Real-Time Computing

Definition of Real-Time Computing

- Real-time computing is computing in which the time of the computation plays an essential role in the result.
- This includes:
  - Computations that measure time
  - Computations that must meet deadlines
  - Computations that synchronize other computations based on time

Obligatory Inspiring Example

(from Briand and Roy, *Meeting deadlines in hard real-time systems*, IEEE Press, 1999)

- July 20, 1969, landing module 10,000 feet above the Moon:
  - Houston: “Eagle, you’re go for a landing.”
  - Houston: “One minute [of fuel left].
    ...
  - Lander: 100 feet, 3 1/2 down, 9 forward.”
  - Houston: “30 Seconds.”
  - Lander: “OK, engine stop.”

Example of Real-Time

(from Briand and Roy, *Meeting deadlines in hard real-time systems*, IEEE Press, 1999)

- “During the descent of the Eagle [landing module], an incorrect switch position caused the analog-to-digital conversion circuit of the rendezvous to send some **bursts of high-priority requests** to the computer.
- After 15 percent of the computer resources were tied up in responding to the spurious requests, **jobs began to miss their deadlines**.
- A hardware recovery mechanism detected the timing fault and restarted the computer.”

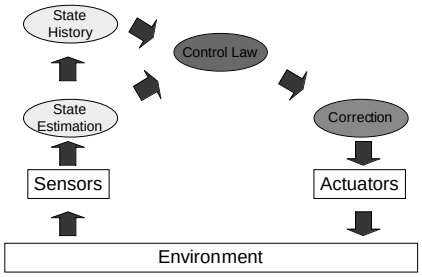
Control Loops

- Autonomous, or semi-autonomous vehicles or robots require control loops to govern their motion.
- Computing equipment may also require such loops (e.g. transfers to/from rotational media).
- Less-regular computational tasks may need to be handled by the same system.

Example of Real-Time: Control Loop

- A vehicle is governed by a **control law**, that takes input from sensors and produces output to actuators.
- From **sensor** input, an estimate of position, velocity, etc. is computed.
- Based on the computed estimate, appropriate adjustment is made to **actuators**.
- For example, the adjustment may be based on difference between estimated state and desired state.
- The control law is based on a sampling and update rate.
- All computations must complete in time for the next sample.

Example of Real-Time: Control Loop



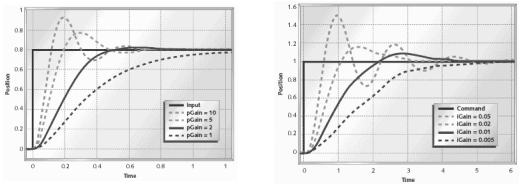
Examples of Control Laws

- Open- vs. Closed-loop control
- Bang-Bang ("On-Off") controllers
- P controller (proportional controller)
- PI controller (proportional-integral controller)
- PID controller (proportional-integral-derivative controller)

Comparison of Control Laws

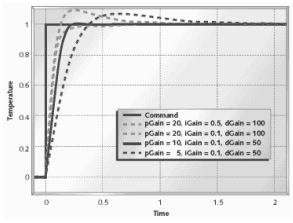
- Bang-Bang:
  {Measure error;
  Fully open the valve for a fixed time (or not)}*
- P controller ("proportional")
  {Measure error;
  Open the valve in proportion to error}*
- PI controller (proportional-integral)
  {Measure error;
  Open the valve in proportion to integral of error}*
- PID controller (proportional-integral-derivative)
  Similar to PI, with "kicker" based on derivative of output

