Mutliprocessor and Real-Time Scheduling

Julien Schmaltz

Institute for Computing and Information Sciences
Radboud University Nijmegen
The Netherlands
julien@cs.ru.nl

June 15, 2008

Part I

Mutliprocessor Scheduling

Multiprocessor Systems

- Loosely coupled multiprocessor, or cluster: autonomous systems, each processor has its own main memory and I/O channels
- Functionally specialized processors: e.g. I/O processor. Slaves used by a master (e.g. general-purpose CPU).
- Tightly couple multiprocessing: processors share a common main memory, they are under the control of an operating system

Chapter 10.1 deals with the last category of systems

Synchronization Granularity

- Fine: Parallelism inherent in a single instruction stream (sync. interval $<$20 instructions)
- Medium: Parallel processing or multitasking within a single application (sync. interval 20–200 inst.)
- Coarse: Mutliprocessing of concurrent processes in a multiprogramming environment (sync. inter. 200–2000)
- Very Coarse: Distributed processing across network nodes to form a single computing environment (sync. inter. 2000–1M)
- Independent: Multiple unrelated processes (see previous lecture)

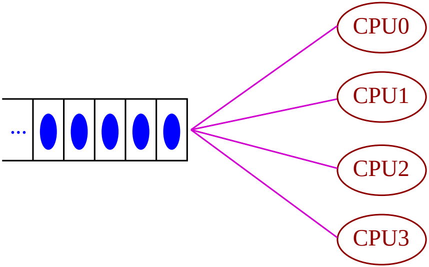
Granulatity $=$ important parameter when designing selection functions

Mainly consider (Coarse) Medium

Basic Problem

- Given a number of threads (or processes), and a number of CPUs, assign threads to CPUs
- Same issues as for uniprocessor scheduling:
  - Response time, fairness, starvation, overhead, ...
- New issues:
  - Ready queue implementation
  - Load balancing
  - Processor affinity

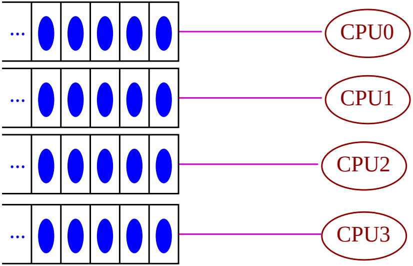
Single Shared Ready Queue



- Global queue
- CPU picks one process when ready

- Pros
  - Queue can be reorganized (e.g. priorities, ... see previous lecture)
  - Load evently distributed
- Cons
  - Synchronization (mutual exclusion of queue accesses)
  - Overhead (caching, context switch, ...)

Per-CPU Ready Queue



- One queue per CPU

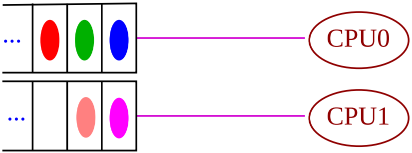
- Pros
  - Simple/ no synchronization needed
  - Strong affinity
- Cons
  - Where put new threads ?
  - Load balancing

Load Balancing

- Try to keep processors as busy as possible
- Global approaches
  - Push model – Kernel daemon checks queue lengths periodically, moves threads to balance
  - Pull model – CPU notices its queue is empty and steals threads from other queues
  - Do both !
- Load sharing
- Gang-scheduling
- Dedicated processor assignment
- Dynamic scheduling

Processor Affinity

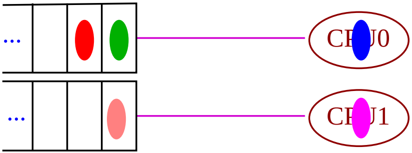
- States of executed threads in the cache of the CPU
- Repeated execution on the same CPU may reuse the cache
- Execution on a different CPU:
  - Requires to load state in the cache
- Try to keep thread–CPU pairs constant



1 thread bound to 1 processor

Processor Affinity

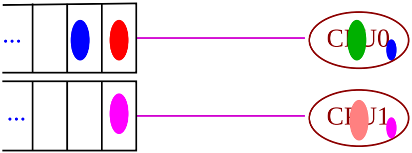
- States of executed threads in the cache of the CPU
- Repeated execution on the same CPU may reuse the cache
- Execution on a different CPU:
  - Requires to load state in the cache
- Try to keep thread–CPU pairs constant



