Scuola Superiore Sant'Anna
di Studi Universitari e di Perfezionamento

Retis
Real-Time Systems Laboratory

SEVENTH FRAMEWORK PROGRAMME

Low-Latency Audio on Linux by Means of Real-Time Scheduling

Tommaso Cucinotta, Dario Faggioli, Giacomo Bagnoli

Real-Time Systems Lab (RETIS)

Scuola Superiore Sant'Anna, Pisa (Italy)

IRMOS
Interactive Realtime Multimedia Applications on Service Oriented Infrastructures

S(o)OS
Service-oriented Operating Systems

Motivations and background

Problem Presentation

General-Purpose Operating Systems

- Very effective for storing & managing multimedia contents
- Designed for
  - **average-case** performance
  - serving applications on a **best-effort** basis
- They are <u>not</u> the best candidate for serving *real-time applications* with **tight timing constraints**
  - like **real-time multimedia**
  - or computing with **precise QoS assurance**

Possible Solutions

Overcoming limitations of a GPOS for multimedia

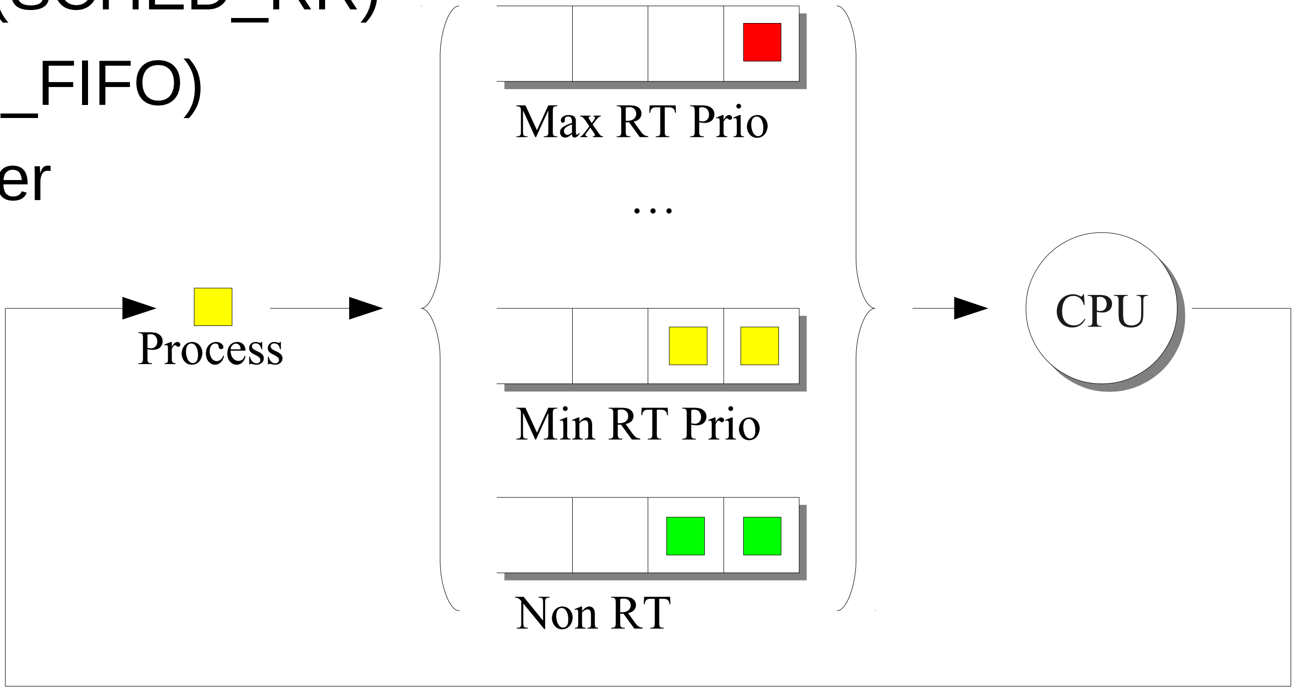
- **Large buffers** used to compensate *unpredictability*
  - ==> **poor** real-time **interactivity** and no low-latency multimedia
- **One-application one-system** paradigm
  - For example, for **low-latency real-time audio processing (jack)**, gaming, CD/DVD burning, plant control, etc...
- **POSIX real-time extensions**
  - Priority-based, **no temporal isolation**
  - Not appropriate for deploying the multitude of (soft) real-time applications populating the systems of tomorrow
- **Linux Real-Time Throttling** extension
  - Designed for **limiting**, not **guaranteeing**

POSIX Real-Time Scheduling

Multi-queue priority-based scheduler

Processes at same priority

- Round-Robin (SCHED_RR)
- FIFO (SCHED_FIFO)
- Sporadic Server (see later)



Traditional RT Systems (and Priority Scheduling)

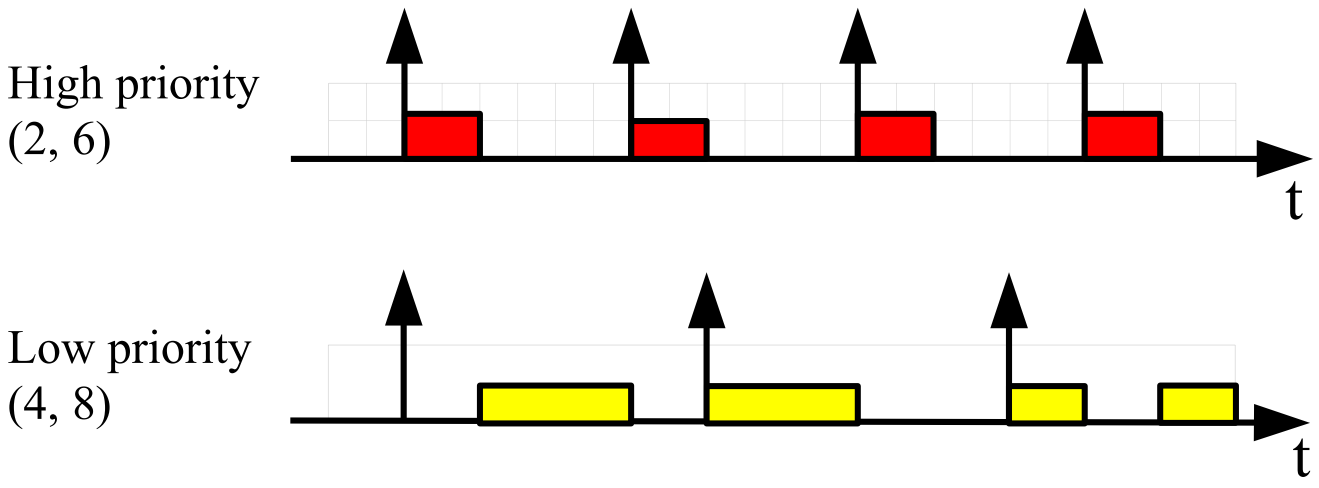
All deadlines respected as far as system behaves as foreseen at design time

- Traditional (C, T) task model
  - C: Worst-Case Execution Time (WCET)
  - T: Minimum inter-arrival period

Admission Control, e.g., for RM:

