Real-Time Systems

Hard Real-Time
Multiprocessor Scheduling

Marcus Völп
Outline

- Introduction
- Terminology, Notation and Assumptions
- Anomalies + Impossibility Results
- Partitioned Scheduling (no migration)
- Global Scheduling (task- / job-level migration)
  - G-FP
  - G-EDF
- Optimal MP Scheduling
- MP – Resource Access Protocols
- Open Research Issues
Lessons Learned From UP

- **Liu-Layland Criterion for fixed task priority algorithms:**
  - can schedule any workload up to a utilization of \( U_{RMS}(n) = n^{\sqrt{2}} - 1 \leq 0.693 \)
  - scheduling of workloads with higher utilization not guaranteed

- **fixed job priority algorithms are optimal:** (e.g., EDF)

- **there are optimal greedy algorithms**
  - with a single measure characterizing the “importance” of a job (e.g., time to deadline, laxity, …)

- **all preemptive FTP, FJP algorithms are predictable**
  - response times cannot increase when decreasing execution times

- **all preemptive FTP algorithms and EDF are sustainable**
  - no period / deadline anomalies

- **simultaneous release is critical instant**

- **response times depend on set but not on order of high-priority tasks**
Taxonomy of Multiprocessor Scheduling

Two problems to solve:

- **Priority Problem:** When to run a given job of the workload?
  - fixed task priority (e.g., RMS, …)
  - fixed job priority (e.g., EDF, …)
  - dynamic job priority (e.g., LST, …)

- **Allocation Problem:** Where to run this job?
  - no migration
  - task-level migration (no migration of running jobs)
  - job-level migration (migrate also running jobs)
Taxonomy of Multiprocessor Scheduling

Two problems to solve:

• Priority Problem: When to run a given job of the workload?
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  - fixed job priority (e.g., EDF, …)
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Preemption Costs – UP / MP

Migration Costs – MP
Preemption Costs

- direct costs:
  - timer / device interrupt
  - save register state
  - manipulate ready list
    - UP: no synchronization required
  - load register state of next thread

- indirect costs
  - cache evictions between two consecutive runs
  - TLB refills after evictions / shootdown
Migration Costs

- job-level migration
  - migration of running job implies preemption at source CPU
- task-level migration
  - job is already preempted

- direct costs
  - manipulate remote / global ready list
    - synchronization
  - fetch register state

- indirect costs
  - fetch active cache working set from remote cache
  - load remaining data from remote memory
Multiprocessor Architectures

- AMD Opteron / Intel Core Duo: SMT + multi core + ccNuma
Multiprocessor Architectures

- Symmetric Multi-Threaded (SMT) Processors
  - \( m \) hardware threads
  - shared pipeline

\( m \) HW threads

Illustration:
- HW Scheduler (picks one HW Thread at a time)
- Fetch
- Decode
- Registers
- EX
- EX
- EX
- EX
- EX
- EX
- LD/ST
- LD/ST
- WB
- WB
- WB
- WB
Multiprocessor Architectures

- Symmetric Multi-Threaded (SMT) Processors
  - m hardware threads
  - shared pipeline

m HW threads

HW Scheduler (picks one HW Thread at a time)

Fetch

Decode

Registers

Execution Unit

EX

EX

WB

EX

EX

WB

EX

EX

WB

EX

EX

WB

LD/ST

LD/ST

Load / Store Unit

Write Back / Commit Results
Multiprocessor Architectures

- Symmetric Multi-Threaded (SMT) Processors
  - operating system multiplexes $n$ SW threads on $m$ HW threads
  - caches + pipeline is shared $\Rightarrow$ no indirect migration costs

![Diagram of a multiprocessor architecture with Core, L1 - D Cache, L2 - Cache, and Memory layers.]
Multiprocessor Architectures

- Multi-Core Processors
  - operating system multiplexes n SW threads on m cores
  - timing of last level cache dominates migration costs

![Diagram of multiprocessor architecture with cores, L1-D caches, L2-cache, and memory.]
Multiprocessor Architectures

