University of Glasgow | School of Computing Science

# Resource Access Control in Real-time Systems

Advanced Operating Systems (M)
Lecture 8

# Lecture Outline

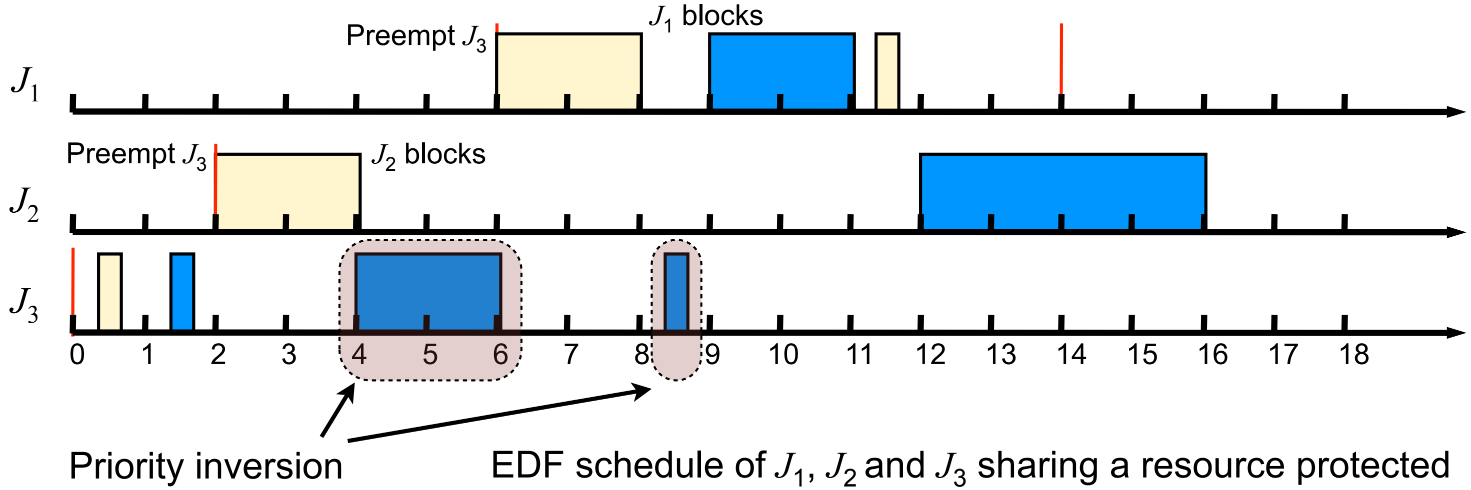
- Definitions of resources
- Resource access control for static systems
  - Basic priority inheritance protocol
  - Basic priority ceiling protocol
  - Enhanced priority ceiling protocols
- Resource access control for dynamic systems
- Effects on scheduling
- Implementing resource access control

# Resources

- A system has $\rho$ types of resource $R_1, R_2, \ldots, R_\rho$
  - Each resource comprises $n_k$ indistinguishable units; plentiful resources have no effect on scheduling and so are ignored
  - Each unit of resource is used in a non-preemptive and mutually exclusive manner; resources are serially reusable
  - If a resource can be used by more than one job at a time, we model that resource as having many units, each used mutually exclusively
- Access to resources is controlled using locks
  - Jobs attempt to lock a resource before starting to use it, and unlock the resource afterwards; the time the resource is locked is the *critical section*
  - If a lock request fails, the requesting job is blocked; a job holding a lock cannot be preempted by a higher priority job needing that lock
  - Critical sections may nest if a job needs multiple simultaneous resources

# Contention for Resources

- Jobs *contend* for a resource if they try to lock it at once




EDF schedule of $J_1$, $J_2$ and $J_3$ sharing a resource protected by locks (blue shading indicated critical sections). The red lines indicate release times and deadlines of jobs.

