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Lecture 4: Deadlock nd Priority Inversion

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The Deadlock Lecture

Reminder from last time

- Multi-Reader Single-Writer (MRSW) locks
- Alternatives to semaphores/locks:
  - Conditional critical regions (CCRs)
  - Monitors
  - Condition variables
  - Signal-and-wait vs. signal-and-continue semantics
- Concurrency primitives in practice
- Concurrency primitives wrap-up

From last time: primitives summary

- Concurrent systems require means to ensure:
  - Safety (mutual exclusion in critical sections), and
  - Progress (condition synchronization)
- Spinlocks (busy wait); semaphores; CCRs and monitors
  - Hardware primitives for synchronisation
  - Signal-and-Wait vs. Signal-and-Continue
- Many of these are still used in practice
  - Subtle minor differences can be dangerous
  - Require care to avoid bugs – e.g., “lost wakeups”
- More detail on implementation in our case study

Progress is particularly difficult, in large part because of primitives themselves, which is the topic of this lecture

This time

- Liveness properties
- Deadlock
  - Requirements
  - Resource allocation graphs and detection
  - Prevention – the Dining Philosophers Problem – and recovery
- Thread priority and the scheduling problem
- Priority inversion
- Priority inheritance

Liveness properties

- From a theoretical viewpoint must ensure that we eventually make progress, i.e. want to avoid
  - Deadlock (threads sleep waiting for one another), and
  - Livelock (threads execute but make no progress)
- Practically speaking, also want good performance
  - No starvation (single thread must make progress)
  - (more generally may aim for fairness)
  - Minimality (no unnecessary waiting or signaling)
- The properties are often at odds with safety :-(

Deadlock

- Set of k threads go asleep and cannot wake up
  - each can only be woken by another who's asleep!
- Real-life example (Kansas, 1920s):

  "When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone."
- In concurrent programs, tends to involve the taking of mutual exclusion locks, e.g.:

```
// thread 1
lock(X);
 ...
 lock(Y);
 // critical section
 unlock(Y);
```

```
// thread 2
lock(Y);
 ...
 if(<cond>) {
   lock(X);
   ...
```

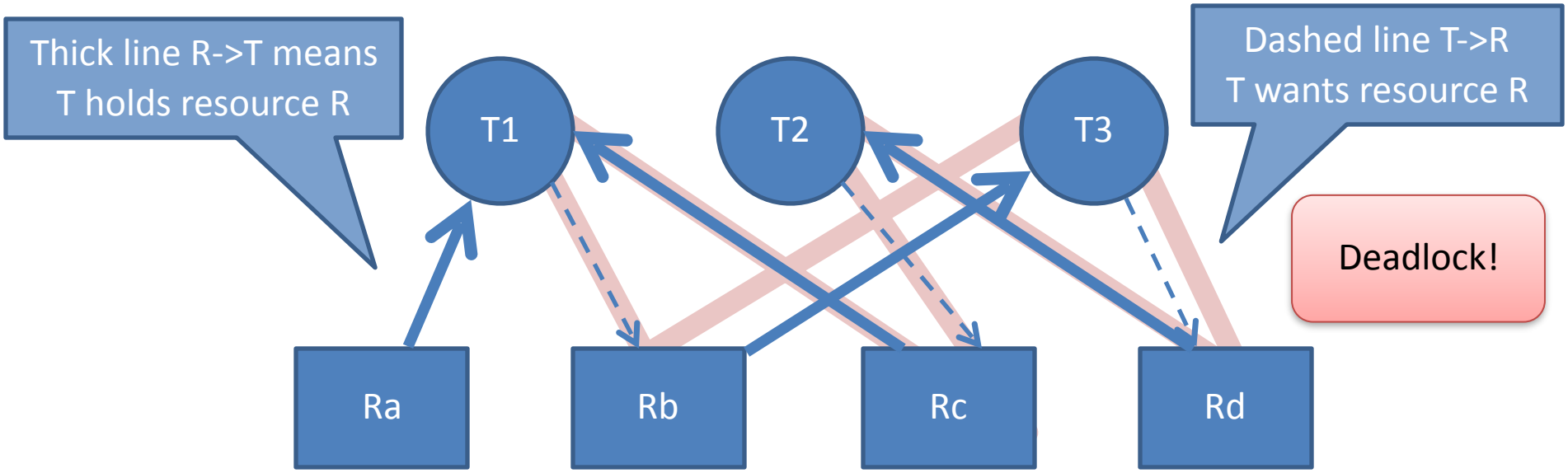
Risk of deadlock if both threads get here simultaneously

