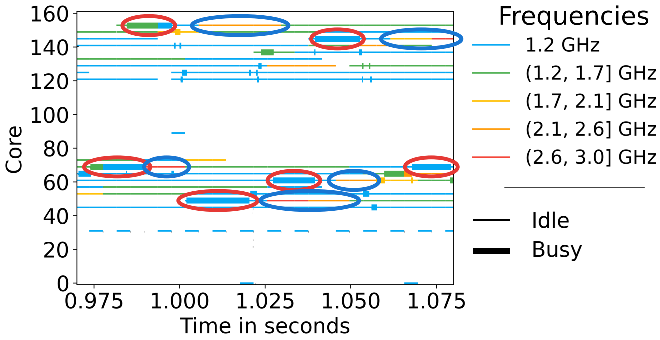

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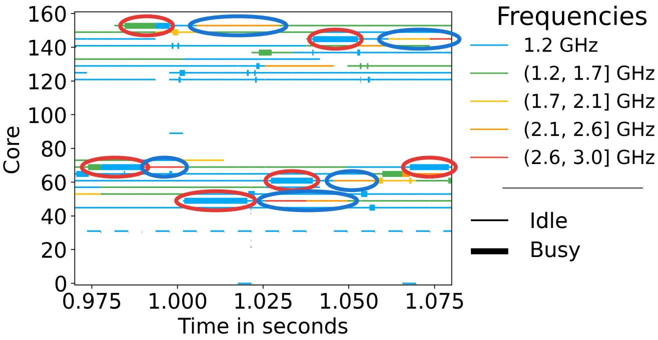

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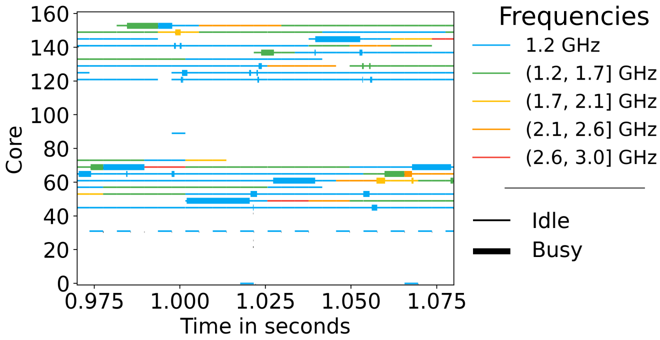

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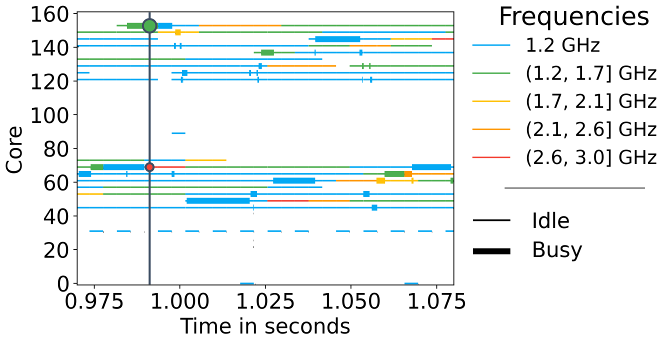


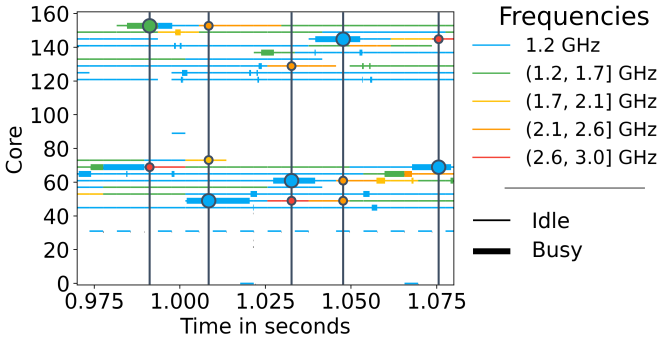
Case Study: Zooming in the Trace

Busy at low frequency
Idle at high frequency

Frequency scaling is too late to be effective!

Busy, low frequency
Idle, high frequency

Better suited cores are available!



Frequency Transition Latency

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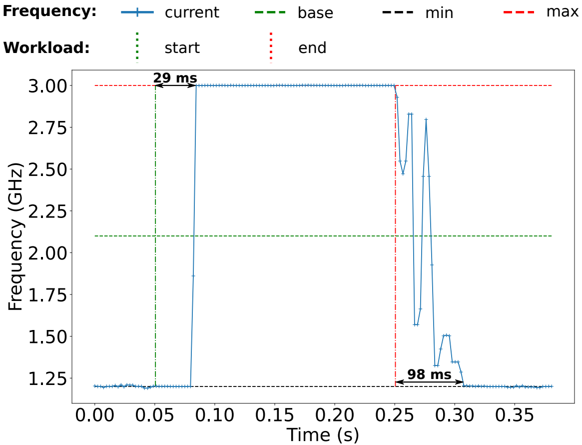
Infinite loop on a single core,
from idleness to 100% load, resp.
from min to max frequency.

0%	→	100%	:	**29 ms**
100%	→	0%	:	**98 ms**



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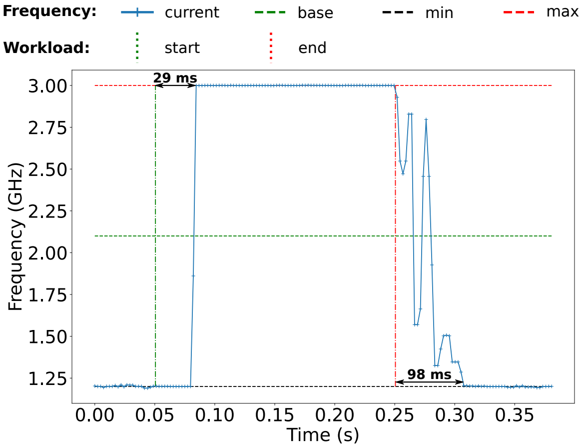
Changing frequency is not instantaneous!