- *Priority inversion* occurs when a low-priority job executes while some ready higher-priority job waits
- *Deadlock* can result from piecemeal acquisition of resources
  - The classic solution is to impose a fixed acquisition order over the set of lockable resources, and all jobs attempt to acquire the resources in that order (typically LIFO order)

# Timing Anomalies

- As seen, contention for resources can cause timing anomalies due to priority inversion and deadlock
- Unless controlled, these anomalies can be arbitrary duration, and can seriously disrupt system timing

- Cannot eliminate these anomalies, but several protocols exist to control them:
  - Priority inheritance protocol
  - Basic priority ceiling protocol
  - Stack-based priority ceiling protocol

# Priority-Inheritance Protocol

- Aim: to adjust the scheduling priorities of jobs during resource access, to reduce the duration of timing anomalies
- Constraints:
  - Works with any pre-emptive, priority-driven scheduling algorithm
  - Does not require any prior knowledge of the jobs' resource requirements
  - Does not prevent deadlock, but if some other mechanism used to prevent deadlock, ensures that no job can block indefinitely due to uncontrolled priority inversion
- We discuss the *basic* priority-inheritance protocol which assumes there is only 1 unit of resource

# Basic Priority-Inheritance Protocol

- Assumptions (for all of the following protocols):
  - Each resource has only 1 unit
  - The priority assigned to a job according to a standard scheduling algorithm is its *assigned* priority
  - At any time $t$, each ready job $J_k$ is scheduled and executes at its *current* priority, $\pi_k(t)$, which may differ from its assigned priority and may vary with time
  - The current priority $\pi_l(t)$ of a job $J_l$ may be raised to the higher priority $\pi_h(t)$ of another job $J_h$. In such a situation, the lower-priority job $J_l$ is said to inherit the priority of the higher-priority job $J_h$, and $J_l$ executes at its inherited priority $\pi_h(t)$

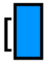
# Basic Priority-Inheritance Protocol

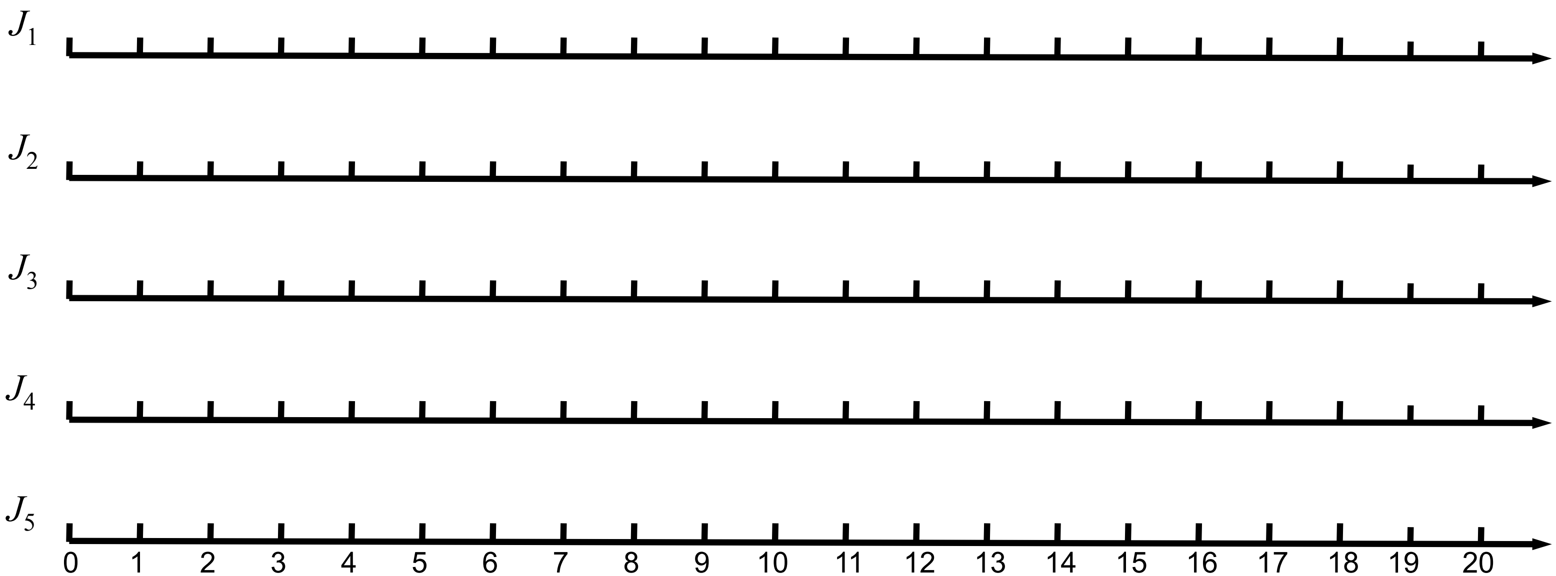
- Jobs are pre-emptively scheduled according to their current priorities
  - At release time, the current priority of a job is equal to its assigned priority
  - The current priority remains equal to the assigned priority, except when the priority-inheritance rule is invoked:
    - When a job, $J$, becomes blocked, the job $J_l$ which blocks $J$ inherits the current priority $\pi(t)$ of $J$
    - $J_l$ executes at its inherited priority until it releases $R$; at that time, the priority of $J_l$ returns to its priority $\pi_l(t')$ at the time $t'$ when it acquired the resource $R$
- When a job $J$ requests a resource $R$ at time $t$:
  - If $R$ is free, $R$ is allocated to $J$ until $J$ releases it
  - If $R$ is not free, the request is denied and $J$ is blocked
  - $J$ is only denied $R$ if the resource is held by another job

