Implementing Scheduling Algorithms

Real-Time and Embedded Systems (M)

Lecture 9

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Lecture Outline

- Implementing real time systems
  - Key concepts and constraints
  - System architectures:
    - Cyclic executive
    - Microkernel with priority scheduler
- Implementing scheduling algorithms
  - Jobs, tasks, and threads
  - Priority scheduling of periodic tasks
    - Rate monotonic
    - Earliest deadline first
  - Priority scheduling of aperiodic and sporadic tasks

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Implementing Real Time Systems

- Key fact from scheduler theory: *need predictable behaviour*
  - Raw performance less critical than consistent and predictable performance; hence focus on scheduling algorithms, schedulability tests
  - Don't want to fairly share resources – be unfair to ensure deadlines met

- Need to run on a wide range of – often custom – hardware
  - Often resource constrained:
    - limited memory, CPU, power consumption, size, weight, budget
  - Embedded and may be difficult to upgrade
    - Closed set of applications, trusted code
    - Strong reliability requirements – may be safety critical
    - How to upgrade software in a car engine? A DVD player? After you shipped millions of devices?

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Implications on Operating Systems

- General purpose operating systems not well suited for real time
  - Assume plentiful resources, fairly shared amongst untrusted users
  - Exactly the opposite of an RTOS!

- Instead want an operating system that is:
  - Small and light on resources
  - Predictable
  - Customisable, modular and extensible
  - Reliable

  …and that can be *demonstrated* or *proven* to be so

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Implications on Operating Systems

- Real-time operating systems typically either *cyclic executive* or *microkernel* designs, rather than a traditional monolithic kernel
  - Limited and well defined functionality
  - Easier to demonstrate correctness
  - Easier to customise
- Provide rich scheduling primitives
- Provide rich support for concurrency
- Expose low-level system details to the applications
  - Control of scheduling
  - Power awareness
  - Interaction with hardware devices

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Cyclic Executive

- The simplest real-time systems use a “nanokernel” design
  - Provides a minimal time service: scheduled clock pulse with fixed period
  - No tasking, virtual memory/memory protection, etc.
  - Allows implementation of a static cyclic schedule, provided:
    - Tasks can be scheduled in a frame-based manner
    - All interactions with hardware to be done on a polled basis
- Operating system becomes a single task cyclic executive

```
setup timer
c = 0;
while (1) {
          suspend until timer expires
          c++;
          do tasks due every cycle
          if (((c+0) % 2) == 0) do tasks due every 2nd cycle
          if (((c+1) % 3) == 0) {
                    do tasks due every 3rd cycle, with phase 1
          }
          ...
}
```

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Microkernel Architecture

- Cyclic executive widely used in low-end embedded devices
  - 8 bit processors with kilobytes of memory
  - Often programmed in C via cross-compiler, or assembler
  - Simple hardware interactions
  - Fixed, simple, and static task set to execute
  - Clock driven scheduler

- But… many real-time embedded systems more complex, need a sophisticated operating system with priority scheduling
- Common approach: a *microkernel* with priority scheduler
  - Configurable and robust, since architected around interactions between cooperating system servers, rather than a monolithic kernel with ad-hoc interactions

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Microkernel Architecture

- A microkernel RTOS typically provides a number of features:
  - Scheduling
  - Timing services, interrupt handling, support for hardware interaction
  - System calls with predictable timing behaviour
  - Messaging, signals and events
  - Synchronization and locking
  - Memory protection

- These features often differ from non-RTOS environments
  - This lecture discussing scheduler implementation
  - Next few lectures discuss programming APIs and other features

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Scheduler Implementation

- Clock driven scheduling trivial to implement via cyclic executive

- Other scheduling algorithms need operating system support:
  - System calls to create, destroy, suspend and resume tasks
  - Implement tasks as either *threads* or *processes*
    - Processes (with separate address space and memory protection) not always supported by the hardware, and often *not useful*
  - Scheduler with multiple priority levels, range of periodic task scheduling algorithms, support for aperiodic tasks, support for sporadic tasks with acceptance tests, etc.

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Jobs, Tasks and Threads

- A system comprises a set of *tasks*, each task is a series of *jobs*
  - Tasks are typed, have various parameters (ϕ, p, e, D), react to events, etc.
  - Acceptance test performed before admitting new tasks

- A *thread* is the basic unit of work handled by the scheduler
  - Threads are the instantiation of tasks that have been admitted to the system
  - [If separate address space, discuss *processes*, but no scheduler changes]

- How are tasks and jobs mapped onto threads and managed by the scheduler?

