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Distributed Embedded Scheduling

Distributed Embedded Systems

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Where Are We Now?

- **Where we've been:**
  - Distributed systems
  - Embedded communications: protocols & performance

- **Where we're going today:**
  - Real Time Scheduling in distributed systems
  - This adds on to what you saw in 18-348/18-349
    - There is overlap, especially since grad students may not have seen this material

- **Where we're going next:**
  - Mid-semester presentations
  - Embedded + Internet Security
  - Distributed Timekeeping
  - How to make sure you build systems right …
    … and how you can actually know that you built them right

Preview

- **Basic real time review**

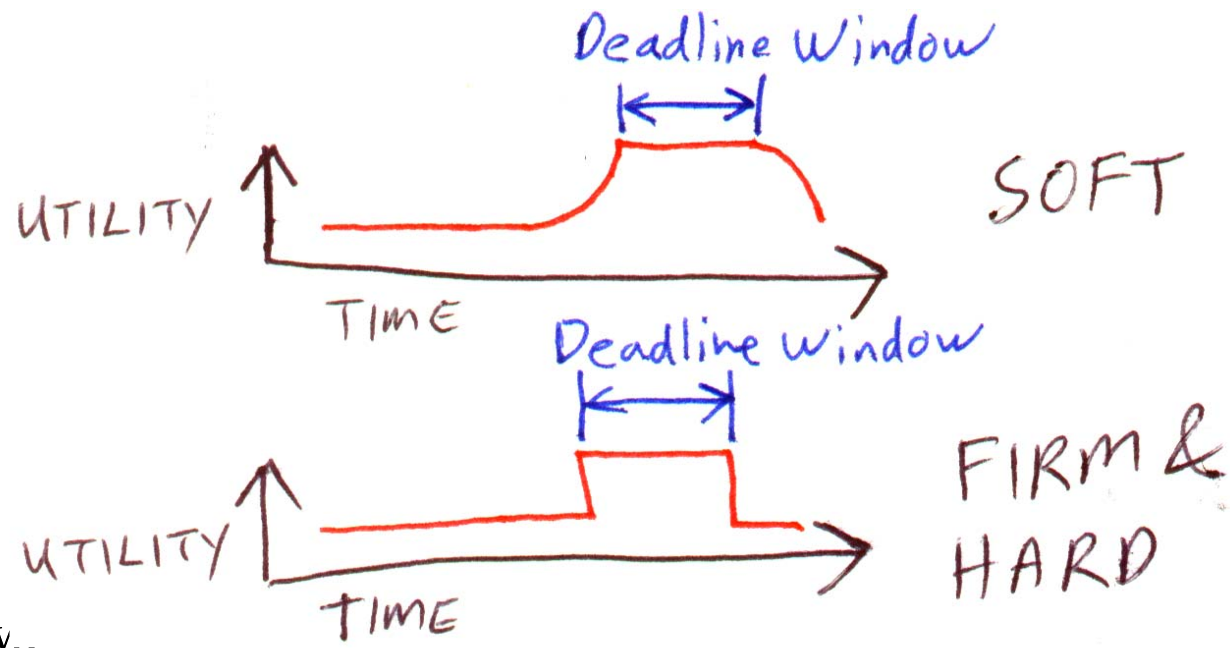
- **Scheduling – does it all fit?**
  - Schedulability
  - Scheduling algorithms, including
    - Distributed system adaptations
    - How they degrade

- **Complications**
  - Aperiodic tasks
  - Task dependencies

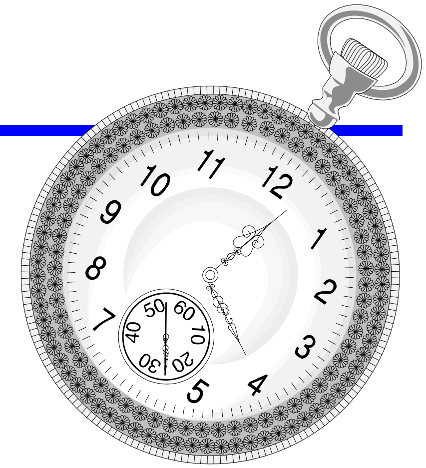
Review: Real Time Review

- **Reactive: computations occur in response to external events**
  - Periodic events (*e.g.*, rotating machinery and control loops)
  - Aperiodic events (*e.g.*, button closures)
  - Real time means that correctness of result depends on both functional correctness and time that the result is delivered

- **Soft real time**
  - Utility degrades with distance from deadline
- **Hard real time**
  - System fails if deadline window is missed
- **Firm real time**
  - Result has no utility outside deadline windov., but system can withstand a few missed results



