Multi-Object Synchronization

Multi-Object Programs

- What happens when we try to synchronize across multiple objects in a large program?
  - Each object with its own lock, condition variables
  - Is locking modular?
- Performance
- Semantics/correctness
- Deadlock
- Eliminating locks

Synchronization Performance

- A program with lots of concurrent threads can still have poor performance on a multiprocessor:
  - Overhead of creating threads, if not needed
  - Lock contention: only one thread at a time can hold a given lock
  - Shared data protected by a lock may ping back and forth between cores
  - False sharing: communication between cores even for data that is not shared

Topics

- Multiprocessor cache coherence
- MCS locks (if locks are mostly busy)
- RCU locks (if locks are mostly busy, and data is mostly read-only)

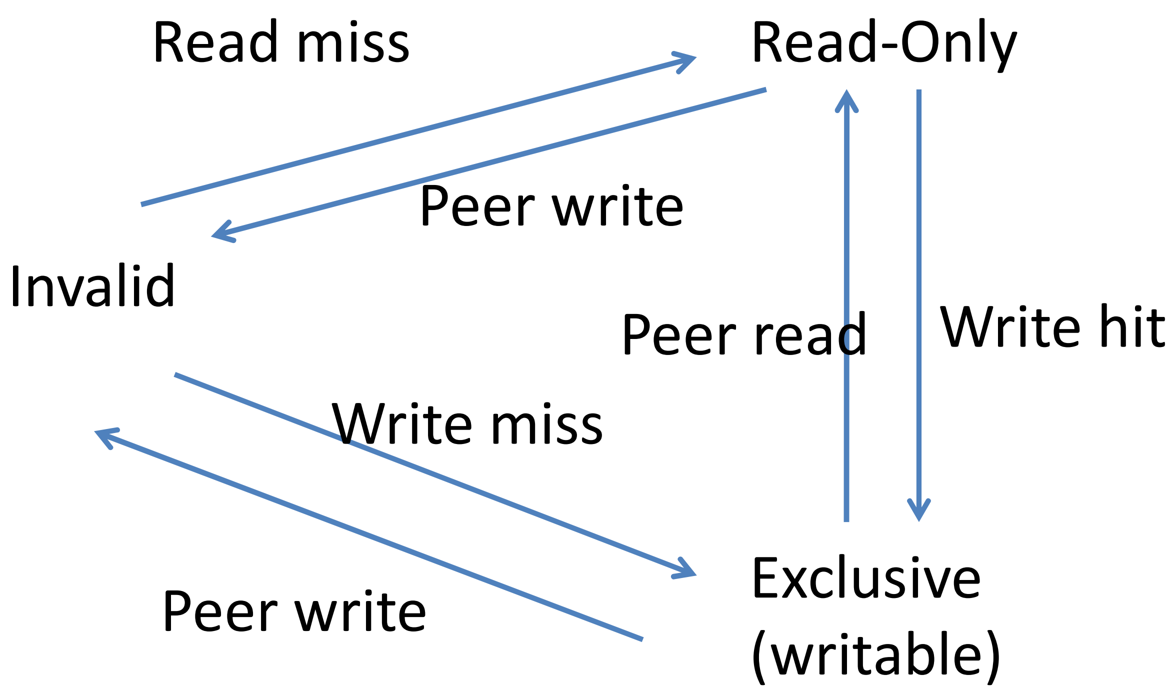
Multiprocessor Cache Coherence

- Scenario:
  - Thread A modifies data inside a critical section and releases lock
  - Thread B acquires lock and reads data
- Easy if all accesses go to main memory
  - Thread A changes main memory; thread B reads it
- What if new data is cached at processor A?
- What if old data is cached at processor B

Write Back Cache Coherence

- Cache coherence = system behaves as if there is one copy of the data
  - If data is only being read, any number of caches can have a copy
  - If data is being modified, at most one cached copy
- On write: (get ownership)
  - Invalidate all cached copies, before doing write
  - Modified data stays in cache ("write back")
- On read:
  - Fetch value from owner or from memory