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Periodic Tasks

- Real time tasks defined to execute periodically

  $T = (\phi, p, e, D)$

- Two implementation strategies:
  - Thread instantiated by system each period, runs single job
    - A periodic thread ⇒ supported by some RTOS
    - Clean abstraction:
      - A function that runs periodically
      - System handles timing
    - High overhead due to repeated thread instantiation
      - Thread pools can mitigate overhead
  - Thread instantiated once, performs job, sleeps until next period, repeats
    - Lower overhead, but relies on programmer to handle timing
      - Pushes conceptual burden of handling timing onto programmer
    - Hard to avoid timing drift due to sleep overruns
    - Most common approach

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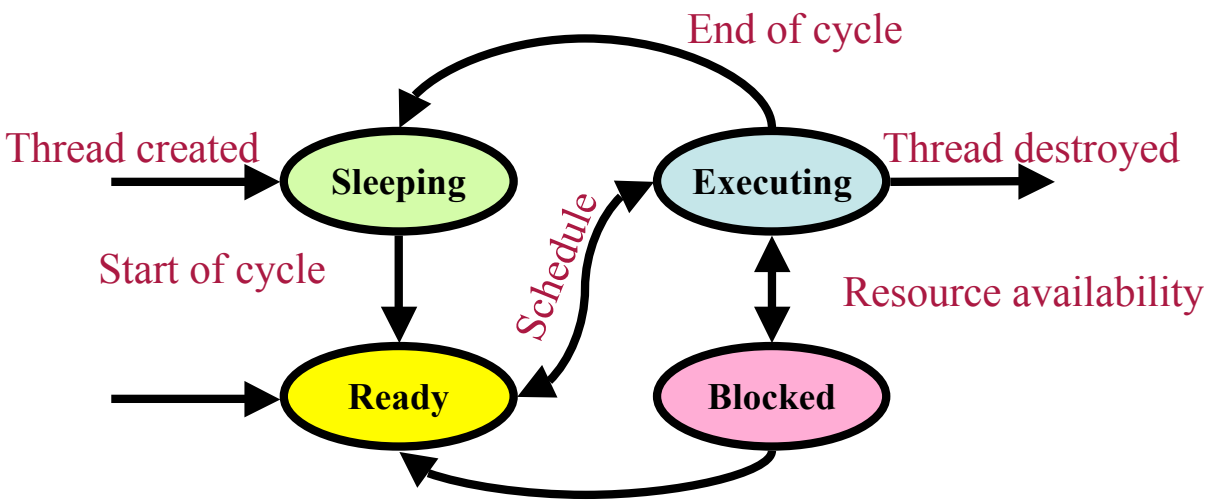
Sporadic and Aperiodic Tasks

- Event list triggers sporadic and aperiodic tasks
  - Might be external (hardware) interrupts
  - Might be signalled by another task

- Several implementation strategies:
  - Job runs as interrupt/signal handler
    - Correctness problems; discussed in lecture 7
    - Handler often used to instantiate sporadic thread or queue job for server task
  - Thread instantiated by system when job released
    - Not well supported for user-level jobs, often used within the kernel
      - E.g. for device drivers; network processing
    - Requires scheduler assistance; high overheads unless thread pool used
  - Job queued for server task
    - A background server (simple, widely implemented)
    - A bandwidth preserving server (useful, but hard to implement)

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Thread States and Transitions