$$\sum_{i=1}^{n} \frac{C_i}{T_i} \leq n\left(\sqrt[n]{2} - 1\right)$$

$$\prod_{i=1}^{n} \left(\frac{C_i}{T_i} + 1\right) \leq 2$$

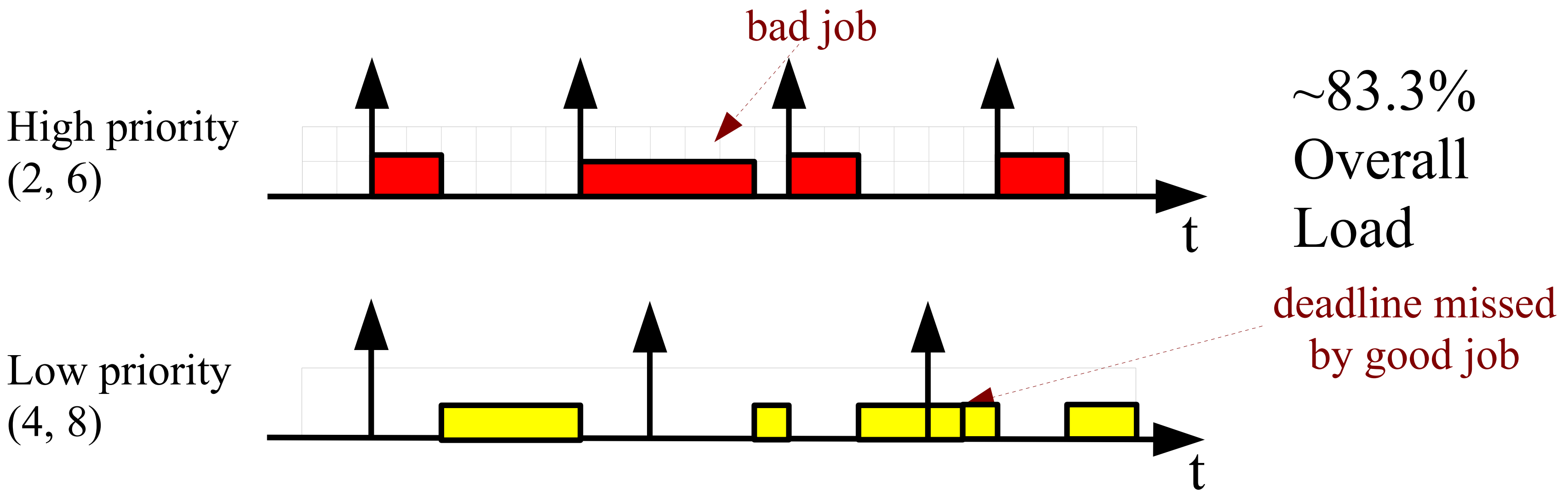


~83.3% Overall Load

Problems of Priority Scheduling

High-priority processes may indefinitely delay low-priority ones

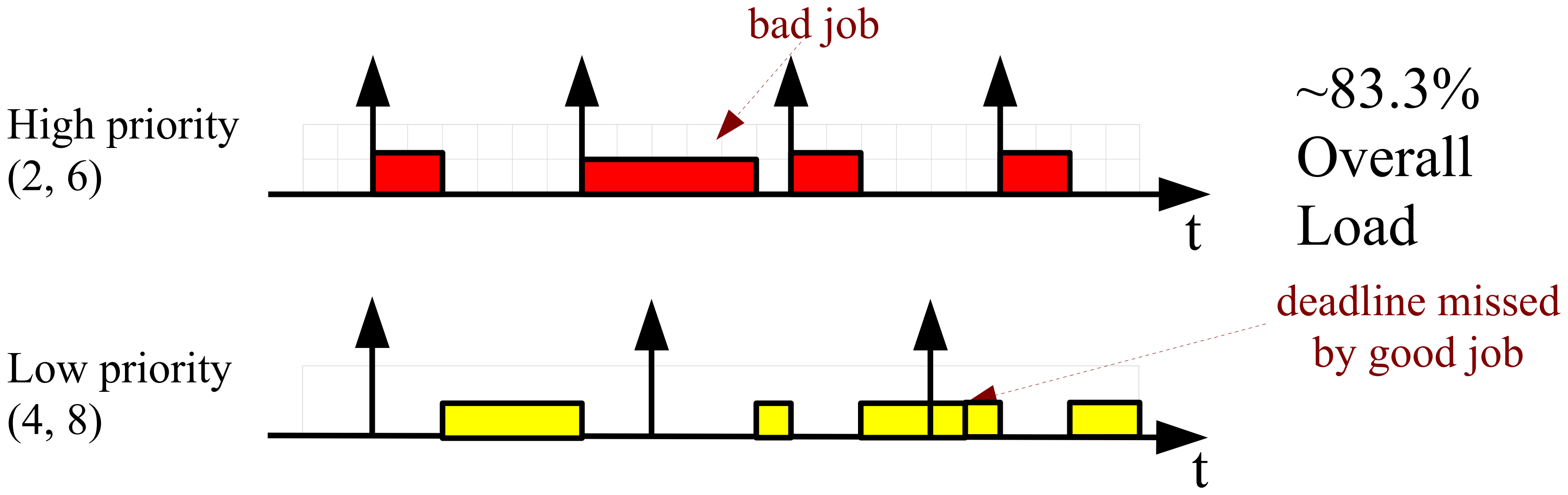
- ➢ Coherent with the typical real-time/embedded scenario
  - Higher-priority processes are **more important** (e.g., safety critical)



Problems of Priority Scheduling

High-priority processes may indefinitely delay low-priority ones

- Coherent with the typical real-time/embedded scenario
  - Higher-priority processes are **more important** (e.g., safety critical)
- What if processes have **same importance/criticality** ?



Recently Proposed Real-Time Scheduler(s)

Features (schedulers implement)

- **Temporal isolation** among **tasks** and **task groups**
- Need for provisioning of reservation parameters (**sporadic real-time task model**)
  - **runtime** every **period**
  - Optional allowance to use more CPU if available (**soft** reservations)
- Simple **admission control** scheme
  - May be **disabled** if custom user-space policy needed
  - Optional **over-subscription** possibility with **graceful, controlled** management of **overloads**
- **Priority**-based, **Deadline**-based, **mixed scheduling**
- **Hierarchical scheduling**
  - Attach **more tasks** as a whole to a **single reservation**
  - **Nesting** of groups and subgroups at arbitrary levels

Recently proposed schedulers and their APIs

AQuoSA EDF-based scheduler

EDF RT Throttling (a.k.a., The IRMOS Scheduler)

- ➢ Parameters: **runtime, period, cpu mask, tasks**
  - **RT priorities** of real-time tasks
- ➢ **cgroup**-based interface
  - Problem of **atomic changes** to scheduling parameters

SCHED_SPORADIC

- ➢ Parameters: **runtime**, **period**, **priority**, **low-priority**
- ➢ POSIX standard system call: sched_setscheduler()
  - **Breaks binary interface** & compatibility
- ➢ Alternative system call: **sched_setscheduler_ex()**

SCHED_DEADLINE

- ➢ Parameters: **runtime, period, flags**
- ➢ system call: **sched_setscheduler_ex()**

Programming Paradigm

SCHED_DEADLINE

```
struct sched_param_ex sp = {
  .sched_runtime = runtime_ts;      // struct timespec
  .sched_deadline = deadline_ts;   // struct timespec
  .flags = 0;
};
sched_setscheduler_ex(pid, SCHED_DEADLINE, &sp);
/* Now you get runtime_ts every deadline_ts guaranteed */
```

Adaptivity & Control of
Resources in Embedded Systems

Programming Paradigm

IRMOS Scheduler

Pre-requisite at run-time: mount cgroups

- mkdir /cg
- mount -t cgroup -o cpu,cpuacct cgroup /cg

Reduce runtime for root-level tasks

- echo 200000 > /cg/cpu.rt_rt_task_runtime_us
  (root-group runtime remains at default of 950000)

Create group, with reservation of 10ms every 100ms

- mkdir /cg/g1
- echo 100000 > /cg/g1/cpu.rt_period_us
- echo 10000 > /cg/g1/cpu.rt_runtime_us
- echo 100000 > /cg/g1/cpu.rt_task_period_us
- echo 10000 > /cg/g1/cpu.rt_task_runtime_us

Attach task with tid=1421

- echo 1421 > /cg/g1/tasks

Detach task

- echo 1421 > /cg/tasks

Attach process with pid=1700

- for tid in \`ls /proc/1700/task\`; do echo $tid > /cg/g1/tasks; done

Destroy group

- rmdir /cg/g1

Interactive Realtime Multimedia Applications on Service Oriented Infrastructures

Programming Paradigm

IRMOS Scheduler with AQuoSA API

AQuoSA

```
qres_params_t p = (qres_params_t) {
  .Q = 10000,
  .Q_min = 10000,
  .P = 40000,
  .flags = 0
};
if (qres_create_server(&params, &sid) == QOS_OK) {
  qres_attach_task(sid, 0, 0);
  /* Now we get 10ms every 40ms guaranteed */
}
```