Cache State Machine



Directory-Based Cache Coherence

- How do we know which cores have a location cached?
  - Hardware keeps track of all cached copies
  - On a read miss, if held exclusive, fetch latest copy and invalidate that copy
  - On a write miss, invalidate all copies
- Read-modify-write instructions
  - Fetch cache entry exclusive, prevent any other cache from reading the data until instruction completes

A Simple Critical Section

```
// A counter protected by a spinlock
Counter::Increment() {
    while (test_and_set(&lock))
        ;
    value++;
    lock = FREE;
    memory_barrier();
}
```

A Simple Test of Cache Behavior

Array of 1K counters, each protected by a separate spinlock

- Array small enough to fit in cache

- Test 1: one thread loops over array
- Test 2: two threads loop over different arrays
- Test 3: two threads loop over single array
- Test 4: two threads loop over alternate elements in single array

Results (64 core AMD Opteron)

One thread, one array	51 cycles
Two threads, two arrays	52
Two threads, one array	197
Two threads, odd/even	127

Reducing Lock Contention

- Fine-grained locking
  - Partition object into subsets, each protected by its own lock
  - Example: hash table buckets
- Per-processor data structures
  - Partition object so that most/all accesses are made by one processor
  - Example: per-processor heap
- Ownership/Staged architecture
  - Only one thread at a time accesses shared data
  - Example: pipeline of threads

What If Locks are Still Mostly Busy?

- MCS Locks
  - Optimize lock implementation for when lock is contended
- RCU (read-copy-update)
  - Efficient readers/writers lock used in Linux kernel
  - Readers proceed without first acquiring lock
  - Writer ensures that readers are done
- Both rely on atomic read-modify-write instructions

The Problem with Test and Set

```
Counter::Increment() {
    while (test_and_set(&lock))
        ;
    value++;
    lock = FREE;
    memory_barrier();
}
```

What happens if many processors try to acquire the lock at the same time?