CFS and the Fork/Wait Pattern

C_0 C_1 C_2 C_3

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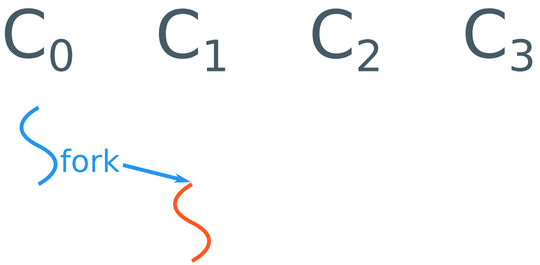
CFS tries to be **work conserving**
→ new and waking threads are placed on **idle** cores if available



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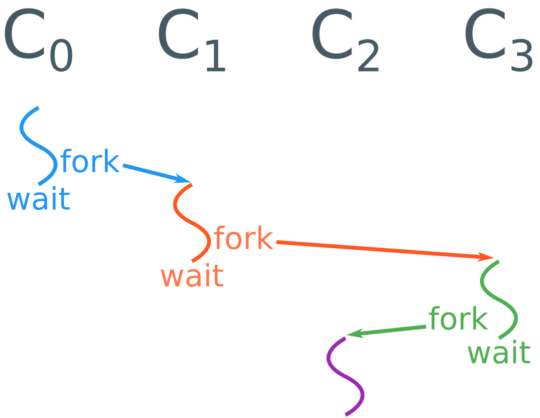

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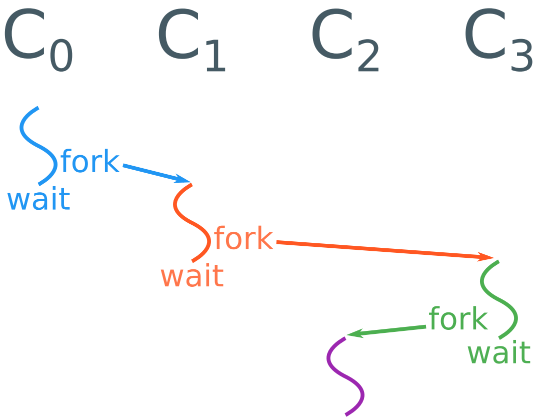
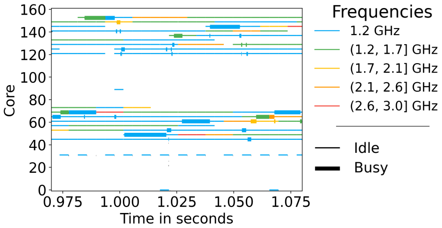
A **sequential** workload uses **multiple CPUs**!



Problem: Frequency Inversion

Long FTLs



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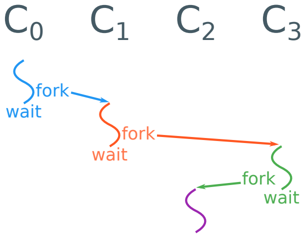
Work conserving scheduler



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The frequencies at which two cores operate are inverted as compared to their load

Solution: Delayed Thread Migration

We propose $\mathbf{S_{move}}$: delaying thread migrations on fork/wakeup.

Parent thread runs on C_0, calls the `fork()` syscall. CFS decides to place **child thread** on C_1.

If C_1 runs at a **low frequency**, instead of placing the **child thread** on C_1, we arm a timer that expires in 50 μs and place the **child thread** on C_0.

When the timer is **triggered** 50 μs later, we migrate the **child thread** to C_1.

We only lose 50 μs compared to CFS.
Without the timer, periodic load balancing would have fixed this situation in tens of milliseconds.

C_0 C_1

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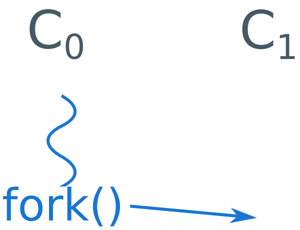

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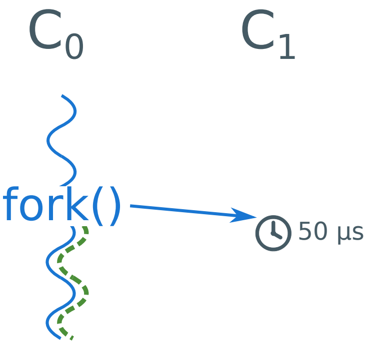

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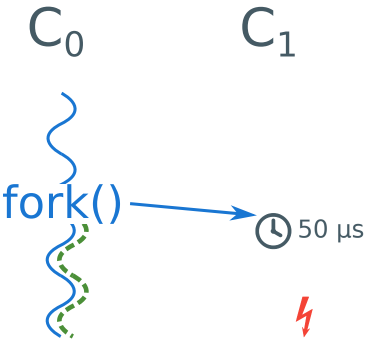

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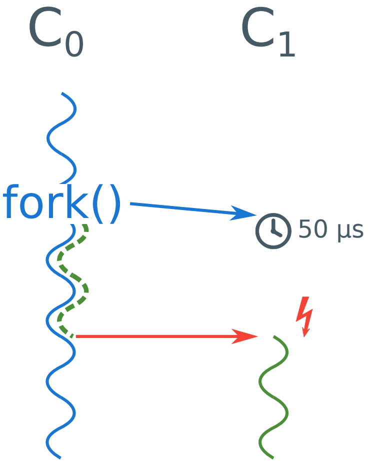

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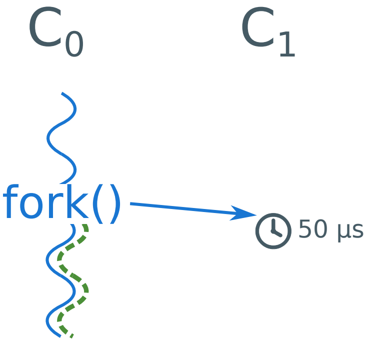

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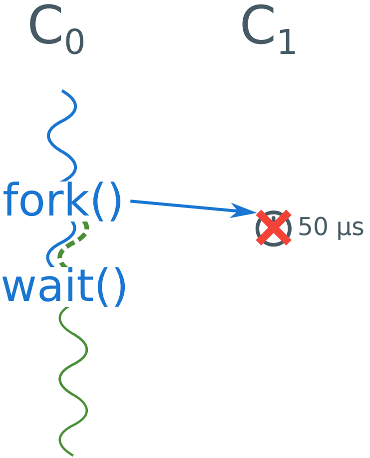

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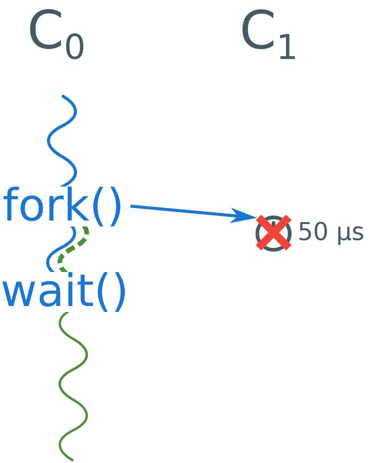

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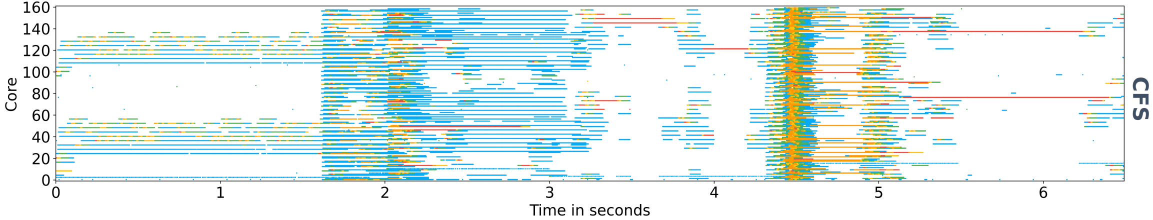