Types of Real-Time Scheduling



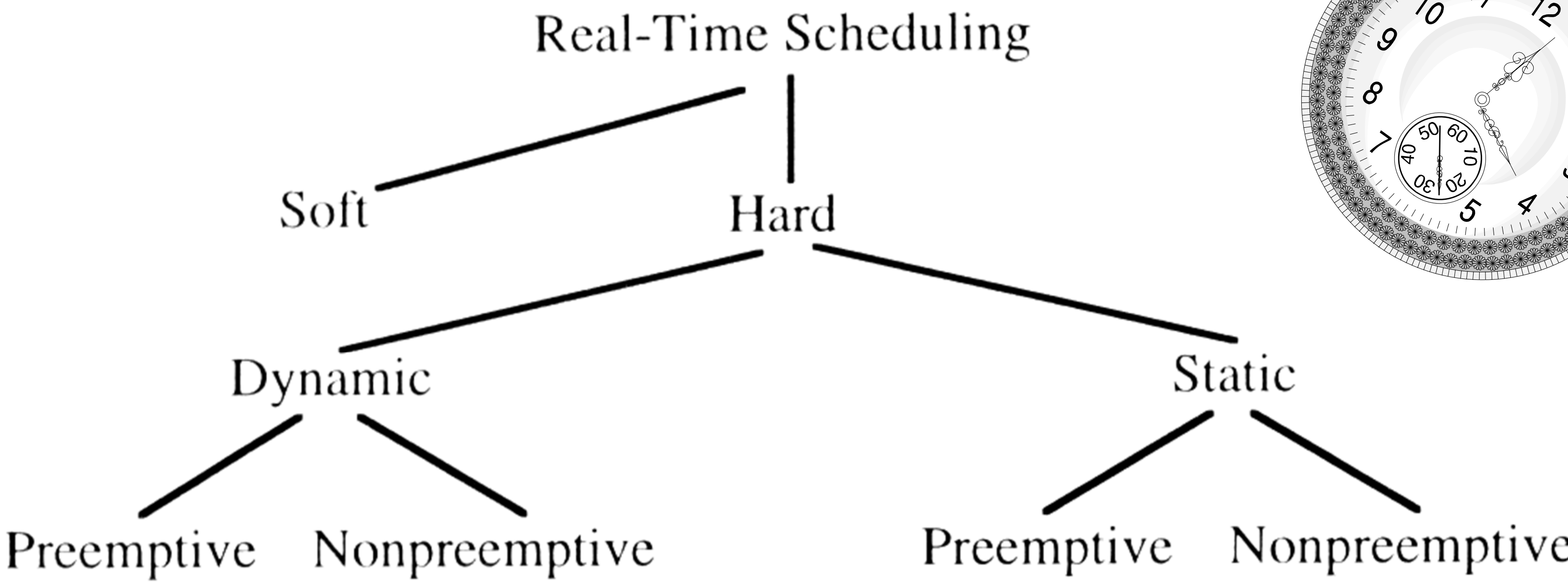


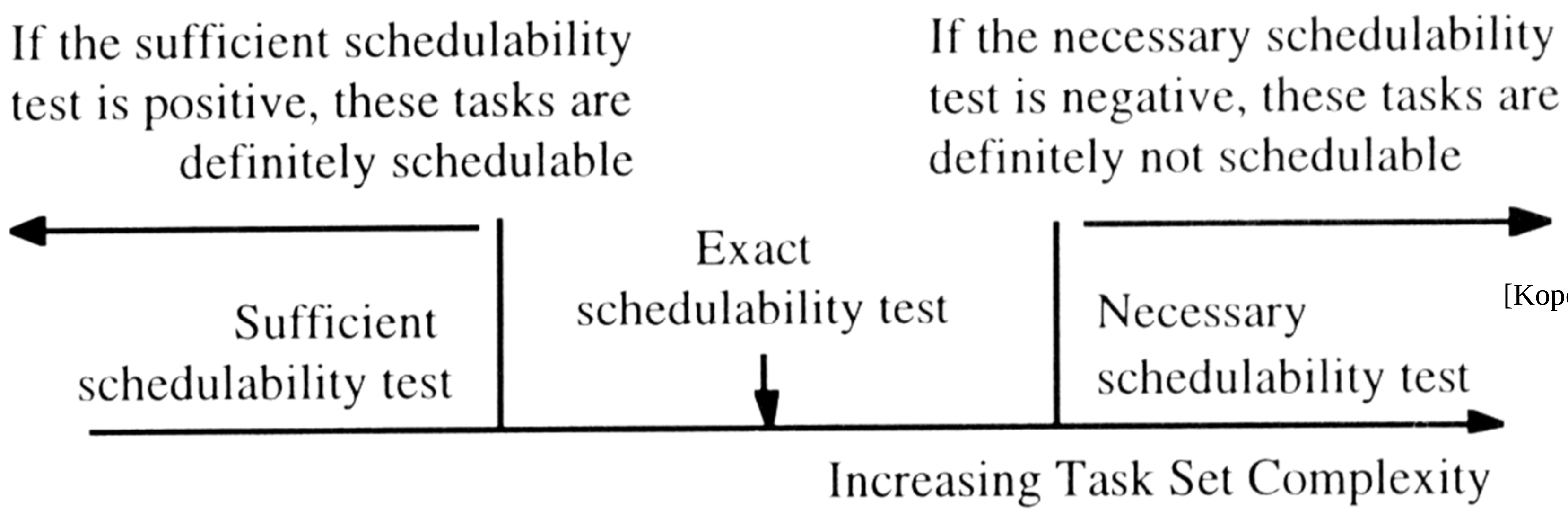
Figure 11.1: Taxonomy of real-time scheduling algorithms.

[Kopetz]

- **Dynamic vs. Static**
  - Dynamic schedule computed at run-time based on tasks really executing
  - Static schedule done at compile time for all *possible* tasks
- **Preemptive permits one task to preempt another one of lower priority**
  - Also, centralized or distributed implementation?

Schedulability

- **NP-hard if there are any resource dependencies at all**
  - So, the trick is to put cheaply computed bounds/heuristics in place
    - Prove it definitely can't be scheduled
    - Find a schedule if it is easy to do so
    - Punt if you're in the middle somewhere

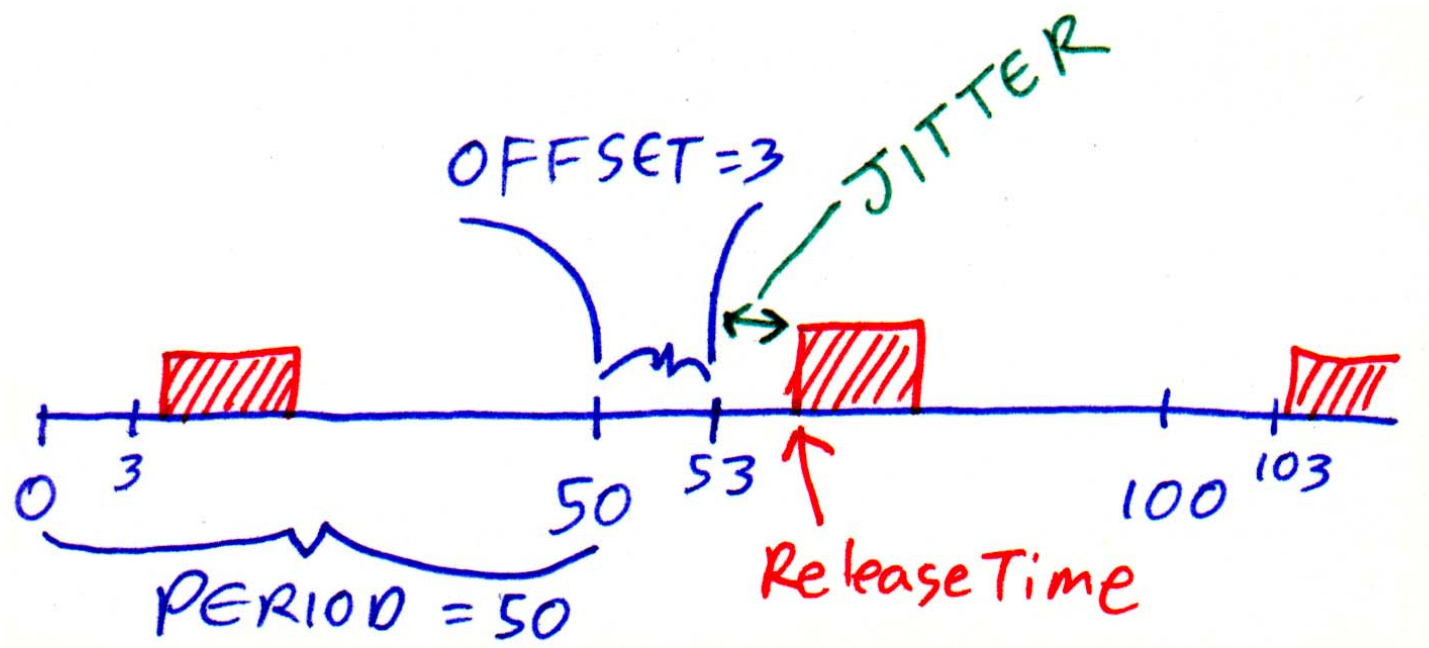


[Kopetz]

Figure 11.2: Necessary and sufficient schedulability test.

Periodic Messages and Tasks

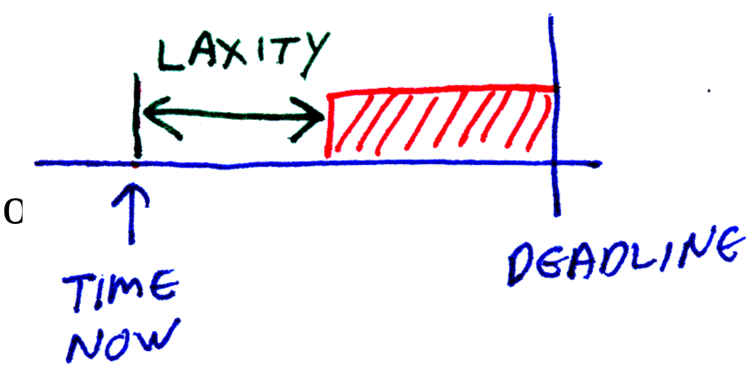
- **"Time-triggered" (periodic) tasks are common in embedded systems**
  - Often via control loops or rotating machinery
- **Components to periodic tasks**
  - Period (e.g, 50 msec)
  - Offset past period (e.g., 3 msec offset/50 msec period -> 53, 103, 153, 203)
  - Jitter is random "noise" in release time (*not* oscillator drift)
  - Release time is when message submitted to transmit queue
  - Release time_n= (n*period) + offset + jitter   ; assuming perfect time precision



Scheduling Parameters

- **Set of tasks $\{T_i\}$**
  - Periods p_i
  - Deadline d_i
    (completion deadline after task is queued)
  - Execution time c_i
    (amount of CPU time to complete)
  - Worst case latency to complete execution W_i
    - This is something we solve for, it's not a given

- **Handy values:**
  - Laxity $l_i = d_i - c_i$
    (amount of slack time before Ti *must* begin execution)
  - Utilization factor $\mu_i = c_i/p_i$ (portion o
    CPU used)



Simple Schedulability

$$\mu = \sum \mu_i = \sum \frac{c_i}{p_i} \le N$$

- **Necessary:**
  "You can't use more that 100%
  of available CPU power!"