- Hardware doesn't prioritize FREE

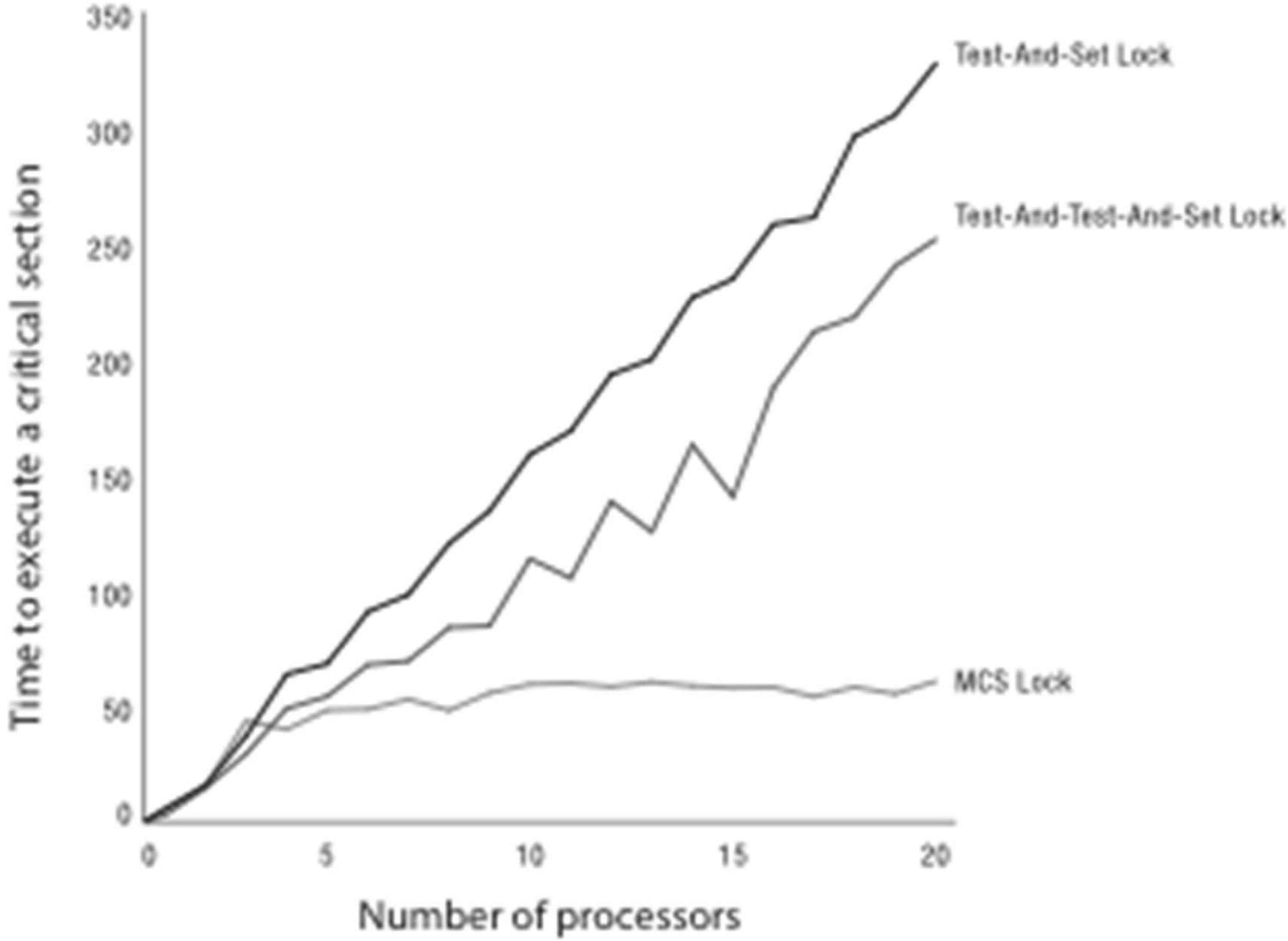
The Problem with Test and Test and Set

```
Counter::Increment() {
   while (lock == BUSY && test_and_set(&lock))
      ;
   value++;
   lock = FREE;
   memory_barrier();
}
```

What happens if many processors try to acquire the lock?

- Lock value pings between caches

Test (and Test) and Set Performance



Some Approaches

- Insert a delay in the spin loop
  - Helps but acquire is slow when not much contention
- Spin adaptively
  - No delay if few waiting
  - Longer delay if many waiting
  - Guess number of waiters by how long you wait
- MCS
  - Create a linked list of waiters using compareAndSwap
  - Spin on a per-processor location

Atomic CompareAndSwap

- Operates on a memory word
- Check that the value of the memory word hasn't changed from what you expect
  - E.g., no other thread did compareAndSwap first
- If it has changed, return an error (and loop)
- If it has not changed, set the memory word to a new value

MCS Lock

- Maintain a list of threads waiting for the lock
  - Front of list holds the lock
  - MCSLock::tail is last thread in list
  - New thread uses CompareAndSwap to add to the tail
- Lock is passed by setting next->needToWait = FALSE;
  - Next thread spins while its needToWait is TRUE

```
TCB {
    TCB *next;            // next in line
    bool needToWait;
}
MCSLock {
    Queue *tail = NULL; // end of line
}
```