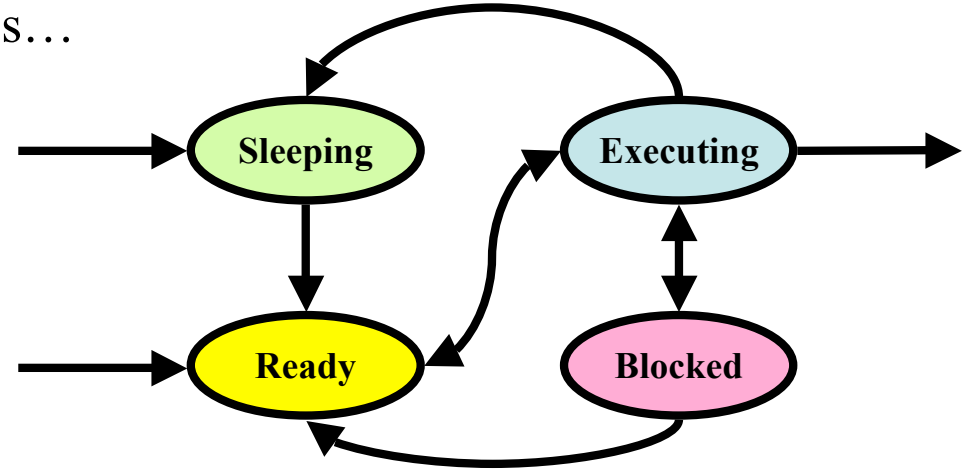
- States represent evolution of thread execution:
  - Sleeping ⇒ Periodic thread queued between cycles
  - Ready ⇒ Queued at some priority, waiting to run
  - Executing ⇒ Running on a processor
  - Blocked ⇒ Queued waiting for a resource

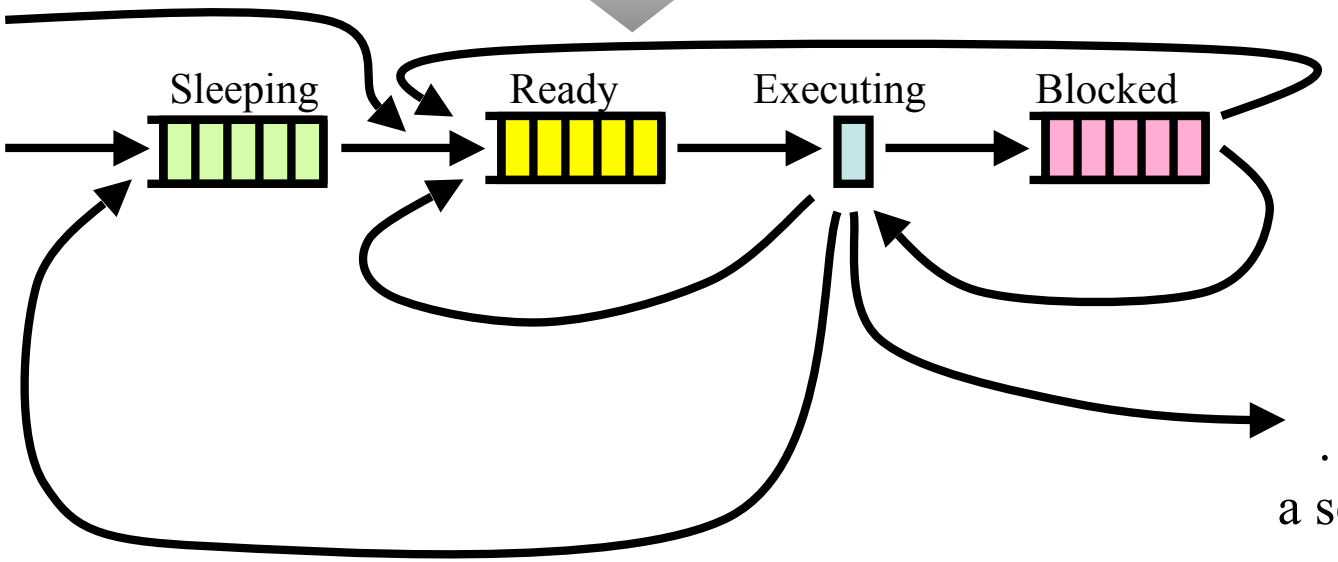
- Transitions happen according to scheduling policy, resource access, external events