- Symmetric Multiprocessors
  - operating system multiplexes $n$ SW threads on $m$ dies
  - timing of interconnect dominates migration costs
Multiprocessor Architectures

- (cache coherent) NUMA
  - like SMP
  - non-uniform memory access: fetch from remote memory
Multiprocessor Architectures

- AMD Opteron [Corey: OSDI '08]

![Diagram of Multiprocessor Architectures]
Migration Costs

- Active Cache Working Set
  - cachelines a thread would access again if it would run
  - varies over time
  - ages out after preemption

ways: 0 1 2 3
Migration Costs

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Migration Costs

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```
ways:  0   1   2   3
```

Diagram showing cache lines and their migration costs.
Migration Costs

• Summary
  
  • migration costs are highly architecture dependent
  • non-trivial to predict
  • may cause a significant delay when a thread resumes execution

• Assumption for the remainder of this lecture:
  
  • zero preemption and migration costs / attributed to WCET
Design Space of MP Scheduling

- **dyn job prio. / partitioned**
- **fixed job prio. / partitioned**
- **fixed task prio. / partitioned**
- **dyn job prio. / task level migration**
- **fixed job prio. / task level migration**
- **fixed task prio. / task level migration**
- **dyn. job prio. / job level migration**
- **fixed job prio. / job level migration**
- **fixed task prio. / job level migration**
Design Space of MP Scheduling

Partitioned
- dyn job prio. / partitioned
- fixed job prio. / partitioned
- fixed task prio. / partitioned

Global
- dyn job prio. / task level migration
- fixed job prio. / task level migration
- fixed task prio. / task level migration
- fixed job prio. / job level migration
- fixed job prio. / job level migration
- fixed task prio. / job level migration
Design Space of MP Scheduling

Relative ordering between classes of scheduling algorithms

- dyn. job prio. / job level migration
- dyn. job prio. / task level migration
- fixed job prio. / partitioned
- dyn. job prio. / partitioned
- fixed job prio. / task level migration
- fixed job prio. / job level migration
- fixed task prio. / partitioned
- fixed task prio. / task level migration
- fixed task prio. / job level migration

Later in this lecture
Outline

- Introduction
- Terminology, Notation and Assumptions
- Anomalies + Impossibility Results
- Partitioned Scheduling
- Global (Task-Lvl migration) Scheduling
  - G-FTP (e.g., G-RMS)
  - G-EDF
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Terminology, Notation and Assumptions

- Periodic Tasks
  - Task $t_i = (P_i, D_i, C_i)$ \quad $P_i = \text{const.}$

- Sporadic Tasks
  - $P_i = \text{Minimal Interrelease Time}$

- Deadlines
  - implicit deadline: $D_i = P_i$ \quad (relative deadline = period)
  - constrained: $D_i \leq P_i$ \quad (relative deadline < period)
  - arbitrary \quad (deadline may be after period end)

- Utilization
  - $U_i = \frac{C_i}{P_i}$

- Density
  - $\vartheta_i = \frac{C_i}{\min(D_i, P_i)}$
Assumptions for the remainder of this lecture

- independent tasks
- fully preemptible / migratable (negligible costs)
- unlimited number of priorities
- tasks are single threaded: a job can utilize only 1 CPU at a time
- jobs do not block (shared resources later in this lecture)

pictures show schedules for 2 CPUs
Terminology: P-DMS / G-RMS / G-EDF

- Scheduling Algorithms:
  - Deadline Monotonic Scheduling:
    - Priorities are inversely proportional to deadline