MCS Lock Implementation

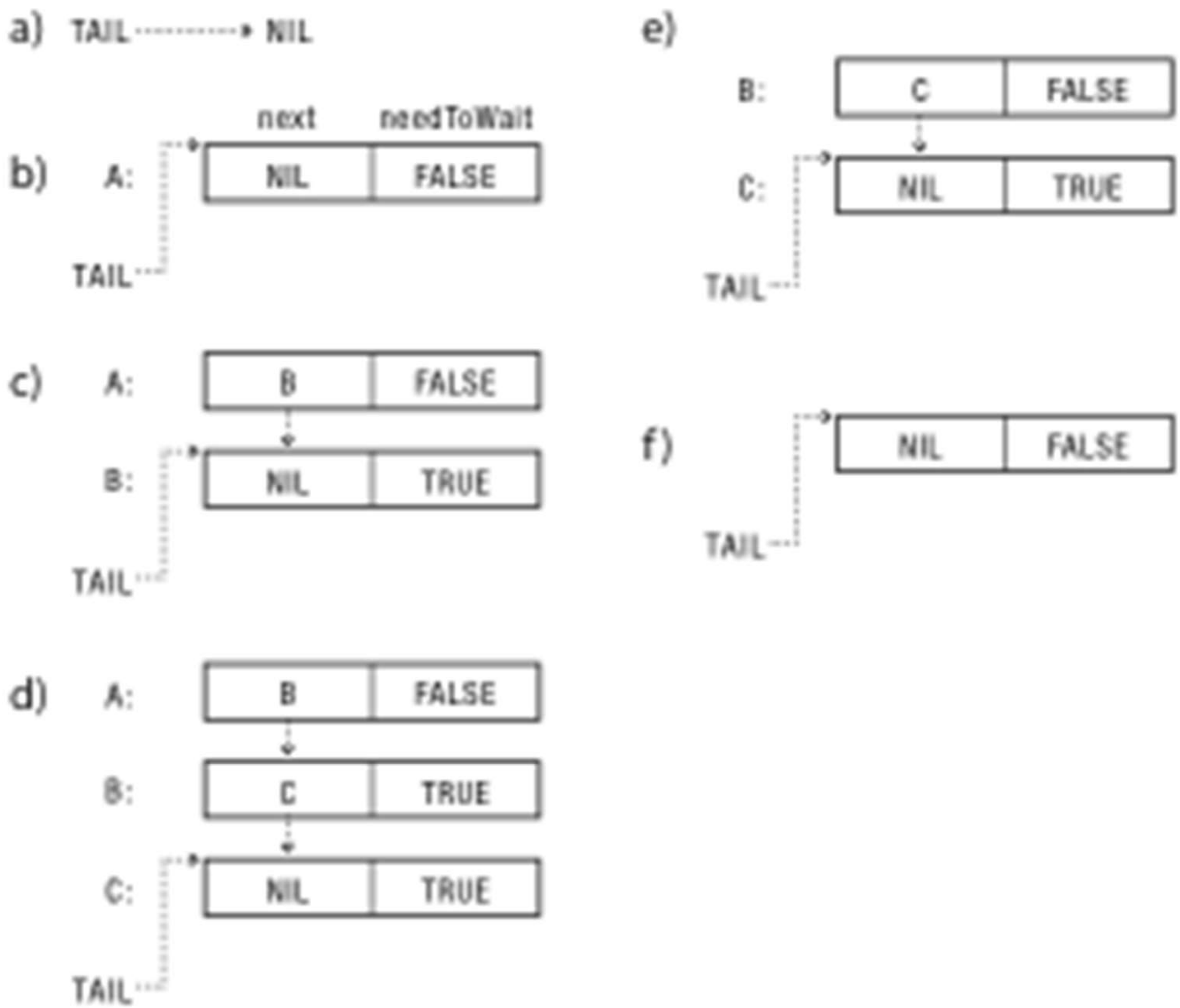
```
MCSLock::acquire() {
   Queue ∗oldTail = tail;

   myTCB−>next = NULL;
   myTCB−>needToWait = TRUE;
   while (!compareAndSwap(&tail,
                oldTail, &myTCB)) {
       oldTail = tail;
   }
   if (oldTail != NULL) {
      oldTail−>next = myTCB;
      memory_barrier();
      while (myTCB−>needToWait)
          ;
   }
}
```

```
MCSLock::release() {
   if (!compareAndSwap(&tail,
                myTCB, NULL)) {
      while (myTCB−>next == NULL)
          ;

     myTCB−>next−>needToWait=FALS
     E;
   }
}
```