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Mapping States onto Queues

Abstract states…



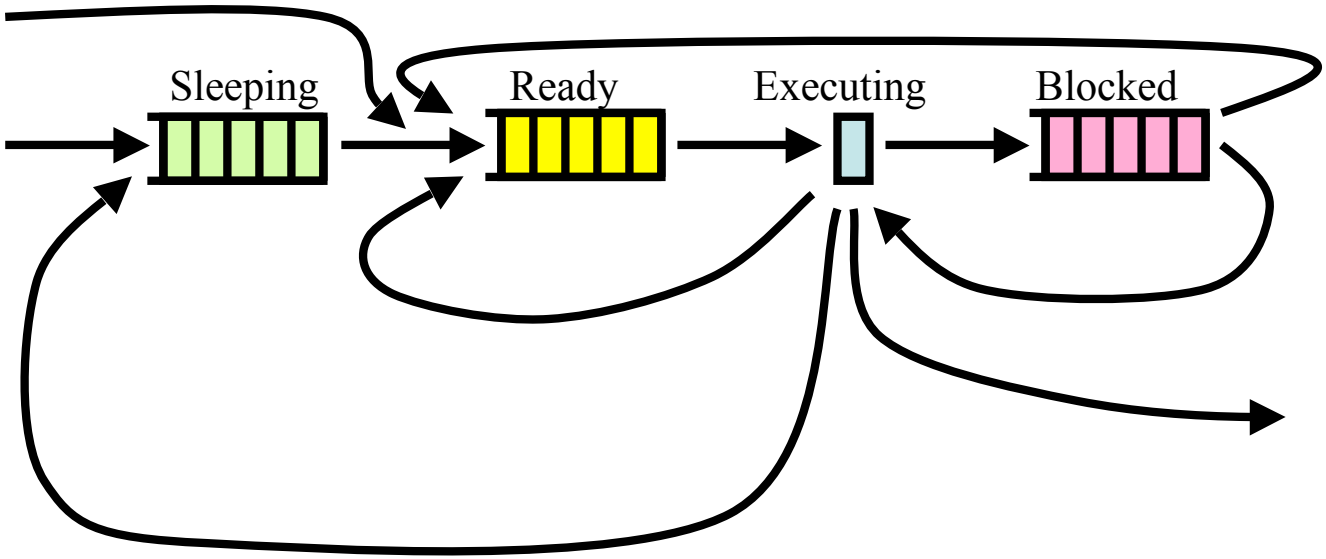


…realised as
a set of queues

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Building a Priority Scheduler

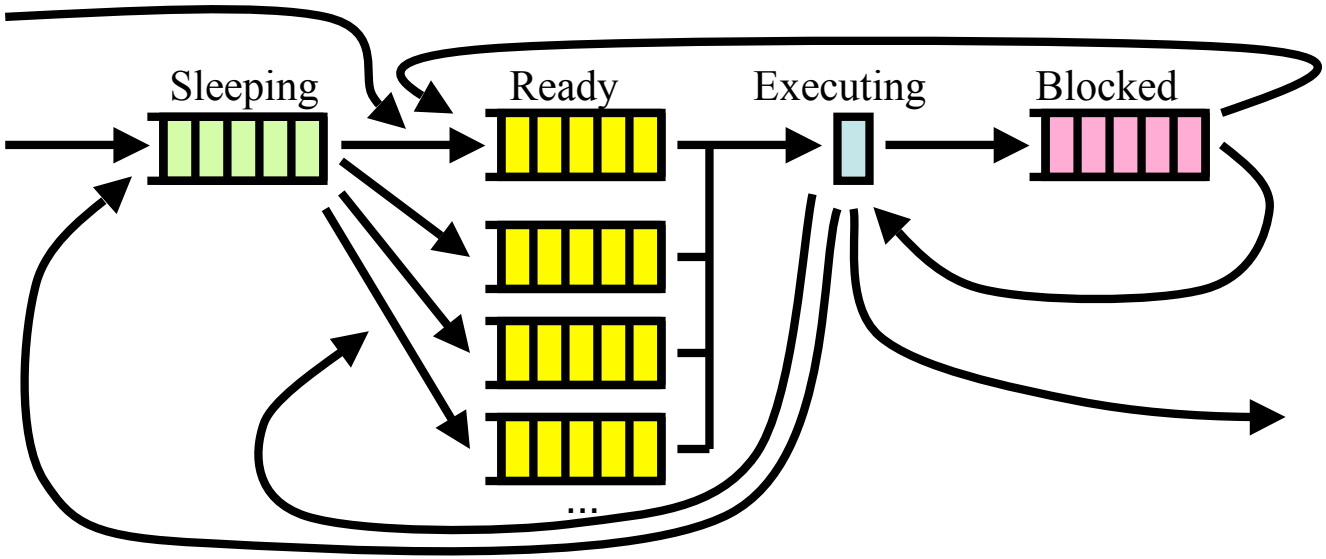
- How to schedule...
  - Periodic fixed priority tasks (RM and DM)?
  - Periodic dynamic priority tasks (EDF and LST)?
  - Sporadic and aperiodic tasks?
- Vary number of queues, the queue selection policy, service discipline
  - How to decide which queue holds a newly released thread?
  - How are the queues ordered?
  - From which queue is the next job to execute taken?



