Implementing Resource Access Control

Real-Time and Embedded Systems (M)

Lecture 14

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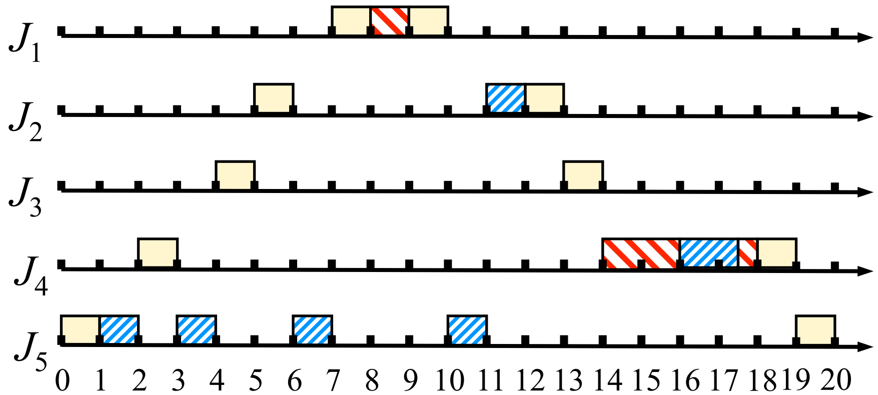
Lecture Outline

- Resources access control (cont’d):
  - Enhancing the priority ceiling protocol
    - Stack-based priority ceiling protocol
    - Ceiling priority protocol
  - Resource access control for dynamic priority systems
- Implementing resource access control
  - Locking primatives
    - Semaphores
    - Mutexes
    - Typical priority inheritance features
  - Messages, signals and events
    - Priority inheritance features for messaging

Enhancing the Priority Ceiling Protocol

- The basic priority ceiling protocol gives good performance, but the defining rules are complex

- Also, the protocol can result in high context switch overheads due to frequent blocking if many jobs contend for resources



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

Stack Based Priority Ceiling Protocol

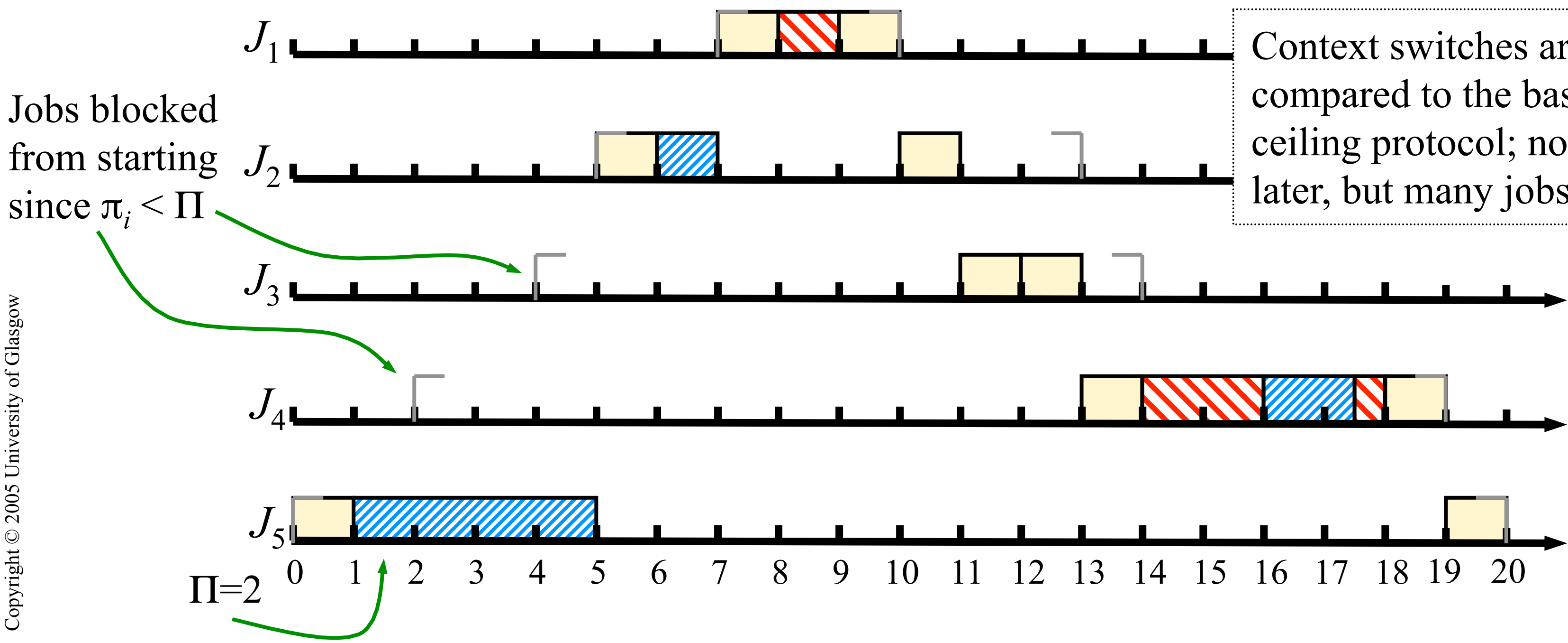
- Based on original work to allow jobs to share a run-time stack, extended to control access to other resources