Requirements for deadlock

- Like all concurrency bugs, deadlock may be rare (e.g. imagine <cond> is mostly false)
- In practice there are four necessary conditions
  1. Mutual Exclusion: resources have bounded #owners
  2. Hold-and-Wait: can acquire Rx and wait for Ry
  3. No Preemption: keep Rx until you release it
  4. Circular Wait: cyclic dependency
- Require all four to be true to get deadlock
  - But most modern systems always satisfy 1, 2, 3
- Tempting to think that his applies only to locks …
  - But it also can occur for many other resource classes whose allocation meets conditions: memory, CPU time, …

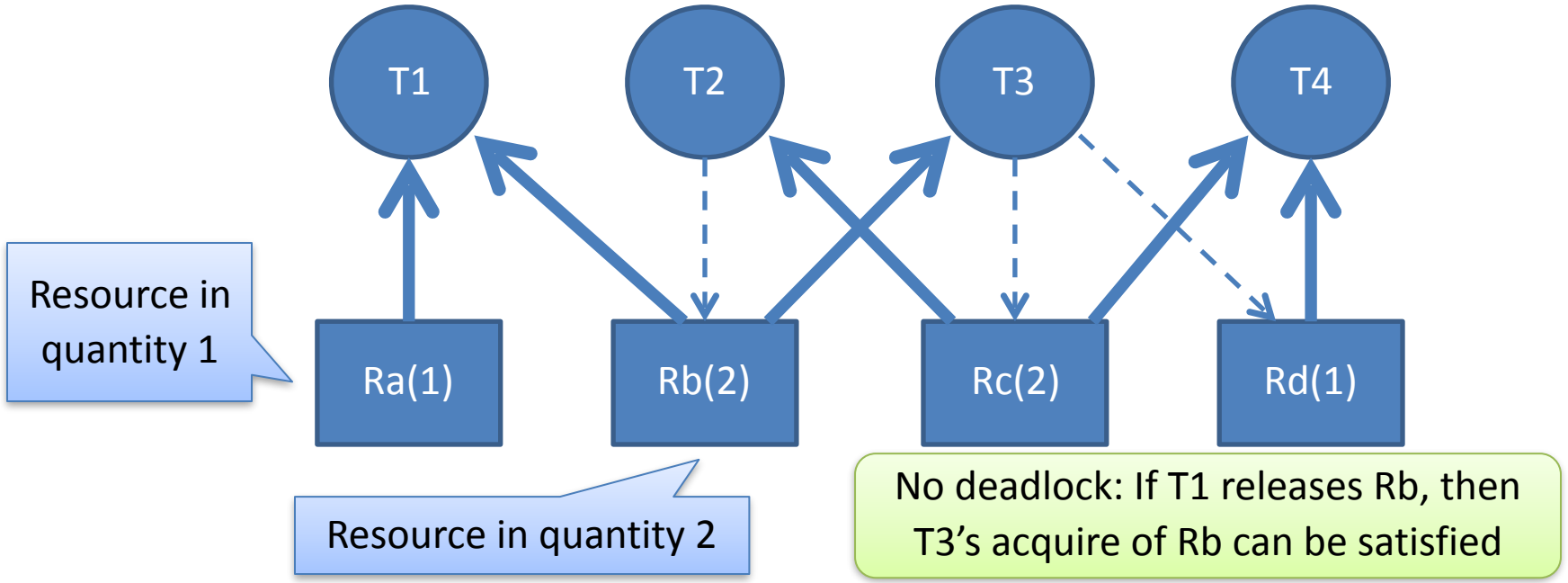
Resource allocation graphs

- Graphical way of thinking about deadlock
  - Circles are threads (or processes)
  - Boxes are single-owner resources (e.g. mutexes)
  - Edges show lock hold and wait conditions
  - A cycle means we (will) have deadlock