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Fixed Priority Scheduling

- Provide several ready queues, each representing a priority level:
  - Tasks inserted according to priority
  - FIFO or round-robin servicing
    - RR task budget depleted on each clock interrupt; yield when budget exhausted
    - FIFO tasks run until sleep, block or yield
  - Run task at the head of highest priority queue with ready tasks
- Used to implement rate monotonic or deadline monotonic

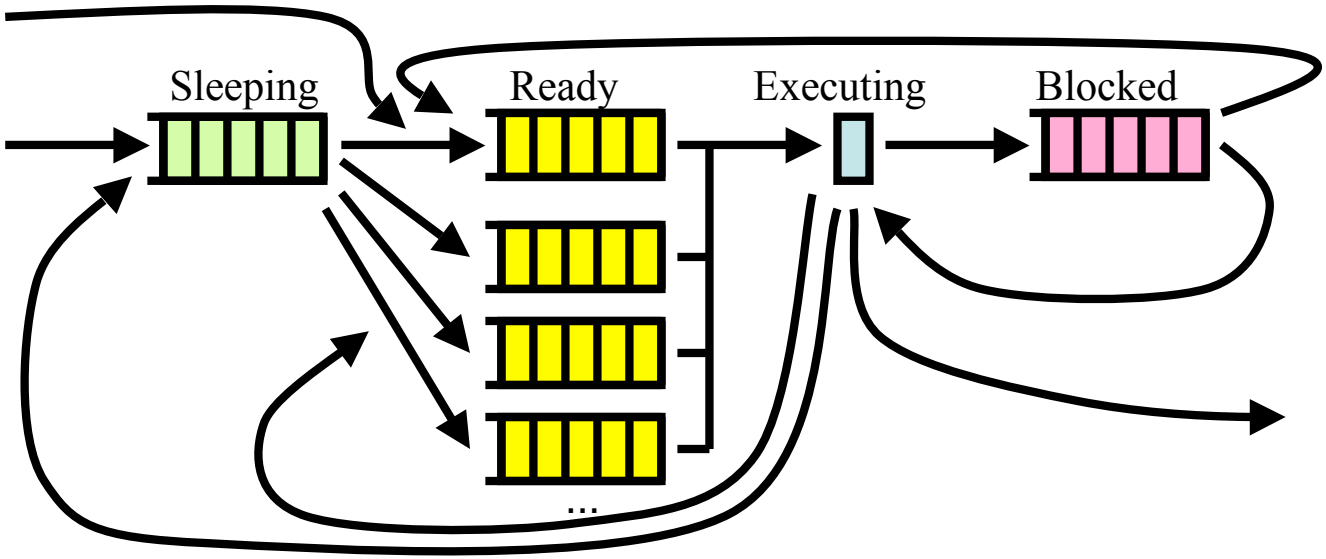


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Fixed Priority Scheduling: Rate Monotonic

- Assign fixed priorities to tasks based on their period, p
  - short period ⇒ higher priority
- Implementation:
  - Task resides in sleep queue until released at phase, ϕ
  - When released, task inserted into a FIFO ready queue
  - One ready queue for each distinct priority
  - Run task at the head of the highest priority queue with ready tasks

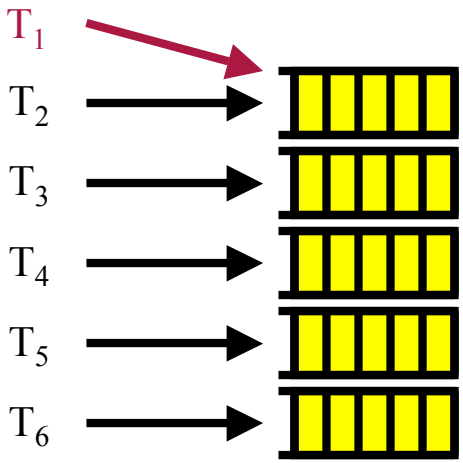
Deadline monotonic scheduler similar



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Practical Considerations: Limited Queues

- When building a rate monotonic system, ensure there are as many ready queues as priority levels
- May be limited by the operating system if present, and need more priority levels than there are queues provided