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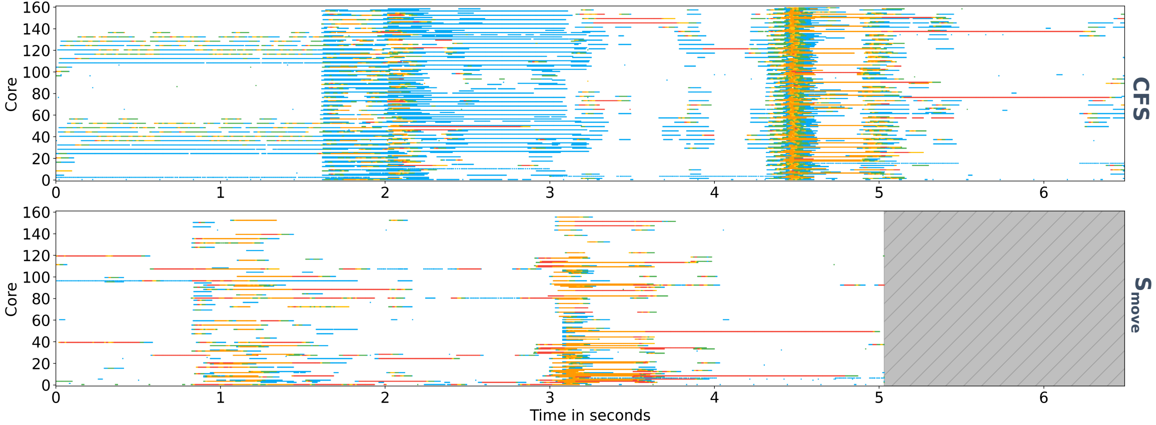

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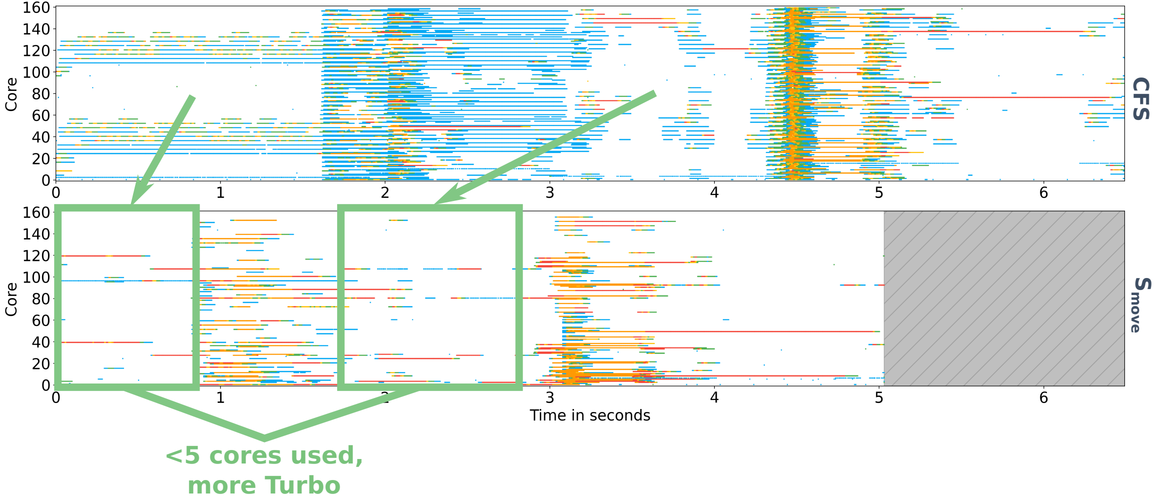

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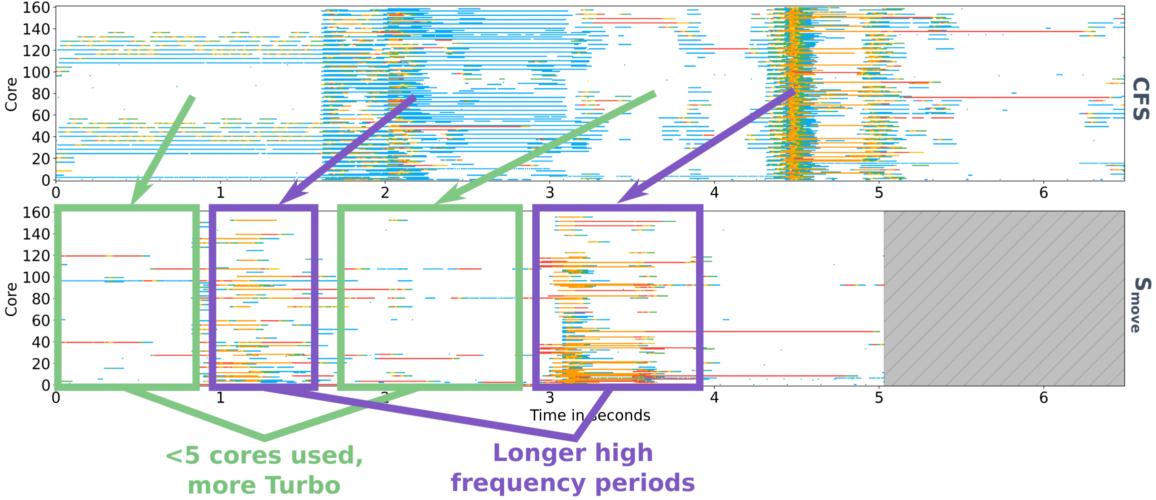

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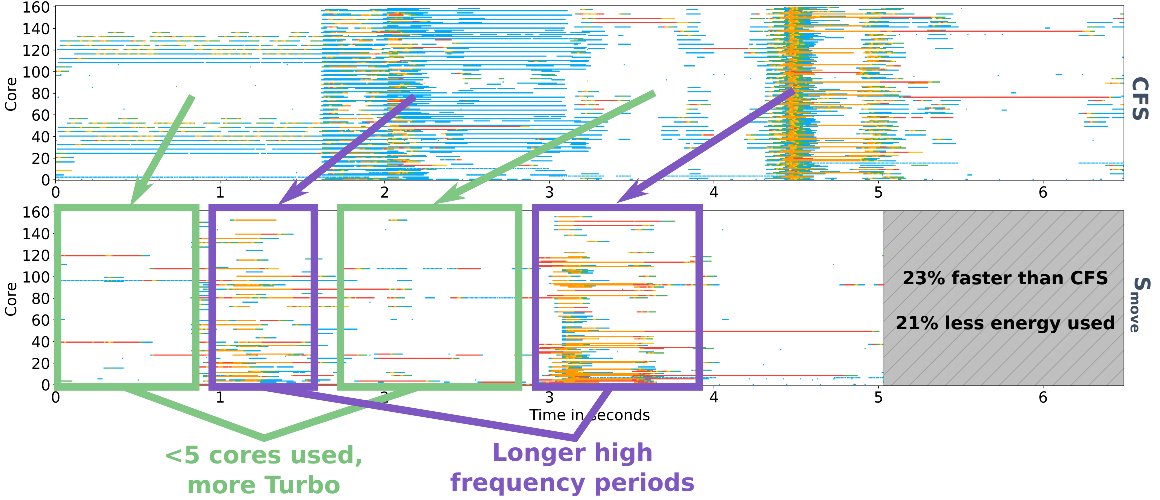