Using resource reservations

(and deadline-based scheduling)

in the Jack low-latency infrastructure

Our Work

We modified Jack so as to

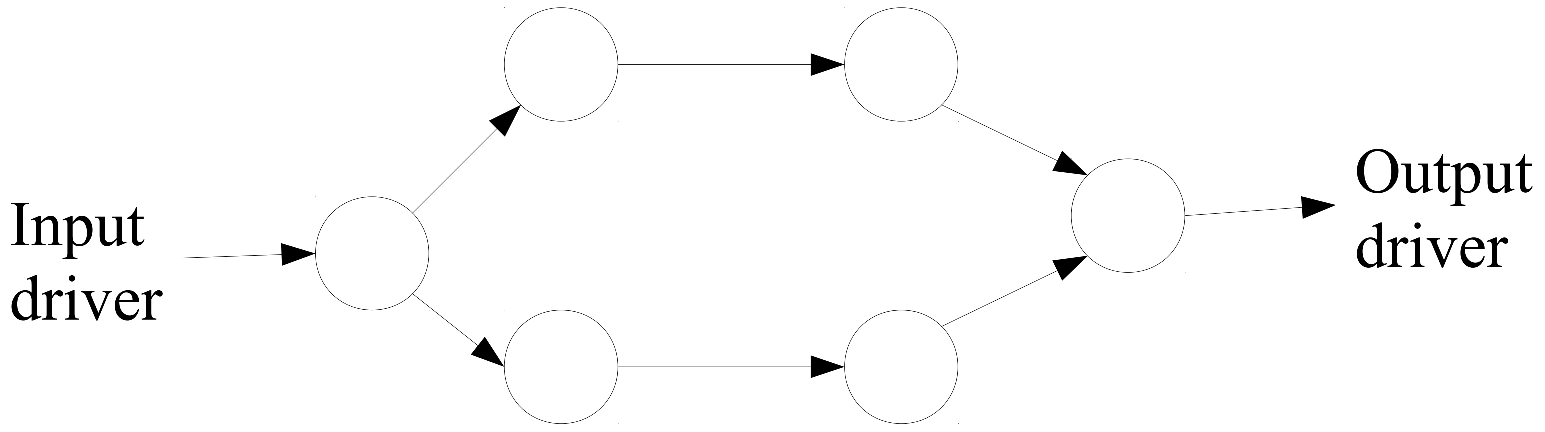
- Use a **deadline-based** real-time **scheduling** policy
- With automatic tuning of **scheduling parameters**
  - Period computed on the basis of the cycle duration/deadline
  - Budget computed through a **feedback-based loop**
- With minimum changes to the Jack daemon and library
- **Without any change required to applications/clients**

We measured the obtained performance

- **No performance drop** when running alone
- Performance is kept despite **other real-time workload**

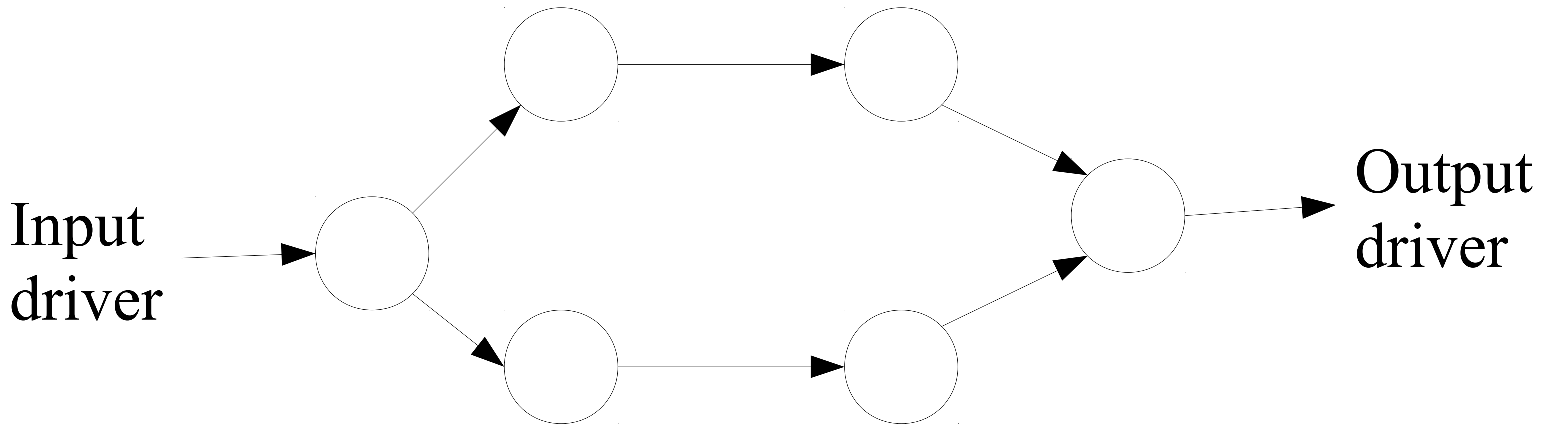
Jack Periodic Cycle

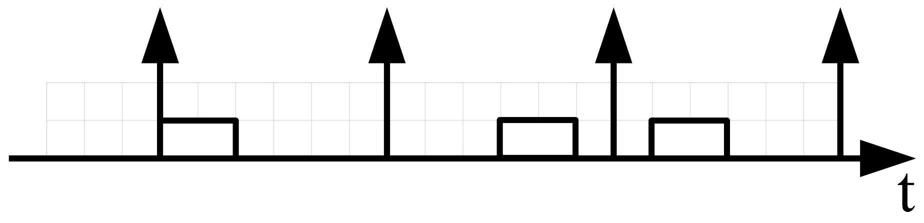
Arbitrary complex DAG of computations



Jack Periodic Cycle

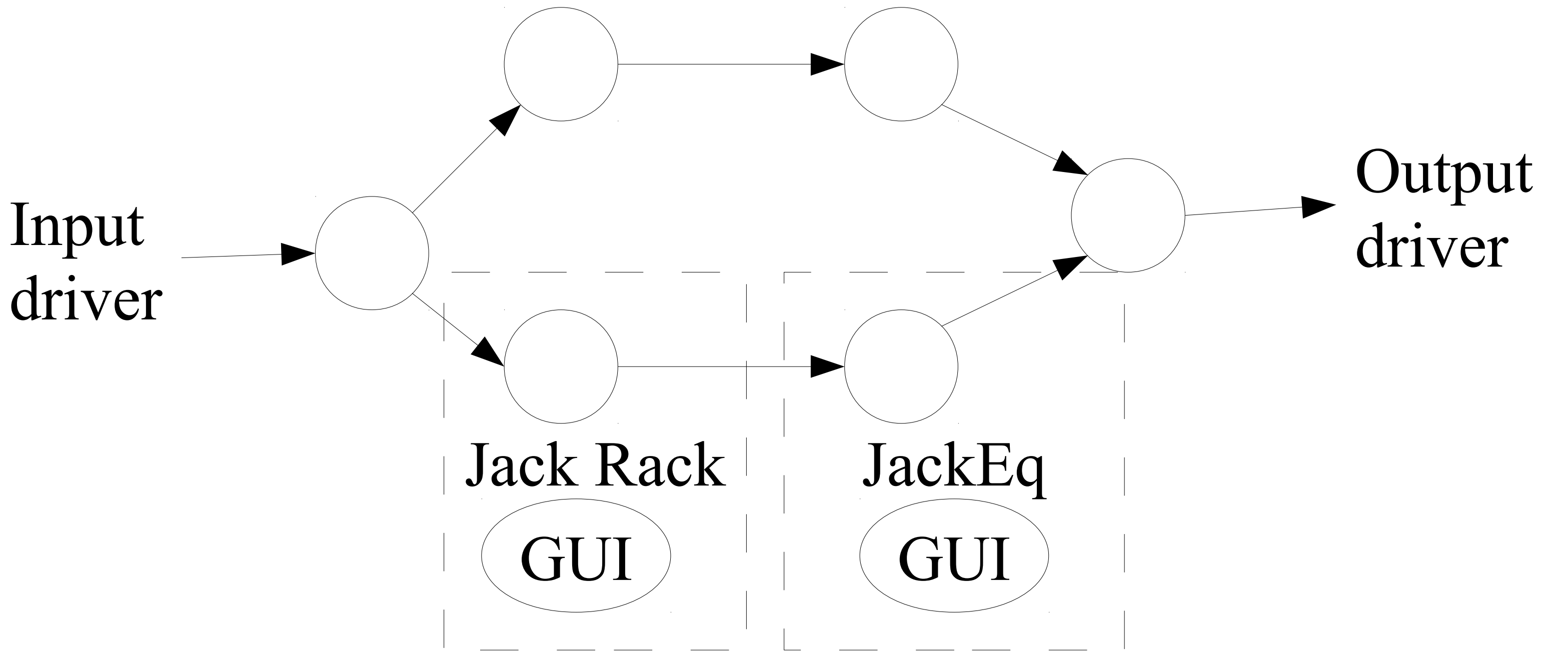
- Arbitrary complex DAG of computations
- All computations must complete within the cycle