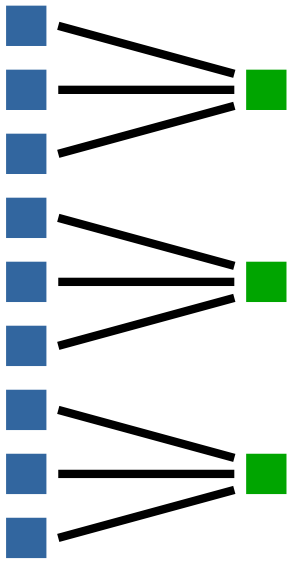


- Implication: non-distinct priorities
- Some tasks will be delayed relative to the "correct" schedule
  - A set of tasks $T_E(i)$ is mapped to the same priority queue as task T_i
  - This may delay T_i up to $\sum_{T_k \in T_E(i)} e_k$
- Schedulable utilization of system will be reduced

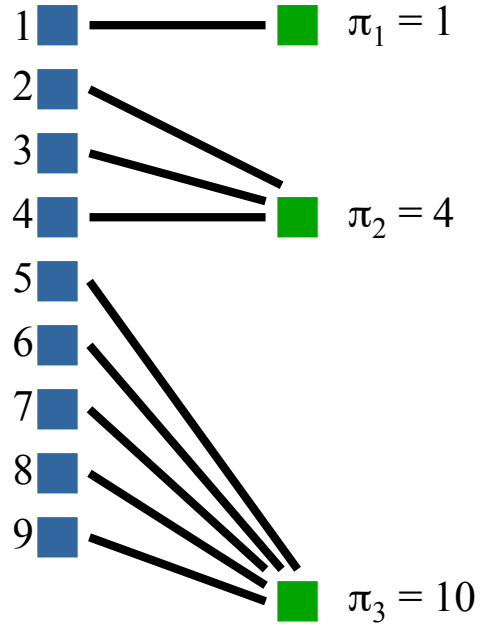
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Practical Considerations: Limited Queues

- How to map a set of tasks needing Ω_n priorities onto a set of Ω_s priority levels, where $\Omega_s < \Omega_n$?



Uniform mapping
$Q = | \Omega_n / \Omega_s |$
tasks map onto each
system priority level



Constant Ratio mapping
$k = (\pi_{i-1}+1)/\pi_i$
tasks where k is a constant map to
each system priority with weight, π_i

Constant ratio mapping better preserves execution times of high priority jobs

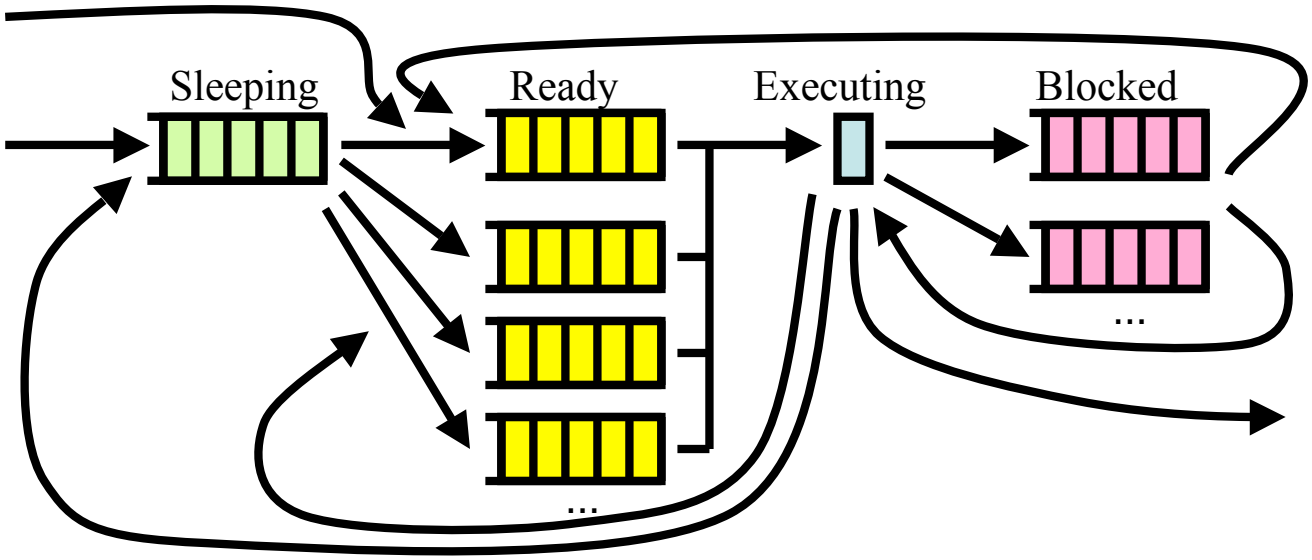
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Blocking on Multiple Events