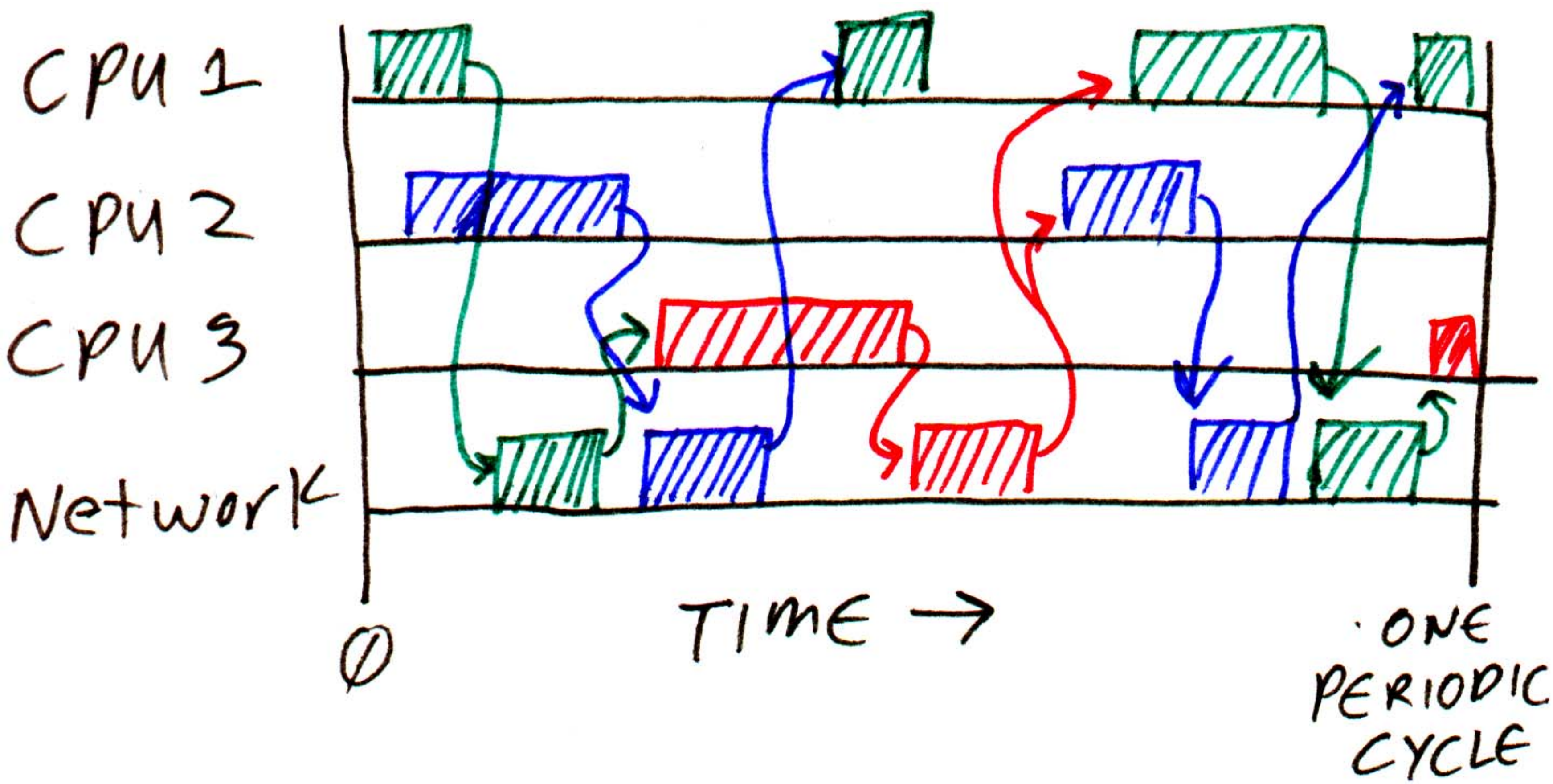
$$\mu_i = \frac{c_i}{p_i} \le 1 \qquad \text{and } 0 \le \text{i} \le \text{N}$$

- **Trivially Sufficient:**
  "One CPU per task always works, if each task fits on a single CPU"

- **Of course, the hard part is putting tighter sufficiency bounds on things…**

Distributed Static Schedule

- **Co-schedule CPUs and Network:**
  - Assign specific network transmission time to each message using a spreadsheet
  - Assign dedicated CPU time to each CPU to compute/transmit each message
  - Assign dedicated CPU time to receive/process applicable incoming messages
  - Iterate until the schedule contains no double-booked resources



Distributed Static Schedule Tradeoffs

- **In a nutshell, this is time-triggered system design taken to extremes**

- **Pro:**
  - Relaxes some of the scheduling assumptions discussed in next slide
  - If it works once, it will always work
    - Assuming that compute time never varies, ignoring message losses, etc.
    - Can adapt by putting in slack space for message retries
  - You can guarantee it works while using 100% of all resources
    - (Assuming that it is statically schedulable)
    - This makes it attractive for safety critical design – easy to know it will really work

- **Con:**
  - Might have to reschedule the whole thing for every change!
    - (build a tool to do this)
  - Probably have a different schedule for each operating mode
    - (build a tool to do this)
  - Might need a different set of schedules for each different model of the design
    - (build a tool to do this)

Major Assumptions

- **Five assumptions are the starting point for this area:**
  1. **Tasks $\{T_i\}$ are periodic, with hard deadlines and no jitter**
     - **Period is P_i**
  2. **Tasks are completely independent**
     - **B=0; Zero blocking time; no use of a mutex; interrupts never masked**
  3. **Deadline = period**
     - **$P_i = D_i$**
  4. **Worst case computation time is known and used for calculations**
     - **C_i worst case is always the same for each execution of the task**
  5. **Context switching is free (zero cost)**
     - **Executive takes zero overhead, and task switching has zero latency**

- **These assumptions are often not realistic**
  - But sometimes they are close enough in practice
  - We're going to show you the common special cases that are "easy" to use
    - And the starting points for dealing with situations in which the rules are bent

EDF: Earliest Deadline First

- **Assume a *preemptive* system with *dynamic* priorities, and { same 5 assumptions}**

- **Scheduling policy:**
  - Always execute the task with the nearest deadline
    - Priority changes on the fly!
    - Results in more complex run-time scheduler logic

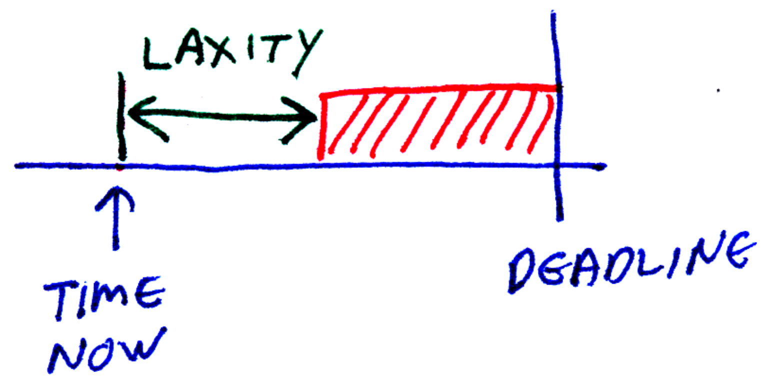
- **Performance**
  - Optimal for uniprocessor (supports up to 100% of CPU usage in all situations)
    - If it can be scheduled – but no guarantee that can happen!
    - Special case where it works is very similar to case where Rate Monotonic can be used:
      - » Each task period must equal task deadline
      - » But, still pay run-time overhead for dynamic priorities

  - If you're overloaded, ensures that a lot of tasks don't complete
    - Gives everyone a chance to fail at the expense of the later tasks

Least Laxity

- **Assume a *preemptive* system with *dynamic* priorities, and { same 5 assumptions }**