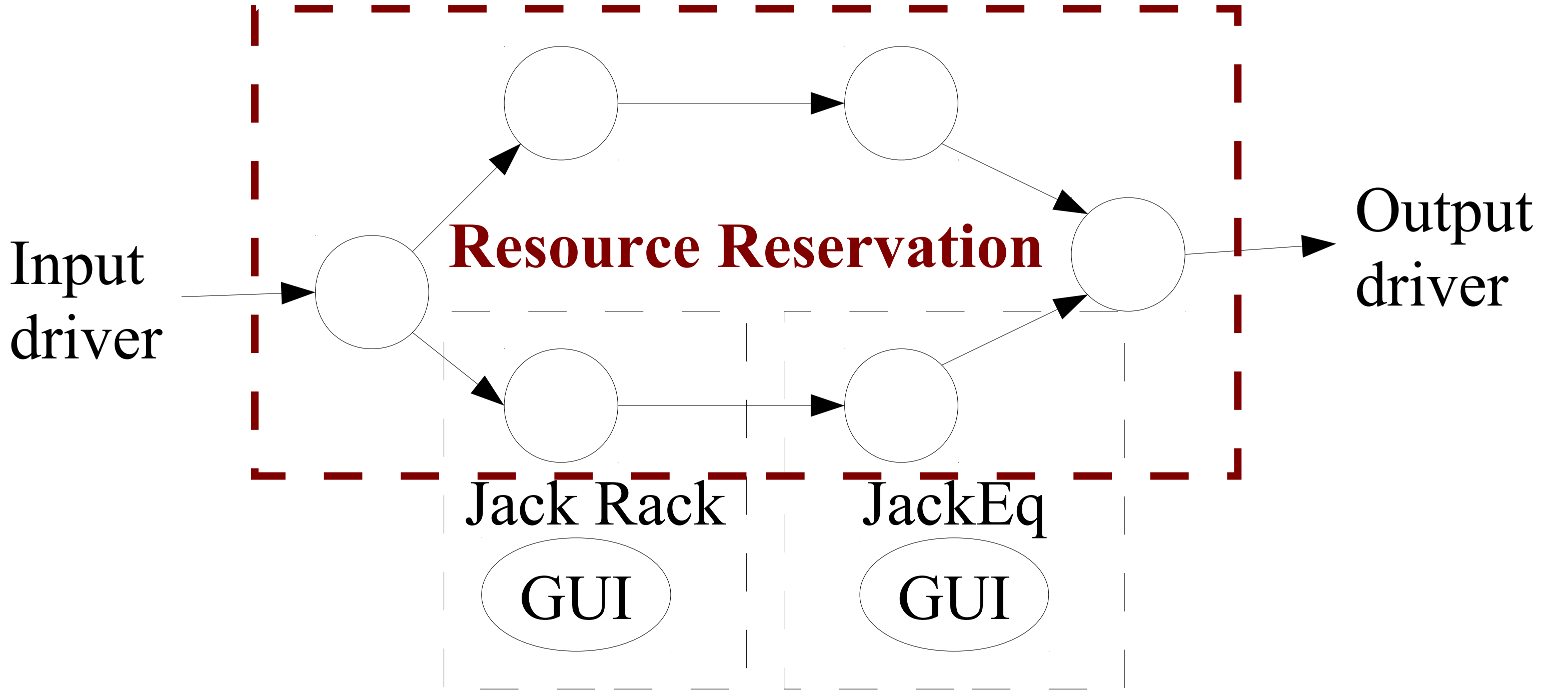
Jack Periodic Cycle

- Arbitrary complex DAG of computations
- All computations must complete within the cycle
- Each computation belongs to a different process



Jack Periodic Cycle

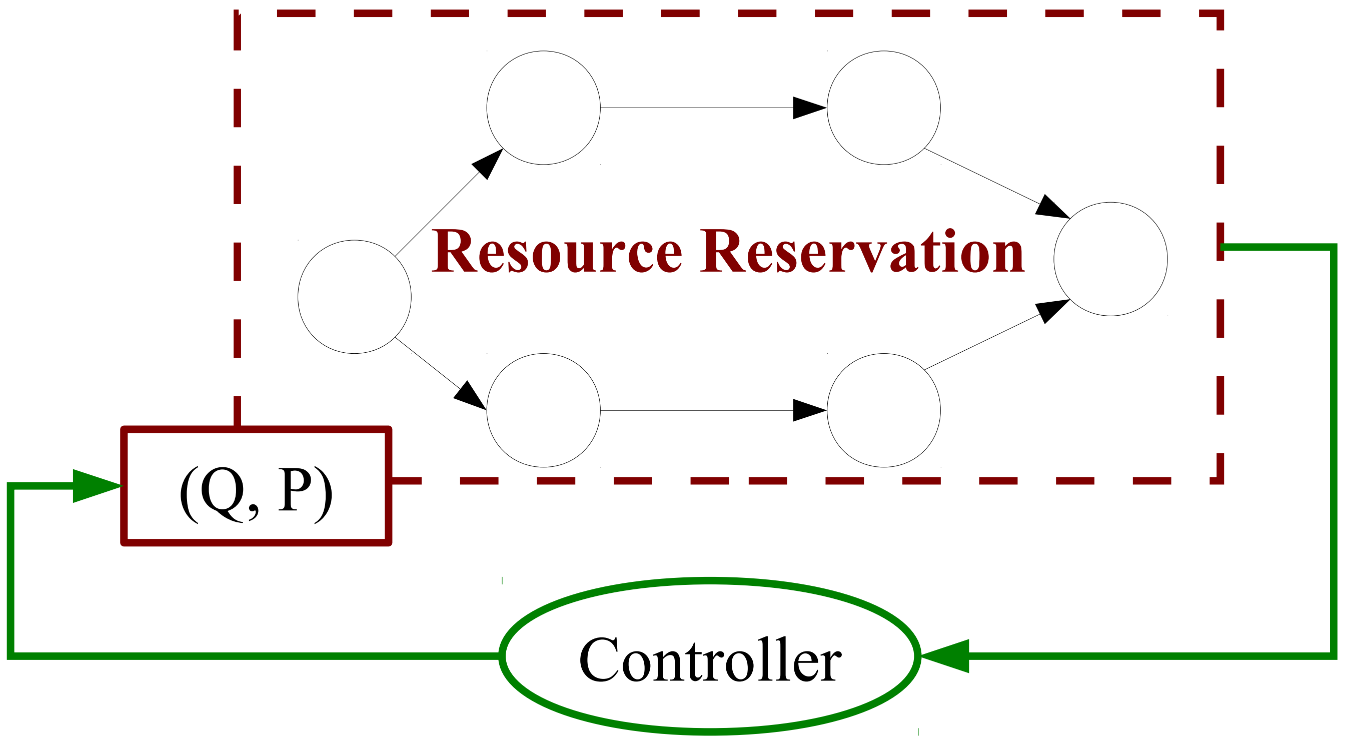
All client threads attached to a single reservation



Jack Periodic Cycle

All client threads attached to a single reservation

Budget identified by feedback-based scheduling



Controller

Percentile estimator

- Can be configured to estimate a **percentile** (can be 100%) of the observed **consumed budget distribution** over a moving window

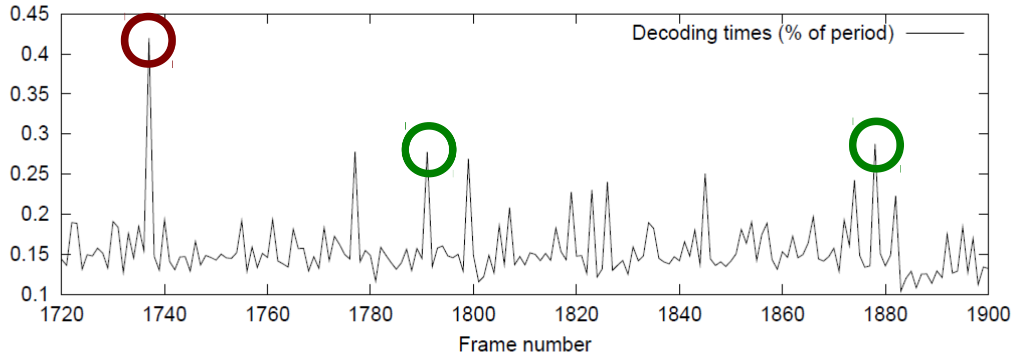
Additional heuristics

- Addition of a **safety threshold** (over-provision)
- Temporary **budget boost on new client**
- Temporary **budget boost on xrun**
  - (prevents further xrun from occurring after an xrun)

Problems

Still we could see some xruns

- Some workload peaks cannot be foreseen
  - e.g., **MPEG decoding** or **MIDI synthesizer**