- Typically there are several reasons why tasks may block
  - Disk I/O, network, inter-process communication, …

⇒ Use multiple blocked queues

- This is a typical priority scheduler provided by most RTOS



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Dynamic Priority Scheduling

- Thread priority can change during execution
- Implies that threads move between ready queues
  - Search through the ready queues to find the thread changing it's priority
  - Remove from the ready queue
  - Calculate new priority
  - Insert at end of new ready queue
- Expensive operation:
  - O(*N*) where *N* is the number of tasks
  - Suitable for system reconfiguration or priority inheritance when the rate of change of priorities is slow
  - Naïve implementation of EDF or LST scheduling inefficient, since require frequent priority changes
    - Too computationally expensive
    - Alternative implementation strategies possible…

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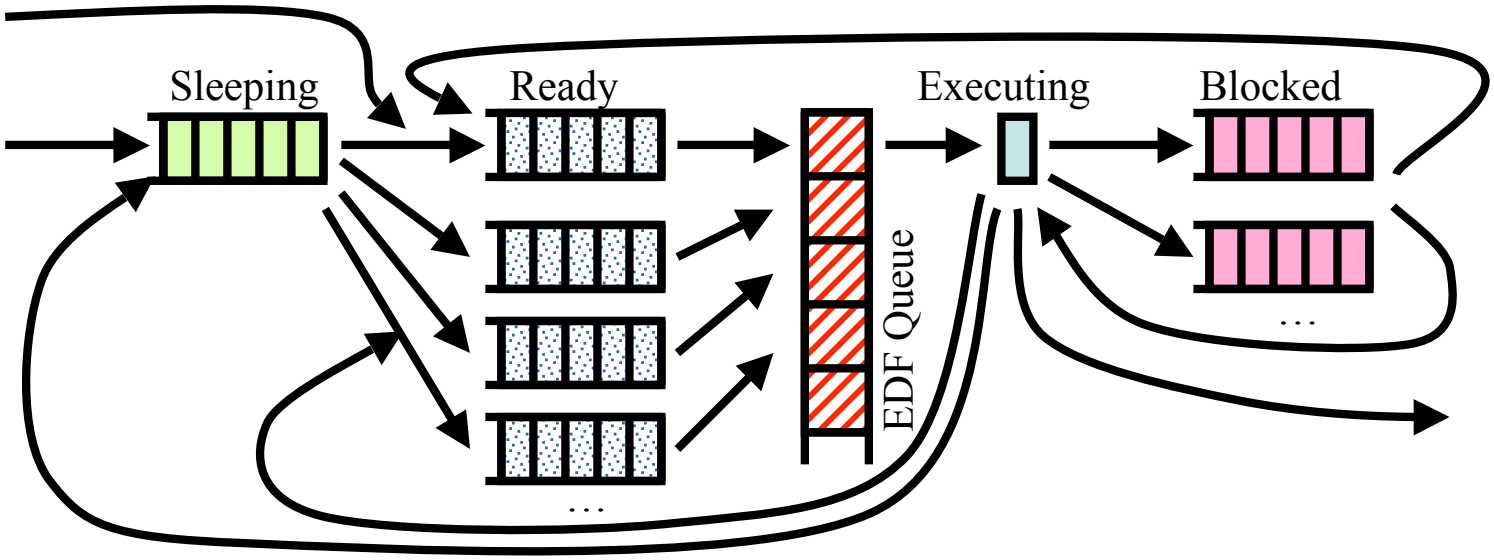
Earliest Deadline First Scheduling

- To directly support EDF scheduling:
  - When each thread is created, its relative deadline is specified
  - When a thread is released, its absolute deadline is calculated from it's relative deadline and release time
- Could maintain a single ready queue:
  - Conceptually simple, threads ordered by absolute deadline
  - Inefficient if many active threads, since scheduling decision involves walking the queue of *N* tasks

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Earliest Deadline First Scheduling

