Scheduling

Advanced Operating Systems
(263-3800-00)

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Scheduling is…

Deciding how to allocate a single resource among multiple clients
- In **what order** and for **how long**

- Usually refers to CPU scheduling
  - Focus of this talk – we will look at selected systems/research
  - OS also schedules other resources (eg. disk and network IO)

- CPU scheduling involves deciding:
  - Which task next on a given CPU?
  - For how long should a given task run?
  - On which processor should a task run?

  Task: process, thread, domain, dispatcher, …

Challenge: complexity of scheduling algorithms

- Scheduler also uses the CPU to decide what to schedule
  - Any time spent in scheduler is "wasted" time
  - Want to minimize overhead of decisions
    - To maximise utilization of CPU
  - But low overhead is no good if your scheduler picks the "wrong" things to run!

⇒Trade-off between:

scheduler complexity/overhead and
optimality of resulting schedule

Challenge: Frequency of scheduling decisions

- Increased scheduling frequency
  ⇒ increasing chance of running something different

Leads to higher **context switching** rates,
⇒ lower throughput
- Flush pipeline, reload register state
- Maybe flush TLB, caches
- Reduces locality (eg. in cache)

L4 Scheduling

- Relatively simple scheduling policy:
  - 256 hard priority levels
  - Round robin within each priority
- Leads to simple scheduler implementation:
  - Keep (circular) list for each priority level
  - Always pick next thread from highest priority list
  - Optimization: bitmap of priority levels in-use
- L4 does lazy scheduling: avoids invoking scheduler on IPC
  - IPC send always runs receiver
  - IPC receive tries to run sender (varies, see reference manual)

L4 Scheduling: Implications

- Low overhead for scheduling, but little control over schedule
  - Can implement more complex scheduler at user-level
  - Extremely expensive, due to extra context switches

⇒ Fundamental problem with (CPU) scheduling:
What policy should the kernel scheduler provide?

Classic UNIX Scheduling

- UNIX uses multiple priorities ("nice levels") with ageing
  - if a task has not run for a long time, its priority is increased
  - conversely, long-running tasks have their priority decreased
- Motivation: give CPU preference to IO-bound tasks
  - Improves interactivity
  - Avoids starvation
  - Hard for any one task to get 100% of the CPU
  - No ability to control/guarantee how much CPU a task will get

Problems with UNIX Scheduling

- UNIX conflates protection domain and resource principal
  - Priorities and scheduling decisions are per-process
- However, may want to allocate resources across processes, or separate resource allocation within a process
  - Eg. web server structure
    - Multi-process
    - Multi-threaded
    - Event-driven
  - If I run more compiler jobs than you, I get more CPU time
- In-kernel processing is accounted to nobody (cf. LRP)

Resource Containers

[Banga et al., 1999]

New OS abstraction for explicit resource management, separate from process structure

- Operations to create/destroy, manage hierarchy, and associate threads or sockets with containers
- Independent of scheduling algorithms used
- All kernel operations and resource usage accounted to a resource container

⇒Explicit and fine-grained control over resource usage

⇒Protects against some forms of DoS attack

Lottery Scheduling

[Waldspurger and Weihl, 1994]

- Each task holds a number of "lottery tickets"
- Scheduler selects a random number, runs task holding winning ticket
- Ticket transfers on blocking RPC (cf. L4 donation)
- Ticket currencies allow local management of allocations (relative to base)
- Compensation tickets granted to tasks that do not use their full share (cf. UNIX ageing)
- Efficient implementation of proportional share resource management
- Allows policies such as "users A and B share the CPU equally"
- Hard to give guarantees

Real-Time Systems

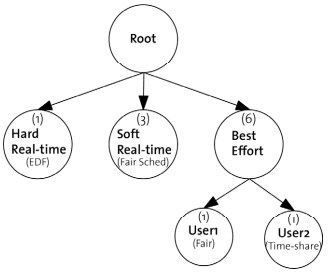
A very brief introduction

- A system where responses to external inputs must occur within a finite and specified period for correctness
- Hard vs. soft-real time
- Schedulers in commodity OSes are bad at this
  - Designed for fairness and starvation-freedom
  - Usually quantative guarantees on CPU time
  - "Real-time" priority in Linux etc. is *not* a real time!
- Search for a "universal" CPU scheduler that integrates real-time and general-purpose requirements