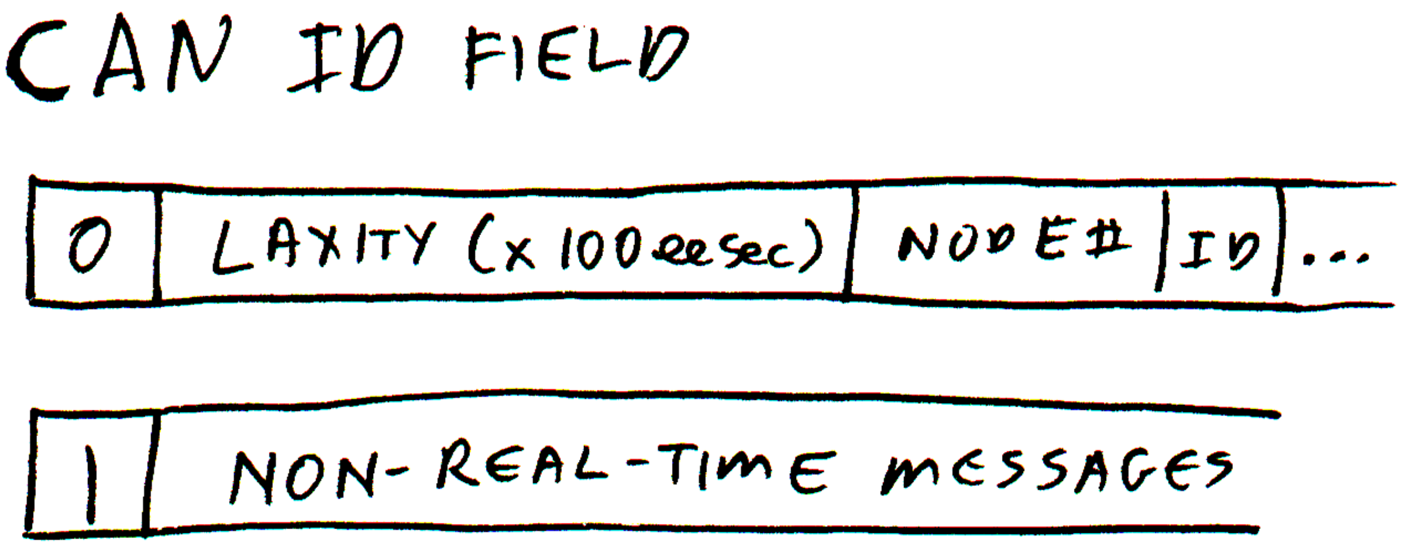
- **Scheduling policy:**
  - Always execute the task with the smallest laxity $l_i = d_i - c_i$



- **Performance:**
  - Optimal for uniprocessor (supports up to 100% of CPU usage in all situations)
    - Similar in properties to EDF
    - If it can be scheduled – but no guarantee that can happen!
  - A little more general than EDF for multiprocessors
    - Takes into account that slack time is more meaningful than deadline for tasks of mixed computing sizes
  - Probably more graceful degradations
    - Laxity measure permits dumping tasks that are hopeless causes

Distributed EDF/Least Laxity

- **Requires using deadline information as priority (use CAN as example)**
  - Each node does EDF CPU scheduling according to an end-to-end deadline
  - Each node locally prioritizes outgoing messages according to EDF *or* laxity
  - Each receiving node prioritizes tasks sparked by received messages EDF
  - Usually *not* globally optimal – not every CPU kept busy all the time



Global laxity priority for a network ([Livani98] has a more sophisticated scheme)

EDF/Least Laxity Tradeoffs

- **Pro:**
  - If it works, it can get 100% efficiency (on a uniprocessor)
  - Does not restrict task periods
  - Special case works if, for each task, Period = Deadline

- **Con:**
  - It is not always feasible to prove that it will work in all cases
    - And having it work for a while doesn't mean it will always work
  - Requires dynamic prioritization
  - EDF has bad behavior for overload situations (LL is better)
  - The laxity time hack for global priority has limits
    - May take too many bits to achieve fine-grain temporal ordering
    - May take too many bits to achieve a long enough time horizon

- **Recommendation:**
  - Avoid EDF/LL if possible
    - Because you don't know if it will really work in the general case!
    - And the special case doesn't buy you much, but comes at expense of dynamic priorities

Rate Monotonic Scheduling

- **Problems with previous approaches**
  - Static scheduling – can be difficult to find a schedule that works
  - EDF & LL – run-time overhead of dynamic priorities
  - Wanted:
    - Easy rule for scheduling
    - Static priorities
    - Guaranteed schedulability

- **Rate Monotonic Scheduling**
  - { same 5 assumptions }

1. Sort tasks by period (i.e., by “rate”)
2. Highest priority goes to task with shortest period (fastest rate)
   - Tie breaking can be done by shortest execution time at same period
3. Use prioritized preemptive scheduler
   - Of all ready to run tasks, task with fastest rate gets to run

Rate Monotonic Characteristics

- **Static priority**
  - Priorities are assigned to tasks at design time; priorities don't change at run time
- **Preemptive**
  - When a high priority task becomes ready to run, it preempts lower priority tasks
  - This means that ISRs have to be so short and infrequent that they don't matter
    - (If they are non-neglible, see Blocking Time discussion later)
- ***Guarantees*** **schedulability if you don't overload CPU (see next slide)**
  - All you have to do is follow the rules for task prioritization
  - (And meet the 5 assumptions)
- **Variation: Deadline Monotonic**
  - Use min(period, deadline) to assign priority rather than just period
  - Works the same way, but handles tasks with deadlines shorter than their period

Example of a Missed Deadline at 79% CPU Load

TOTAL CPU LOAD:		79%	for all tasks	
	Task 1	Task 2	Task 3	Task 4
Period:	19	24	29	34
Compute:	5	5	5	5
Utilization:	26.3%	20.8%	17.2%	14.7%

No Place To Schedule RUN 5
Task 4 Misses Its Deadline of 34

- ◆ **Task 4 misses deadline**
  - This is the worst case launch time scenario
- ◆ **Missed deadlines can be difficult to find in system testing**
  - 5 time units per task is worst case
    - – Average case is often a bit lighter load
  - Tasks only launch all at same time once every 224,808 time units

LCM(19,24,29,34) = 224,808
(LCM = Least Common Multiple)

Time	Task 1	Task 2	Task 3	Task 4	Running Task
0	RUN 1				1
1	RUN 2				1
2	RUN 3				1
3	RUN 4				1
4	RUN 5				1
5	..sleep..	RUN 1			2
6	..sleep..	RUN 2			2
7	..sleep..	RUN 3			2
8	..sleep..	RUN 4			2
9	..sleep..	RUN 5			2
10	..sleep..		RUN 1		3
11	..sleep..		RUN 2		3
12	..sleep..		RUN 3		3
13	..sleep..		RUN 4		3
14	..sleep..		RUN 5		3
15	..sleep..			RUN 1	4
16	..sleep..			RUN 2	4
17	..sleep..			RUN 3	4
18	..sleep..			RUN 4	4
19	RUN 1				1
20	RUN 2				1
21	RUN 3				1
22	RUN 4				1
23	RUN 5				1
24		RUN 1			2
25		RUN 2			2
26		RUN 3			2
27		RUN 4			2
28		RUN 5			2
29			RUN 1		3
30			RUN 2		3
31			RUN 3		3
32			RUN 4		3
33			RUN 5		3

RUN 5???

Harmonic RMS or DMS

- **For arbitrary periods, only works for ~70% CPU loading**

$$\mu = \sum_{i=1}^{n} \frac{C_i}{P_i} \le n\left(\sqrt[n]{2} - 1\right); \qquad \lim_{n\to\infty}(\mu) \le 69.3\%$$

  – Most systems don't want to pay 30% tribute to the gods of schedulability… so…

- **Make all periods "harmonic"**
  - P_i is evenly divisible by all shorter P_j
  - This period set is harmonic: {5, 10, 50, 100}
    – <u>10</u> = <u>5</u>*2; <u>50</u> = <u>10</u>*<u>5</u>; <u>100</u> = <u>50</u>*2; <u>100</u> = <u>10</u>*<u>5</u>*2
  - This period set is ***not*** harmonic: {3, 5, 7, 11, 13}
    – 5 = 3 * 1.67 *(non-integer)*, etc.
- **If all periods are harmonic, works for <u>CPU load of 100%</u>**
  - Harmonic periods can't drift in and out of phase – avoids worst case situation

$$\mu = \sum_{i} \frac{c_i}{p_i} \le 1 \ ; \ \forall_{p_j < p_k} \{p_j \text{ evenly divides } p_k\}$$

Example Deadline Monotonic Schedule

Task #	Period (P_i)	Deadline (D_i)	Compute (C_i)
T1	5	15	1
T2	16	23	2
T3	30	6	2
T4	60	60	3
T5	60	30	4

Task #	Priority	μ
T1	1	1/5 = 0.200
T3	2	2/6 = 0.333
T2	3	2/16 = 0.125
T5	4	4/30 = 0.133
T4	5	3/60 = .05
	TOTAL:	0.841

$$\mu = \sum \frac{c_i}{p_i} \leq N(\sqrt[N]{2} - 1) \qquad ; \mathrm{N} = 5$$

$$\mu = 0.841 \quad (not \leq) \quad 0.743$$

Not Schedulable!