Solution

- Use **soft resource reservations**
  - Tasks are allowed to run **beyond budget exhaustion**
  - The budget is still a **minimum guarantee** for the tasks
- We used the **SHRUB** algorithm
  - **Fair redistribution of unused bandwidth** to active RT tasks

Experimental Results

Testbed set-up

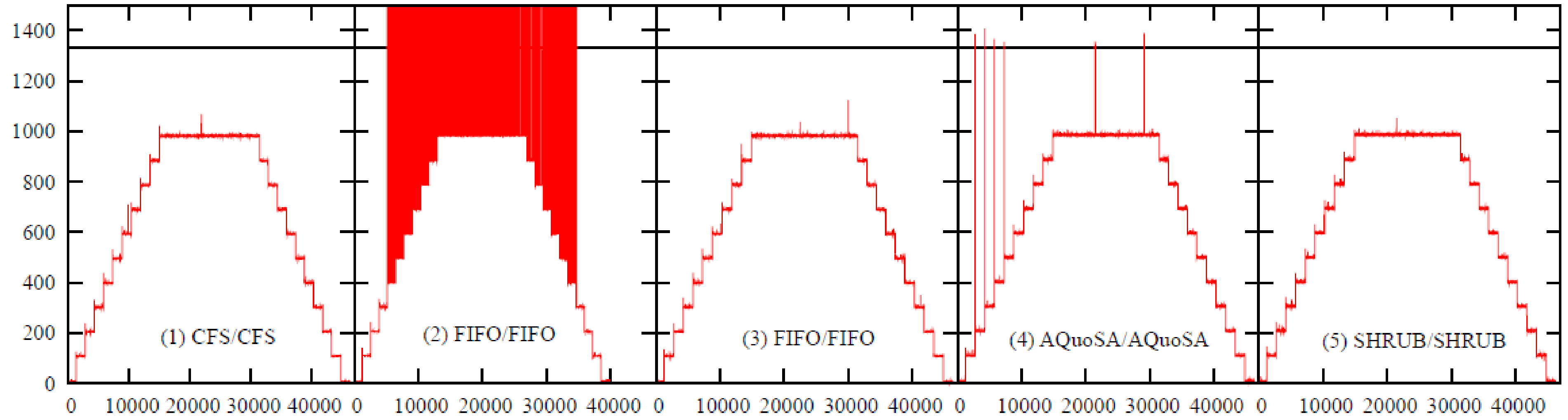
Hardware

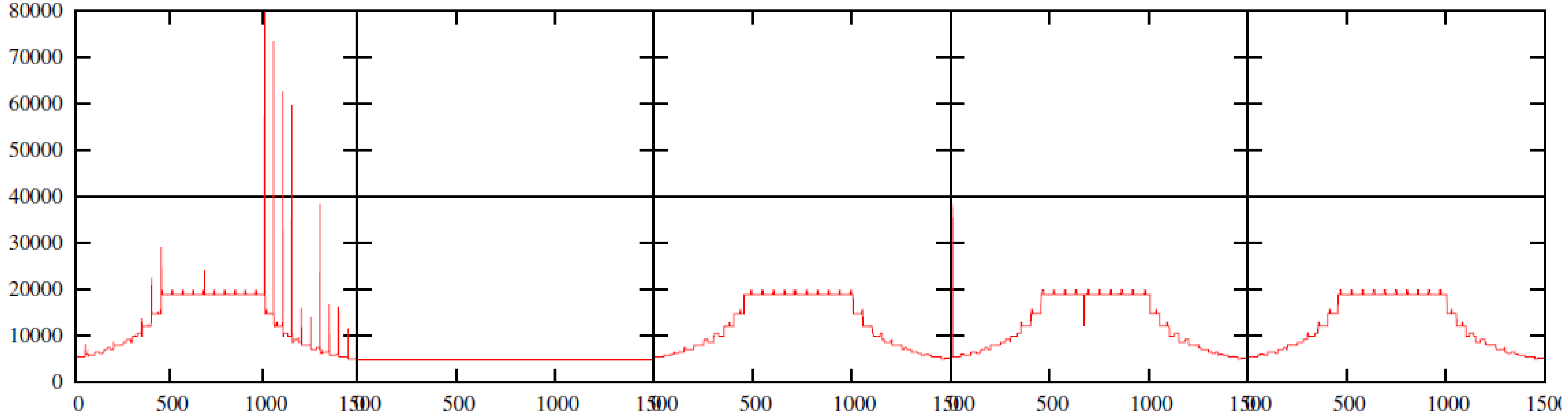
- Processor: Intel E8400 @ 3GHz
- Sound Card: Terratec EWX24/96 PCI

Software

- Linux Kernel: 2.6.29
- RT Scheduler: POSIX and AQuoSA scheduler
- Workload: jack and rt-app
- rt-app parameters: 5ms every 40ms

Jack @ 1333 us
96 kHz, 128 samples





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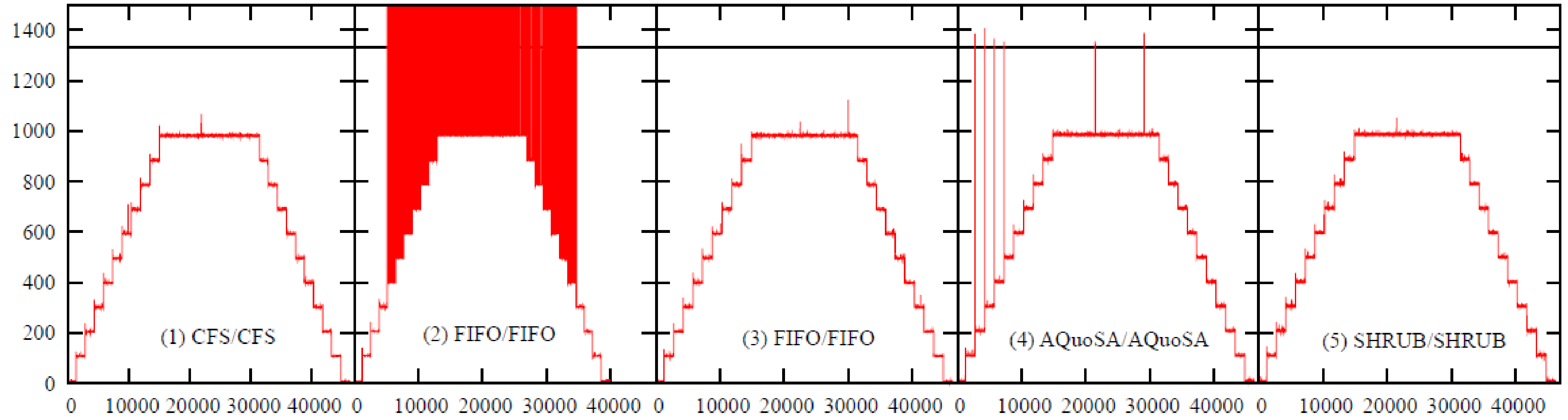
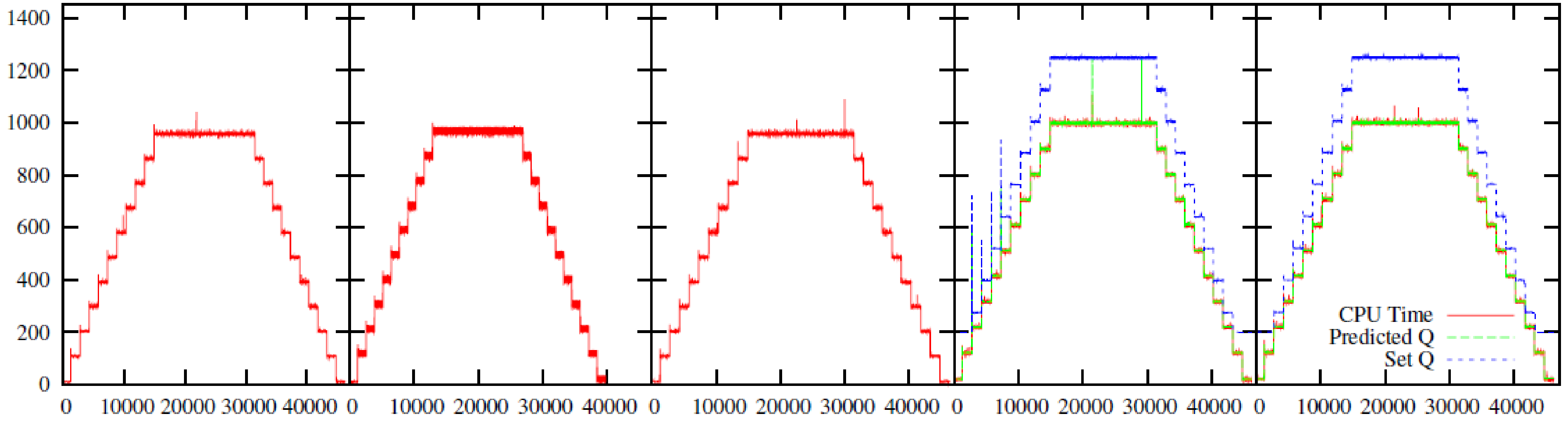