Resource allocation graphs

- Can generalize to resources which can have K distinct users (c/f semaphores)
- Absence of a cycle means no deadlock…
  - but presence only means may have deadlock, e.g.



Dealing with deadlock

1. Ensure it never happens
   - Deadlock prevention
   - Deadlock avoidance (Banker's Algorithm)
2. Let it happen, but recover
   - Deadlock detection & recovery
3. Ignore it!
   - The so-called "Ostrich Algorithm" ;-)
   - "Have you tried turning it off and back on again?"
   - Very widely used in practice!

Deadlock prevention

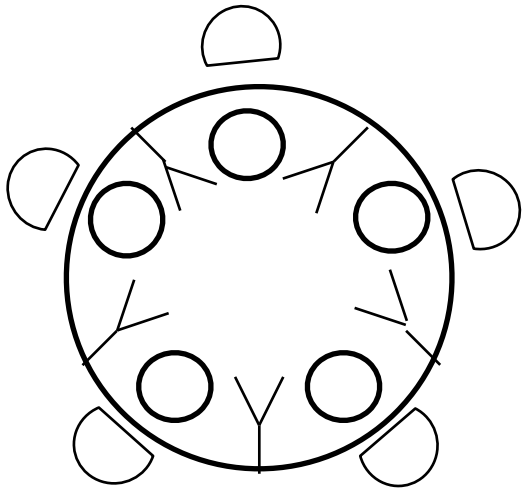
1. Mutual Exclusion: resources have bounded #owners
   - Could always allow access… but probably unsafe ;-(
   - However can help e.g. by using MRSW locks
2. Hold-and-Wait: can get Rx and wait for Ry
   - Require that we request all resources simultaneously; deny the request if any resource is not available now
   - But must know maximal resource set in advance = hard?
3. No Preemption: keep Rx until you release it
   - Stealing a resource generally unsafe (but see later)
4. Circular Wait: cyclic dependency
   - Impose a partial order on resource acquisition
   - Can work: but requires programmer discipline
   - Lock order enforcement rules used in many systems e.g., FreeBSD WITNESS – static and dynamic orders checked

Example: Dining Philosophers

- 5 philosophers, 5 forks, round table…

```
Semaphore forks[] = new Semaphore[5];
```

```
while(true) {          // philosopher i
    think();
    wait(fork[i]);
    wait(fork[(i+1) % 5];
    eat();
    signal(fork[i]);
    signal(fork[(i+1) % 5];
}
```



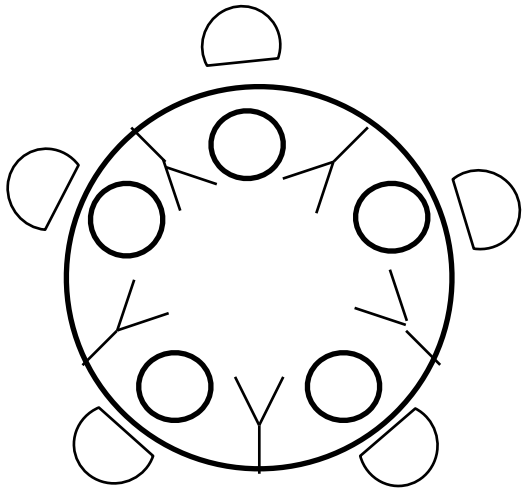
- Possible for everyone to acquire ‘left’ fork
  - Q: what happens if we swap order of signal()s?