P vs. PI Controller Response

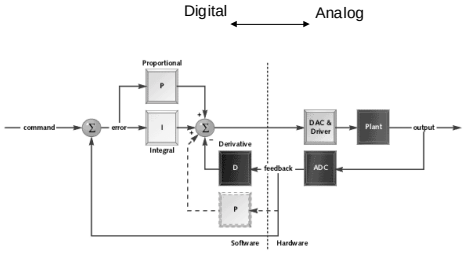


Figures from:
`http://www.embedded.com/2000/0010/0010feat3.htm`

PID Response



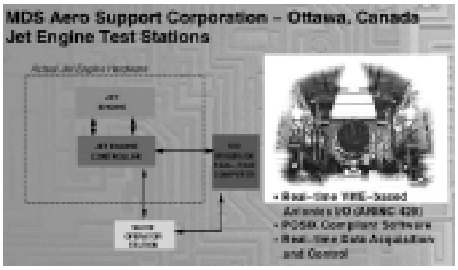
PID Controller



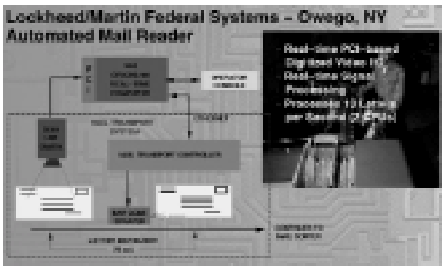
Sample PID Controller Code

```
typedef struct
  {
    double dState;        // Last position input
    double iState;        // Integrator state
    double iMax, iMin;    // Maximum and minimum allowable integrator state

    double        iGain,          // integral gain
                  pGain,          // proportional gain
                  dGain;          // derivative gain
  } SPid;

  double UpdatePID(SPid * pid, double error, double position)
  {
    double pTerm, dTerm, iTerm;

    pTerm = pid->pGain * error;   // calculate the proportional term

   // calculate the integral state with appropriate limiting
    pid->iState += error;
    if (pid->iState > pid->iMax) pid->iState = pid->iMax;
    else if (pid->iState < pid->iMin) pid->iState = pid->iMin;

    iTerm = pid->iGain * iState;  // calculate the integral term

    dTerm = pid->dGain * (pid->dState - position);
    pid->dState = position;

    return pTerm + dTerm + iTerm;
  }
```

High-Level Applications



High-Level Applications



High-Level Applications

Other Real-Time Computation Issues

- Database and networking access
- Image/video/speech processing
- Rendering
- Performance monitoring
- Fault monitoring
- Fault recovery
- Security checks, certification
- Integrity checking
- Logging
- Planning

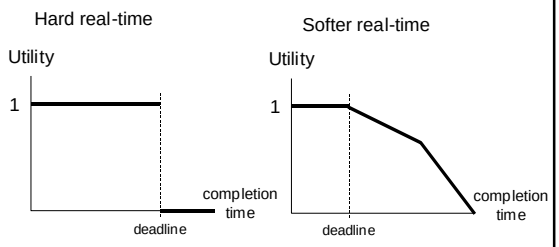
Distinctions

- **Hard** real-time: Deadlines must be met in order for the system to be **correct**.
- **Soft** real-time: It is **desirable** for deadlines to be met, but if not, the system can still be correct.
- “Real-time” does not necessarily mean “fast”.

Hard Real-Time Examples

- Vehicular fuel or rendezvous problems
  - Lunar lander
  - Train scheduling
  - Baggage handlers
  - Assembly lines
- Production deadlines
  - Newspaper
  - Live TV show
  - Graduation

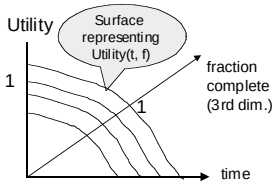
Hardness Expressed as a **Utility** Function



Progressive Utility

- A generalization of the preceding concept regards Utility as a function of **both** time *and* fraction of the task completed.

Utility(t, f) is the utility of completing fraction f of the task by time t.



Real-Time includes Communication

- Obviously communication, as well as computation, must be taken into account if the system consists of multiple components

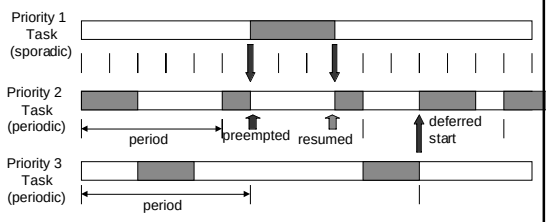
Common Aspects of Real-Time Systems

- Deadlines
- Scheduled task start times
- Timeouts
- Periodic & Aperiodic (Sporadic, Episodic) tasks
- Priorities among tasks
- Preemption/resumption of lower priority tasks (interrupts)

Real-Time Operating Systems

- Solaris, when generated with real-time features
- VxWorks (Wind River Systems, Inc.)
- QNX (POSIX.1 certified).
- RTMX (POSIX RT extensions to free BSD)
- Windows Embedded
- Many others, see `http://www.ipi.com/page2.html`

Example Real-Time Task Considerations



Scheduling Algorithms

- Choices of performance metric to meet requirement:
  - **Overall** completion time among all tasks
  - **Average** response time over all tasks
  - **Weighted** sum of completion times
  - **Maximum** lateness
  - **Number** of late tasks
- each of these to be minimized.

Scheduling to Meet **Deadlines**

- Assume a set of tasks $\{T_i\}$
- Associate with each task T_i:
  - computation time C_i
  - deadline D_i
- Suppose we want to minimize **maximum lateness**

Scheduling to Meet Deadlines

- Minimize maximum lateness
- 1-processor case
- Jackson's Rule:
  EDF (Earliest Deadline First):

  Execute tasks in order of decreasing deadlines.

Proof that Jackson's Rule works

(typical of reasoning used in proofs)

- Let S' be a schedule that executes the tasks in some order **other** than by Jackson's Rule.
- Let S be a schedule that executes an pair of tasks out-of-order in S' in order of decreasing deadline.
- We want to show that the maximum lateness of S is no more than that of S'.