# Basic Priority-Inheritance Protocol

What does the schedule look like?

Jobs 1, 2, 4, 5 acquire resource after 1 time unit
Job 4 acquires blue after further 2 units

| Job | $r_i$ | $e_i$ | $\pi_i$ | Critical Sections |
|---|---|---|---|---|
| $J_1$ | 7 | 3 | 1 | [; 1] |
| $J_2$ | 5 | 3 | 2 | [; 1] |
| $J_3$ | 4 | 2 | 3 | |
| $J_4$ | 2 | 6 | 4 | [; 4 [; 1.5]] |
| $J_5$ | 0 | 6 | 5 | [; 4] |



# Basic Priority-Inheritance Protocol

- Properties of the Priority-inheritance Protocol
  - Simple to implement, needs no prior knowledge of resource requirements
  - Jobs exhibit different types of blocking
    - Direct blocking due to resource locks
    - Priority-inheritance blocking
    - Transitive blocking
  - Lower blocking time than prohibiting preemption during critical sections, but does not guarantee to minimise blocking
  - Deadlock is *not* prevented: need to manage lock acquisition order in addition

# Basic Priority-Ceiling Protocol

- Sometimes desirable to further reduce blocking times due to resource contention
- The *basic priority-ceiling* protocol provides a means to do this, provided:
  - The assigned priorities of all jobs are fixed (e.g. RM scheduling, not EDF)
  - The resources required by all jobs are known a priori
- Need two additional terms to define the protocol:
  - The priority ceiling of any resource $R_k$ is the highest priority of all the jobs that require $R_k$ and is denoted by $\Pi(R_k)$
  - At any time $t$, the current priority ceiling $\Pi(t)$ of the system is equal to the highest priority ceiling of the resources that are in use at the time
  - If all resources are free, $\Pi(t)$ is equal to $\Omega$, a nonexistent priority level that is lower than the lowest priority level of all jobs