  - Rate Monotonic Scheduling:
    - Priorities are inversely proportional to period
  - Earliest Deadline First:
    - Job priorities are inversely proportional to deadline
Terminology: P-DMS / G-RMS / G-EDF

- Scheduling Algorithms:

  **Deadline Monotonic Scheduling:**
  prio inverse proportional to deadline

  **Rate Monotonic Scheduling:**
  prio inverse proportional to period

  **Earliest Deadline First:**
  job prio. inverse proportional to deadline

- P-DMS

  **Partitioned:**
  - assign threads to processors
  - scheduler picks threads from local (per CPU) ready queue
  - no synchronization overhead for accessing the ready queue

- G-RMS / G-EDF

  **Global:**
  - threads may migrate to other CPUs
  - scheduler picks thread from global ready queue
  - accesses to ready queue must be synchronized
Anomalies

- Simultaneous Release is not Critical Instance [Lauzac '98]
  - longer response time in second period

simultaneous release of all tasks

yellow misses its deadline
Anomalies

- Response time (of green) depends not only on set of higher prioritized tasks but also on their relative priority ordering.
Sustainability [Baruah '06]

- A schedulable workload remains schedulable if we
  - decrease the execution time of a task (predicability)
    - otherwise, WCET won't work as admission criterion
  - increase the minimal interrelease time (period) of a task
    - otherwise, more frequent recurrence is no safe approximation
  - increase the relative deadline of a task
    - otherwise, earlier deadline is no safe approximation

- G-FTP + G-EDF are not sustainable if #CPUs > 1

- all preemptive FJP / FTP algorithms are predictable

  Fixed Job Priority  Fixed Task Priority
Dhall Effect

- The utilization bound of Global EDF is as low as $U_{EDF} = 1 + \varepsilon$
  - $m$ tasks with short periods and infinitesimal low $U_i$ (e.g., $U_i = \varepsilon$)
  - 1 task with larger period and $U_j$ close to 1 (e.g., $U_j > (2 - \varepsilon) / 2$)

- Dhall Effect does not manifest if $U_i < 41\%$
Dhall Effect

- The utilization bound of Global EDF is as low as $U_{\text{EDF}} = 1 + \varepsilon$
  
  - $m$ tasks with short periods and infinitesimal low $U_i$ (e.g., $U_i = \varepsilon$)
  
  - 1 task with larger period and $U_j$ close to 1 (e.g., $U_j > (2 - \varepsilon) / 2$)

- Dhall Effect does not manifest if $U_i < 41\%$
some Impossibility Results

- [Hong '88]
  - No optimal online MP scheduling algorithm for arbitrary collections of jobs, unless all jobs have the same relative deadline.

- [Dertouzos '89]
  - Even if execution times are known precisely, clairvoyance for job arrivals is necessary for optimality.

- [Fisher '07]
  - No optimal online algorithm for sporadic tasksets with constrained or arbitrary deadlines.
Partitioned Scheduling

- **Partitioned**
  - dyn job prio. / partitioned
  - fixed job prio. / partitioned
  - fixed task prio. / partitioned
  - dyn job prio. / task level migration
  - fixed job prio. / task level migration
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  - dyn. job prio. / job level migration
  - fixed job prio. / job level migration
  - fixed task prio. / job level migration
Partitioned Scheduling

- Split workload by allocating tasks to CPUs
- Run allocated task with UP scheduling algorithm
  - reap benefit of well known UP results
  - optimal task allocation is NP complete:
    - pack $n$ tasks with density $d_i$ on $m$ CPUs with capacity $d_{\text{max}} = 1$
    - Bin-packing