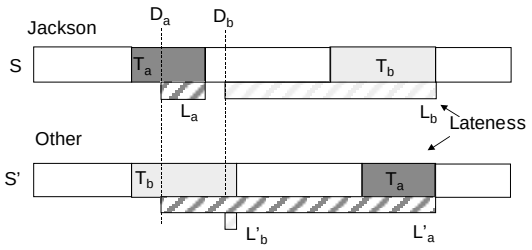
Proof that Jackson's Rule works

- In S' there are two tasks T_a and T_b such that $D_a \leq D_b$ but T_b precedes T_a.
- Let L_i be the *lateness* of task T_i, defined as
  $L_i = F_i - D_i$
  = Finish time - Deadline
- In schedule S, the combined lateness of T_a and T_b is:
  $\max(L_a, L_b)$

Proof that Jackson's Rule works

- We want to show that:
  $\max(L_a, L_b) \leq \max(L'_a, L'_b)$ (*)
  where the ' designates S' vs. S.
- Consider two cases:
  - $L_a < L_b$
  - $L_a \geq L_b$
- We will show that the inequality holds in either case.

Jackson's Rule with $L_a < L_b$

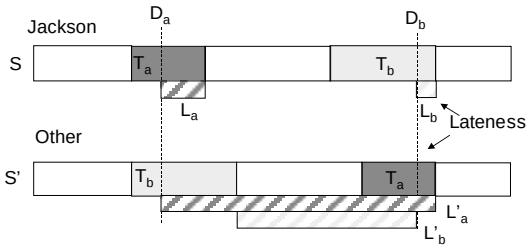


Proof of Jackson's Rule

- Case $L_a < L_b$:

$\max(L_a, L_b) = L_b$		def'n of max, since $L_a < L_b$
	$= F_b - D_b$	def'n of L
	$= F'_a - D_b$	a and b are flipped in S' vs S
	$\leq F'_a - D_a$	assumption $D_a \leq D_b$
	$= L'_a$	
	$\leq \max(L'_a, L'_b)$	

Jackson's Rule with $L_a \geq L_b$



Proof of Jackson's Rule

- Case $L_a \geq L_b$:

$\max(L_a, L_b) = L_a$		def'n of max
	$= F_a - D_a$	def'n of L
	$< F'_a - D_a$	assumption that T_b precedes T_a in S'
	$= L'_a$	def'n of L
	$\leq \max(L'_a, L'_b)$	def'n of max

Corollary to Jackson's Rule

- Assume that tasks are numbered in order of increasing deadlines D_i.
- Let C_i be the corresponding computation time.
- Then all tasks can be executed so as to meet their deadline provided that
  $(\forall\ i)$
  $\text{sum}(C_i, k = 1 \text{ to } i) \leq D_i$

Limitation of Jackson's Rule

- The set of all tasks is not always presented in advance.
- New tasks may arrive at arbitrary times.
- To minimize maximum lateness in this setting, it may be necessary to *preempt* a task already being executed.
- This issue is addressed by **Horn's rule**.

Horn's Rule (1974)

- Arrange execution, using **preemption** if necessary, so that:
  - At every instant the task with the current earliest deadline is being executed.
- Horn's rule can be proved to minimize maximum lateness in a manner similar to the proof of Jackson's rule.

Horn's Rule (1974)

- Horn's rule is based on preemptability of tasks.
- If **preemption is not allowed**, then Horn's rule does **not** minimize maximum lateness.

Horn's Rule (1974)

- Example:

Task	Time	Deadline	Arrival
T_1	4	7	0
T_2	2	5	1

- Horn's rule says: start T_1 at time 0, which would make T_2 wait to time 4. The max lateness would be 1.
- The optimum way would be do nothing at time 0, start T_2 at time 1, then start T_1 at time 3. The maximum lateness would be 0.

Exercise

- What happens in the previous example if preemption is allowed?

Hard Problem

- Finding an **optimal non-preemptive** schedule when arrival times are arbitrary is NP-hard.
- An enumerative, branching, algorithm can be used.

Lawler's Algorithm (1973)

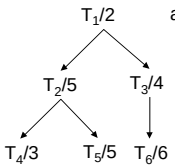
- Schedules a set of simultaneously arriving tasks on one process subject to **precedence constraints**.
- Minimizes maximum lateness for 1 processor, among all **non-preemptive** algorithms.

Lawler's Algorithm (1973)

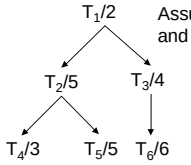
- Build a stack, selecting tasks with latest deadline first (LDF), subject to precedence constraints.
- Execute the tasks in order of popping from the stack.

Example: Lawler's Algorithm

Assume all computation times are 1 and deadlines are as shown.



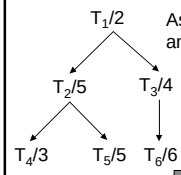
Example: Lawler's Algorithm



Assume all computation times are 1 and deadlines are as shown.