(Might be OK with exact schedulability math…
… but then you have to use fancy math!)

Example Harmonic Deadline Monotonic Schedule

Task #	Period (P_i)	Deadline (D_i)	Compute (C_i)
T1	5	15	1
T2	***15***	23	2
T3	30	***5***	2
T4	60	60	3
T5	60	30	4

Task #	Priority	μ
T1	1	1/5 = 0.200
T3	2	2/5 = 0.400
T2	3	2/15 = 0.133
T5	4	4/30 = 0.133
T4	5	3/60 = .05
	TOTAL:	0.916

$$\mu = \sum \frac{c_i}{p_i} \leq 1 \qquad ; Harmonic\ periods\ \{5, 15, 30, 60\}$$

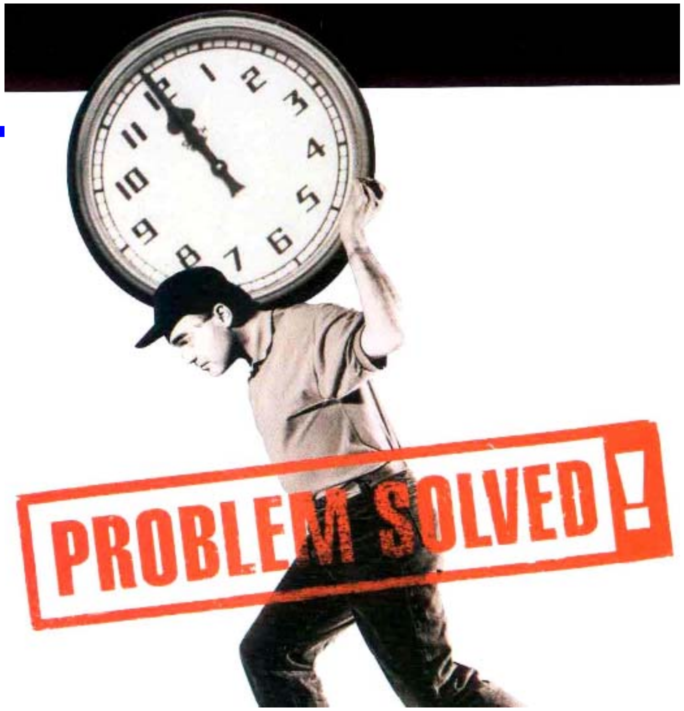
$$\mu = 0.916 \quad \leq \quad 1$$

Schedulable, even though usage is higher!

Distributed Rate/Deadline Monotonic

- **Schedule network using Deadline Monotonic assignment**
  - Implement by assigning CAN priorities according to period length
    - This is what is done in CAN most of the time anyway
  - Network is non-preemptable, but assume it's close enough because each message (=task) is short compared to deadlines
    - Add longest message as blocking time
    - Look up the blocking time math in an RMS/DMS paper (it's a bit complex)
- **Schedule each node using Deadline Monotonic assignment**
  - Static priorities and pre-emptive prioritized scheduler
- **Is that enough?**
  - Should work for piecewise compute+transmit+compute deadlines
  - But for each "hop" you might lose out on one local period extra latency

Dealing With Background Tasks



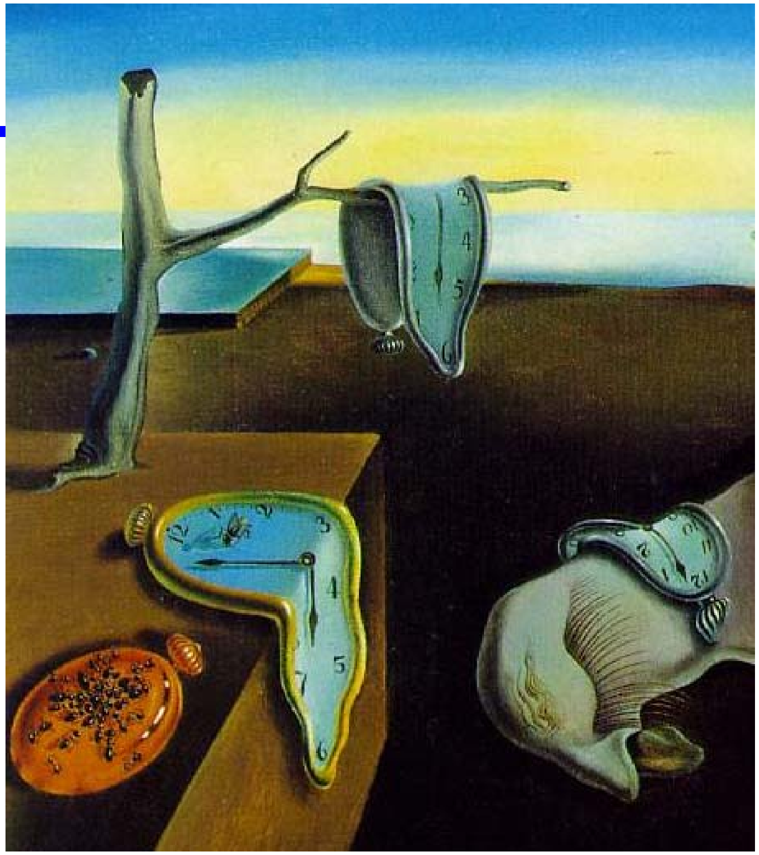
- **"Other" tasks need to be executed without deadlines**

- **Several possible approaches:**
  - Dedicate a fixed number of CPUs to routine tasks
  - Assign all routine tasks lowest priority, and execute round-robin
    - Effectively equivalent to an "other task server" but also uses any leftover time from other tasks that run short, are blocked, or aren't in execution
  - Assign an "other task server" for routine tasks
    - Each "other task" is executed from the server's budget
    - Has the advantage of giving consistent CPU proportion for system validation

- **Distributed version: do the same thing with network bandwidth**

But Wait, There's More

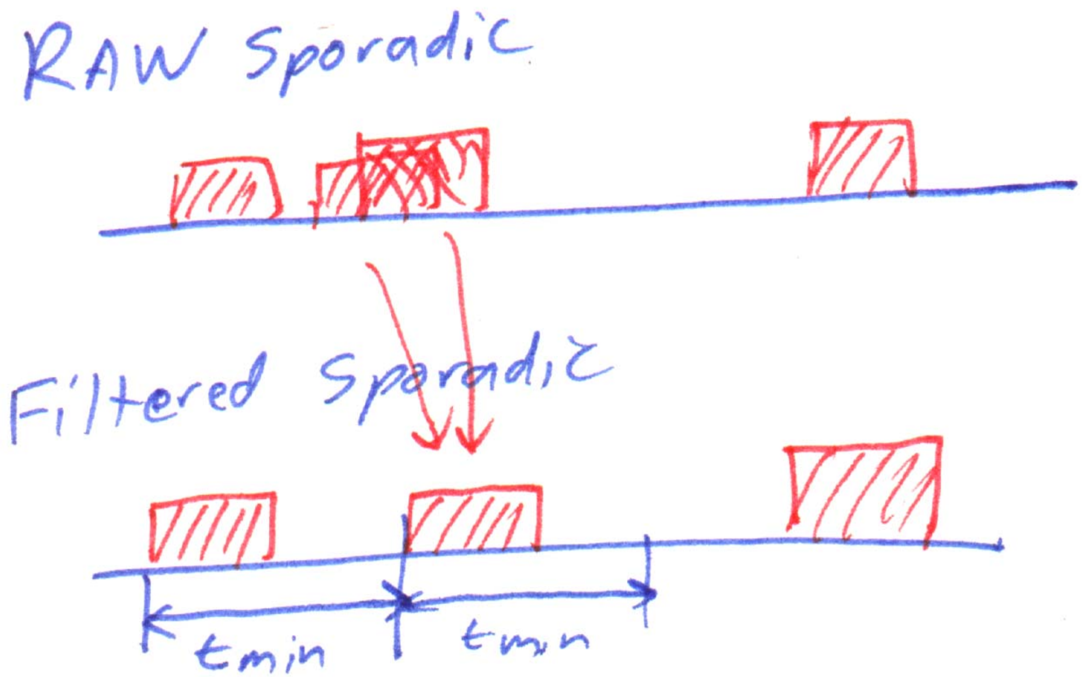
- **WHAT IF:**
  1. Tasks $\{T_i\}$ are NOT periodic
     – Use Sporadic techniques **(stay tuned)**
  2. Tasks are NOT completely independent
     – Worry about dependencies **(stay tuned)**
  3. Deadline NOT = period
     – Use Deadline monotonic