# Basic Priority-Ceiling Protocol

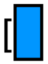
- Scheduling rules:
  - Priority-driven scheduling; jobs can be preempted
  - The current priority of a job equals its assigned priority, except when the priority-inheritance rule (see next slide) is invoked
- Resource allocation rule:
  - When a job $J$ requests a resource $R$ held by another job, the request fails and the requesting job blocks
  - When a job $J$ requests a resource $R$ that is available:
    - if $J$'s priority $\pi(t)$ is higher than current priority ceiling $\Pi(t)$:
      | $R$ is allocated to $J$
      else
      | if $J$ is the job holding the resource(s) whose priority ceiling is equal to $\Pi(t)$:
      | | $R$ is allocated to $J$
      | else
      | | the request is denied, and $J$ becomes blocked
  - Unlike priority inheritance: can deny access to an available resource

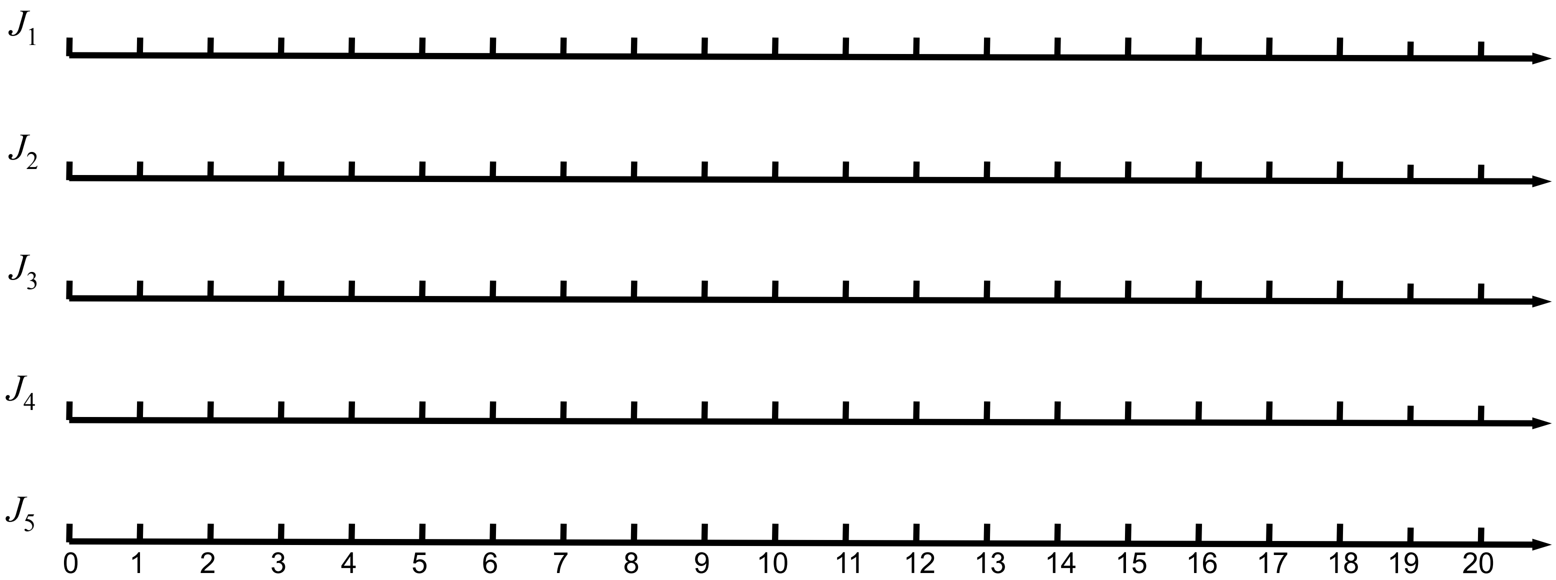
# Basic Priority-Ceiling Protocol

- Priority-inheritance rule:
  - When the requesting job, $J$, becomes blocked, the job $J_l$ which blocks $J$ inherits the current priority $\pi(t)$ of $J$
  - $J_l$ executes at its inherited priority until the time when it releases every resource whose priority ceiling is equal to or higher than $\pi(t)$; then, the priority of $J_l$ returns to its priority $\pi_l(t')$ at the time $t'$ when it was granted the resource(s)