1 thread bound to 1 processor

Processor Affinity

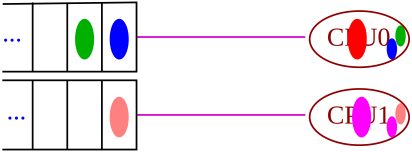
- States of executed threads in the cache of the CPU
- Repeated execution on the same CPU may reuse the cache
- Execution on a different CPU:
  - Requires to load state in the cache
- Try to keep thread–CPU pairs constant



Previous state stored in cache

Processor Affinity

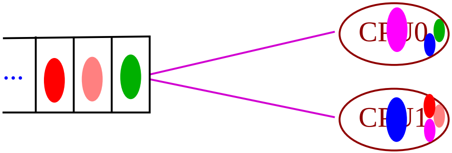
- States of executed threads in the cache of the CPU
- Repeated execution on the same CPU may reuse the cache
- Execution on a different CPU:
  - Requires to load state in the cache
- Try to keep thread–CPU pairs constant



No (less) cache misses

Processor Affinity

- States of executed threads in the cache of the CPU
- Repeated execution on the same CPU may reuse the cache
- Execution on a different CPU:
  - Requires to load state in the cache
- Try to keep thread–CPU pairs constant



Need to load cache !

Job Scheduling

- Job = a set of processes (or threads) that work together (to solve some problem or provide some service)
- Performance depends on scheduling of job components
- Two major strategies
  - Space sharing
  - Time sharing

Why it matters ?

!!! Threads in a job are not independent !!!

- Synchronize on shared variables
- Cause/effect relationship
  - e.g. Consumer/Producer problem
  - Consumer is waiting for data but Producer which is not running
- Synchronizing phases of execution (barriers)
  - Entire job proceeds at pace of slowest thread

Space Sharing

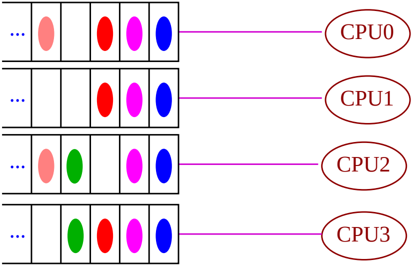
- Define groups of processors
  - Fixed, variable, or adaptive
- Assign one job to one group of processors
  - Ideal: one CPU/thread in job
- Pros
  - Low context switch
  - Strong affinity
  - All runnable threads execute at same time
- Cons
  - One partition may have pending threads/jobs while another is idle
  - Hard to deal with dynamically-changing job sizes

Time Sharing

- Divide one processor time between several jobs
- Each CPU may execute threads from different jobs
  - Key: keep awareness of jobs
- Pros
  - Allow gang-scheduling
  - Easier to deal with dynamically-changing
- Cons
  - Filling available CPU slots with runnable jobs equiv. to the bin packing problem
  - Heuristic based – (bad worst case)

Gang-Scheduling (1)

- CPUs perform context switch together
- CPUs execute threads from different jobs (time sharing)
- Thread of one job bound to one processor (space sharing)
- Strong affinity

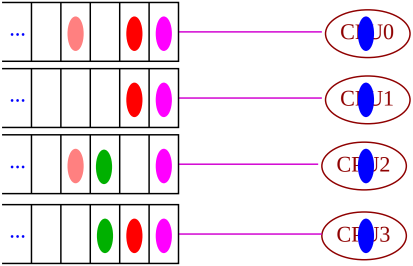


First execute blue for t_b seconds, which is enough to complete the job

Green bound to CPU2 and CPU3, Pink to CPU0 and CPU2

Gang-Scheduling (1)

- CPUs perform context switch together
- CPUs execute threads from different jobs (time sharing)
- Thread of one job bound to one processor (space sharing)
- Strong affinity

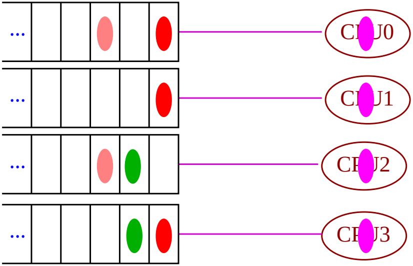


First execute blue for t_b seconds, which is enough to complete the job

Green bound to CPU2 and CPU3, Pink to CPU0 and CPU2

Gang-Scheduling (1)