- 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
    - Ω 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: Whenever a job requests a resource, it is allocated the resource
    - The allocation rule looks greedy, but the scheduling rule is not

Stack Based Priority-Ceiling Protocol

- Consider an example system, with parameters are shown on the right →
- Jobs J_1, J_2, J_4 and J_5 attempt to lock their first resource after one unit of execution; J4 accesses blue after an additional 2 units of execution

Job	r_i	e_i	π_i	Critical Sections
J_1	7	3	1	[Red; 1]
J_2	5	3	2	[Blue; 1]
J_3	4	2	3	
J_4	2	6	4	[Red; 4 [Blue; 1.5]]
J_5	0	6	5	[Blue; 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 can never occur
  - Longest blocking time provably not worse than the basic priority ceiling protocol

Ceiling Priority Protocol

- A similar algorithm is the *ceiling priority protocol*
- Defining rules:
  - Scheduling:
    - Every job executes at its assigned priority when it does not hold any resource. Jobs of the same priority are scheduled on a FIFO basis
    - The priority of each job holding resources is equal to the highest of the priority ceilings of all resources held by the job
  - Allocation: whenever a job requests a resource, it is allocated
- When jobs never self-yield, gives *identical* schedules to the stack-based priority ceiling protocol
- Again, simpler than the basic priority ceiling protocol

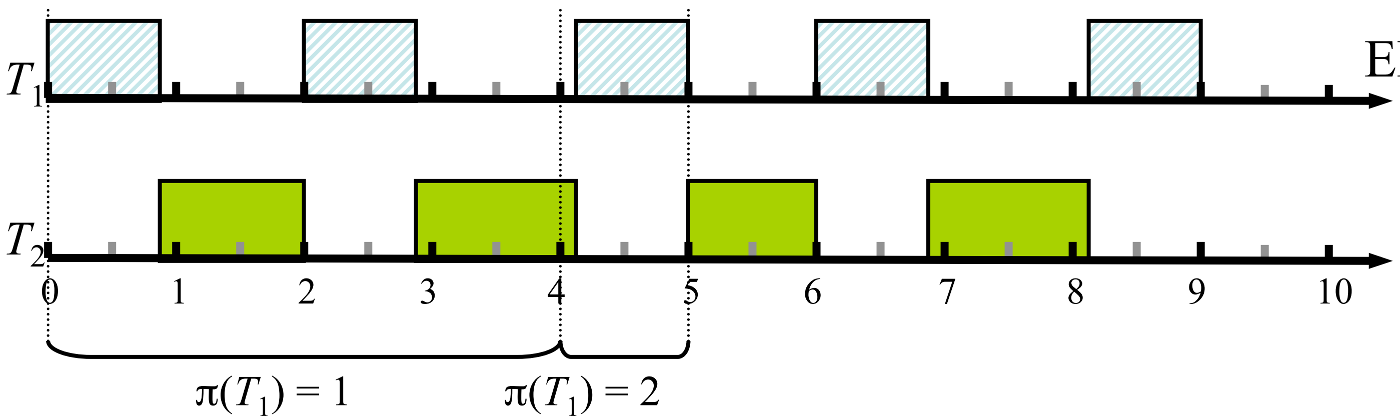
Choice of Priority Ceiling Protocol

- If tasks never self yield, the stack based priority ceiling protocol or the ceiling priority protocol is a better choice than the basic priority ceiling protocol
  - Simpler
  - Reduce number of context switches

- Stack based can be used to allow sharing of the run-time stack, to save memory resources
- The ceiling priority protocol is included in the real-time systems annex of Ada95

Resources in Dynamic Priority Systems

- The priority ceiling protocols assume fixed priority scheduling
- In a dynamic priority system, the priorities each 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:



EDF schedule:
$T_1 = (2, 0.9)$
$T_2 = (5, 2.3)$

  - T_1 uses resource X, but T_2 does not
  - Priority ceiling of X us 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
    - Example: Earliest Deadline Scheduling
  - Update the priority ceilings of all jobs each time a new job is introduced; use until updated on next job release

- Has been proven to work and have the same properties as priority ceiling protocol in fixed priority systems
  - But: very inefficient, since priority ceilings updated frequently