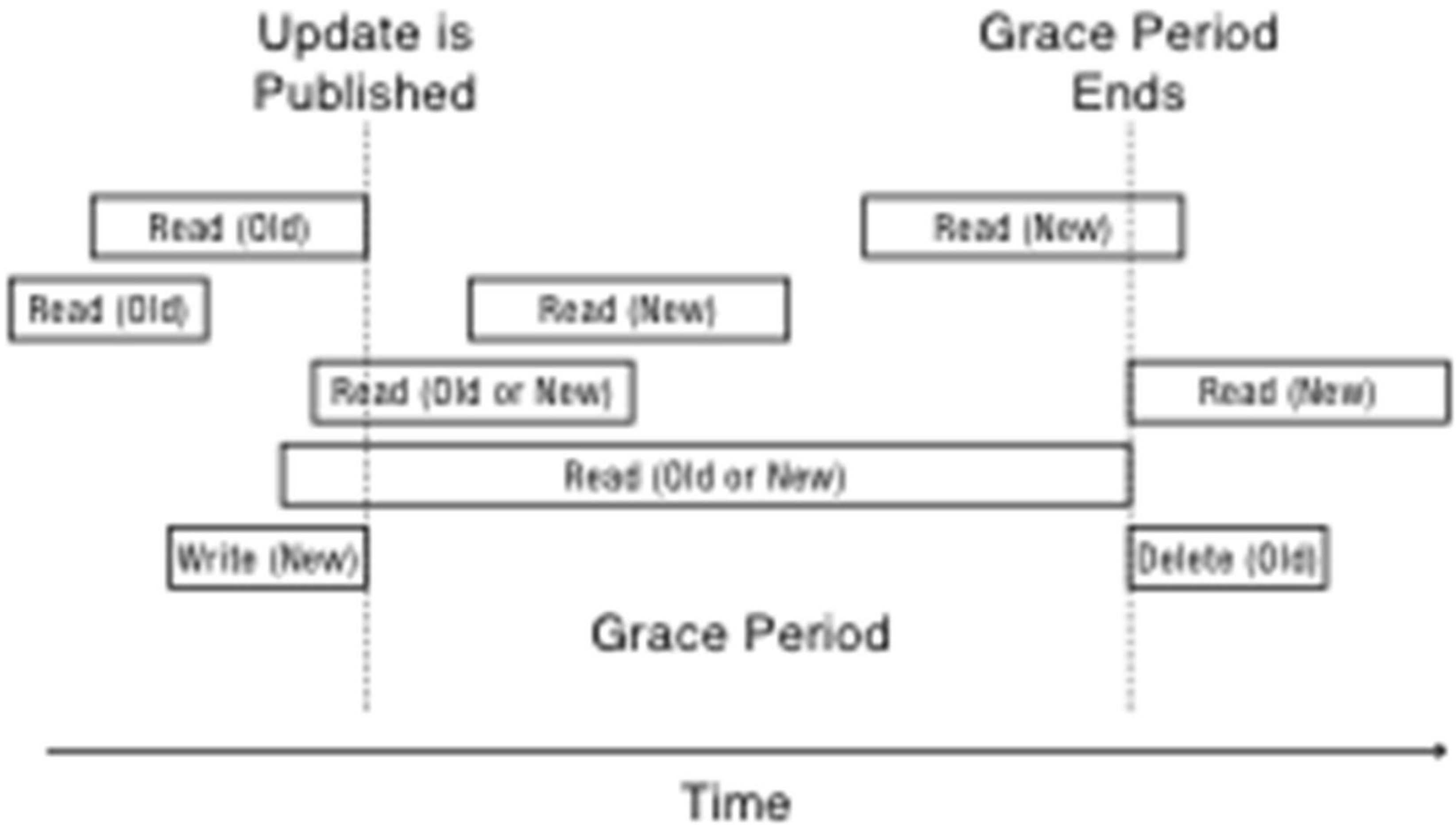
MCS In Operation



Read-Copy-Update

- Goal: very fast reads to shared data
  - Reads proceed without first acquiring a lock
  - OK if write is (very) slow
- Restricted update
  - Writer computes new version of data structure
  - Publishes new version with a single atomic instruction
- Multiple concurrent versions
  - Readers may see old or new version
- Integration with thread scheduler
  - Guarantee all readers complete within grace period, and then garbage collect old version

Read-Copy-Update



Read-Copy-Update Implementation

- Readers disable interrupts on entry
  - Guarantees they complete critical section in a timely fashion
  - No read or write lock
- Writer
  - Acquire write lock
  - Compute new data structure
  - Publish new version with atomic instruction
  - Release write lock
  - Wait for time slice on each CPU
  - Only then, garbage collect old version of data structure

Deadlock Definition