# Basic Priority-Ceiling Protocol

What does the schedule look like?

| Job | $r_i$ | $e_i$ | $\pi_i$ | Critical Sections |
|---|---|---|---|---|
| $J_1$ | 7 | 3 | 1 | [; 1] |
| $J_2$ | 5 | 3 | 2 | [; 1] |
| $J_3$ | 4 | 2 | 3 | |
| $J_4$ | 2 | 6 | 4 | [; 4 [; 1.5]] |
| $J_5$ | 0 | 6 | 5 | [; 4] |



# Basic Priority-Ceiling Protocol

- If resource access in a system of preemptable, fixed priority jobs on one processor is controlled by the priority-ceiling protocol:
    - Deadlock can never occur
    - A job can be blocked for at most the duration of one critical section: there is no transitive blocking
- Differences between the priority-inheritance and priority-ceiling protocols:
    - Priority inheritance is greedy, while priority ceiling is not
        - The priority ceiling protocol may withhold access to a free resource, causing a job to be blocked by a lower-priority job which does not hold the requested resource – termed avoidance blocking
    - The priority ceiling protocol forces a fixed order onto resource accesses, thus eliminating deadlock

# Enhancing the Priority Ceiling Protocol

- The basic priority ceiling protocol performs well, but is complex, and can result in high context switch overheads

- This has led to two modifications to the protocol:
  - The stack-based priority ceiling protocol
  - The ceiling priority protocol

# Stack-Based Priority Ceiling Protocol

- Based on original work to allow jobs to share a run-time stack, extended to control access to other resources

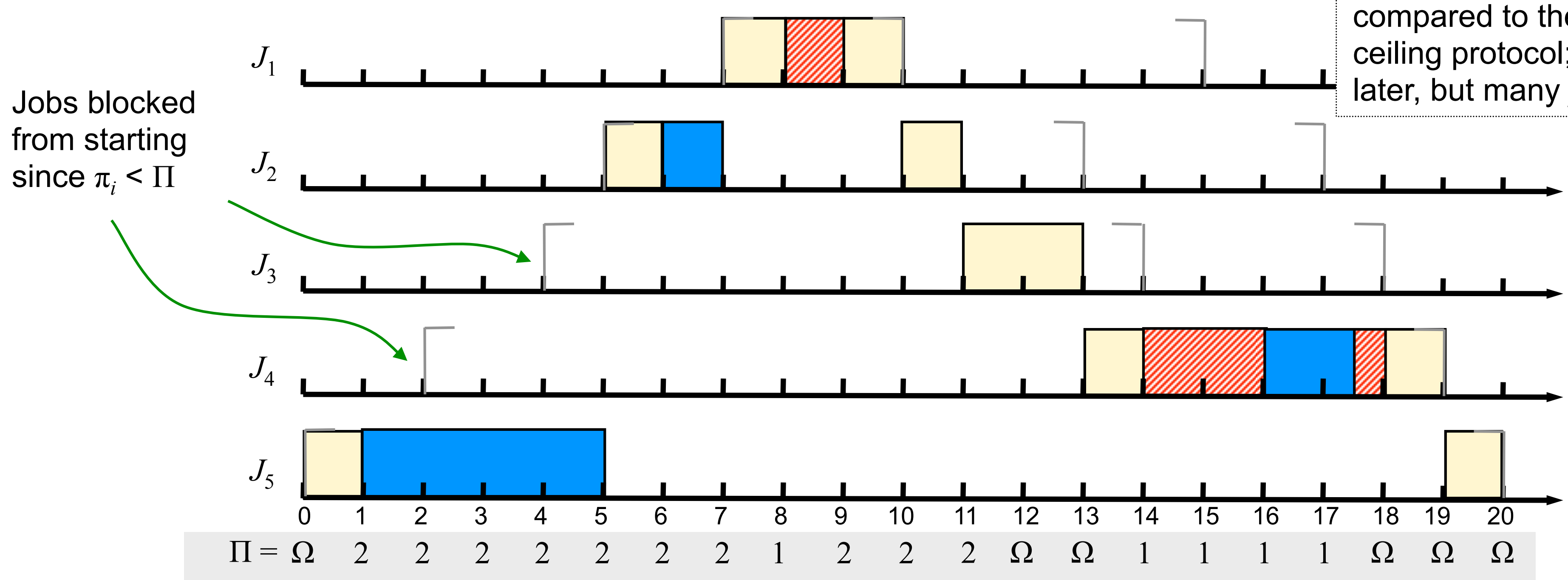
- Defining rules:
  - Ceiling: When all resources are free, $\Pi(t) = \Omega$; $\Pi(t)$ updated each time a resource is allocated or freed
    - $\Pi(t)$ current priority ceiling of all resources in currently use; $\Omega$ non-existing lowest priority level
  - Scheduling:
    - After a job is released, it is blocked from starting execution until its assigned priority is higher than $\Pi(t)$
    - Non-blocked jobs are scheduled in a pre-emptive priority manner; tasks never self-yield
  - Allocation: when a job requests a resource, it is allocated
    - The allocation rule looks greedy, but the scheduling rule is not