Performance and Energy Evaluation

Hardware:

- **Server**: 80-core Intel Xeon E7-8870 v4 (160 HW threads)
- **Desktop**: 4-core AMD Ryzen 5 3400G (8 HW threads)

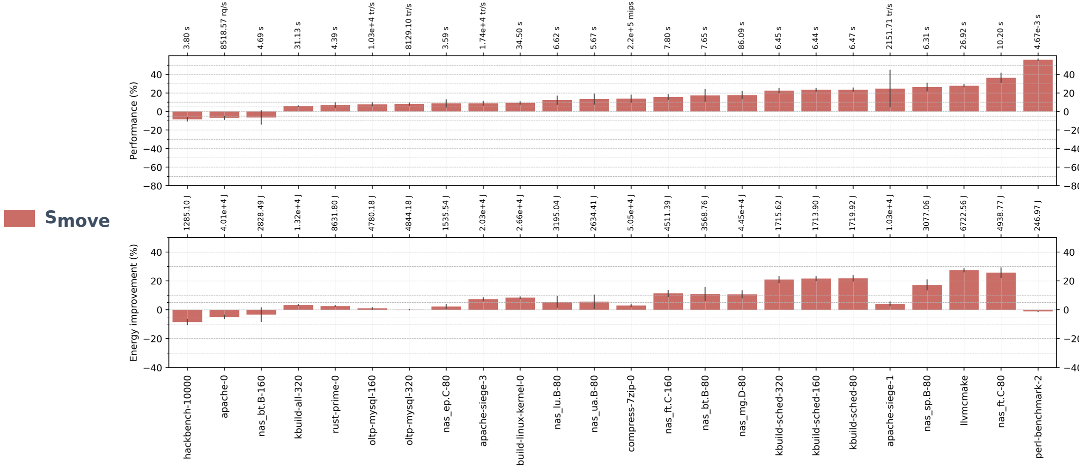
Benchmarks: 60 applications from

- NAS: HPC applications
- Phoronix: web servers, compilations, DNN libs, compression, databases, ...
- hackbench and sysbench OLTP

Frequency scaling governors:

- powersave
- schedutil

Compared to CFS, server machine, powersave governor, higher is better



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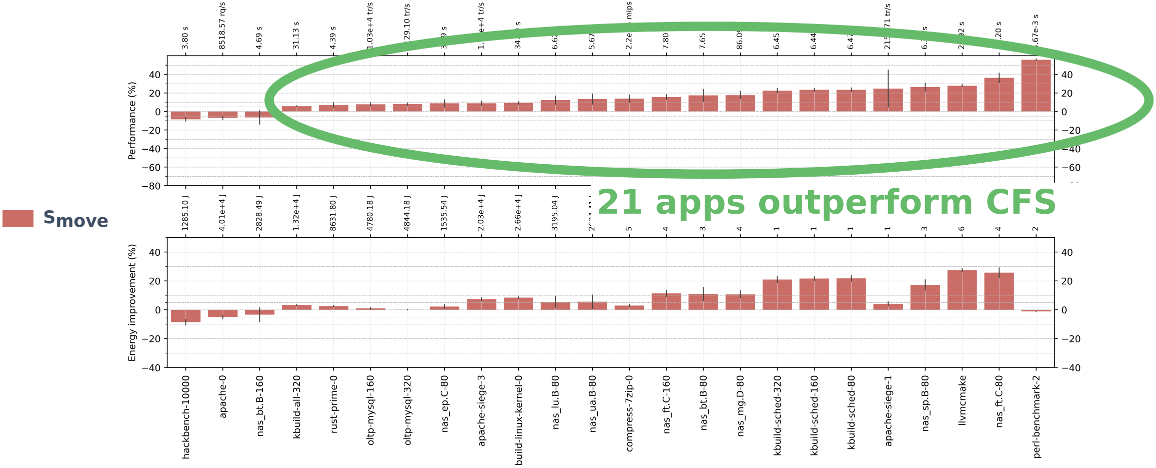

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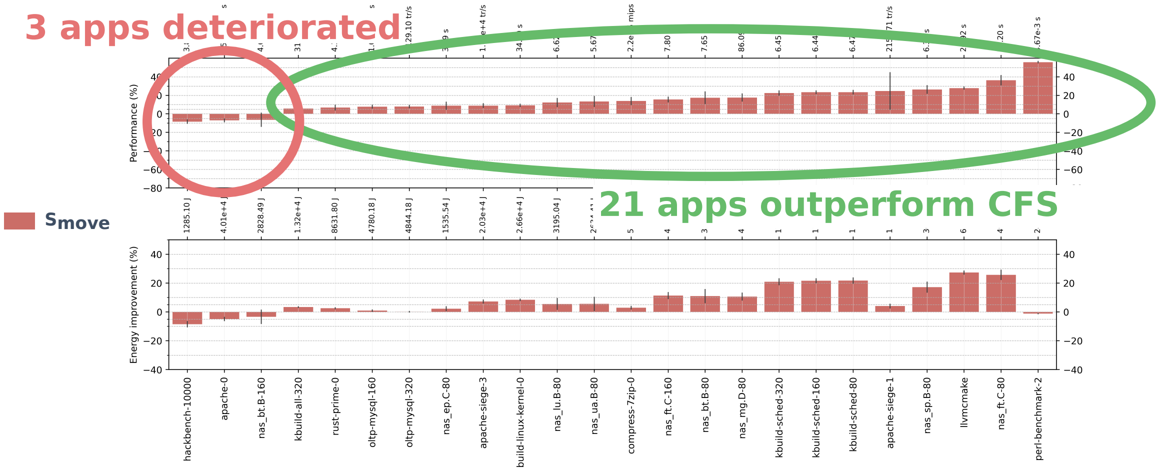

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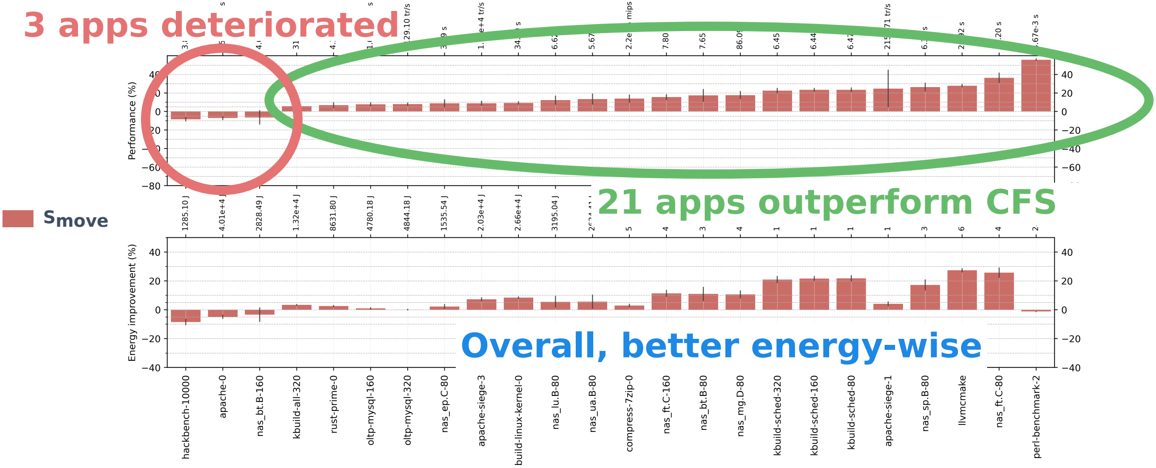