- CPUs perform context switch together
- CPUs execute threads from different jobs (time sharing)
- Thread of one job bound to one processor (space sharing)
- Strong affinity

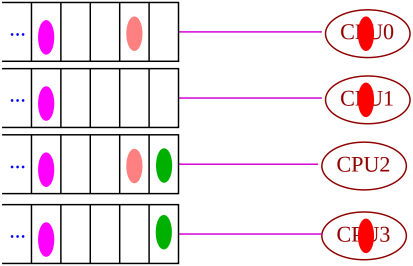


Then, execute magenta for t_m seconds, and put magenta back in the queue

Green bound to CPU2 and CPU3, Pink to CPU0 and CPU2

Gang-Scheduling (1)

- CPUs perform context switch together
- CPUs execute threads from different jobs (time sharing)
- Thread of one job bound to one processor (space sharing)
- Strong affinity

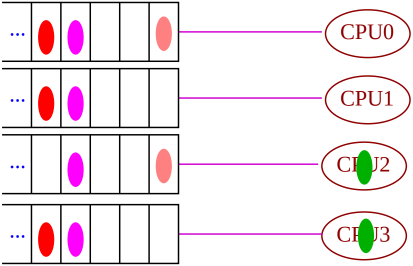


Execute red job

Green bound to CPU2 and CPU3, Pink to CPU0 and CPU2

Gang-Scheduling (1)

- CPUs perform context switch together
- CPUs execute threads from different jobs (time sharing)
- Thread of one job bound to one processor (space sharing)
- Strong affinity

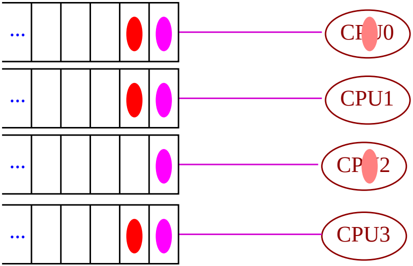


Execute green job, pink job blocked by green

Green bound to CPU2 and CPU3, Pink to CPU0 and CPU2

Gang-Scheduling (1)

- CPUs perform context switch together
- CPUs execute threads from different jobs (time sharing)
- Thread of one job bound to one processor (space sharing)
- Strong affinity

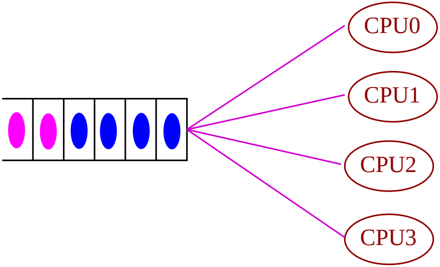


Execute pink job

Green bound to CPU2 and CPU3, Pink to CPU0 and CPU2

Gang-scheduling (2)

- CPUs perform context switch together
- Execute only all threads of one job
- Weak affinity but strong usage

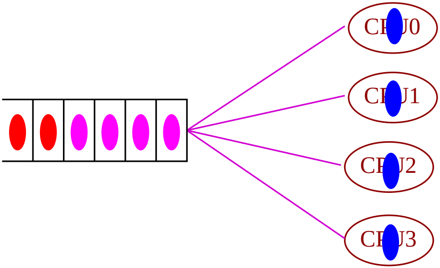


Execute blue.

No fixed thread/processor assignment

Gang-scheduling (2)

- CPUs perform context switch together
- Execute only all threads of one job
- Weak affinity but strong usage

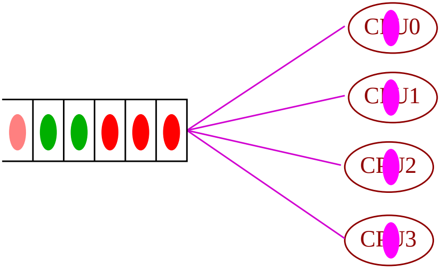


Execute blue.