  4. Computation time c_i isn't known and constant
     – Use worst case computation time (WCET), if known
     – Can be tricky to compute – for example what if number of times through a loop is data dependent? (**stay tuned**)
  5. Context switching is free (zero cost)
     – If it isn't free add this to blocking time (see assumption 2 above)

Aperiodic Tasks

- **Asynchronous tasks**
  - External events with no limits on inter-arrival rates
  - Often Poisson processes (exponential inter-arrival times)
- **How can we schedule these?**
  - Mean inter-arrival rate? (only useful over long time periods)
  - Minimum inter-arrival time with "filtering" (limit rate to equal deadline)
    - Artificial limit on inter-arrival rate to avoid swamping system
    - May miss arrivals if multiple arrivals occur within the filtering window length



Dealing With Sporadic Tasks

- "Sporadic" means there is a limit on maximum repetition time
- "Aperiodic" means all bets are off – none of the theories handle this case

Approach #1: pretend sporadic tasks are periodic

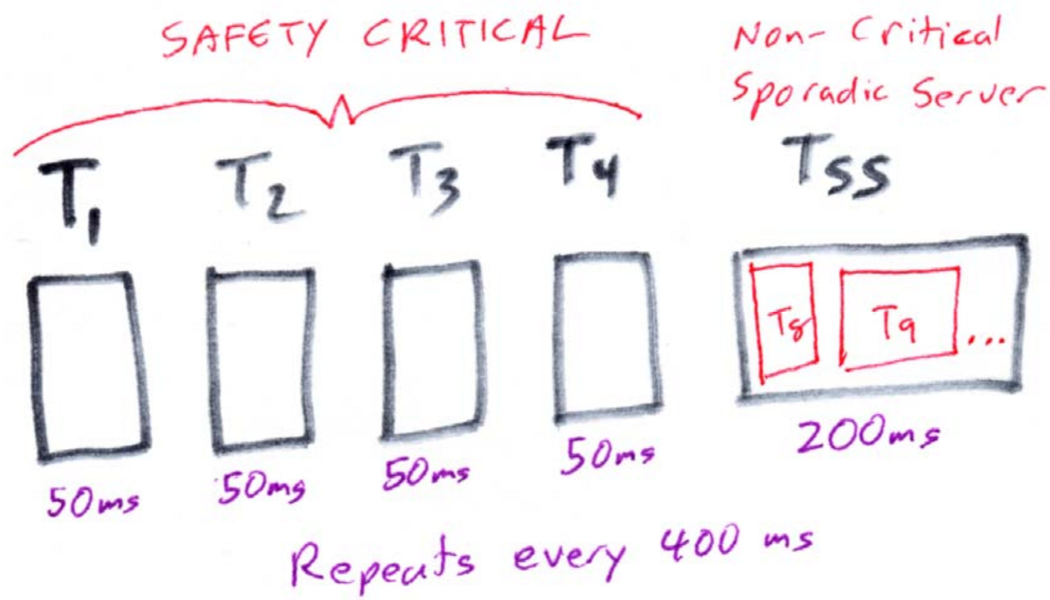
- Schedule time for a sporadic task at maximum possible needed execution rate
- Simplest approach if you have capacity
- But, this can be wasteful, because reserves CPU for tasks that seldom arrive

Approach #2: Use a sporadic server (this is a simplified description)

- Schedule a periodic task that is itself a scheduler for sporadic tasks
  - For example, might serve sporadic tasks in FIFO or round robin order
  - But, sporadic server limits itself to a maximum C_i and runs once every P_i
  - This might look like a preemptive mini-tasker living as a single RTOS task
- Use sporadic server time for any sporadic task that is available
- Decouples timing analysis for sporadic server from other tasks
- Can also handle aperiodic tasks without disrupting other main tasks
  - But, no magic – still can't make guarantees for those aperiodic tasks
  - Need some specialty math to manage and size the sporadic server task

Special Case For Mixed Safety/Non-Safety Systems

- **Two-phase schedule to ensure safety critical task service times**
  1. Critical: Round robin schedule with maximum times per task
     - Non-preemptive tasking with deterministic timing and fixed ordering
  2. Non-Critical: Prioritized task segment with maximum *total* time
     - Basically a sporadic server, for example first-in/first-out ordering within time slice
     - <u>Terminates or suspends tasks at end of its designated slice</u>



- **For example, the FlexRay automotive network protocol does this**
  - Except it applies it to scheduling network messages, not CPU tasks

Blocking Time: Mutex + Priorities Leads To Problems

- **Scenario: Higher priority task waits for release of shared resource**
  - Task L (low prio) acquires resource X via mutex
  - Task H (high prio) wants mutex for resource X and waits for it

- **Simplistic outcome with no remedies to problems (don't do this!)**
  - Task H hogs CPU in an infinite test-and-set loop waiting for resource X
  - Task L never gets CPU time, and never releases resource X

  - Strictly speaking, this is "starvation" rather than "deadlock"

[Renwick04] *modified*

Bounded Priority Inversion

- **An possible approach (BUT, this has problems…)**
  - Task H returns to scheduler every time mutex for resource X is busy
  - Somehow, scheduler knows to run Task L instead
    - If it is a round-robin preemptive scheduler, this will help
    - In prioritized scheduler, task H will have to reschedule itself for later
      - » Can get fancy with mutex release re-activating waiting tasks, whatever ….
  - Priority inversion is bounded – Task L will eventually release Mutex
    - And, if we keep critical regions short, this blocking time B won't be too bad

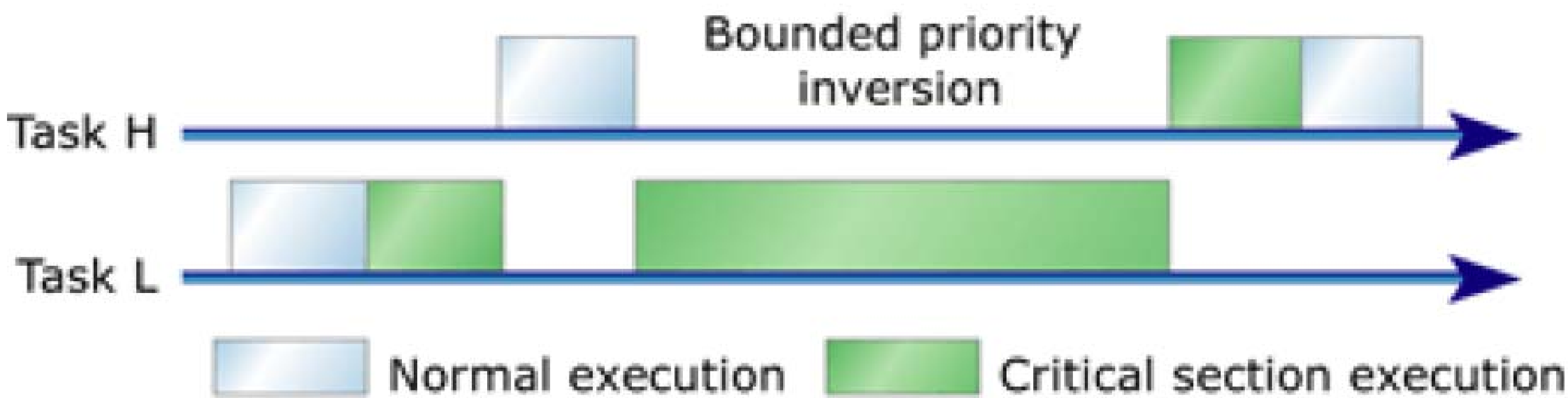


Figure 1: Bounded priority inversion

[Renwick04]

Unbounded Priority Inversion

- **But, simply having Task H relinquish the CPU isn't enough**
  - Task L acquires mutex X
  - Task H sees mutex X is busy, and goes to sleep for a while; Task L resumes
  - Task M preempts task L, and runs for a long time
  - Now task H is waiting for task M ➔ Priority Inversion
    - Task H is *effectively* running at the priority of task L because of this inversion