Performance Enhancement

1. **Monitoring tools** for the scheduler subsystem
2. Discovery of the **frequency inversion problem**
   - Long FTLs + work conserving scheduler
   - New problem with per-core dynamic frequency scaling
3. **Two solutions implemented in Linux**
   - S_{local}: simple, aggressive, relies on load balancing
   - S_{move}: frequency-aware, efficient. Submitted to the Linux kernel community

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- Fully frequency-aware scheduler
- Modeling the frequency behavior of CPUs (active cores, temperature, instruction set, . . .)
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Axis 3

Application-Specific Schedulers

Fifty Shades of Scheduling

Scheduling comes in various flavors:

- fair (CFS, ULE)
- enforce real-time deadlines (EDF)
- optimize data locality
- reduce contention on caches, memory, disks, . . .
- and so on . . .

One Scheduler Cannot Rule Them All . . .

Existing studies show varying levels of performance depending on the application.

- blog posts from users (e.g. PostgreSQL)
- comparisons from the benchmarking community (e.g. Phoronix)
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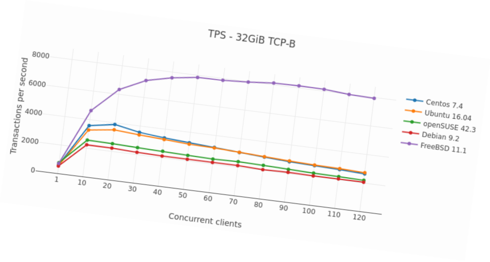

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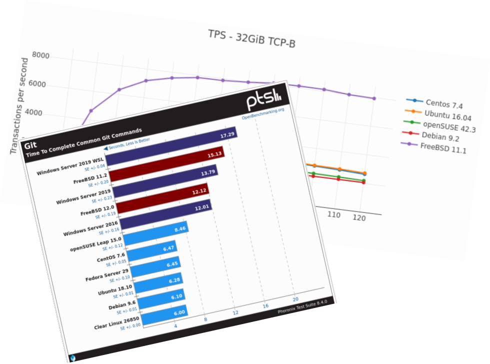

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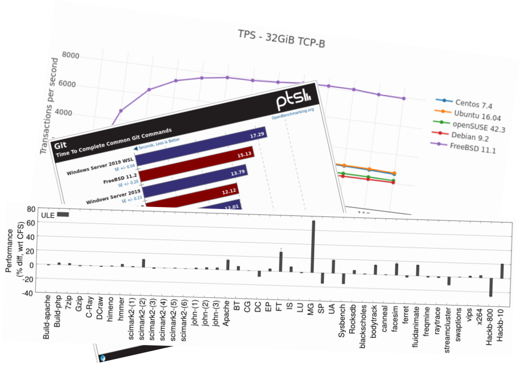

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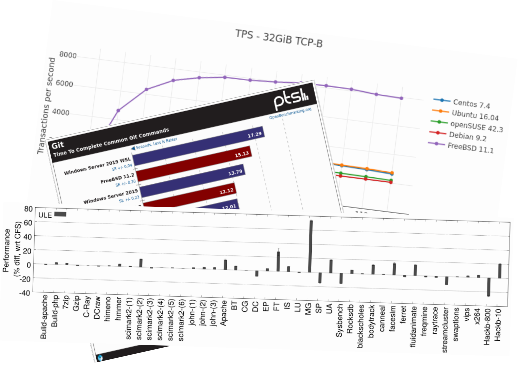

There is no silver bullet in scheduling!

Building Application-Specific Schedulers

Could we leverage Ipanema and SaaKM to write application-specific schedulers?

We propose the following approach:

- Develop a **feature-oriented model** of schedulers
- Implement a **library of features** to build modular schedulers
- Propose an **evaluation methodology** for these produced schedulers
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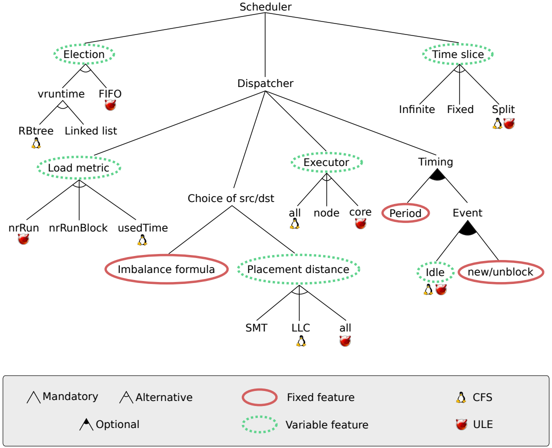
Scheduler Feature Model

Model



Implementation

Implemented as a **kernel library**.

SaaKM compliant.

Features are **independent** from each other.

16 features in current model
→ **486 combinations** can be generated.

Experimental Setup

Hardware:

- CPU: Intel Xeon E5645 (12 cores, 24 HW threads, 2 sockets)
- RAM: 64 GiB
- OS: Debian 8 with Linux 4.19 kernel

Applications:

- 7 *PARSEC* applications
- 7 *Phoronix* applications
- 2 *HiBench* applications
- 3 *sysbench* applications
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Each application is run **10 times** with each scheduler

Total experiment time of **1,925 hours**, distributed on 8 identical machines

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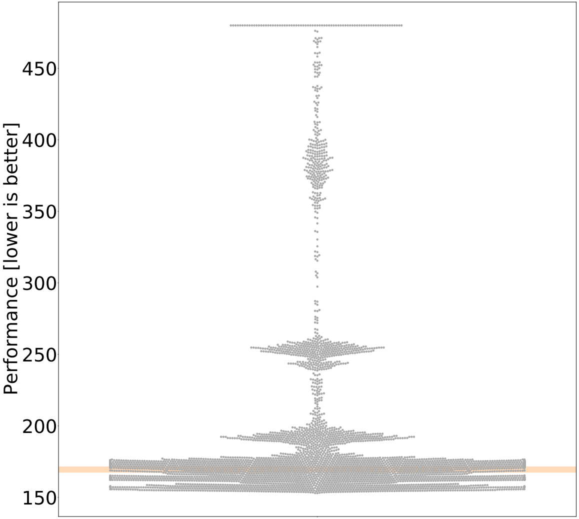
Feature Evaluation: the `facesim` Example



Initial state: (*facesim application*)

- 10 runs × 486 schedulers = **4,860 points**
- **CFS** as a baseline, in the background.