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

Resource Types and Locking

- Program objects and data structures
- Files
- Devices
- Network interfaces

Access arbitrated by the operating system

Need to be locked by applications to ensure exclusive access

Semaphores

Mutexes

Condition Variables

Message Queues

Provided by POSIX and/or by real-time operating systems

POSIX Semaphores

- Semaphores provide a simple locking abstraction:

```
int sem_init(sem_t *sem, int inter_process, unsigned init_val);
int sem_destroy(sem_t *sem);
int sem_wait(sem_t *sem);
int sem_trywait(sem_t *sem);
int sem_post(sem_t *sem);
```

- Embed a semaphore within an object for resource access control:

```
struct my_object {
     sem_t   lock;
     char   *data;  // For example…
     int     data_len;
}
struct my_object *m = malloc(sizeof(my_object));
sem_init(&m->lock, 1, 1);
```

- No special real-time features, priority control

POSIX Mutexes

- A higher level locking mechanism for real-time applications is a POSIX mutex, which controls priority during resource access
  - As with semaphores, a mutex is embedded in an object at a location of the programmers choosing to control access to that object/resource

```
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 Mutexes: Priority Inheritance

- A useful feature of POSIX threads is the ability to specify a 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:
    - **`pthread_mutexattr_getprioceiling(…)`**
    - **`pthread_mutexattr_setprioceiling(…)`**

- Useful in conjunction with real-time scheduling extensions
  - Allow implementation of fixed priority scheduling with a resource access control protocol
  - Controls priority inversion, scheduling; allows reasoning about a system

POSIX Condition Variables

```
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)

Messages, Signals and Events

- In addition to controlling access to resources, tasks often need to communicate information to other tasks
- Can be implemented using a shared data structure – a resource – that is managed as described previously
  - Example: a queue protected by a mutex and condition variable
  - Requires synchronisation between tasks
- May wish to communicate with another task without an explicit synchronisation step
  - Send another task a message
  - Signal another task that an event has occurred

POSIX Message Queues

- A message queue abstraction provided for this purpose:

```
mpd_t mq_open(char *mqname, int flags, mode_t mode,
                   struct mq_attr attrs);
int   mq_close(mpd_t mq);
int   mq_unlink(char *mqname);


int   mq_send(mpd_t mq, char *msg, size_t len, unsigned prio);
int   mq_receive(mqd_t mq, char *msg, size_t len, unsigned *prio);

int  mq_setattr(pqd_t mq, struct mq_attr *newattr,
                          struct mq_attr *oldattr);
int  mq_getattr(mpd_t mq, struct mq_attr *attrbuf);
```

POSIX Message Queues

- Message queues are usually blocking:
  - **`mq_send()`** will block until there is space in the queue to send a message
  - **`mq_receive()`** will delay the caller until there is a message
- Can be set to non-blocking, if desired
- A receiver can register to receive a signal when a queue has data to receiver, rather than blocking

- Messages have priority, inserted in the queue in priority order
- Messages with equal priority are delivered in FIFO order

Message Based Priority Inheritance

- Messages not read until receiving thread executes **`mq_receive()`**
- Problem:
  - Sending a high priority message to a low priority thread
  - The thread will not be scheduled to receive the message

- Solution: message based priority inheritance
  - Assume message priorities map to task priorities
  - When a task is sent a message, it provides a one-shot work thread to process that message, which inherits the priority of the message
  - Allows message processing to be scheduled as any other job
  - Implemented by some RTOS (e.g. QNX); not common
    - Typically simulate using a queue with a priority inheriting mutex

Signalling Events

- Need a way of signalling a task that an event has occurred
  - Completion of asynchronous I/O request
  - Expiration of a timer
  - Receipt of a message
  - Etc.

- Many different approaches:
  - Unix signals
    - Event number *N* has occurred; no parameters; unreliable (non-queued)
  - POSIX signals
    - Allow data to be piggybacked onto the signal (a **`void *`** pointer)
    - Signals are queued, and not lost if a second signal arrives while the first is being processed
    - Signals are prioritised
  - Windows asynchronous procedure call and event loop

Signalling Events

- Signals are delivered asynchronously at high priority
  - As a result of a timer event
  - As a result of a kernel operation completing
  - As a result of action by another process
- High overhead: require a kernel trap, context switch, etc
- Add unpredictable delay
  - Executing process is delayed when a signal occurs, by the time taken to switch to the signal handler of the signalled task, run the signal handler, and switch back to the original task

- May be better to use synchronous communication where possible in real time systems, since easier to predict

Implementing Resource Access Control

- 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
  - E.g The Ada language supports resource access control with the priority ceiling protocol
  - E.g. QNX support message based priority inheritance

Summary

- Illustrated operation of additional resource access control protocols, simplifying priority ceiling protocol
- Described some practical methods used to implement resource access control:
  - Use of POSIX real-time extensions and mutexes for locking, to directly implement the ideas described
  - Other mechanisms: semaphores, message queues, signals, etc.