Hierarchical Scheduling

[Goyal et al., 1996]

- Each task belongs to one leaf node
- Each leaf has a weight & scheduler
- Nodes scheduled hierarchically
- SFQ used to schedule non-leaf nodes



Start-time Fair Queueing (SFQ)

[Goyal et al., 1996]

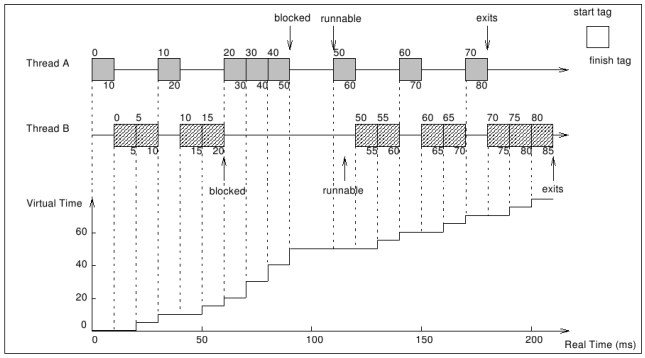
- Tasks are serviced in increasing order of start tags
- Start tag S_f and finish tag F_f defined as:

$$S_f = \max\{v(a(q_f^j)), F_j\} \quad \text{and} \quad F_f = S_f + \frac{l_f^j}{r_f}$$

- Where:
  - q_f^j = j'th quantum of task f
  - l_f^j = length of q_f^j
  - $A(q_f^j)$: time at which the jth quantum is requested
  - r_f : weight of task f
- Virtual time $v(t)$: start tag of the task in service at time t

SFQ Example

[Goyal et al., 1996, page 5]



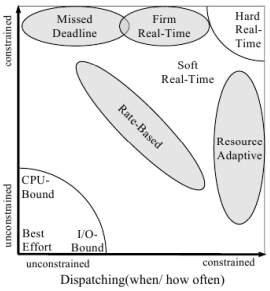
SFQ Summary

- SFQ provides hierarchical partitioning
  - Suitable for soft real-time video applications
- Hierarchical CPU scheduling claimed to:
  - Enable co-existence of heterogeneous schedulers
  - Protect application classes from each other
  - Impose similar overhead to conventional time-sharing schedulers

RAD: Resource Allocation and Dispatching

[Brandt et al., 2003]

- Resource allocation:
  - **How much** resource to allocate to each task
- Dispatching:
  - **When** to give a task the resources it has been allocated
- Most schedulers integrate management of these



(a) RAD model and real-time classes
Figure 1. Real

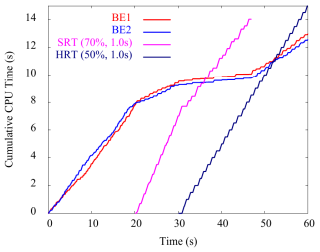
Rate-Based Earliest Deadline (RBED)

[Brandt et al., 2003]

- Earliest deadline first (EDF): run task with nearest deadline
  - How to determine "deadlines" for a non-real-time system?
- RBED policy:
  - Resource allocation: target **rate** of progress for each process
  - Dispatching: **period** based on process timeliness needs
- RBED mechanism:
  - Rate-enforcing EDF
  - Timer set for period of each task (no regular ticker!)
- **Slack** (idle/unallocated time) management important for soft real-time and background tasks
- Integrated scheduling of hard real-time, soft real-time, rate-based and best-effort tasks