- Resource: any (passive) thing needed by a thread to do its job (CPU, disk space, memory, lock)
  - Preemptable: can be taken away by OS
  - Non-preemptable: must leave with thread
- Starvation: thread waits indefinitely
- Deadlock: circular waiting for resources
  - Deadlock => starvation, but not vice versa

Example: two locks

Thread A	Thread B
lock1.acquire();	lock2.acquire();
lock2.acquire();	lock1.acquire();
lock2.release();	lock1.release();
lock1.release();	lock2.release();

Bidirectional Bounded Buffer

Thread A	Thread B
buffer1.put(data);	buffer2.put(data);
buffer1.put(data);	buffer2.put(data);
buffer2.get();	buffer1.get();
buffer2.get();	buffer1.get();

Suppose buffer1 and buffer2 both start almost full.

Two locks and a condition variable

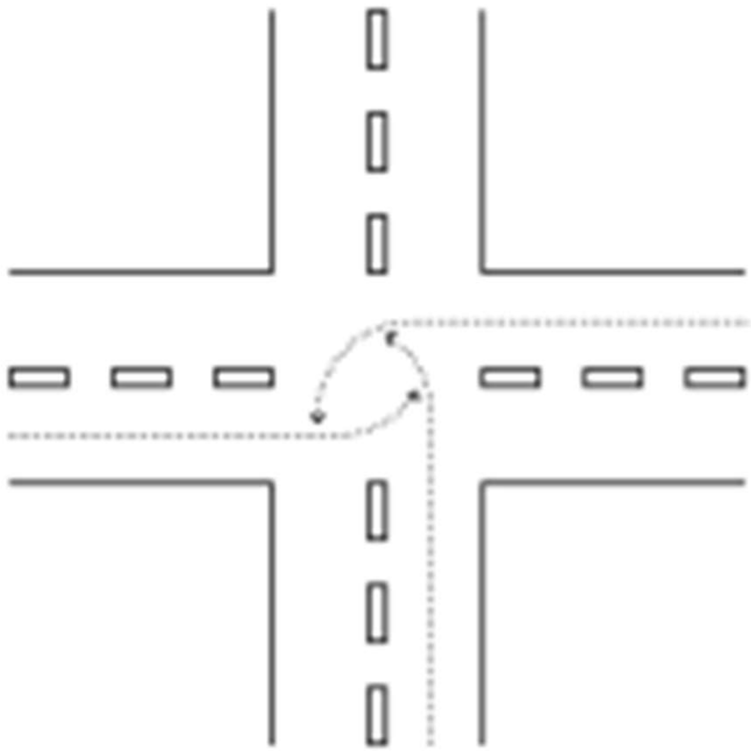
Thread A

```
lock1.acquire();
…
lock2.acquire();
while (need to wait) {
    condition.wait(lock2);
}
lock2.release();
…
lock1.release();
```