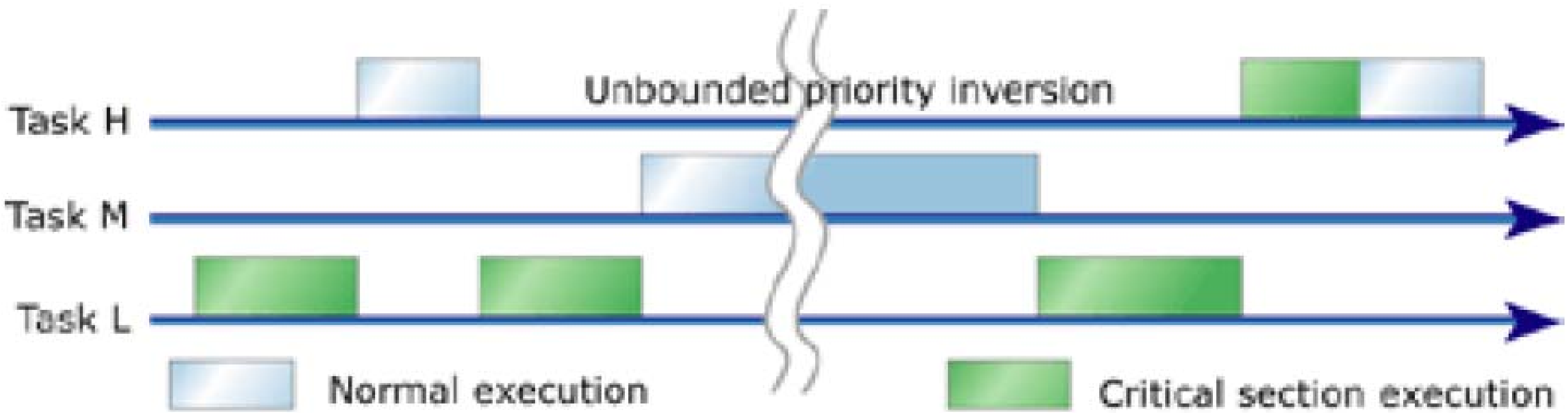


Figure 2: Unbounded priority inversion

[Renwick04]

Solution: Priority Inheritance

- **When task H finds a lock occupied:**
  - It elevates task L to at least as high a priority as task H
  - Task L runs until it releases the lock, but with priority of at least H
  - Task L is demoted back to its normal priority
  - Task H gets its lock as fast as possible; lock release by L ran at prio H
- **Idea: since mutex is delaying task H, free mutex as fast as you can**
  - Without suspending tasks having higher priority than H!
  - For previous slide picture, L would execute with higher prio than M

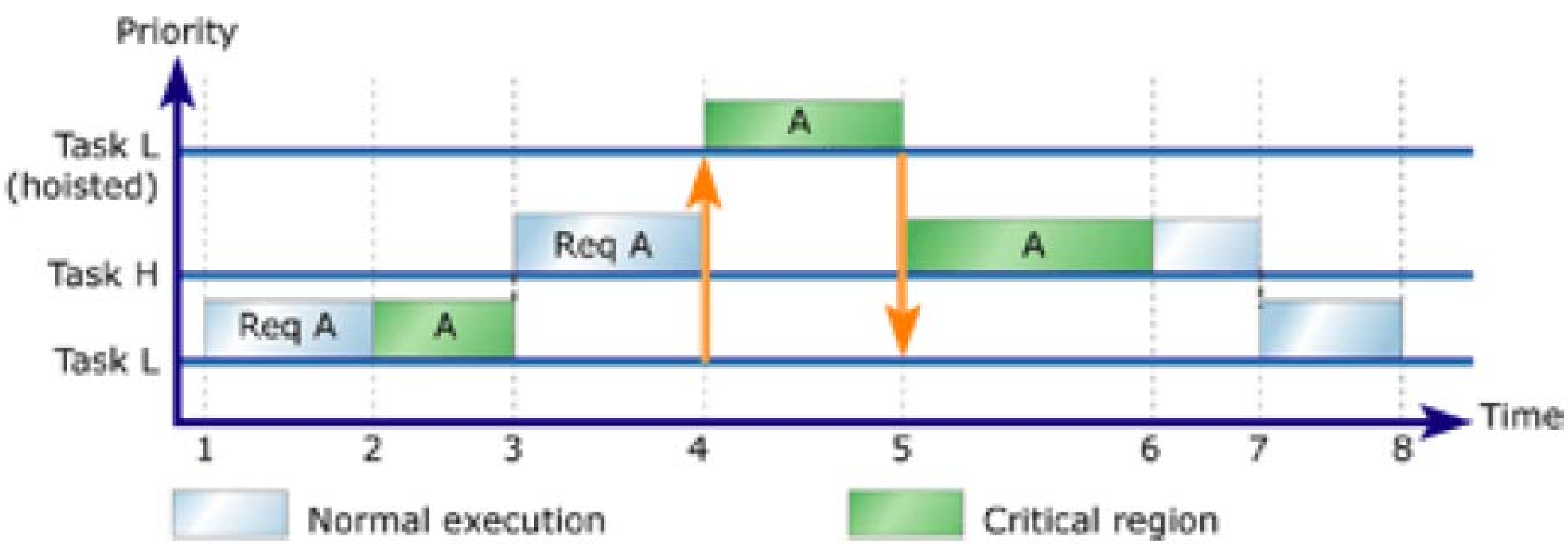


Figure 5: Simple priority inheritance

[Renwick04]

Priority Inheritance Pro/Con

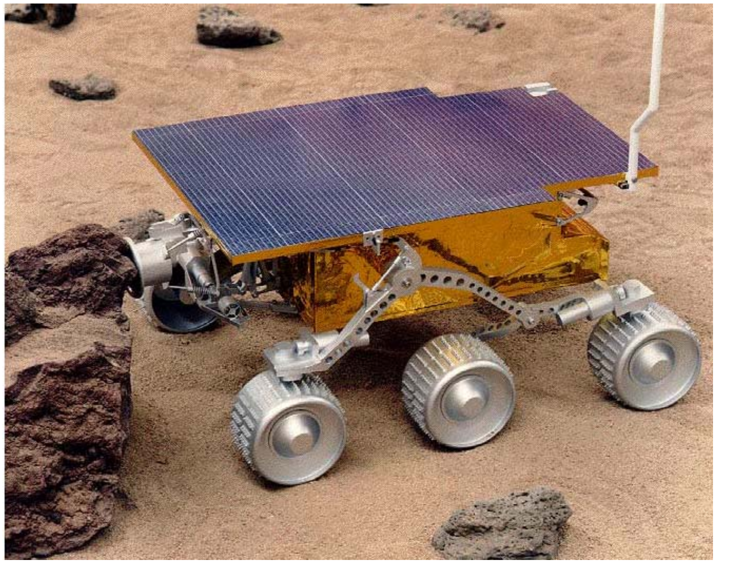
- **Pro: it avoids many deadlocks and starvation scenarios!**
  - Only elevates priority when needed (only when high prio task wants mutex)
  - (An alternative is “priority ceiling” which is a similar idea)

- **Run-time scheduling cost is perhaps neutral**
  - Task H burns up extra CPU time to run Task L at its priority
  - Blocking time B costs per the scheduling math are:
    - L runs at prio H, which effectively increases H’s CPU usage
    - But, H would be “charged” with blocking time B regardless, so no big loss

- **Con: complexity can be high**
  - Almost-static priorities, not fully static
    - But, only changes when mutex encountered, not on every scheduling cycle
  - Nested priority elevations can be tricky to unwind as tasks complete
  - Multi-resource implementations are even trickier

- **If you can avoid need for a mutex, that helps a lot**
  - But sometimes you need a mutex; then you need priority inheritance too!