Stacking order (LDF, obeying precedence):
$T_6/6, T_5/5, T_3/4, T_4/3, T_2/5, T_1/2$

Example: Lawler's Algorithm



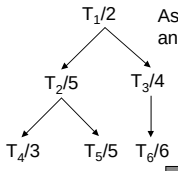
Assume all computation times are 1 and deadlines are as shown.

Stacking order (LDF, obeying precedence):
$T_6/6, T_5/5, T_3/4, T_4/3, T_2/5, T_1/2$

Execution order:

	$T_1/2$	$T_2/5$	$T_4/3$	$T_3/4$	$T_5/5$	$T_6/6$
Completion:	1	2	3	4	5	6

Example: Lawler's Algorithm



Assume all computation times are 1 and deadlines are as shown.

Stacking order (LDF, obeying precedence):
$T_6/6, T_5/5, T_3/4, T_4/3, T_2/5, T_1/2$

Execution order:

	$T_1/2$	$T_2/5$	$T_4/3$	$T_3/4$	$T_5/5$	$T_6/6$
Completion:	1	2	3	4	5	6

Using EDF, the order would be:

	$T_1/2$	$T_3/4$	$T_2/5$	$T_4/3$	$T_5/5$	$T_6/6$
Completion:	1	2	3	4	5	6

One task would be late, so max. lateness = 1.

Other Algorithms

- An optimal method for the **preemptive** arbitrary-arrival case is also known (run time $O(n^2)$).
- This and the previous methods may be found in reference:
  - G.C. Buttazo
    Hard Real-Time Computing Systems
    Kluwer Academic Publishers, 1977.

Periodic Tasks

- Many realtime systems are based on **periodic** tasks, where each task T_i has:
  - Computation time C_i
  - Period P_i
  - Phase ϕ_i
- The meaning of "period" is that, for each i, T_i must execute once every time P_i units.
- The meaning of "phase" is that, for each i, the earliest time at which T_i is available within the current period is at relative time ϕ_i.

"Release Time"

- "phase" is typically not used to describe real-time schedulers, although it has an obvious engineering significance.
- Instead, "release time" is used to mean "the time at which a task is next available for scheduling"; the "release" is releasing the task ***into*** the system, not out of it.
- In less we indicate otherwise, the release time for a task will coincide with the beginning of the period for the task, i.e. a periodic task with duration 2 and period 20 will be "released" at times 0, 20, 40, ...

Preemptability

- Preemptability is a common assumption in real-time systems:

  A lower priority task may need to be preempted to give the processor to a higher priority one.

- Typically it is assumed that preempted tasks can be **resumed**.

Preemption Costs

- In general, there will be a cost (delay) associated with preempting a task.
- For now, we assume that this cost is negligible.

Utilization

- The **utilization** in a system of periodic tasks by a task is defined as

  $$\frac{\text{compute time}}{\text{period}}$$

- A necessary condition for a set of period tasks to be schedulable is that the **sum** of their utilizations be ≤ 1.

Exercise

- Three periodic tasks:

Task	Time	Period
T_1	1	3
T_2	1	4
T_3	3	8

- See if you can construct a (1 processor) schedule that schedules these tasks periodically.
- Remember that tasks can be preempted.

EDF Revisited

- Recall Horn's rule: Preemptive EDF (Earliest Deadline First)
- It works for ***arbitrary*** arrivals.
- Therefore it will work for periodic tasks as well.

"Dynamic Priority"

- EDF is *dynamic* because the relative priorities will depend on what is being executed when a task arrives. This could be:
  - A task with a longer period but nearer deadline.
  - A task with a shorter period but more distant deadline.

Example

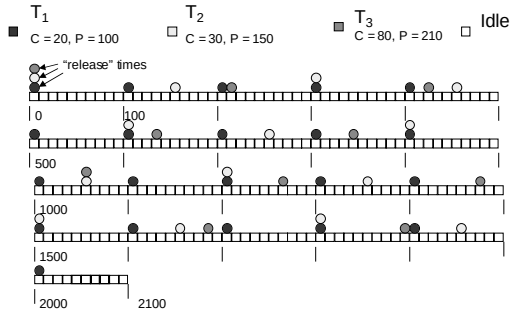
T_1 C = 20, P = 100

T_2 C = 30, P = 150

T_3 C = 80, P = 210

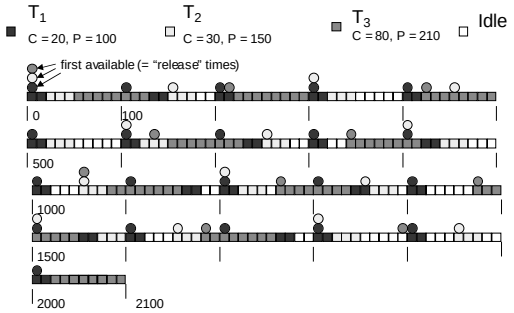
Constructing An EDF Schedule

(each box = 10 time units)



An EDF Schedule

(each box = 10 time units)



Utilization Bounds for Dynamic Priority Assignment

- For dynamic priority assignment, any system with a total utilization ≤ 1 can be scheduled.
- EDF is adequate for constructing such a schedule.