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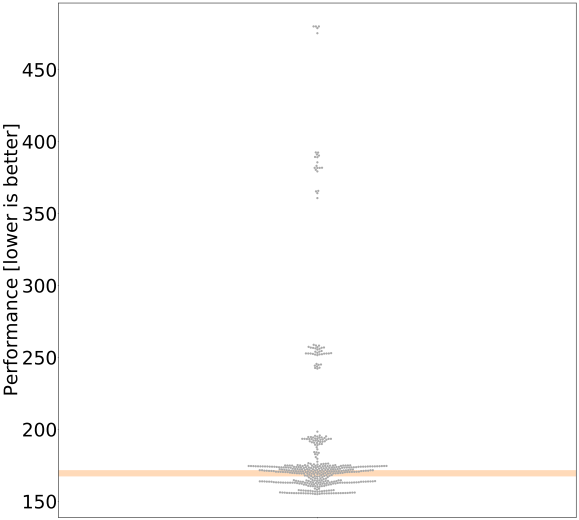

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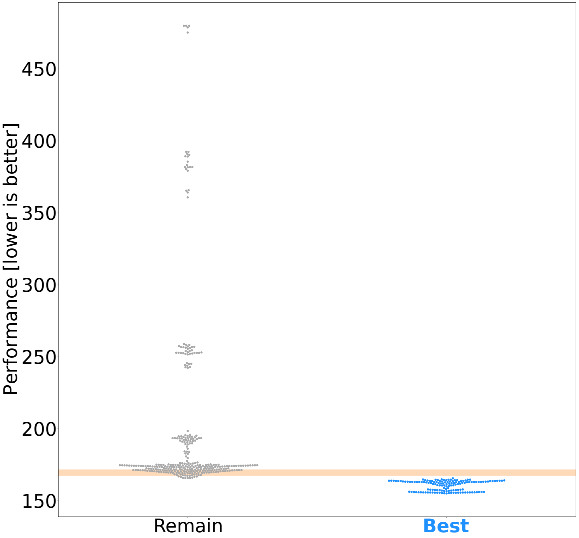

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Finding the best:

Isolate the schedulers at most 10% from the best one

⇒ Set of **Best** schedulers

Preliminary Results

Raw results confirm the **value of building application-specific schedulers**:

Out of 20 applications:

- For **17 applications (85%)**, we build simple schedulers **on par** with CFS
- For **7 applications (35%)**, we build simple schedulers **better** than CFS

In terms of stability, CFS is **less stable** than most generated schedulers on **5 applications**.
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Finding the Best Application-Specific Scheduler

Brute-force approach: Run all generated schedulers and keep the best one.

+ Gives **the best** scheduler for the application
– Impractical (for 10 runs and 486 schedulers, 1,925 hours for all tested applications)
– Does not scale realistically with the number of features and applications

We need a more practical way of finding the best scheduler for an application!

The new approach should:

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– Impractical (for 10 runs and 486 schedulers, 1,925 hours for all tested applications)
– Does not scale realistically with the number of features and applications

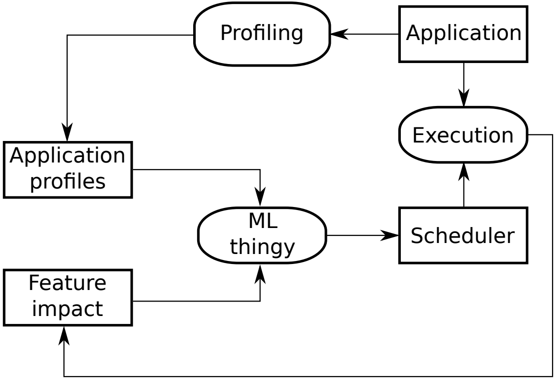
We need a more practical way of finding the best scheduler for an application!

The new approach should:

- Find a good scheduler without testing all schedulers
- Be able to use one application's results for other applications

Performance-Driven Feature Search

We propose the following framework:



We already have:

- **Execution framework:** SaaKM
- **Scheduler generator:** library of features
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What we still need:

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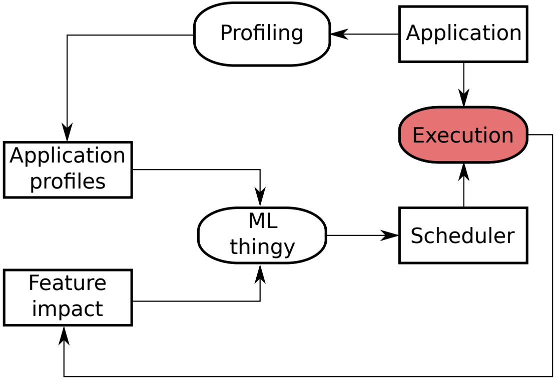

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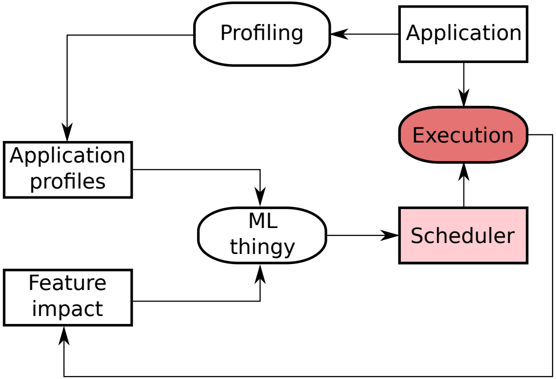

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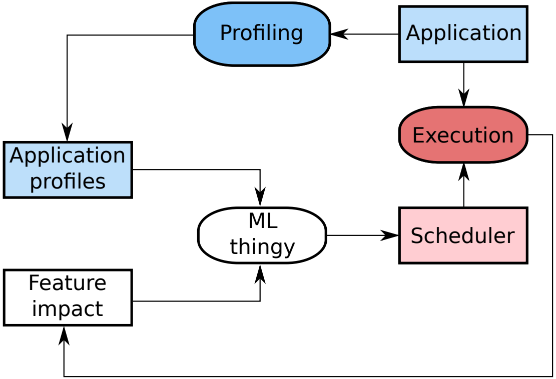

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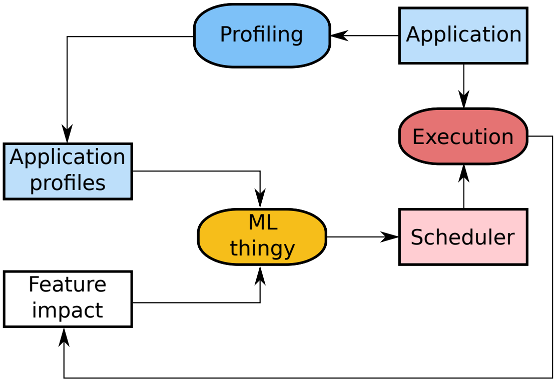

