Last Time

- Priority-based scheduling
  - Static priorities
  - Dynamic priorities
- Schedulable utilization
- Rate monotonic rule: Keep utilization below 69%

Today

- Response time analysis
- Blocking terms
- Priority inversion
  - And solutions
- Release jitter
- Other extensions

Response Time vs. RM

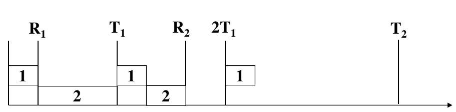
- Rate monotonic result
  - Tells us that a broad class of embedded systems meet their time constraints:
    - Scheduled using fixed priorities with RM or DM priority assignment
    - Total utilization not above 69%
  - However, doesn't give very good feedback about what is going on with a specific system
- Response time analysis
  - Tells us for each task, what is the longest time between when it is released and when it finishes
  - Then these can be compared with deadlines
  - Gives insight into how close the system is to meeting / not meeting its deadline
  - Is more precise (rejects fewer systems)

Computing Response Time

- WC response time of highest priority task R_1
  - $R_1 = C_1$
  - Hopefully obvious
- WC response time of second-priority task R_2
  - Case 1: $R_2 \leq T_1$
    - $R_2 = C_2 + C_1$

More Second-Priority

- Case 2: $T_1 < R_2 \leq 2T_1$
  - $R_2 = C_2 + 2C_1$



- Case 3: $2T_1 < R_2 \leq 3T_1$
  - $R_2 = C_2 + 3C_1$
- General case of the second-priority task:
  - $R_2 = C_2 + \text{ceiling}\ (R_2 / T_1)\ C_1$

Task i Response Time

- General case: $$R_i = C_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$
- hp(i) is the set of tasks with priority higher than I
  - Only higher-priority tasks can delay a task
- Problem with using this equation in practice?

Computing Response Times

- Rewrite as a recurrence relation and solve by iterating:

$$R_i^{n+1} = C_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{R_i^n}{T_j} \right\rceil C_j$$

- Finished when $R_i^{n+1} = R_i^n$
  - Or when $R_i^n > D_i$
- Choose $R_i^0 = 0$ or $R_i^0 = C_i$
  - There may be many solutions to the recurrence
  - These starting points guarantee convergence to the smallest solution (unless there is divergence)
- Result is invalid if $R_i > T_i$
  - Why?

Response Time Example

- Task 1: T = 30, D = 30, C = 10
- Task 2: T = 40, D = 40, C = 10
- Task 3: T = 52, D = 52, C = 12
- Utilization = 81% – Rejected by the rate monotonic test!

$$R_i^{n+1} = C_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{R_i^n}{T_j} \right\rceil C_j$$

- $R_1 = 10$
- $R_2 = 20$
- $R_3 = 52$

Sharing Resources

- So far tasks are assumed to be independent
  - Not allowed to block (e.g. on a network device)
  - Not allowed to contend for shared resources
- Big problem in practice!
- Solution:
  - Compute *worst-case blocking time* for each task
  - Longest time that task is delayed by a lower-priority task
  - Why just lower priority?
- Now we can analyze the system again:

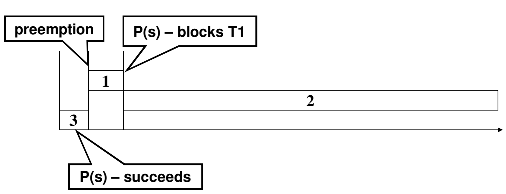
$$R_i^{n+1} = C_i + B_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{R_i^n}{T_j} \right\rceil C_j$$

Computing Blocking Terms

- How do we compute blocking terms?
  - Depends on the synchronization protocol
- Tasks synchronize by disabling interrupts
  - Best answer: Each task gets blocking term with length of the longest critical section in a lower-priority task
  - Simpler answer: Each task gets blocking term with length of the longest critical section in any task
  - Why do these work?
- Tasks synchronize using mutexes
  - Blocking term generally impossible to bound – oops!
  - Standard thread locks are unfriendly to real-time systems
    - Lock wait queue is FIFO
  - Possible solution: Priority queues for mutexes