Rate-Monotonic Assumption (RMA)

- A task that is preempted by another is said to have ***lower priority***.
- Obviously tasks with **shorter periods** should generally have higher priority, since lower priority tasks can be preempted, then resumed, to allow higher priority tasks to meet their periodic deadlines.
- Assuming that shorter period $\Rightarrow$ higher rate is called the **rate-monotonic assumption** (RMA).

Note on RMA Assumption

- RMA is a mathematical notion.
- It should **not** be inferred that every set of **user priorities** will agree with RMA.
- However, if priorities don't align this way, it may be best to revisit the required periodicities.

Exercise

- Revisit your schedule from the previous exercise. Is it rate-monotonic?

Theorem (Liu & Layland, 1973)

- A ***sufficient*** condition for a set of n tasks to be rate-monotonically schedulable on 1 processor, regardless of phasing, is:

  total utilization $\leq n*(2^{1/n} -1)$

- where *total utilization* is defined as $\text{sum}(C_i/P_i, i = 1 \text{ to } n)$
- The condition is sufficient, but not necessary.

Numeric Values for Liu & Layland Rule

tasks	bound on total utilization
1	1
2	0.828427
3	0.779763
4	0.756828
8	0.724062
16	0.707472
32	0.700709
64	0.696914
…	
∞	ln(2) ≈ 0.693147

Rationale behind Liu & Layland

- Assume all phases are 0.
- Case of 1 task, T_1, period P_1, time C_1.
  - Obviously this will be schedulable iff
    $C_1 \leq P_1$,
    which is the same as
    $\text{sum}(C_i/P_i, i = 1 \text{ to } 1) \leq 1$.

RMA Rationale

- Case of n tasks, $T_1, \ldots, T_n$, periods $P_1 \leq \ldots \leq P_n$, times $C_1, \ldots, C_n$.
  - Consider an interval of time [0, t].
  - During the interval each T_i must execute $\lfloor t/P_i \rfloor$ times.
  - The total time used for T_i during the interval will be $C_i * \lfloor t/P_i \rfloor$.
  - In order for each T_i to execute the appropriate number of times in the interval, we need $(\forall t' < t)$ $t' \geq \text{sum}(C_i * \lfloor t/P_i \rfloor)$.
  - If we can find a $t \leq \text{lcm}(P_1, \ldots, P_n)$ having this property, then all tasks can be scheduled.

Observation

- $(\forall t' < t)$ $t' \geq \text{sum}(C_i * \lfloor t/P_i \rfloor)$
  iff
  $(\forall t' < t)$ t' is a time corresponding to the end of some task's period $\Rightarrow t' \geq \text{sum}(C_i * \lfloor t/P_i \rfloor)$.
- So it suffices to consider only times that end the period of some task.

Example

- $P_1 = 100$, $P_2 = 150$,
  $C_1 = 20$, $C_2 = 30$.
- Consider an interval of time [0, 300], during which T_1 must complete $\lceil 300/100 \rceil = 3$ times and T_2 must complete 2 times.
- The total time required is $3*20 + 2*30 = 120 \leq 300$.
- What schedule realizes the requirements?

task	T_1	T_2	T_1	T_2	T_1
start	0	20	100	150	200
end	20	50	120	180	220

Example
(L&L rule not necessary)

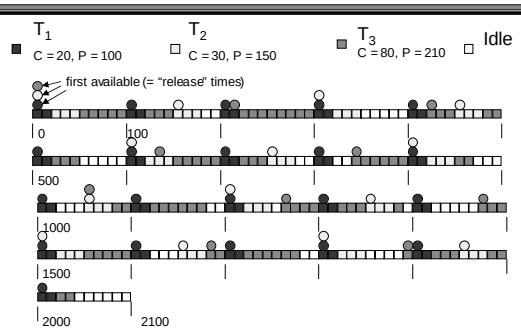
- Consider adding a third task:
  $P_1 = 100$, $P_2 = 150$, $P_3 = 210$,
  $C_1 = 20$, $C_2 = 30$, $C_3 = 80$.
- The Liu and Layland rule computes total utilization: $20/100 + 30/150 + 80/210 = 0.780952$ which is not realizable for 3 tasks (0.7796).
- Since the Liu and Layland rule is sufficient, but not necessary, there still might be a schedule.
- Can you construct one?