Example: Dining Philosophers

- (one) Solution: always take lower fork first

```
Semaphore forks[] = new Semaphore[5];
```

```
while(true) {          // philosopher i
   think();
   first = MIN(i, (i+1) % 5);
   second = MAX(i, (i+1) % 5);
   wait(fork[first]);
   wait(fork[second];
   eat();
   signal(fork[second]);
   signal(fork[first]);
}
```



- Now even if 0, 1, 2, 3 are held, 4 will not acquire final fork

Deadlock avoidance

- Prevention aims for deadlock-free "by design"
- Deadlock avoidance is a dynamic scheme:
  - Assumption: We know maximum possible resource allocation for every process / thread
  - Assumption: A process granted all desired resources will complete, terminate, and free its resources
  - Track actual allocations in real-time
  - When a request is made, only grant if guaranteed no deadlock even if all others take max resources
- E.g. Banker's Algorithm – see textbooks
  - Not really useful in general as need a priori knowledge of #processes/threads, and their max resource needs

Deadlock detection

- Deadlock detection is a dynamic scheme that determines if deadlock exists
  - Principle: At a some moment in execution, examine resource allocations and graph
  - Determine if there is at least one plausible sequence of events in which all threads could make progress
  - I.e., check that we are not in an unsafe state in which no further sequences can complete without deadlock
- When only a single instance of each resource, can explicitly check for a cycle:
  - Keep track which object each thread is waiting for
  - From time to time, iterate over all threads and build the resource allocation graph
  - Run a cycle detection algorithm on graph $O(n^2)$
- More difficult if have multi-instance resources

Deadlock detection

- Have m distinct resources and n threads
- V[0:m-1], vector of currently available resources
- A, the m x n resource allocation matrix, and
  R, the m x n (outstanding) request matrix
  - $A_{i,j}$ is the number of objects of type j owned by i
  - $R_{i,j}$ is the number of objects of type j needed by i
- Proceed by successively marking rows in A for threads that are not part of a deadlocked set
  - If we cannot mark all rows of A we have deadlock

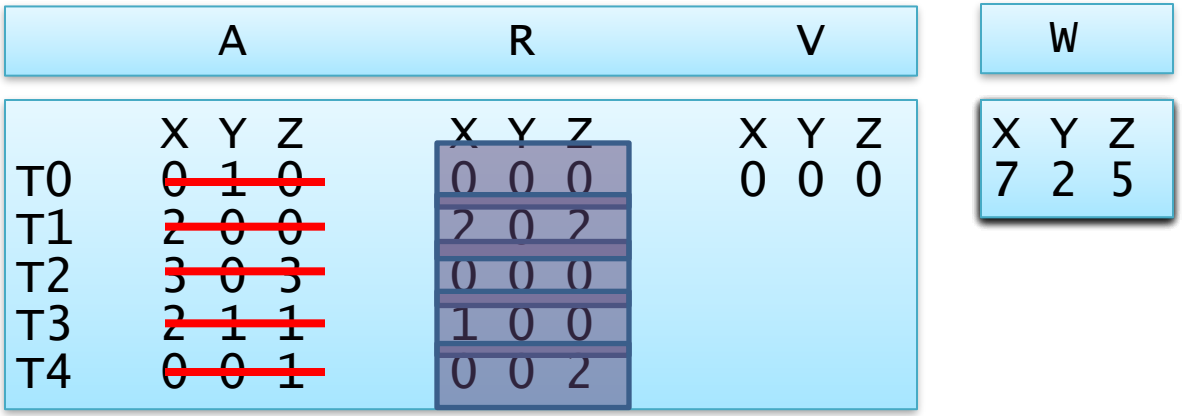
Optimistic assumption: if we can fulfill thread i's request R_i, then it will run to completion and release held resources for other threads to allocate.