No fixed thread/processor assignment

Gang-scheduling (2)

- CPUs perform context switch together
- Execute only all threads of one job
- Weak affinity but strong usage

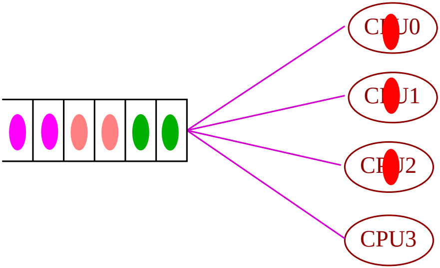


Execute Magenta

No fixed thread/processor assignment

Gang-scheduling (2)

- CPUs perform context switch together
- Execute only all threads of one job
- Weak affinity but strong usage

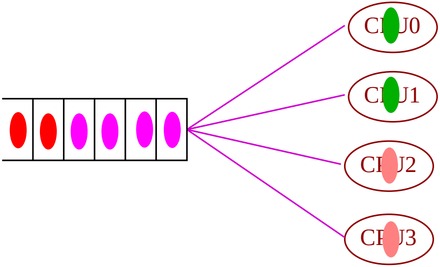


Not enough CPUs for green.

No fixed thread/processor assignment

Gang-scheduling (2)

- CPUs perform context switch together
- Execute only all threads of one job
- Weak affinity but strong usage



Enough CPUs for green AND pink

No fixed thread/processor assignment

Dynamic Scheduling

- Number of threads can be altered dynamically by applications
- O/S adjust the load to improve utilization
  - Assign idle processors
  - New arrivals may be assigned to a processor that is used by a job currently using more than one processor
  - Hold request until processor is available
  - Assign processor a job in the list that currently has no processor (i.e., to all waiting new arrivals)

Part II

Real-Time Scheduling

Real-Time Systems (1)

- Correct executions depend not only on computation results but also on the time when the results are available
- "Events occur in real-time"
  - Tasks reaction/control w.r.t. events that take place in the outside world
  - Dynamic process, talks must keep up with these events

Real-Time Systems (2)

- Control of laboratory experiments
- Process control in industrial plants
- Robotics
- Air traffic control
- Telecommunications
- Military command and control systems

Real-Time Tasks

- Tasks have deadlines (to start or finish)
- Hard vs. soft deadlines
  - **hard real-time tasks** must meet them deadlines
    Space shuttle rendez-vous, Nuclear powerplants, ...
  - **soft real-time tasks** may not meet their deadline, this has no "dramatic" consequences
    Execution of the tasks even after its deadline !
- Periodic vs. aperiodic
  - Aperiodic: fixed deadline that must (or may) be met.
  - Periodic: "once per period T" or "exactly T units appart"

Characteristics of Real-Time Operating Systems (1)

Determinism

- Operations are performed at fixed, predetermined times, or within predetermined time intervals
- Concerned with maximum delay before interrupt acknowledgment and the capacity to handle all the requests within the required time

Characteristics of Real-Time Operating Systems (2)

- Responsiveness
  - Delay after acknowledgment to service the interrupt
  - Includes time to begin the execution of the interrupt
  - Includes time to perform the interrupt
  - Effect of interrupt nesting
- Response time to external events = determinism + responsiveness

Characteristics of Real-Time Operating Systems (3)

User control

- User specified priorities
- User specified paging
- What processes must always reside in main memory
- User specified disk algorithms
- User specified processes rights

Characteristics of Real-Time Operating Systems (4)

- Reliability
  - Degradation of performance may have catastophic consequences (e.g. nuclear meltdowns)
- Fail-soft operation
  - Fail in such a way as to preserve capability and data
  - Stability: deadlines of most critical tasks always met

Features of RTOS (1)

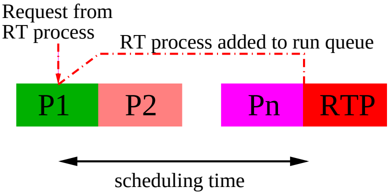
- Fast process or thread switch
- Small size (minimal functionality)
- Quick response to interrupts
- Multitasking with interprocess communication tools such as semaphores, signals, and events

Features of RTOS (2)

- Use of specifal sequential files that can accumulate data at fast rate
- Preemptive scheduling based on priority
- Minimization of intervals during which interrupts are disabled
- Delay tasks for fixed amount of time
- Special alarms and timeouts

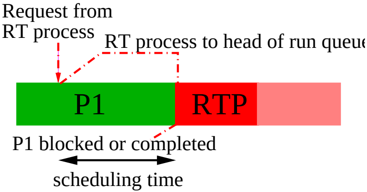
Scheduling (1)

- Round-robin preemptive scheduling



- RT to run queue to await next time slice
- Scheduling time unacceptable for RT apps