Example

- $P_1 = 100$, $P_2 = 150$, $P_3 = 210$,
  $C_1 = 20$, $C_2 = 30$, $C_3 = 80$.
- Consider an interval of time [0, 2100], (2100 is the lcm of 100, 150, and 210) during which T_1 must complete 21 times, T_2 14 times, and T_3 10 times.
- The total time required is $21*20 + 14*30 + 10*80 = 420+720+800 = 1940 \leq 2100$. So it is at least *plausible* that there is a schedule.
- On the next page, we construct a schedule.

A Rate-Monotone Schedule

(each box = 10 time units)



We didn't have to compute that whole thing:
Lehoczky, Sha, and Ding Theorem (1987)

- Under RM scheduling, if each task meets its **first** deadline, then all deadlines will be met.

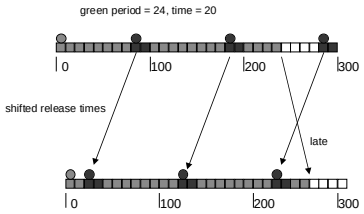
Example

- Consider adding a fourth task:
  $P_1 = 100$, $P_2 = 150$, $P_3 = 210$, $P_4 = 400$,
  $C_1 = 20$, $C_2 = 30$, $C_3 = 80$, $C_4 = 100$.
- Total utilization: 20/100 + 30/150 + 80/210 + 100/400 = 1.03095 > 1, so this set is not realizable.

2nd Theorem of Liu & Layland

- If a set of tasks is schedulable under any **fixed priority** scheme, then it is schedulable using rate-monotonic scheduling.
- In other words, rate-monotonic is optimal among fixed priority schemes.

How release time of a higher-priority task can affect the response of a task in RM scheduling



Priorities Revisited

- RMA is an example of a **fixed priority** scheme: priority is determined in order opposite periods.
- EDF is an example of a dynamic priority scheme.

Exercise

- Devise a system of two periodic tasks such that:
  - There is no rate-monotonic schedule
  - There is an EDF schedule

Hint

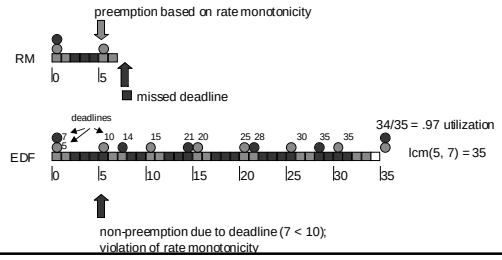
- Make the longer-period task have a relatively high utilization, so that deferring it will make it miss its deadline.

Hint

- $P_1 = 5, C_1 = 2$
- $P_2 = 7, C_2 = 4$

Example

- $P_1 = 5, C_1 = 2$
- $P_2 = 7, C_2 = 4$



Generalization of Periodic Tasks

- So far,
  deadline of a periodic task
  = end of period
- Generalization:
  periodic tasks with fixed **deadlines *relative*** to start of period
  (deadlines possibly *sooner* than end of period).

Deadline-Monotonic (DM) Scheduling

- Assume relative deadlines are *constant*.
- Assign **priorities** in order of nearest relative deadline.
- Since the relative deadlines are constant, this is a *static* priority assignment.
- DM has been shown *optimal* for this more general case (Leung and Whitehead, 1982).

If relative deadlines are ≤ period and not constant

- EDF again works
- Schedulability can be checked using "processor demand" approach:
  - Processor demand in an interval [0, L] is the computation time required in order for all tasks to complete by their deadlines in that interval.
  - Check that processor demand <= length of interval.
  - Need only check at release times between 0 and lcm(periods).

Summary of Applicability

	Deadline = Period	Deadline ≤ Period
Static Priority	Rate Monotonic	Deadline Monotonic
Dynamic Priority	EDF	EDF

References

- C. L. Liu and J. W. Layland. *Scheduling Algorithms for Multiprogramming in a Hard Real Time Environment*. Journal of the Association of Computing Machinery. January 1973. pp. 46-61.
- John Lehoczky, Lui Sha, and Ye Ding. *The Rate Monotonic Scheduling Algorithm: Exact Characterization and Average Case Behavior*. IEEE Real-Time Systems Symposium, 1989. pp.166-171.
- S.K. Baruah, L.E. Rosier, and R.R. Howell. *Algorithms and complexity concerning the preemptive scheduling of periodic, real-time tasks on one processor*. Journal of Real-Time Systems, **2**, 1990.

Resource Access

- Semaphores can be used to control access to resources in a real-time system.
- Some interesting issues associated with priority arise.

Priority Inversion

- Consider two tasks, one high priority, one low, that share a resource protected by a critical section.
- If the high-priority task becomes schedulable during the time the low-priority one is in its critical section:
  The high-priority task is **blocked** by the low priority one.

Push-Through Blocking

- The low-priority task, with the resource locked, could be preempted by a medium priority task that doesn't necessarily use the resource.
- This task could go on indefinitely, in-effect blocking the higher-priority task through the lower-priority one.