Deadlock detection algorithm

- Mark all zero rows of A (since a thread holding zero resources can't be part of deadlock set)
- Initialize a working vector W[0:m-1] to V
  - W[] describes any free resources at start, plus any resources released by a hypothesized sequence of satisfied threads freeing and terminating
- Select an unmarked row i of A s.t. R[i] <= W
  - (i.e. find a thread who's request can be satisfied)
  - Set W = W + A[i]; mark row i, and repeat
- Terminate when no such row can be found
  - Unmarked rows (if any) are in the deadlock set

Deadlock detection example 1

- Five threads and three resources (none free)

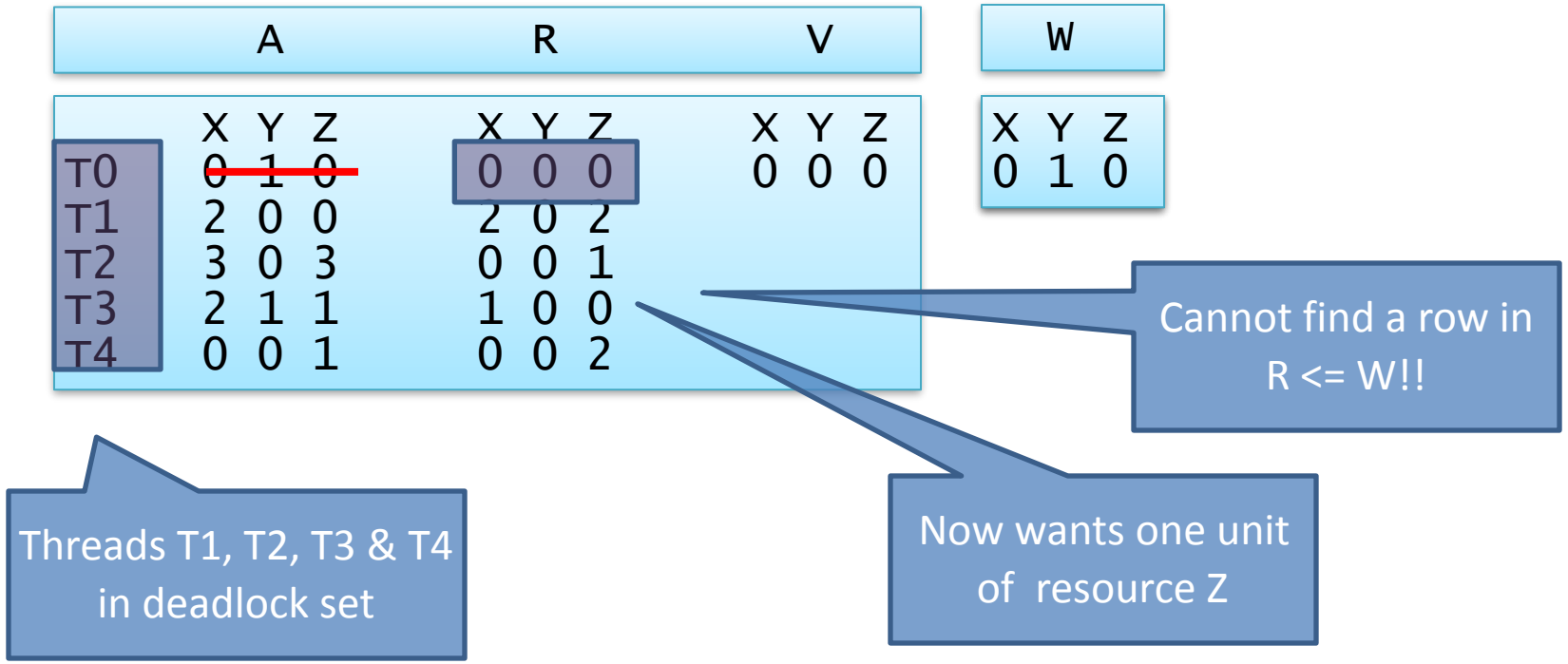


- Find an unmarked row, mark it, and update W
  - T0, T2, T3, T4, T1

At the end of the algorithm, all rows are marked: the deadlock set is empty.