Mars Pathfinder Incident (Sojourner Rover)



- **July 4, 1997 – Pathfinder lands on Mars**
  - First US Mars landing since Vikings in 1976
  - First rover to land (in one piece) on Mars
  - Uses VxWorks RTOS
- **But, a few days later…**
  - Multiple system resets occur
    - Watchdog timer saves the day!
    - System reset to safe state instead of unrecoverable crash
  - Reproduced on ground; patch uploaded to fix it
    - Developers didn't have Priority Inheritance turned on!
    - Scenario pretty much identical to H/M/L picture a couple slides back
    - Rough cause: "The data bus task executes very frequently and is time-critical -- we shouldn't spend the extra time in it to perform priority inheritance" [Jones07]

Applied Deadline Monotonic Analysis With Blocking

- **Blocking time B_i is worst case time that Task i can be blocked**
  - Combination of blocking from semaphores, bounded length priority inversion, etc.

- **For each task, ensure that task plus its blocking time uses less than 100% of CPU:**

$$\mu_1 = \left(\frac{c_1}{p_1}\right) + \frac{B_1}{p_1} \le 1$$

$$\mu_2 = \left(\frac{c_1}{p_1}\right) + \left(\frac{c_2}{p_2}\right) + \frac{B_2}{p_2} \le 1$$

$$\mu_3 = \left(\frac{c_1}{p_1}\right) + \left(\frac{c_2}{p_2}\right) + \left(\frac{c_3}{p_3}\right) + \frac{B_3}{p_3} \le 1$$

$$\forall k; \mu_k = \sum_{i \le k} \mu_i = \sum_{i \le k} \left(\frac{c_i}{p_i}\right) + \frac{B_k}{p_k} \le 1 \text{ ; for harmonic periods}$$

- **Pessimistic bound – penalize all tasks with worst case blocking time:**

$$\mu = \left(\sum_i \frac{c_i}{p_i}\right) + \frac{\max(B_j)}{p_j} \le 1 \quad ; \quad \text{for harmonic periods}$$

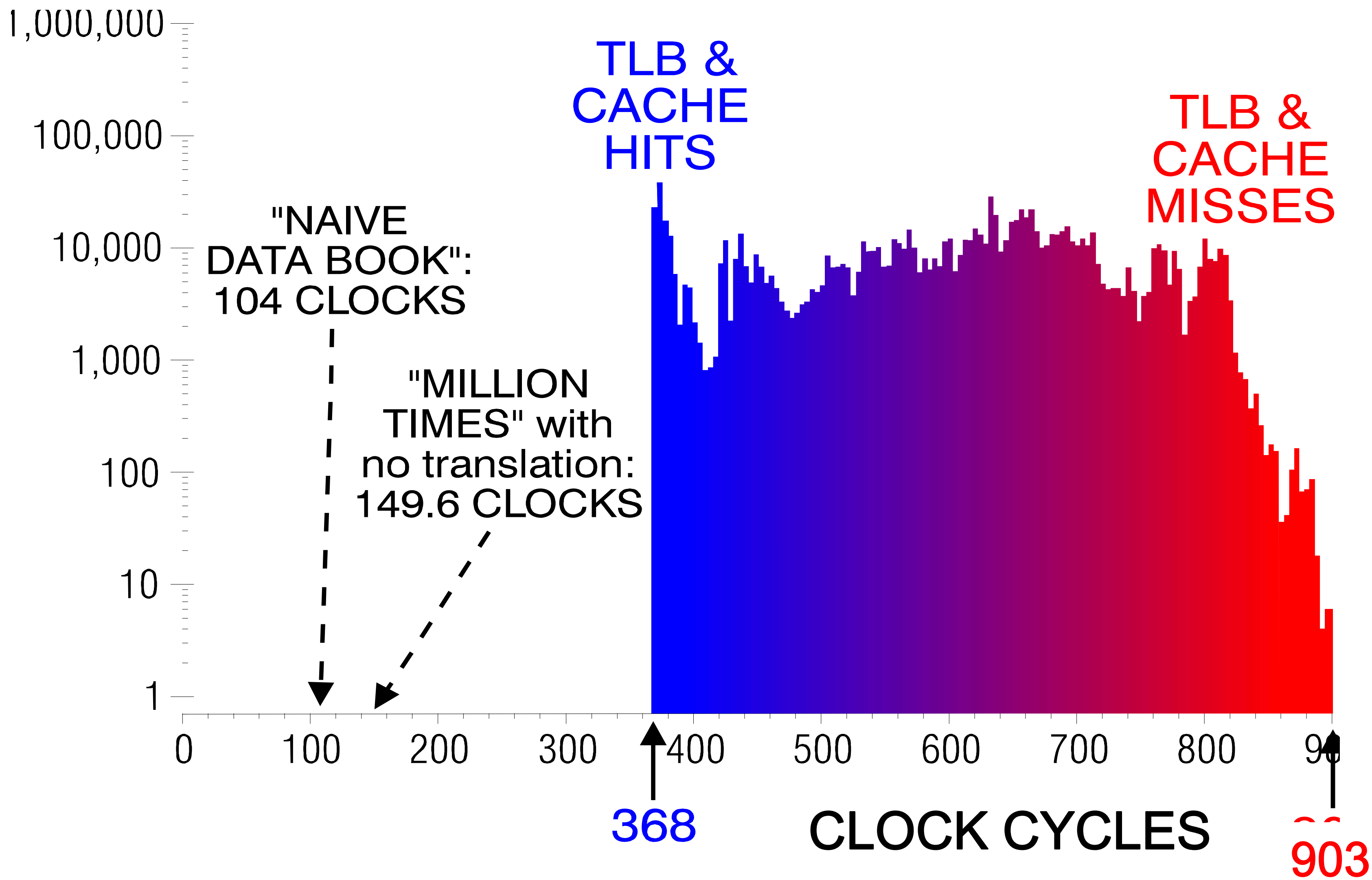
Determinacy & Predictability (the "C" term)

- **Determinacy = same performance every time**
  - Low determinacy can cause control loop instabilities
    - If it's non-deterministic, how do you know you certified/tested the worst case?
  - System-level mechanisms can cause non-determinism:
    - Cache memory; speculative execution; virtual memory; disk drive seek times
    - Context switching overhead; interrupts
    - Prioritized network/task interactions (depends on situation; <u>this is controversial</u>)
  - Determinacy can be improved
    - Insert waits to ensure results are always delivered with worst case delay
    - Avoid/turn off non-deterministic hardware & software features
    - Ensure conditional paths through software are the same length
    - Use only static iteration counts for loops
    - Extreme case – end-to-end cyclic static schedule for everything

- **Predictability = designer can readily predict performance**
  - High end processors are nearly impossible to understand clock-by-clock
    - Some have ways to make things predictable & deterministic (e.g. Power PC 603e)

How Hard Is It To Predict Performance?

- **Computing worst-case “C” is difficult for high performance CPUs**
  - Data from an 80486 (cache, but no speculative execution)



Watch Out For Network Problems!

- **Corrupted network messages**
  - Do you re-transmit?
    - Introduces jitter for that message
    - Delays all subsequent messages
    - Need to reserve extra space to avoid later messages missing deadlines
  - Do you ignore?
    - Use stale data or introduce large jitter for one variable

- **Network blackout**
  - What if entire network is disrupted for 100+ msec?
    - (What if the cable gets cut?)

- **Alternate strategies for dealing with network noise**
  - Maintain freshness counters for all network data
  - Send every message twice
    - Or, run control loops faster than necessary (including message traffic)
  - Forward error correction codes (but won't help with blackout)

Review

- **Scheduling – does it all fit?**
  - Schedulability – necessary vs. sufficient
  - Scheduling algorithms – static, EDF, LL, RM
    - Distributed versions as well as single-CPU versions
- **Complications**
  - Aperiodic tasks
  - Inter-task dependencies
  - Worst case execution time
- **Assumptions… (next slide)**

Review – Assumptions

- **Assume non-preemptive system with 5 Restrictions:**
  1. **Tasks $\{T_i\}$ are periodic & predictable, with hard deadlines and no jitter**
     - **Various hacks to make things look periodic**
     - **Various hacks to increase determinacy**
  2. **Tasks are completely independent**
     - **Pretend a string of tasks is really one task for scheduling**
  3. **Deadline = period** $p_i = d_i$
     - **Use worse case of deadline or period for scheduling**
  4. **Worst case computation time c_i is known and used for calculations**
     - **For a pessimistic approximation, turn off caches to take measurements**
  5. **Context switching is free (zero cost) INCLUDING network messages to send context to another CPU(!)**
     - **It's not free, but as CPUs gets faster it gets cheaper compared to real time**

- Don't forget that the theory does not account for dropped messages!