# Stack-Based Priority Ceiling Protocol

What does the schedule look like?

| Job | $r_i$ | $e_i$ | $\pi_i$ | Critical Sections |
|---|---|---|---|---|
| $J_1$ | 7 | 3 | 1 | [ ; 1] |
| $J_2$ | 5 | 3 | 2 | [ ; 1] |
| $J_3$ | 4 | 2 | 3 | |
| $J_4$ | 2 | 6 | 4 | [ ; 4 [ ; 1.5]] |
| $J_5$ | 0 | 6 | 5 | [ ; 4] |

Context switches are reduced compared to the basic priority ceiling protocol; no jobs finish later, but many jobs start later



# Stack-Based Priority Ceiling Protocol

- Characteristics:
  - When a job starts to run, all the resource it will ever need are free (since otherwise the ceiling would be ≥ priority)
    - No job ever blocks waiting for a resource once its execution has begun
    - Implies low context switch overhead
  - When a job is pre-empted, all the resources the pre-empting job will require are free, ensuring it will run to completion; deadlock cannot occur
  - Longest blocking time provably not worse than the basic priority ceiling protocol, i.e., not worse than the duration of one critical section

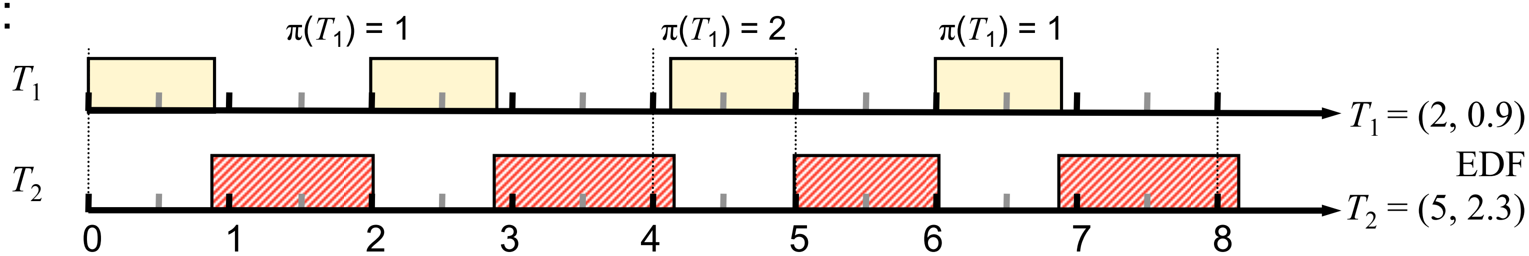
# Choice of Priority Ceiling Protocol

- If tasks never self yield, the stack based priority ceiling protocol is a better choice than the basic priority ceiling protocol
  - Simpler
  - Reduce number of context switches
  - Can also be used to allow sharing of the run-time stack, to save memory resources