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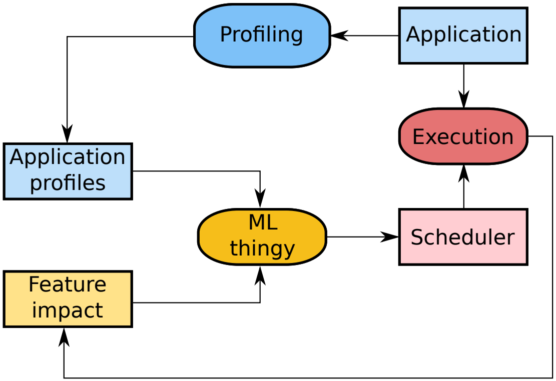

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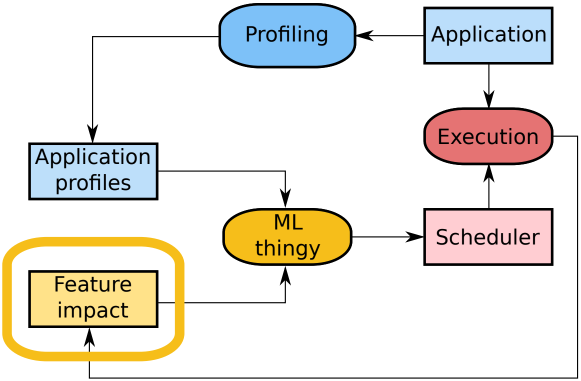

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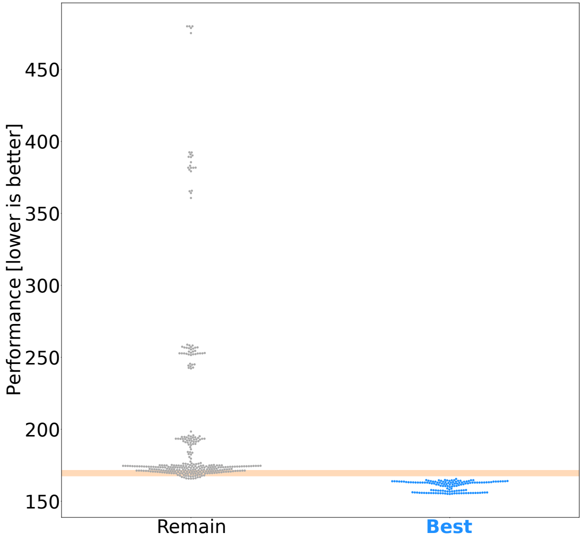
Feature Evaluation: the `facesim` Example



Isolating Features

Count the occurrences of each feature in **Best**:
$> 80\% \Rightarrow$ **good**, $< 20\% \Rightarrow$ **bad**

FitBest: schedulers with all **good** features and no **bad** ones in **Best**.

Fit: schedulers with all **good** features and no **bad** ones **not** in **Best**.

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{ idle = yes
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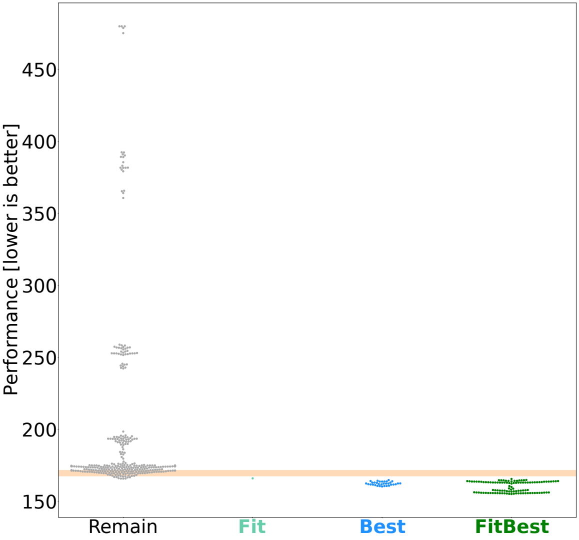

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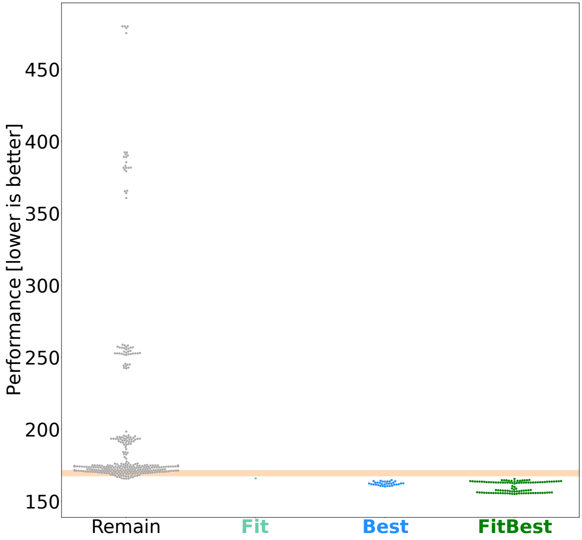

Conclusion

We **isolate** the **best features** for an application.

Representativeness: $\mathcal{R}=\frac{|FitBest|}{|Best|}=76\%$

Precision, *i.e. false positives*: $\mathcal{P}=\frac{|FitBest|}{|Fit \cup FitBest|}=99\%$

We reduce the noise in experimental data and pave the way for ML-based approaches.

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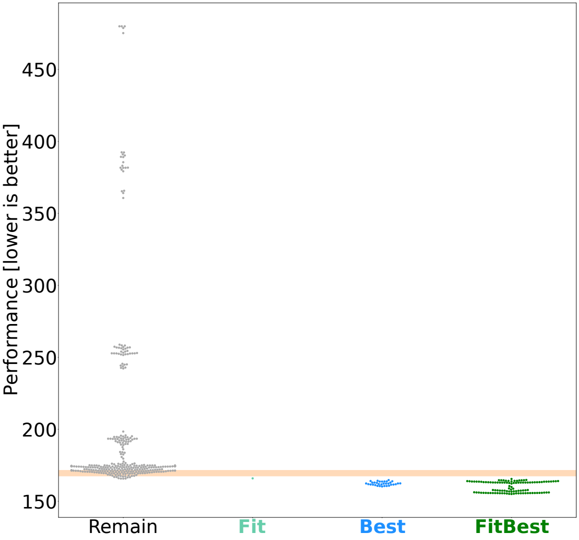