```
CPU_0 → ● → ● → ● → ●
CPU_1 → ●
...
CPU_m → ● → ● → ●
```
Partitioned Scheduling

- Utilization bound for implicit deadline workloads [Anderson '01]

\[ U_{opt} = \frac{m + 1}{2} \]

No partitioning scheduling algorithm can produce a feasible schedule of \( m+1 \) tasks with execution time \( 1+e \) and period of 2 on \( m \) processors.
Partitioned Scheduling

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Easy if blue and green can migrate to CPU\(_2\)
Can we improve on Anderson's Utilization Bound?
  - by allowing a few jobs to migrate

- **PDMS** Partitioned Deadline Monotonic Scheduling
- **HPTS** Split Highest Priority Task
- **DS** Allocate according to Highest Density First
\[
\begin{align*}
\tau_1 &= (4,3,1) & u_1 &= 0.25 & \delta_1 &= 1/3 = 0.33 \\
\tau_2 &= (6,2,2) & u_2 &= 0.33 & \delta_2 &= 1 \\
\tau_3 &= (4,4,1) & u_3 &= 0.25 & \delta_3 &= 1/4 = 0.25 \\
\tau_4 &= (6,4,2) & u_4 &= 0.33 & \delta_4 &= 1/2 = 0.5 \\
\tau_5 &= (6,5,1) & u_5 &= 0.16 & \delta_5 &= 1/5 = 0.2 \\
\end{align*}
\]

\[
u_{\text{sum}} = 1.33 \Rightarrow u_{\text{sum}} / 2 = 0.66\%
\]
\( \tau_1 = (4,3,1) \) \hspace{1cm} u_1 = 0.25 \hspace{0.5cm} \delta_1 = 1/3 = 0.33

\( \tau_2 = (6,2,2) \) \hspace{1cm} u_2 = 0.33 \hspace{0.5cm} \delta_2 = 1

\( \tau_3 = (4,4,1) \) \hspace{1cm} u_3 = 0.25 \hspace{0.5cm} \delta_3 = 1/4 = 0.25

\( \tau_4 = (6,4,2) \) \hspace{1cm} u_4 = 0.33 \hspace{0.5cm} \delta_4 = 1/2 = 0.5

\( \tau_5 = (6,5,1) \) \hspace{1cm} u_5 = 0.16 \hspace{0.5cm} \delta_5 = 1/5 = 0.2

\[ \begin{align*}
\text{CPU}_0 & \quad \text{CPU}_1 \\
\hline
& \hspace{1.5cm} \hspace{1.5cm} & \\
\text{CPU}_0 & \quad \text{CPU}_1
\end{align*} \]

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\[ \frac{u_{\text{sum}}}{2} = 0.66\% \]
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\( \tau_5 = (6,5,1) \quad u_5 = 0.16 \quad \delta_5 = 1/5 = 0.2 \)

\[ u_{\text{sum}} = 1.33 \Rightarrow u_{\text{sum}} / 2 = 0.66\% \]
\[ \tau_1 = (4,3,1) \]
\[ \tau_2' = (6,2,1) \]
\[ \tau_2'' = (5,1,1) \]
\[ \tau_3 = (4,4,1) \]
\[ \tau_4 = (6,4,2) \]
\[ \tau_5 = (6,5,1) \]

\[ u_2 = 0.33 \quad \delta_2 = 1 \]
\[ u_3 = 0.25 \quad \delta_3 = \frac{1}{4} = 0.25 \]
\[ u_4 = 0.33 \quad \delta_4 = \frac{1}{2} = 0.5 \]
\[ u_5 = 0.16 \quad \delta_5 = \frac{1}{5} = 0.2 \]

\[ u_{\text{sum}} = 1.33 \quad \Rightarrow u_{\text{sum}} / 2 = 0.66\% \]

Splitting HP Task into \( D' - R' = D'' = C' \)

\[ \Rightarrow \text{deadline of } \tau'' \text{ maximized} \]
\( \tau_1 = (4,3,1) \)
\( u_1 = 0.25 \quad \delta_1 = 1/3 = 0.33 \)
\( \tau_2' = (6,2,1) \)
\( u_2 = 0.33 \quad \delta_2 = 1 \)
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\( u_5 = 0.16 \quad \delta_5 = 1/5 = 0.2 \)

\[
u_{\text{sum}} = 1.33 \Rightarrow \frac{u_{\text{sum}}}{2} = 0.66\%
\]
PDMS-HPTS-DS

- $U_{PDMS-HPTS-DS} = 69.3\%$ if all tasks have a utilization $U_i < 41\%$
Global Scheduling

- **Dynamic Job Priority / Partitioned**
  - Dynamic Job Priority / Task Level Migration
  - Fixed Job Priority / Task Level Migration
  - Fixed Task Priority / Task Level Migration

- **Fixed Job Priority / Partitioned**
  - Fixed Job Priority / Job Level Migration
  - Fixed Task Priority / Job Level Migration

- **Fixed Task Priority / Partitioned**
  - Fixed Task Priority / Job Level Migration
Global Scheduling

- Always pick the ready jobs of the m most "important" tasks
- A task may migrate
  - When a new job of a task is released it may receive a different CPU; once started, a job is no longer migrated
- No need for allocation / load balancing
  - Load balancing is automatic