Concluding Remarks

Summarizing

- We tackled a challenging case-study for using resource reservations in Linux
- We modified Jack to use a deadline scheduler
- The critical issue was budget identification
- The performance of Jack alone doesn't get worse
- The set-up and deployment of a complex mix of real-time applications is simplified
  - Each one declares its own timing requirements

Future Work

This work is far from being finished

- ➢ Better handling of budget boost for new clients
- ➢ Collaboration from clients with **very dynamic workloads**
  - e.g., MIDI synthesizer
- ➢ Use a more recent scheduler
- ➢ Experiment with the PREEMPT_RT version of the deadline scheduler
- ➢ Experiment with SMP and parallelization

Related Publications

- *Hierarchical Multiprocessor CPU Reservations for the Linux Kernel*
  F. Checconi, T. Cucinotta, D. Faggioli, G. Lipari
  OSPERT 2009, Dublin, Ireland, June 2009
- *An EDF Scheduling class for the Linux kernel*
  D. Faggioli, F. Checconi, M. Trimarchi, C. Scordino
  RTLWS 2009, Dresden, October 2009
- *Access Control for Adaptive Reservations on Multi-User Systems*
  T. Cucinotta
  RTAS 2008, St. Louis, MO, United States, April 2008
- *Self-tuning Schedulers for Legacy Real-Time Applications*
  T. Cucinotta, F. Checconi, L. Abeni, L. Palopoli
  EuroSys 2010, Paris, April 2010
- *Respecting temporal constraints in virtualised services*
  T. Cucinotta, G. Anastasi, L. Abeni
  RTSOAA 2009, Seattle, Washington, July 2009

Thanks for your attention

Questions?

http://retis.sssup.it/people/tommaso

Deadline-based Scheduling for Temporal Isolation in Linux

Deadline-based Scheduling

Optimum for single-processor systems

- Necessary and sufficient admission control test for simple task model: $$\sum_{i=1}^{n} \frac{C_i}{T_i} \le 1$$

Same problems of PS

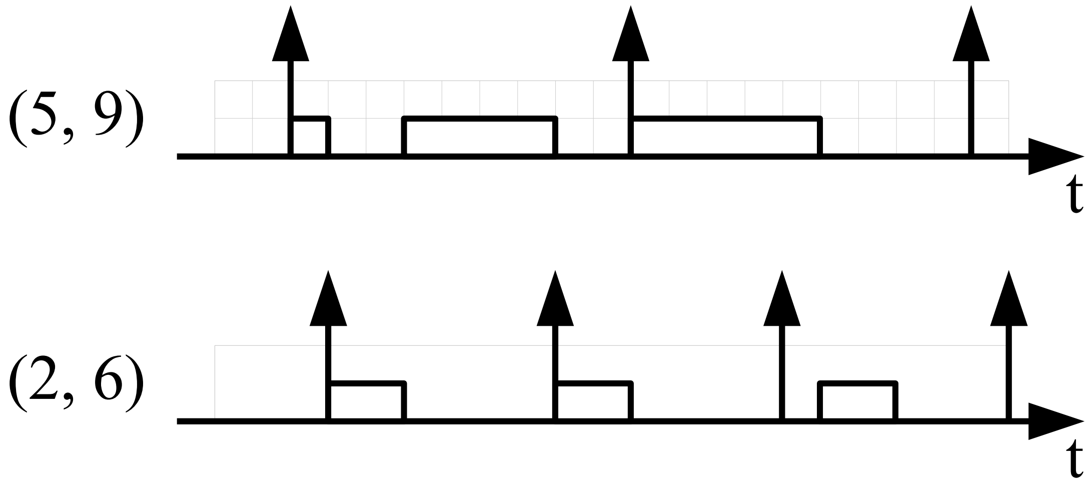
- Deadlines respected as far as the WCETs are respected
- Things may go bad when
  - One or more tasks exhibit higher computation times than foreseen
  - One or more tasks behaves differently than foreseen
    - e.g., it blocks on a critical section for more than foreseen
- The task that suffers may not be the misbehaving one

Cannot provide Temporal Isolation unless . . .

Real-time theory

Reservation-based scheduling: (Q_i, P_i)

- “Q_i time units **guaranteed** on a CPU every P_i time units”



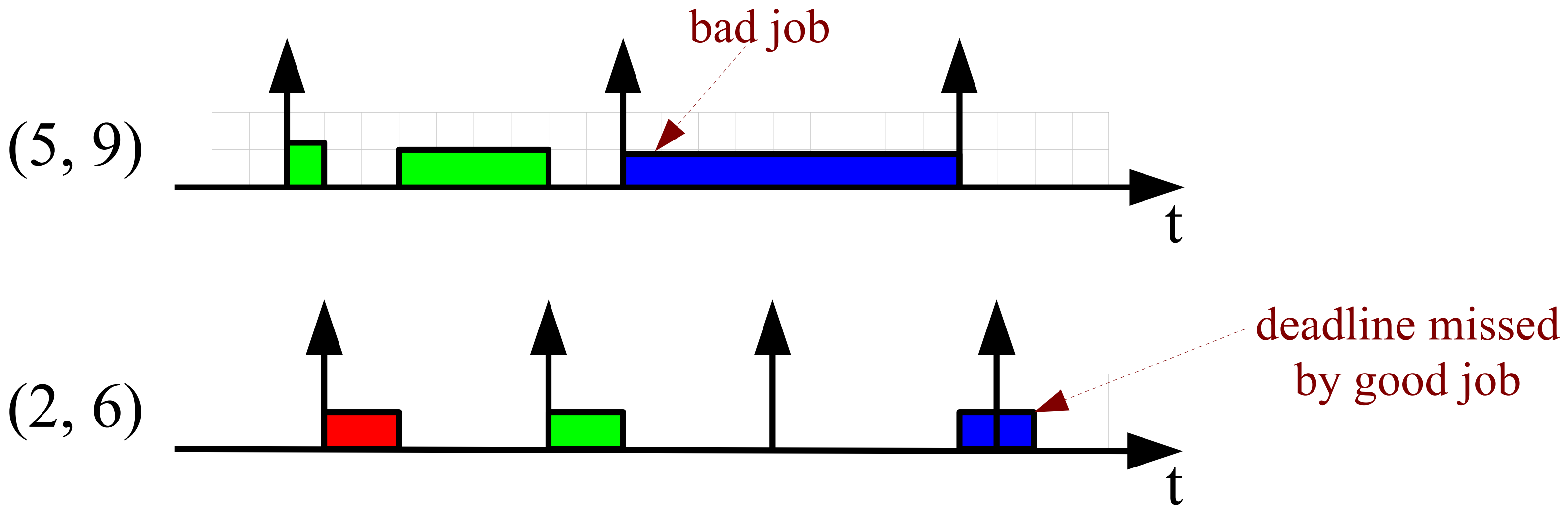
~88.9% Overall Load

- Independently of how others behave (**temporal isolation**)