RBED Results

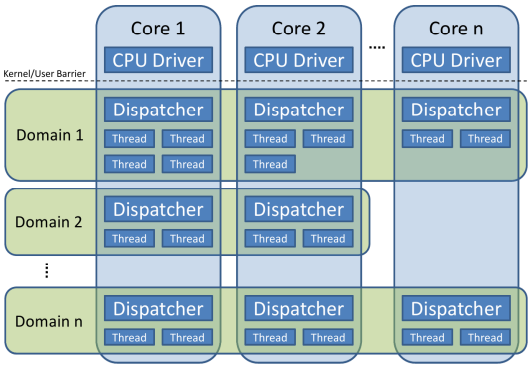
- HRT performance guaranteed by EDF
  - RBED guarantees isolation
  - Admission control resource availability
- SRT performance based on resource availability
  - Rates & periods vary when HRT or SRT task enters or exits
- Best effort tasks get whatever is left



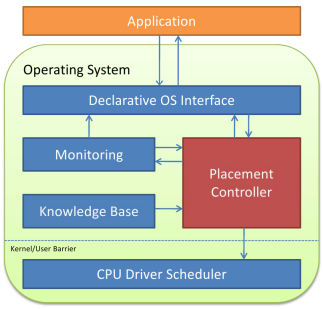
Scheduling in Barrelfish

- Biggest problem is diversity of cores, workloads
- One size doesn't fit all:
  need to concurrently support different schedulers
- Placement problem: which cores run which workloads with which schedulers / scheduler parameters?

Recap: Dispatch in Barrelfish



Scheduling in Barrelfish



- Which scheduler for the CPU driver?
  - Currently RBED
- Design of placement controller open
- How to coordinate co-scheduling?

Summary

- Priorities are cheap to implement and easy to understand
  - Poor sharing behavior, poor control, unsuitable for real-time
- Real-time is now a real problem for general-purpose operating systems, due to changing workloads
- Lottery scheduling gives flexible proportional sharing
  - Doesn't (heavily) consider real-time issues
- Contrast weighted fair-queueing (SFQ, BVT) with reservation-based (classic RT, RBED) schedulers for real-time
  - Haven't discussed scheduling of other resources (eg. disk/network IO)

References

- Banga, G., Druschel, P., and Mogul, J. C. (1999). **Resource containers: A new facility for resource management in server systems**. In 3rd OSDI, pages 45–58.
- Brandt, S. A., Banachowski, S., Lin, C., and Bisson, T. (2003). **Dynamic integrated scheduling of hard real-time, soft real-time and non-real-time processes**. In 24th RTSS, pages 396–409.
- Duda, K. J. and Cheriton, D. R. (1999). **Borrowed-virtual-time (BVT) scheduling: supporting latency-sensitive threads in a general-purpose scheduler**. In 17th SOSP, pages 261–276.
- C. L. Liu and James W. Layland. 1973. **Scheduling Algorithms for Multiprogramming in a Hard-Real-Time Environment**. J. ACM 20, 1 (January 1973), pages 46-61.
- Goyal, P., Guo, X., and Vin, H. M. (1996). **A hierarchical CPU scheduler for multimedia operating systems**. In 2nd OSDI, pages 107–122.
- Waldspurger, C. A. and Weihl, W. E. (1994). **Lottery scheduling: Flexible proportional-share resource management**. In 1st OSDI, pages 1–11.

Course wrap-up: The Exam

- Form: 15 minute oral examination
- Date: TBA (but likely in first two weeks of February)
- Location: Mothy's office CAB F 79 (not IFW!)
- Content:
  - Material from the lectures
  - Concepts you should have learned in the labs
- Focus:
  - Principles and concepts
  - Not implementation details, dates, or personalities

Concluding remarks

- Thanks for participating, and congratulations!
- If you want more, Barrelfish masters theses are available:
  - OS support for heterogeneous cores
  - Scalable storage layer
  - {Haskell,JVM,. . . } on Barrelfish
  - Multi-core resource management
  - Multi-core performance analysis and tracing
  - Online performance modelling of parallel applications
  - Making device drivers safer
  - ...

  See http://www.systems.ethz.ch/education/theses or ask us