```
CPU_0
CPU_1
...
CPU_m
```

```
|<--|<--|<--|<--|<--|<--|<--|
```

Real-Time Systems, Multiprocessor Scheduling / Marcus Völp
Global Scheduling – Utilization Bound

- Utilization bound for global fixed-job priority algorithms

- on m CPUs, G-FJP algorithms cannot schedule m+1 tasks with $C_i = 1 + e$, $P_i = 2$ ($e \to 0$)

\[
U_{OPT} = \lim_{e \to 0} \frac{(m+1)(1 + e)}{2} = \frac{m+1}{2}
\]
Global Scheduling - Job Level Migration

- **Dynamic Job Priorities / Partitioned**
  - Task Level Migration

- **Fixed Job Priorities / Partitioned**
  - Task Level Migration

- **Fixed Task Priorities / Partitioned**
  - Task Level Migration

- **Dynamic Job Priorities / Job Level Migration**
PFAIR [Baruah '96]

- Divide timeline into equal length quanta
- At each quanta of length $t$, allocate tasks to processors such that the accumulated processor time is either $[tu_i]$ or $[tu_i]$
PFAIR [Baruah '96]

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PFAIR [Baruah '96]

- Divide timeline into equal length quanta

- At each quanta of length $t$, allocate tasks to processors such that the accumulated processor time is either $[tu_i]$ or $[tu_i]$

- PFAIR is optimal for periodic implicit deadline tasksets: $U_{OPT} = m$

- Very high preemption and migration costs
DP-Fair [Brandt '10]

- DP-Fair
  - Optimal scheduler for periodic implicit deadline tasksets with a minimal number of preemptions / migrations?
  - Recall [Hong '88]:
    - No optimal MP scheduling algorithm for arbitrary tasksets if not all tasks have the same relative deadline

- deadline partitioning
  - any task’s deadline becomes a deadline for all tasks
- always run zero laxity jobs
  - laxity = time to deadline – remaining execution time
  - zero laxity => job may miss its deadline if it is not run
- jobs that twine themselves around the fluid rate curve are somehow in good shape
DP-Fair [Brandt '10]

- Fluid Rate Curve

![Diagram showing fluid rate curve and actual work remaining curve.

- Zero laxity event: no more time to run others.
DP-Fair [Brandt '10]

- DP-Fair:
  - a family of optimal, deadline partitioning scheduling algorithms
- Split timeline into chunks according to job deadlines
- Allocate work to a chunk proportional to $U_i$
  - local execution time: $C_{i,j} = (t_{j+1} - t_j) U_i$
- Rule 1: always run a job with zero local laxity
  - jobs with remaining local execution time = time to end of chunk
- Rule 2: never run a job with no remaining local work
- Rule 3: split up idle time proportional to length of chunk
  - allocate at most $(m - U_{\text{sum}}) (t_{j+1} - t_j)$ idle time to chunk $j$
Deadline partitioning

Introduce additional releases / deadlines for all jobs whenever there is such an event for one job in the original schedule => chunks
Treat idle time as just another job to schedule.
Allocate work proportional to $U_i$

Allocate execution (and idle) time of a job proportionally to its utilization

$\Rightarrow$ amount of time that this job must run in a given chunk
DP-Fair [Brandt '10]

Jobs hit their fluid rate curve at the end of each chunk

some arbitrary ordering
DP-Wrap – a DP-Fair Scheduler

Work allocated to a chunk:
find a schedule
DP-Wrap – a DP-Fair Scheduler

Work allocated to a chunk:
find a schedule

arrange jobs consecutively

wrap around to obtain schedule for 2nd CPU, ...
DP-Wrap – a DP-Fair Scheduler

Work allocated to a chunk: find a schedule

arrange jobs consecutively

wrap around to obtain schedule for 2nd CPU, ...

m – 1 migrations per chunk
n – 1 context switches per chunk
DP-Wrap – a DP-Fair Scheduler