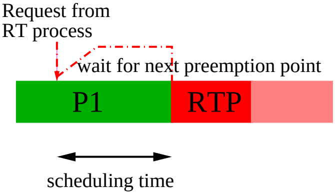
- Priority-driven non-preemptive scheduler



- RT process to head of run queue
- Issue if P1 low prior. and slow

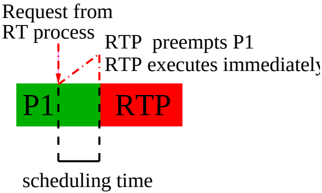
Scheduling (2)

- Priority-driven, preemptive at preemption points



- RT preempts current process
- Wait until next preemption point
- Which may come before end of P1

- Immediate preemptive



- RTP preempts current process
- RTP is executed immediately

Real-Time Scheduling

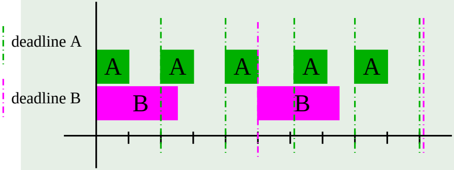
- Static table-driven
  - Static analysis if feasible schedules
  - Determines at run time when a task starts
- Static priority-driven preemptive
  - Analysis used to assign priority to tasks
  - Traditional priority-driven preemptive scheduler
- Dynamic planning-based
  - Feasibility determined at run time
- Dynamic best effort
  - No feasibility analysis is done

Deadline Scheduling

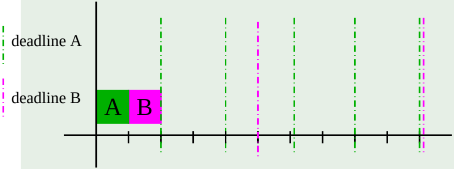
- Important metrics: meet deadlines (not too early, not too late) rather than speed
- Information used:
  - Ready time
  - Starting time
  - Completion deadline
  - Processing time
  - Resource requirements
  - Priority
  - Subtask structure

Example

- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Fixed priority: A has priority



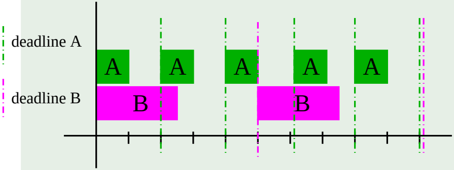
- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms



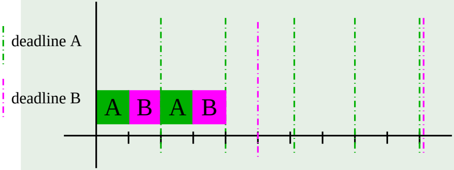
- A runs for 10ms
- B interrupted by A

Example

- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Fixed priority: A has priority



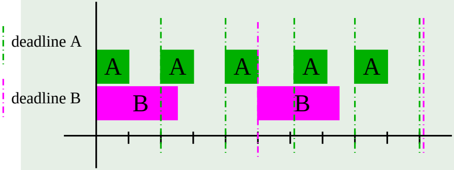
- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms



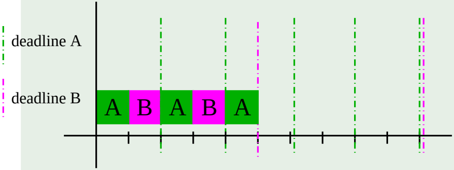
- A runs for 10ms
- B interrupted by A

Example

- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Fixed priority: A has priority



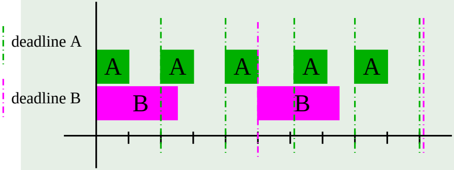
- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms



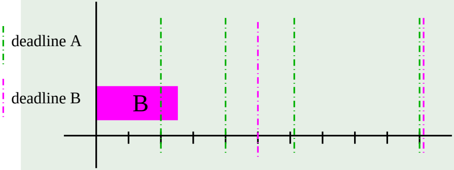
- A runs for 10ms
- B interrupted by A
- Deadline of B missed !