Possible Resolutions of Priority Inversion

- Abort the low-priority task:
  - Messy, since this could leave the system in an inconsistent state.
- Priority Inheritance Protocol
- Priority Ceiling Protocol

Priority Inheritance Protocol (PIP)

- During the time the low-priority task is in its critical section, **and** while the high-priority task is blocked because of this, the low-priority task **inherits** the priority of the high-priority task.

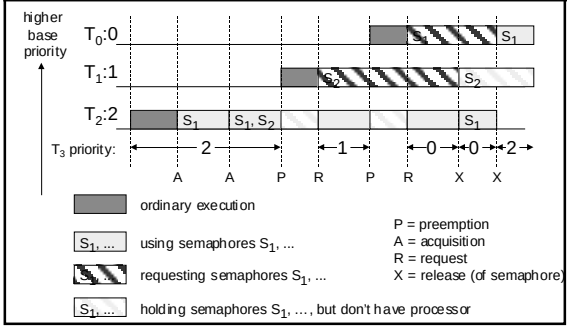
Possible Resolution of Blocking

- **Priority Inheritance Protocol**:
  - More precisely: A task locking a shared resource inherits the priority of the highest-priority task blocked because of locking.
  - The locking task's priority is *recomputed* whenever:
    - Other tasks request or release the shared resource, or
    - the locking task leaves the critical section, in which case the highest-priority blocked task is awakened.

Transitivity

- **Priority Inheritance must be made Transitive**:
  - If T_1 blocks T_2, and T_2 blocks T_3, then T_1 inherits the priority of T_3.
- Note that transitive inheritance occurs only with nested critical sections (different semaphores). If there were only *one* semaphore, then T_1 would be blocking T_3 directly.

PIP Example



Implementation Note

- Implementing priority inheritance in semaphores requires added sophistication beyond the basic semaphore mechanism.

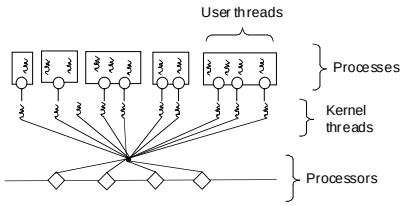
Computing Blocking Time

- If the computation time (without block) within critical sections is known, then the blocking time due to priority inheritance can be computed.
- This can be used in determining schedulability of a system of tasks with shared resources.

Example: Solaris Operating System

- Solaris kernel schedules based on LWP's (Light-Weight Processes).
- Regard LWP's as schedulable units of processor time ("slots").
- A new LWP can be created as an optional aspect of creating a new thread.

Solaris LWP's vs. Processes



Example: Solaris Operating System

- Each LWP has a priority, in one of three coarse classes:
  - RT (real-time) is highest.
  - System class is middle (not used by user processes).
  - TS (time-share) is lowest.

Example: Solaris Operating System

- For the time-sharing class, the dispatch priority is calculated from
  - amount of CPU used since last I/O (less ⇒ higher-priority)
  - its *nice* level (set by the user)
- For the real-time class,
  - the highest-priority LWP runs until it blocks, terminates, reaches end of time-slice, or is preempted.

Example: Solaris Operating System

- When a process is created, its LWP gets the scheduling class and priority of the parent process.
- A **thread** can be either:
  - ***bound*** to a specific LWP
  - ***unbound*** (multiplexed among various LWP's)
- All unbound threads in a process have the same class and priority.
- Bound threads have the class and priority of the LWP to which they are bound.

Example: Solaris Operating System Priority Inheritance

- Solaris implements basic priority inheritance protocol:
  - When a higher-priority thread is blocked, its priority is given to the lower-priority thread blocking it.
  - When the lower-priority thread ceases to block a higher priority one, its priority is set back to the original priority.
- Source: Ben Catanzaro, *Multiprocessor System Architectures*, Sun Microsystems, 1994.

From VxWorks FAQ

The priority inheritance protocol also accounts for the ownership of more than one mutual exclusion semaphore at a given time. A task in such a situation will execute at the priority of the highest priority task blocked on any of the owned resources. The task will return to its normal, or standard, priority only after relinquishing **all** of the mutual exclusion semaphores with the inversion safety option enabled.

If you use nested mutex semaphores with priority inheritance turned on then when a task inherits a high priority due to some inner semaphore it owns, it doesn't lose that priority until it relinquishes **all** the semaphores it holds. This doesn't quite follow the rules for priority inheritance (to the extent that there really are any rules) in that normally, a task's inherited priority should decrease as it releases each nested semaphore to whatever the priority ceiling is for the semaphores it still holds. Getting this incremental priority reduction to work right in practice, though, is extremely difficult (some of the SUN papers on the Solaris real time scheduling indicate that this was one of the hardest things for SUN to get right in their OS upgrades).