Unnecessary migration of red task at chunk boundaries
=> mirror processor assignment of every second chunk
DP-Wrap (mirrored)
Design Space of MP Scheduling

- Dynamic job priority / partitioned
- Dynamic job priority / task level migration
- Dynamic job priority / job level migration
- Fixed job priority / partitioned
- Fixed job priority / task level migration
- Fixed job priority / job level migration
- Fixed task priority / partitioned
- Fixed task priority / task level migration
- Fixed task priority / job level migration
Design Space of MP Scheduling

\[ U_{\text{opt}} = m \]
\[ U_{\text{opt}} = \frac{m+1}{2} \]

- dyn. job prio. / job level migration
- dyn. job prio. / task level migration
- fixed job prio. / partitioned
- fixed task prio. / partitioned

\[ U_{\text{opt}} = m \]
- = dyn job prio. / partitioned
- = fixed job prio. / partitioned
- = fixed task prio. / partitioned

A \rightarrow B => A can schedule any taskset that B can schedule and more
A \leftrightarrow B => dominance is not yet known
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MP Resource Access Protocols

- UP-BPCP in a nutshell
  - resource holders inherits priority from blocked threads
  - resource granted if $\text{prio}(t_j) > \hat{S}$
  - only the resource holder, which holds a resource with $\hat{R}_i = \hat{S}$ receives additional resources

- UP-SRP (actually UP-CPP) in a nutshell
  - resource holder runs at max $\hat{R}_i$ of held resources
  => only higher prioritized threads may run (acquire resources)
MP Resource Access Protocols

- UP:
  - Basic Priority Ceiling Protocol BPCP
  - Stack Resource Protocol SRP (Ceiling Priority Protocol CPP)
    - bounded priority inversion: $|CS|$
    - BPCP does not influence unrelated threads
- General Idea:
  - run UP protocol on every CPU of MP system
- Ceiling Priority $i$ of Resource $R_i$: $\hat{\bar{R}}_i = \max \text{prio}(t_j)$
  - here, priorities have a global meaning
- System Ceiling $\hat{S} = \max \hat{\bar{R}}_i$ of held resources
- Synchronization Processor: CPU on which $R_i$ is executed
Locking for Clustered Scheduling

- [Brandenburg '11]:
  - clustered scheduling: global within the cluster; partitioned in between

  ![Diagram]

  Idea:
  - Every task helps out resource holders for a bounded time
  - Only the n-highest prioritized threads may acquire resources
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Open Issues [Burns '09]

- Limited processor Utilization
  - minimally dynamic algorithms
  - novel partitioning approaches
    - increase the guaranteed processing capability; overheads
- Ineffective Schedulability Tests (in particular, sporadic workloads)
  - large gap between feasibility / infeasibility tests
  - identify finite collection of worst-case job arrival sequences
- Overheads
  - migration costs; run queue manipulations; context switching
  - algorithms that permit intra-cluster migration; task-level migr.
- Task Models
  - intra-task parallelism, runtime integration
  - heterogeneous resources, Turbo Boost, GPUs
References

- [Burns '09]

- [Colette]

- [Edmonds]

- [Brandt '10]

- [Hong '88]

- [Anderson '01]

- [Lakshmanan '09]
  K. Lakshmanan, R. Rajkumar, J. Lehoczky, “Partitioned Fixed-Priority Preemptive Scheduling for Multi-Core Processors”, ECRTS, 2009
References

- [Fisher '07]

- [Dertouzos '89]

- [Dhall]

- [Baruah '06]
  S. Baruah, A. Burns, “Sustainable Scheduling Analysis,” RTSS, 2006

- [Corey '08]

- [Carpenter '04]

- [Whitehead]

- [Brandenburg '08]
References

- [Gai '03]

- [Block]

- [MSRP]

- [MPCP]

- [Lauzac '98]

- [Baruah '96]

- [Brandenburg'11]