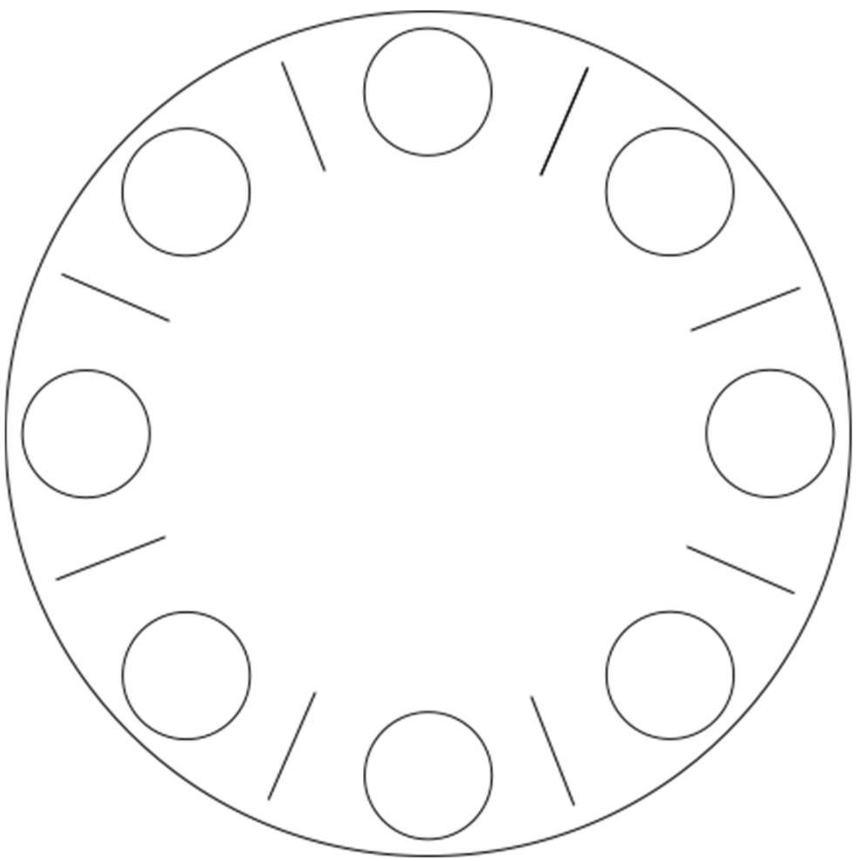
Thread B

```
lock1.acquire();
…
lock2.acquire();
…
condition.signal(lock2);
…
lock2.release();
…
lock1.release();
```

Yet another Example



Dining Lawyers



Each lawyer needs two chopsticks to eat.
Each grabs chopstick on the right first.

Necessary Conditions for Deadlock

- Limited access to resources
  - If infinite resources, no deadlock!
- No preemption
  - If resources are virtual, can break deadlock
- Multiple independent requests
  - “wait while holding”
- Circular chain of requests

Question

- How does Dining Lawyers meet the necessary conditions for deadlock?
  - Limited access to resources
  - No preemption
  - Multiple independent requests (wait while holding)
  - Circular chain of requests

- How can we modify Dining Lawyers to prevent deadlock?

Preventing Deadlock

- Exploit or limit program behavior
  - Limit program from doing anything that might lead to deadlock
- Predict the future
  - If we know what program will do, we can tell if granting a resource might lead to deadlock
- Detect and recover
  - If we can rollback a thread, we can fix a deadlock once it occurs

Exploit or Limit Behavior

- Provide enough resources
  - How many chopsticks are enough?
- Eliminate wait while holding
  - Release lock when calling out of module
  - Telephone circuit setup
- Eliminate circular waiting
  - Lock ordering: always acquire locks in a fixed order
  - Example: move file from one directory to another