Priority Ceiling Protocol (PCP)

- A more involved form of priority inheritance.
- The PIP does not prevent a high priority task from being blocked **multiple times** by lower priority ones, extending the blocking time indefinitely.
- The PCP does prevent this: Once a task gains entry to a critical section, it cannot *subsequently* be blocked by a lower priority task.

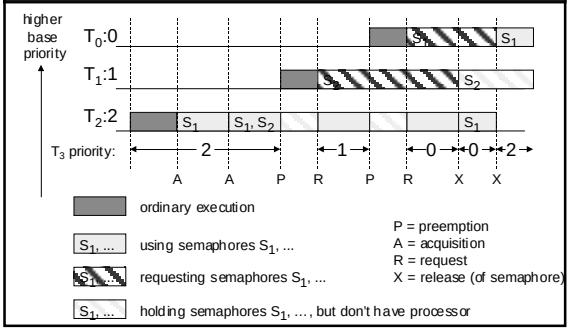
Priority Ceiling Protocol (PCP)

- Each **semaphore** has a (static) priority **ceiling** equal to the priority of the **highest-priority task** that could possibly lock it.
- A task is allowed to enter a critical section only if its priority is ***higher* than the priority *ceilings*** of **all** semaphores ***currently* locked** by other tasks. Otherwise the task is "**blocked**" on the semaphore (it hasn't really **locked** it yet).
- If a task is **blocked** on a semaphore, the task **locking** that semaphore **inherits** the priority of the blocked task (as in PIP).

Priority Ceiling Protocol (PCP)

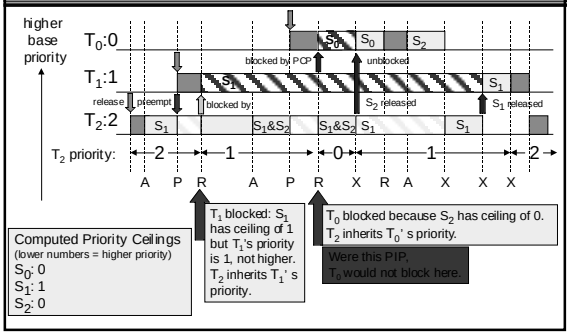
- When a task **locking** a semaphore **unlocks it,** its priority is set to that of the highest priority resource that it now holds (or to its base priority, if none).
- Priority inheritance is constrained to be transitive, as with the PIP.

PIP Example (presented earlier, use for legend)



PCP Example

(from Buttazzo, Hard Real-Time Computing Systems, Kluwer, 1997)



Comparison: PIP vs. PCP

- PCP is more efficient at run-time, in that a high priority task cannot be blocked more than once at the same level.
- PIP is less demanding, in that it does not require a thorough analysis of a task's behavior (in terms of which semaphores in might request).
- PCP automatically **prevents deadlocks**, since it induces an **ordering** on the way that resources can be requested.

References

- L. Sha, R. Rajkumar, J. Lehoczky, *Priority Inheritance Protocols*, IEEE Trans. Computers, **20**, 9, pp. 1175-1185, Sep. 1990.

An Implemention of PCP (in MKS)

pthread_mutex_setprioceiling()

set the priority ceiling of a mutex

SYNOPSIS

#include <pthread.h>
int pthread_mutex_setprioceiling(pthread_mutex_t *mutex, int ceiling, int *oldceiling);

DESCRIPTION

The pthread_mutex_setprioceiling() function either locks the mutex if it is unlocked, or blocks until it can successfully lock the mutex, then it changes the mutex's priority ceiling and releases the mutex. When the change is successful, the previous value of the priority ceiling is returned in oldceiling. The process of locking the mutex need not adhere to the priority ceiling protocol.

In the Commercial World

(e.g. Tri-Pacific Software PERTS simulation tool)

Included in the new PERTS 3.0 is support for BIP, **Basic Inheritance Protocol**, that allows users to analyze systems with single nodes and have dependencies between tasks that are not necessarily in an end-to-end or path dependency structure. BIP, a simpler version of **PCP (Priority Ceiling Protocol)**, is easier to implement from an application standpoint and mirrors more closely the resource protocol in VxWorks. PCP allows for one blocking instance, at most, and no deadlock situations regarding resources. With BIP, on the other hand, a user can be blocked multiple times for each instance, as well as deal with resource contention deadlocks. PERTS 3.0 offers **Rate Monotonic** and **Deadline Monotonic** analysis with support for BIP, PCP, and SBP (Stack Based Protocol).

SRP (Stack Resource Protocol)

- All tasks share a single stack
  - Greatly simplifies stack management
  - However, a task cannot suspend itself (which would "block" the stack)
- Similar to PCP
  - PCP: Task is blocked when it wants to lock resource, vs.
  - SRP: Task is blocked when it attempts to preempt.