Deadlock detection example 2

- Five threads and three resources (none free)



- One minor tweak to T2's request vector…

Deadlock recovery

- What can we do when we detect deadlock?
- Simplest solution: kill something!
  - Ideally someone in the deadlock set ;-)
- Brutal, and not guaranteed to work
  - But sometimes the best (only) we can do
  - E.g. Linux OOM killer (better than system reboot?)
  - … Or not – often kills the X server!
- Could also resume from checkpoint
  - Assuming we have one
- In practice computer systems seldom detect or recover from deadlock: rely on programmer

Note: “kill someone” breaks the no preemption precondition for deadlock.

Livelock

- Deadlock is at least ‘easy’ to detect by humans
  - System basically blocks & stops making any progress
- Livelock is less easy to detect as threads continue to run… but do nothing useful
- Often occurs from trying to be clever, e.g.:

```
// thread 1
lock(X);
 ...
 while (!trylock(Y)) {
   unlock(X);
   yield();
   lock(X);
 }
 ...
```

```
// thread 2
lock(Y);
 ...
 while(!trylock(X)) {
   unlock(Y);
   yield();
   lock(Y);
 }
 ...
```

Livelock if both threads get here simultaneously

Scheduling and thread priorities

- Which thread should run when >1 runnable? E.g., if:
  - A thread releases a contended lock and continues to run
  - CV broadcast wakes up several waiting threads
- Many possible scheduling policies; e.g.,
  - Round robin – rotate between threads to ensure progress
  - Fixed priorities – assign priorities to threads, schedule highest– e.g., real-time > interactive > bulk > idle-time
  - Dynamic priorities – adjust priorities to balance goals – e.g., boost priority after I/O to improve interactivity
  - Gang scheduling – schedule for patterns such as P-C
  - Affinity – schedule for efficient resource use (e.g., caches)
- Goals: latency vs. throughput, energy, "fairness", …
  - NB: These competing goals cannot generally all be satisfied

Priority inversion

- Another liveness problem…
  - Due to interaction between locking and scheduler
- Consider three threads: T1, T2, T3
  - T1 is high priority, T2 medium priority, T3 is low
  - T3 gets lucky and acquires lock L…
  - … T1 preempts T3 and sleeps waiting for L…
  - … then T2 runs, preventing T3 from releasing L!
  - Priority inversion: despite having higher priority and no shared lock, T1 waits for lower priority thread T2
- This is not deadlock or livelock
  - But not desirable (particularly in real-time systems)!
  - Disabled Mars Pathfinder robot for several months

Priority inheritance

- Typical solution is priority inheritance:
  - Temporarily boost priority of lock holder to that of the highest waiting thread
  - T3 would have run with T1's priority while holding a lock T1 was waiting for – preventing T2 from preempting T3
  - Concrete benefits to system interactivity
  - (some RT systems (like VxWorks) allow you specify on a per-mutex basis [to Rover's detriment ;-])
- Windows "solution"
  - Check if any ready thread hasn't run for 300 ticks
  - If so, double its quantum and boost its priority to 15
  - ☺

Problems with priority inheritance

- Hard to reason about resulting behaviour: heuristic
- Works for locks
  - More complex than it appears: propagation might need to be propagated across chains containing multiple locks
  - How might we handle reader-writer locks?
- How about condition synchronisation, res. allocation?
  - With locks, we know what thread holds the lock
  - Semaphores do not record which thread might issue a signal or release an allocated resource
  - Must compose across multiple waiting types: e.g., “waiting for a signal while holding a lock”
- Where possible, avoid the need for priority inheritance
  - Avoid sharing between threads of differing priorities

Summary + next time

- Liveness properties
- Deadlock
  - Requirements
  - Resource allocation graphs and detection
  - Prevention – the Dining Philosophers Problem – and recovery
- Thread priority and the scheduling problem
- Priority inversion
- Priority inheritance

- Next time:
  - Concurrency without shared data
  - Active objects; message passing
  - Composite operations; transactions
  - ACID properties; isolation; serialisability