- Both give better performance than priority inheritance protocol
  - Assuming fixed priority scheduling, resource usage known in advance

# Resources in Dynamic Priority Systems

- The priority ceiling protocols assume fixed priority scheduling
- In a dynamic priority system, the priorities of the periodic tasks change over time, while the set of resources required by each task remains constant
  - As a consequence, the priority ceiling of each resource changes over time
  - Example:



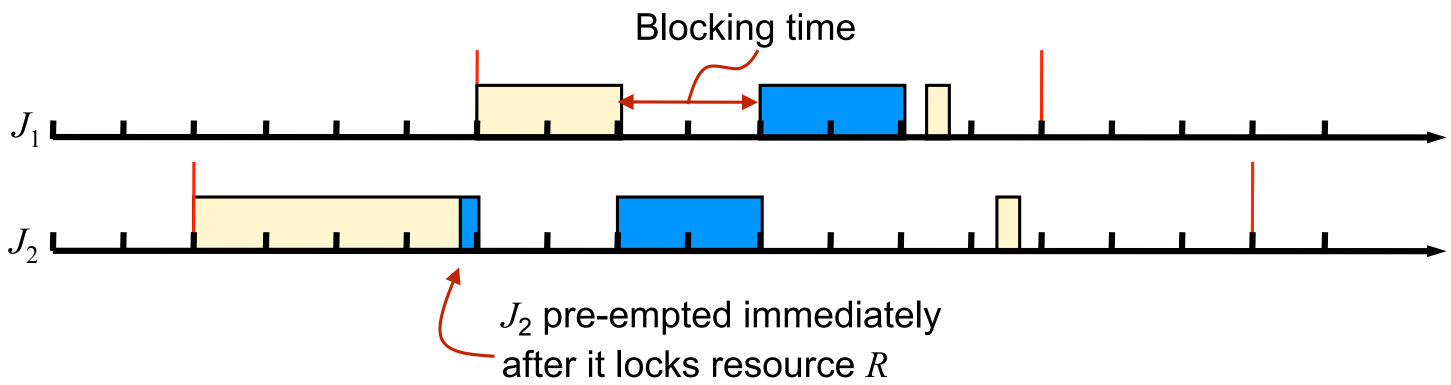

  - What happens if $T_1$ uses resource $X$, but $T_2$ does not?
    - Priority ceiling of $X$ is 1 for $0 \leq t \leq 4$, becomes 2 for $4 \leq t \leq 5$, etc. even though the set of resources required by the tasks remains unchanged

# Resources in Dynamic Priority Systems

- If a system is job-level fixed priority, but task-level dynamic priority, a priority ceiling protocol can still be applied
  - Each job in a task has a fixed priority once it is scheduled, but may be scheduled at different priority to other jobs in the task (e.g., EDF)
  - Update the priority ceilings of all jobs each time a new job is introduced; use until updated on next job release
- Proven to work and have the same properties as priority ceiling protocol in fixed priority systems
  - But very inefficient, since priority ceilings updated frequently
  - May be better to use priority inheritance protocol, accept longer blocking

# Maximum Duration of Blocking

- Assume $J_1$ and $J_2$ contend for a resource, $R$, where $J_1$ is the higher priority job
  - Worst case blocking time → duration of $J_2$'s critical section over $R$




- When using priority inheritance protocol, $J_2$ might be transitively blocked for the duration of the next priority job's critical section
  - Worst case: it is blocked by every other lower priority job, for the full duration of each lower priority job's critical section