Temporal Isolation

Enforcement of temporal isolation

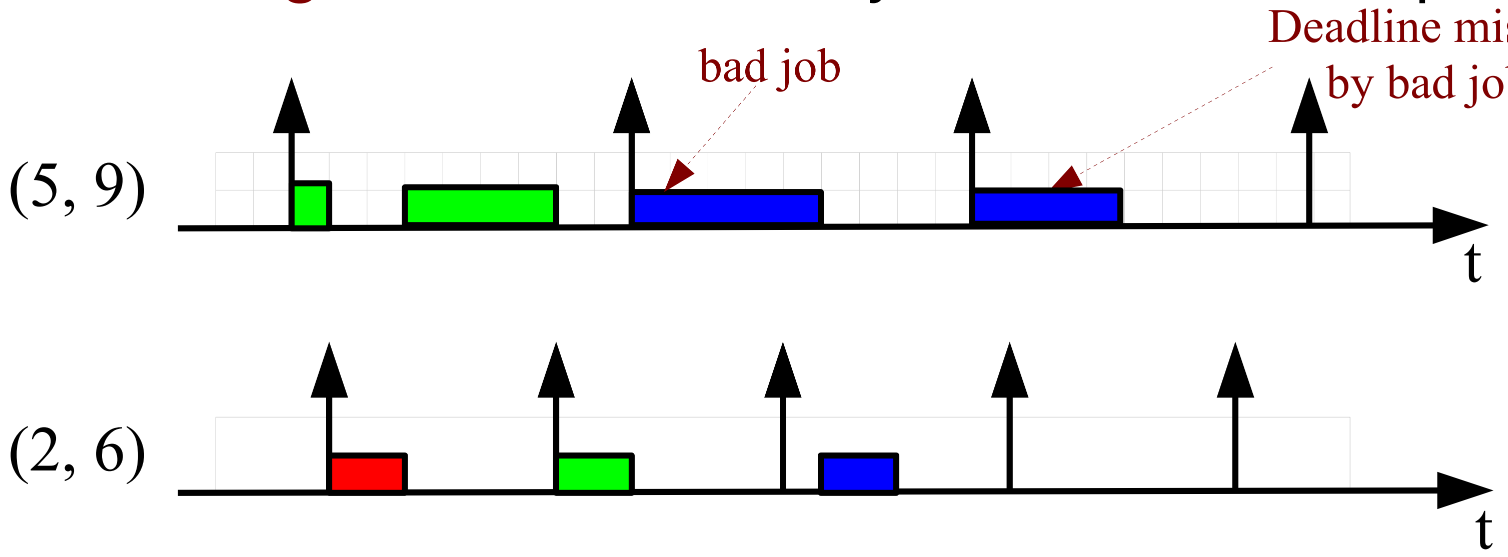
- Not only EDF scheduling



Temporal Isolation

Enforcement of temporal isolation

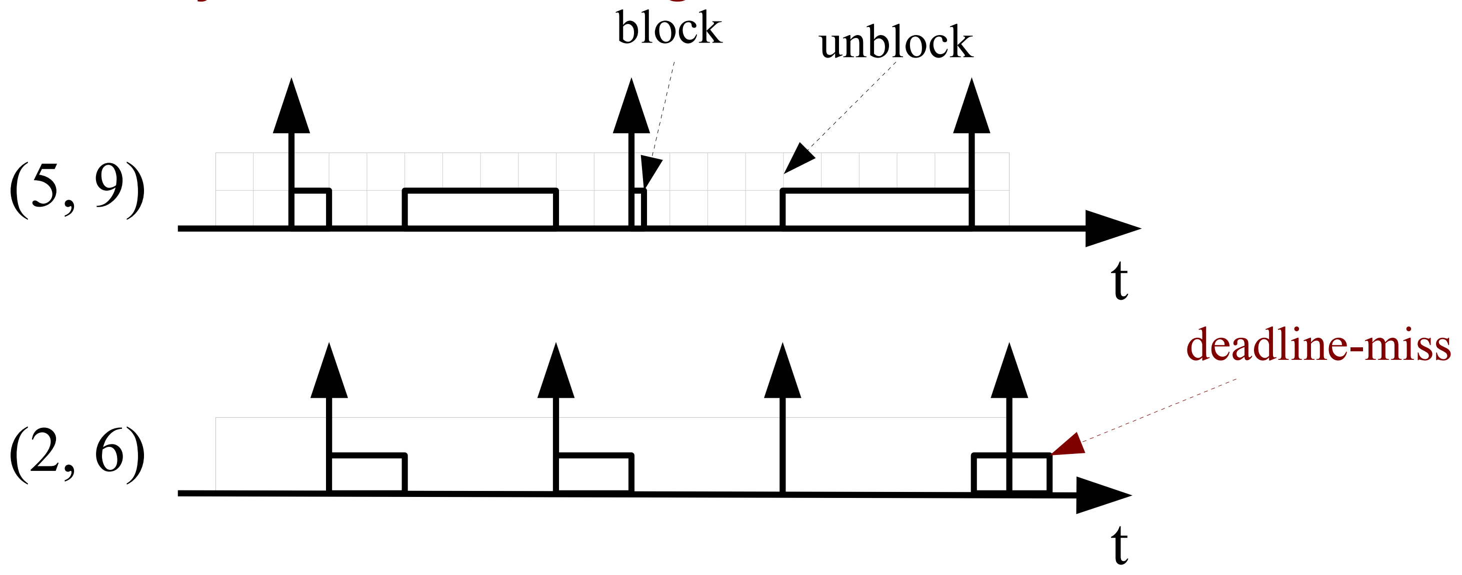
- Once **budget exhausted**, delay to next activation period



Temporal Isolation

Is needed despite blocks/unblocks

- Not only EDF scheduling



Temporal Isolation

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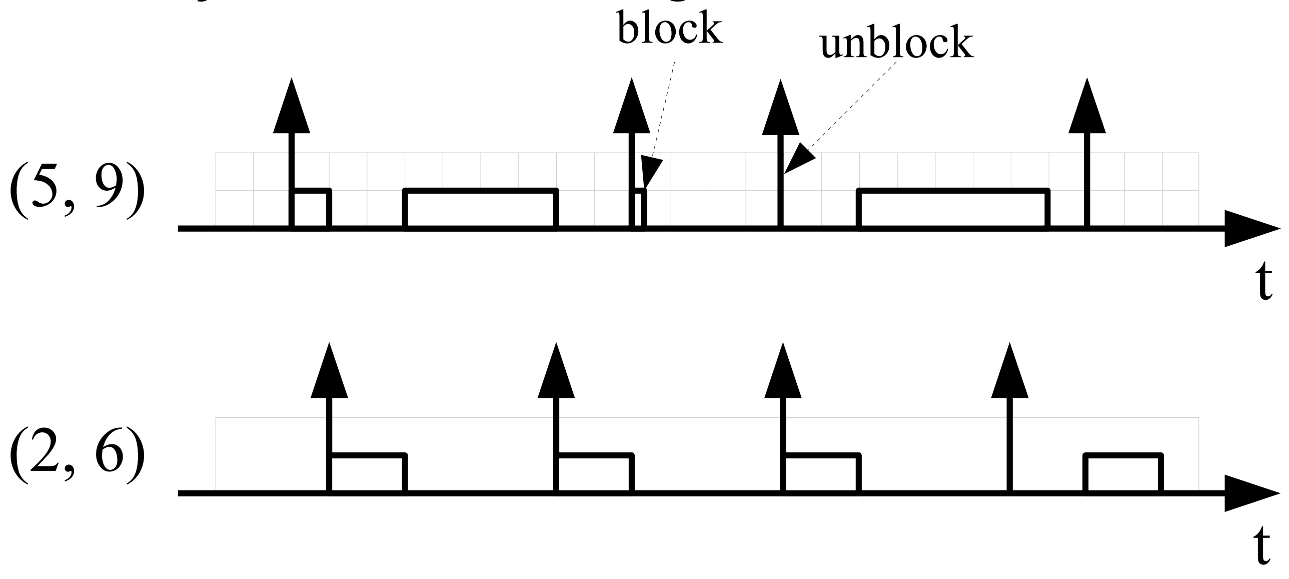
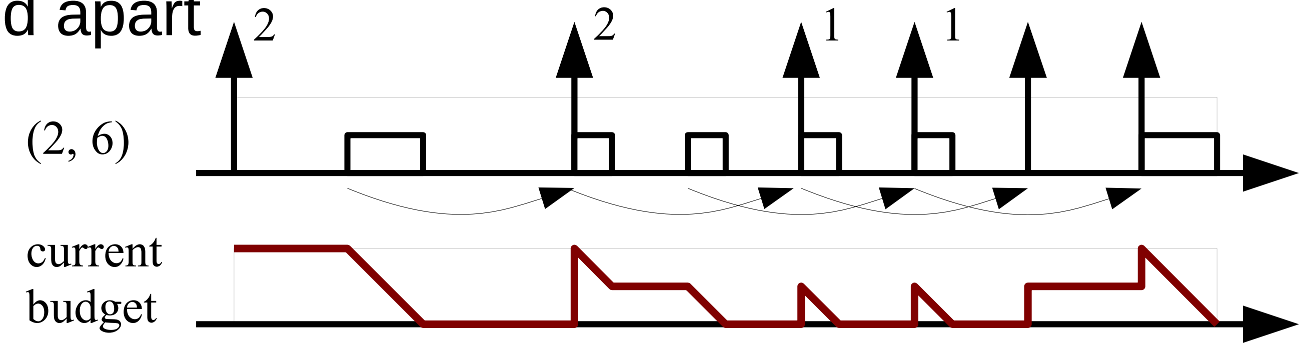