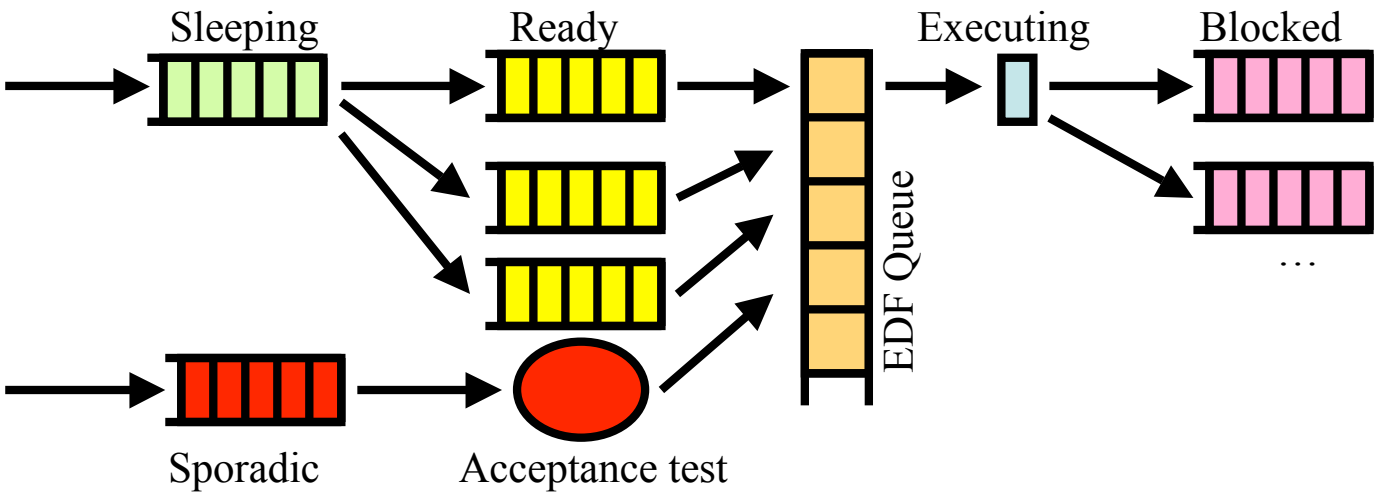
- Maintain a ready queue for each *relative* deadline 
  - Tasks enter these queues in order of release
  - $\Omega' < N$ queues
- Maintain a queue, sorted by *absolute* deadline, pointing to tasks at the head of each ready queue 
  - Updated when tasks complete; when tasks added to empty ready queue
  - Always execute the task at the head of this queue
  - More efficient, since only perform a linear scan through active tasks



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Scheduling Sporadic Tasks

- Straight-forward to schedule using EDF:
  - Add to separate queue of ready sporadic tasks on release
  - Perform acceptance test
  - If accepted, insert into the EDF queue according to deadline
- Difficult if using fixed priority scheduling:
  - Need a bandwidth preserving server



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Scheduling Aperiodic Tasks

- Trivial to implement in as a background server, using a single lowest priority queue
  - All the problems described in lecture 7:
    - Excessive delay of aperiodic jobs
    - Potential for priority inversion if the aperiodic jobs use resources
      - Most operating systems have exactly this issue with idle-priority jobs
  - Better to use a bandwidth preserving server

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Bandwidth Preserving Servers

- Server scheduled as a periodic task, with some priority
  - When ready and selected to execute, given scheduling quantum equal to the current budget
    - Runs until pre-empted or blocked; or
    - Runs until the quantum expires, sleeps until replenished
  - At each scheduling event in the system
    - Update budget consumption considering:
      - time for which the BP server has executed
      - time for which other tasks have executed
      - algorithm depends on BP server type
    - Replenish budget if necessary
    - Keep remaining budget in the thread control block
    - Fairly complex calculations, e.g. for sporadic server
- Not widely supported… typically have to use background server

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Summary

- Implementing real time systems
  - Key concepts and constraints
  - System architectures:
    - Cyclic executive
    - Microkernel with priority scheduler
- Implementing scheduling algorithms
  - Jobs, tasks, and threads
  - Priority scheduling of periodic tasks
    - Rate monotonic
    - Earliest deadline first
  - Priority scheduling of aperiodic and sporadic tasks

- Next lecture: practical real time operating systems and languages

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