# Maximum Duration of Blocking

- The priority ceiling protocols implement avoidance blocking, and so do not exhibit transient blocking
  - Block for *at most* the duration of one low priority critical section
    - Direct blocking: low priority jobs locks resource; can be blocked for up to the duration of the critical section of that job
    - Avoidance blocking: resource is free, but priority ceiling rules deny access
- Calculate worst case blocking duration:
  - Simple:
    - Assume can block for duration of longest critical section of lower priority jobs
    - Probably overestimates blocking duration; likely not too significant
  - More efficient:
    - Trace direct conflicts with lower priority jobs, find longest critical section
    - Trace indirect conflicts with lower priority jobs that may inherit priority and cause avoidance blocking, find longest critical section
    - Greatest of these is maximum possible blocking time

# Effects on Scheduling Tests

- Jobs which block due to resource access affect whether a system can be scheduled
- How to adjust scheduling test?
  - Incorporate maximum blocking time as part of execution time of job; scheduling test then runs as normal
  - Priority ceiling protocols clearly preferred where possible

# Implementing Resource Access Control

- Have focussed on resource access control algorithms which can be implemented by an operating system
- How are these made available to applications?
    - Some implemented by the operating system
    - Some implemented at the application level

# POSIX Mutex API

- Control access to resource using a mutex
  - A mutex is embedded in an object at a location of the programmers choosing to control access to that object/resource
  - Basic API:

```
int pthread_mutex_init(pthread_mutex_t *mutex, pthread_mutexattr_t *attr);
int pthread_mutex_destroy(pthread_mutex_t *mutex);

int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);

int pthread_mutexattr_init(pthread_mutexattr_t *attr);
int pthread_mutexattr_destroy(pthread_mutexattr_t *attr);

int pthread_mutexattr_setprotocol(pthread_mutex_attr_t *attr, int  proto);
int pthread_mutexattr_getprotocol(pthread_mutex_attr_t *attr, int *proto);
```

# POSIX Mutex: Priority Inheritance

- Can specify resource access protocol for a mutex:
  - Use `pthread_mutexattr_setprotocol()` during mutex creation
    - `PTHREAD_PRIO_INHERIT` Priority inheritance protocol applies
    - `PTHREAD_PRIO_PROTECT` Priority ceiling protocol applies
    - `PTHREAD_PRIO_NONE` Priority remains unchanged
  - If the priority ceiling protocol is used, can adjust the ceiling to match changes in thread priority (e.g. dynamic priority scheduling):
    - `pthread_mutexattr_getprioceiling(…)`
    - `pthread_mutexattr_setprioceiling(…)`
- Used with POSIX real-time scheduling:
  - Allow implementation of fixed priority scheduling with a known resource access control protocol
  - Controls priority inversion, scheduling; allows reasoning about a system

# POSIX Condition Variables

- POSIX also defines a condition variable API:

```
int pthread_cond_init(pthread_cond_t *cond, pthread_condattr_t *attr);
int pthread_cond_destroy(pthread_cond_t *cond);

int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
int pthread_cond_timedwait(pthread_cond_t *cond, pthread_mutex_t *mutex
                           struct timespec *wait_time);

int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

- Combine a condition variable with a mutex to wait for a condition to be satisfied:

```
lock associated mutex
while (condition not satisfied) {
    wait on condition variable
}
do work
unlock associated mutex
```

(timed wait with priority inheritance)

# Implementation Summary

- As seen, many approaches to implementing resource access control
- POSIX provides useful baseline functionality
    - Priority scheduling abstraction, to implement Rate Monotonic schedules
    - A mutex abstraction using either priority inheritance or priority ceiling protocols to arbitrate resource access
- Similar, sometimes more advanced features, provided by other real-time operating systems
    - Examples: Ada supports the priority ceiling protocol; QNX supports message based priority inheritance

# Summary

- Defined resources, explaining timing anomalies and the need for resource access control
- Illustrated operation of three resource access control protocols:
  - Basic priority inheritance protocol
  - Basic priority ceiling protocol
  - Stack-based priority ceiling protocol
- Discussed impact on scheduling tests
- Implementation of resource access control in POSIX applications