Priority Inversion

- Priority inversion: Low-priority task delays a high priority task
  - Mutexes (even with priority queuing) provide unbounded priority inversion



Priority Inversion Case Study

- Mars Pathfinder
  - Lands on Mars July 4 1997
  - Mission is successful
- Behind the scenes…
  - Sporadic total system resets on the rover
  - Caused by priority inversion
  - Debugged on the ground, software patch uploaded to fix things
- Details
  - Rover controlled by a single RS6000 running vxWorks
  - Rover devices polled over 1553 bus
  - At 8 Hz bc_sched task sets up bus transactions
  - bc_dist task runs (also at 8 Hz) to read back data

More Pathfinder

- Symptom:
  - bc_sched sometimes was not finished by the time bc_dist ran
  - This triggered a system reset
    - Should never happen since these tasks are high priority
- Problem: bc_sched shared a mutex with ASI/MET task, which does meteorological science at low priority
  - Occasionally the classic priority inversion happened when there were long-running medium priority tasks
- Solution:
  - vxWorks supports "priority inheritance" with a global flag
  - They turned it on

Priority Inversion Solutions

1. Avoid blocking – disable interrupts instead
   - Pros:
     - Efficient
     - Simple
   - Con:
     - Also delays unrelated, high priority tasks
2. Immediate priority ceiling protocol – before locking, raise priority to highest priority of any thread that can touch that semaphore
   - Pros:
     - Fairly simple
     - Less blocking of unrelated tasks
   - Cons:
     - Requires ahead-of-time system analysis
     - Still has some pessimistic blocking

Priority Inversion Solutions

3. Priority inheritance protocol – When a task is blocking other tasks (by holding a mutex) it executes at the priority of the highest-priority blocked task
   - Pros
     - No pessimistic blocking
   - Cons
     - Complicated in presence of nested locking
     - Not that efficient
     - Blocking terms larger than IPCP

- Other solutions exist, such as lock-free synchronization

IPCP Bonus

- In IPCP, raising priority prevents anyone else who might access a resource from running
  - So why take a lock at all?
  - Turns out that locking is not necessary – raising priority is enough
  - HOWEVER: Task must not voluntarily block (e.g. on disk or network) while in a critical section

Overheads

- A real RTOS requires time to:
  - Block a task
  - Make a scheduling decision
  - Dispatch a new task
  - Handle timer interrupts
- For a well-designed RTOS these times can be bounded
  - Worst-case blocking time of the RTOS needs to be added to each task's blocking term
  - 2x worst-case context switch time needs to be added to each task's WCET
    - We always "charge" the cost of a context switch to the higher-priority task

Release Jitter

- Release jitter J_i – Time between invocation of task i and time at which it can actually run
  - E.g. task becomes conceptually runnable at the start of its period
    - But must wait for the next timer interrupt before the scheduler sees it and dispatches it
  - Or, task would like to run but must wait for network data to arrive before it actually runs

$$R_i = C_i + B_i + \sum_{\forall j \in hp(i)} \left\lceil \frac{R_i + J_i}{T_j} \right\rceil C_j$$

Other Extensions

- Sporadically periodic tasks
  - Task has an "outer period" and smaller "inner period"
  - Models bursty processing like network interrupts
- Sporadic servers
  - Provide rate-limiting for truly aperiodic processing
    - E.g. interrupts from an untrusted device
- Arbitrary deadlines
  - When $D_i > T_i$ previous equations do not apply
  - Can rewrite
- Precedence constraints
  - Task A cannot run until Task B has completed
    - Models scenario where tasks feed data to each other
  - Makes it harder to schedule a system

Summary

- Priority based scheduling
  - It's what RTOSs support
  - A strong body of theory can be used to analyze these systems
  - Theory is practical: Many real-world factors can be modeled
- Response time analysis – supports worst-case response time for each priority-based task
  - Blocking terms
  - Release jitter
- Priority inversion can be a major problem
  - Solutions have interesting tradeoffs