Example

- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Fixed priority: B has priority



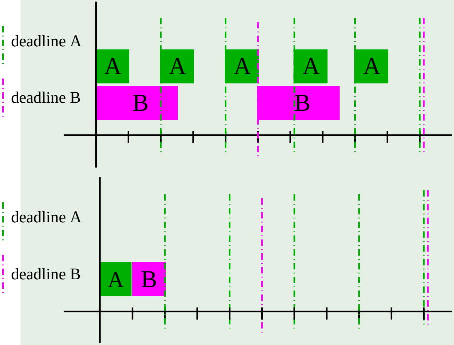
- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms



- B has priority
- Deadline of A missed !

Example

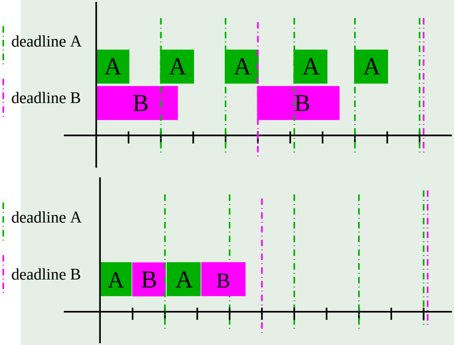
- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Earlier Deadline First (EDF)



- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms
- A deadline before B deadline

Example

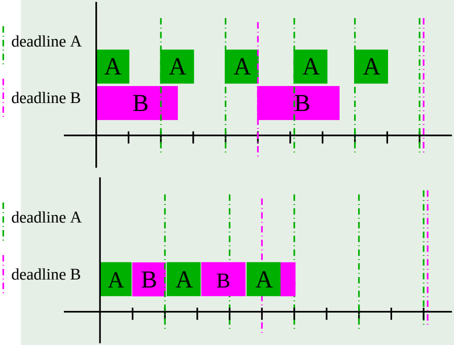
- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Earlier Deadline First (EDF)



- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms
- B interr. because of A deadline

Example

- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Earlier Deadline First (EDF)

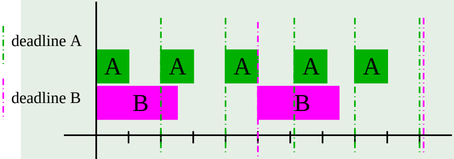


- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms

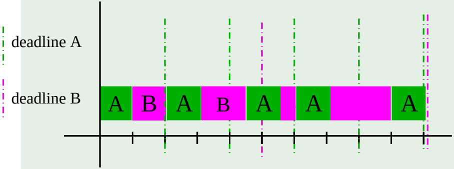
- B completes because earliest deadline

Example

- Collecting data from sensors A and B
- Scheduling decision every 10ms and based on completion deadlines
- Earlier Deadline First (EDF)



- Sensor A: 10ms, every 20ms
- Sensor B: 25ms, every 50ms



- Last B and A complete

Rate-Monotonic Scheduling (RMS)

- Proposed by Liu and Layland 1973
- Use frequency to assign priority
- Highest priority to shortest period
- Priority is a monotonic function of the period
- Static priority

Example

Previously we had $T_A = 20ms$, $C_A = 10ms$ and $T_B = 50ms$, $C_B = 25ms$, so RMS would choose A. Issue: $\frac{C_A}{T_A} + \frac{C_B}{T_B} = 1$!

Liu and Layland Result

- One cannot use more than the full processor time

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \cdots + \frac{C_n}{T_n} \leq 1$$

- For RMS, the following condition is sufficient for schedulability

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \cdots + \frac{C_n}{T_n} \leq n \cdot (2^{\frac{1}{n}} - 1)$$

Example

name	C	T	U
P_1	20	100	0.02
P_2	40	150	0.267
P_3	100	350	0.286

Bound $= 3 \cdot (2^{\frac{1}{3}} - 1) = 0.779$

Sum of $U_i = 0.753$

Summary

- Interrupt based system design is challenging
- Priority assignment: a Black Art. Great body of litterature; many negative results.
- We presented 2 positive results for important special cases:
  - RATE MONOTONIC (RMS) Liu&Layland, 1973
    Case: Periodic, static priority
    Rule: priority based on frequency
    Not always applicable (auto impact sensor gets LOWEST priority)
  - EARLIER DEADLINES (EDF) Knuth, Mok *et al.* '70
    Case: deadline specified at each request
    Rule: schedule earliest deadline first
    Optimal for 1 processor; no extension to optimal N-processor scheme