See the "unblock rule" of the Constant Bandwidth Server (CBS, Abeni '98)

POSIX Sporadic Server

SCHED_SS

- Provides a form of temporal isolation
- Parameters: (Q, P, RT Priority, Low RT Priority)
- Budget exhausted => lower the priority till next recharge
- For every time interval in which the task executes, post a recharge of budget equal to the consumed CPU time one period apart



SCHED_SS may be analysed using FP techniques

- Patching the standard for getting rid of the “bug”

IRMOS RT Scheduler Design Goals

Replace real-time throttling

Tight integration in Linux kernel

- ➢Modification to the Linux RT scheduler

Reuse as many Linux features as possible

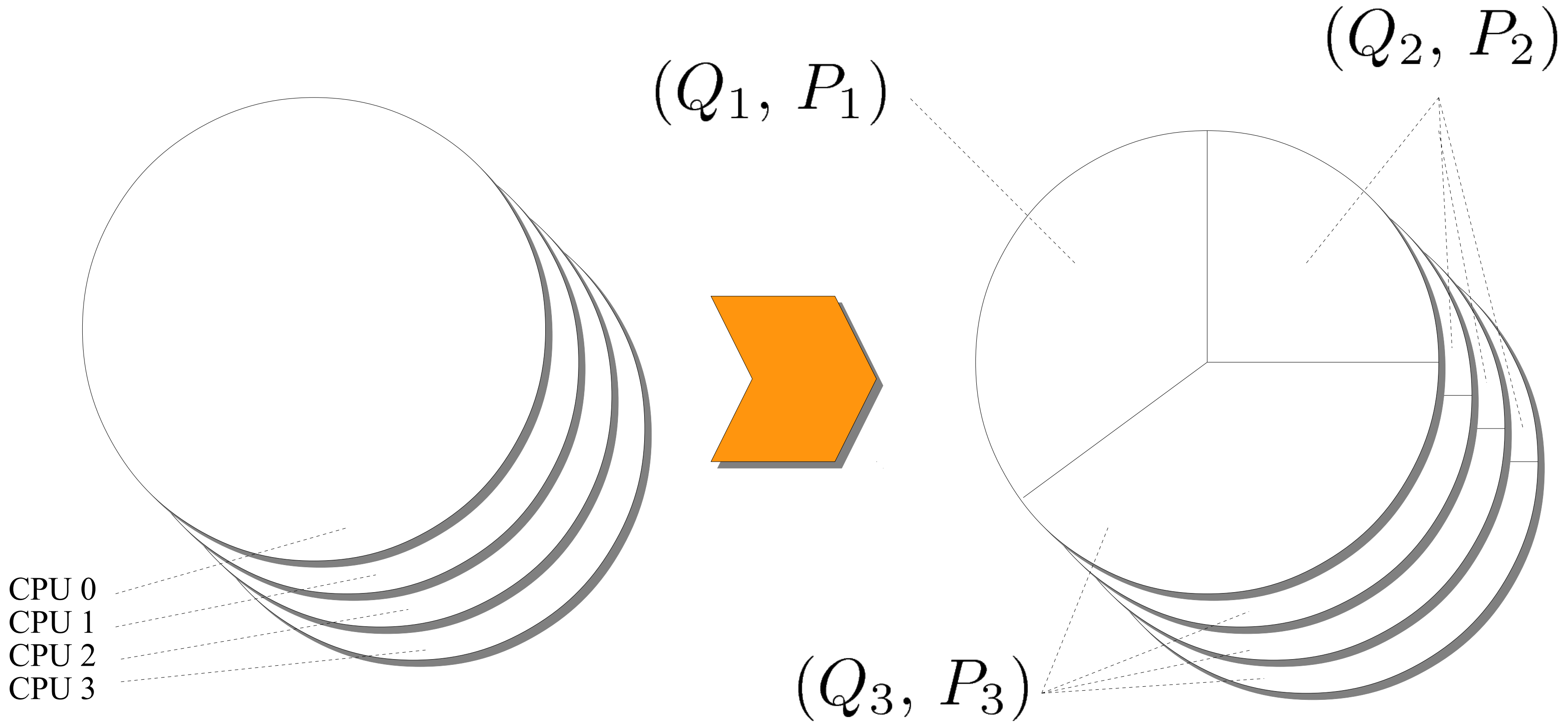
- ➢Management of task hierarchies and scheduling parameters via **cgroups**
- ➢**POSIX compatibility** and API

Efficient for SMP

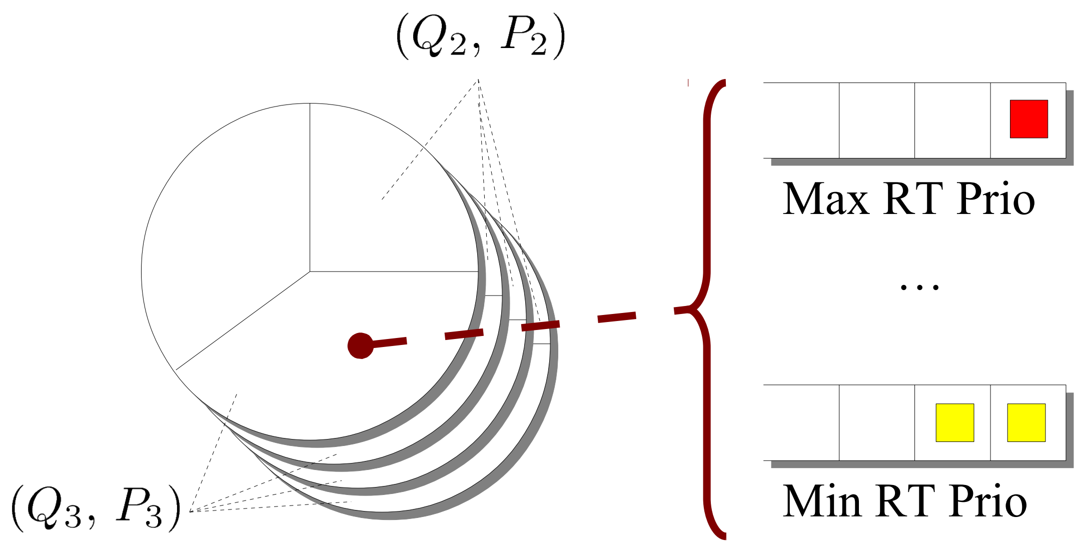
- ➢Independent runqueues

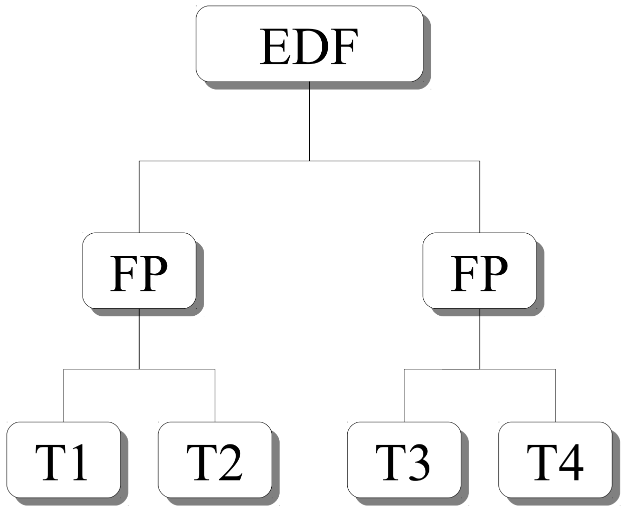
IRMOS Scheduler

Slice the available computing power into reservations



Hierarchical Scheduling





Needed operations

- **create** & **destroy** reservations
- **attach** & **detach** tasks ↔ reservations
- **list tasks** attached to reservations (and **list reservations**)
- Standard operations: **get & set parameters**

Other Features

Warning: features & parameters may easily grow

- Addition of parameters, such as
  - **deadline**
  - **desired** vs **guaranteed** runtime (for **adaptive reservations**)
- Set of **flags** for controlling variations on behaviour
  - **work conserving** vs **non-conserving** reservations
  - what happens at **fork()** time
  - what happens on tasks **death** (**automatic reclamation**)
  - **notifications** from kernel (e.g., **runtime exhaustion**)
- **Controlled access** to RT scheduling by **unprivileged applications** (e.g., per-user “quotas”)
- **Monitoring** (e.g., residual runtime, available bandwidth)
- Integration/interaction with **power management**