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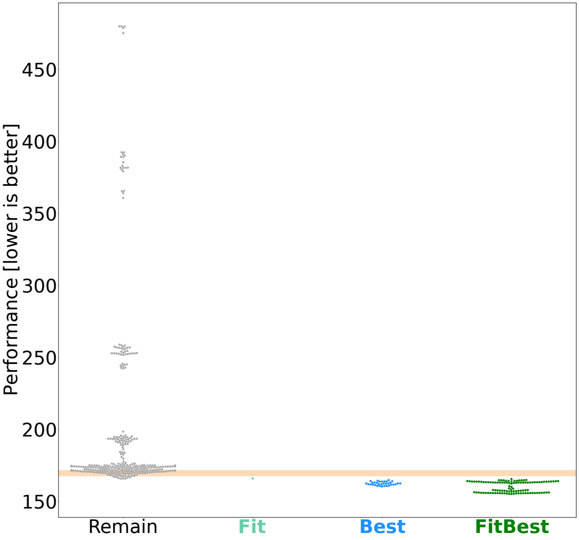

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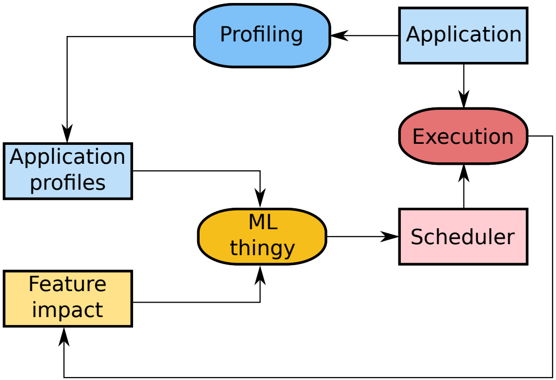

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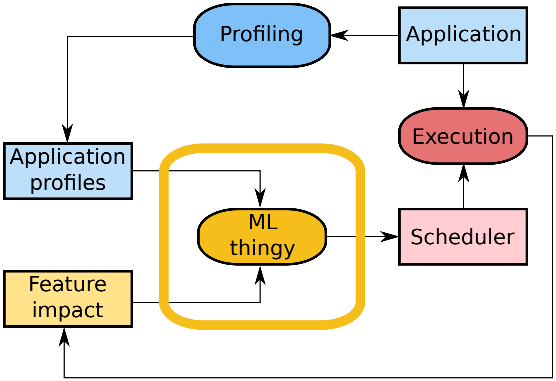

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Application-Specific Schedulers

1. A **feature model** representing schedulers as independent features
   - Implemented as a library such that features can be evaluated independently
   - 16 features, 486 generated schedulers in its current state, complies with SaaKM
2. An **ML-based approach** to build application-specific schedulers
   - Application profiling
   - Feature impact analysis
3. A **methodology** to understand the impact of each feature
   - Evaluate the stability of applications and schedulers
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- Expand the model with new features
- Implement our ML engine to automatically build application-specific schedulers

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Ipanema DSL
SaaKM API
Property verification

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Performance Enhancement

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S_{move} solution submitted

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Long Term Perspectives

Axes 1 and 2:

- Extend the Ipanema standard library with more hardware features (e.g. frequency)

Axes 1 and 3:

- Extend the Ipanema standard library and the feature model to better account for other resources such as memory, disks, network, etc ...

Axes 2 and 3:

- Expand feature model with more hardware-specific features (frequency, heterogeneity, ...)

Publications

- **Towards Proving Optimistic Multicore Schedulers**. *Baptiste Lepers, Willy Zwaenepoel, Jean-Pierre Lozi, Nicolas Palix, Redha Gouicem, Julien Sopena, Julia Lawall and Gilles Muller*. **HotOS, 2017**
- **Ipanema : un Langage Dédié pour le Développement d'Ordonnanceurs Multi-Coeur Sûrs**. *Redha Gouicem, Julien Sopena, Julia Lawall, Gilles Muller, Baptiste Lepers, Willy Zwaenepoel, Jean-Pierre Lozi and Nicolas Palix*. **ComPAS, 2017**
- **The Battle of the Schedulers: FreeBSD ULE vs. Linux CFS**. *Justinien Bouron, Sebastien Chevalley, Baptiste Lepers, Willy Zwaenepoel, Redha Gouicem, Julia Lawall, Gilles Muller and Julien Sopena*. **ATC, 2018**
- **Understanding Scheduler Performance: a Feature-Based Approach**. *Redha Gouicem, Julien Sopena, Julia Lawall, Gilles Muller, Baptiste Lepers, Willy Zwaenepoel, Jean-Pierre Lozi and Nicolas Palix*. **ComPAS, 2019**
- **Fork/Wait and Multicore Frequency Scaling: a Generational Clash**. *Damien Carver, Redha Gouicem, Jean-Pierre Lozi, Julien Sopena, Baptiste Lepers, Willy Zwaenepoel, Nicolas Palix, Julia Lawall and Gilles Muller*. **PLOS, 2019**
- **Fewer Cores, More Hertz: Leveraging High-Frequency Cores in the OS Scheduler for Improved Application Performance**. *Redha Gouicem, Damien Carver, Jean-Pierre Lozi, Julien Sopena, Baptiste Lepers, Willy Zwaenepoel, Nicolas Palix, Julia Lawall and Gilles Muller*. **ATC, 2020**
- **Provable Multicore Schedulers with Ipanema: Application to Work Conservation**. *Baptiste Lepers, Redha Gouicem, Damien Carver, Jean-Pierre Lozi, Nicolas Palix, Maria-Virginia Aponte, Willy Zwaenepoel, Julien Sopena, Julia Lawall and Gilles Muller*. **EuroSys, 2020**

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References

1. **A Framework for Simplifying the Development of Kernel Schedulers: Design and Performance Evaluation**. *Gilles Muller, Julia L. Lawall, Hervé Duchesne*. **HASE, 2005**
2. **Scheduling for Reduced CPU Energy**. *Mark Weiser, Brent B. Welch, Alan J. Demers, Scott Shenker*. **OSDI, 1994**
3. **Resource-conscious Scheduling for Energy Efficiency on Multicore Processors**. *Andreas Merkel, Jan Stoess, Frank Bellosa*. **EuroSys, 2010**
4. **An Evaluation of Per-chip Nonuniform Frequency Scaling on Multicores**. *Xiao Zhang, Sandhya Dwarkadas, Rongrong Zhong*. **ATC, 2010**
5. **Power and Energy Management for Server Systems**. *Ricardo Bianchini, Ram Rajamony*. **Computer, 2004**

Backup Slides

Feature Evaluation: the `facesim` Example

Election	RBtree 44 (31.43%)	Linked list 48 (34.29%)	FIFO 48 (34.29%)
Time slice	Infinite 47 (33.57%)	Fixed 46 (32.86%)	Split 47 (33.57%)
Load metric	nrRun 54 (38.57%)	nrRunBlock 33 (23.57%)	usedTime 53 (37.86%)
Placement distance	SMT 33 (23.57%)	LLC 54 (38.57%)	all 53 (37.86%)
Executor	all 36 (25.71%)	node 51 (36.43%)	core 53 (37.86%)
Idle	no 16 (11.43%)	yes 124 (88.57%)	

Phase 3: Isolating the best features

Count the occurrences of each feature in **Best**.

If feature is $> 80\% \Rightarrow$ **good**
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We call this set of features a **scheduler frame**.