Example

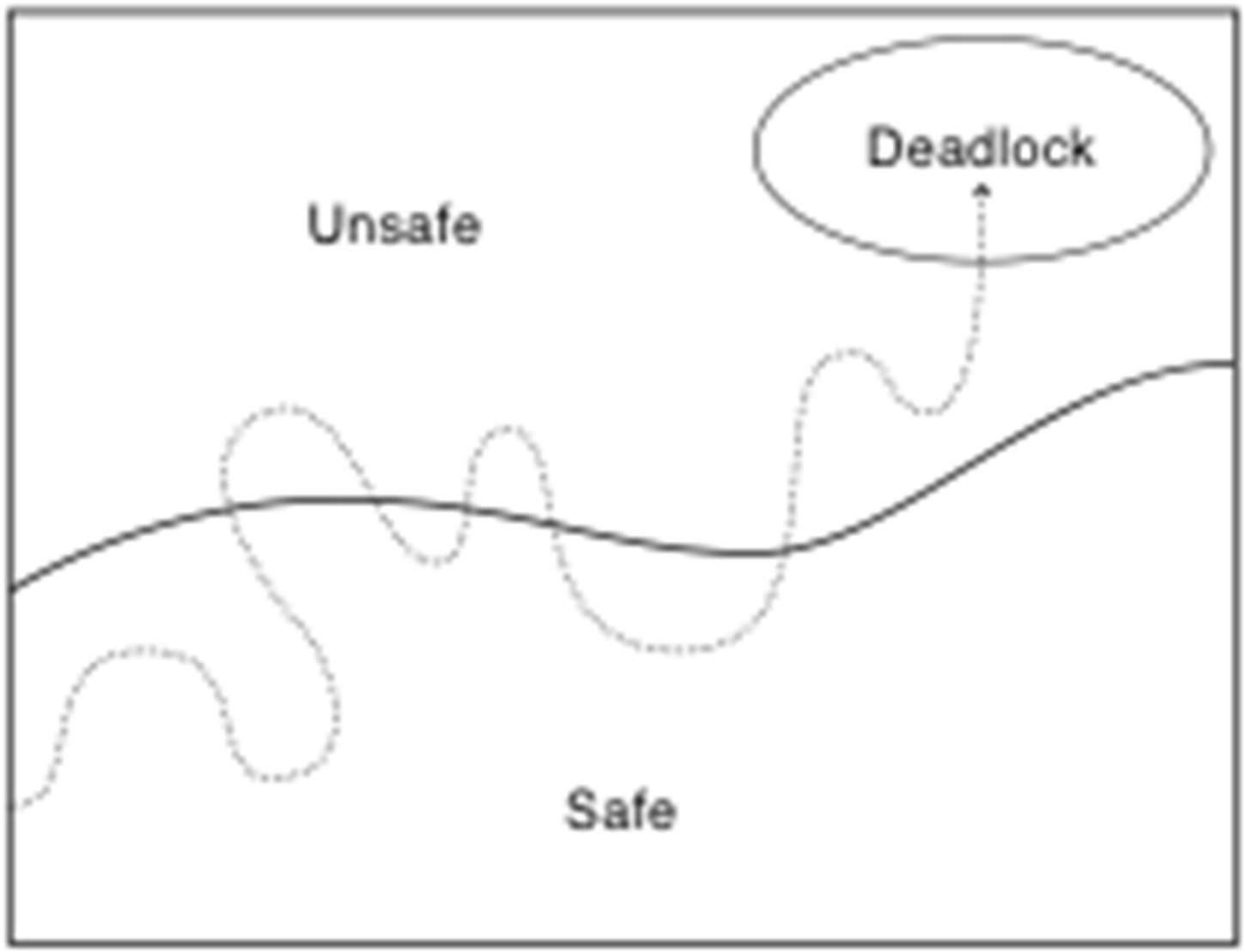
Thread 1	Thread 2
1. Acquire A	1.
2.	2. Acquire B
3. Acquire C	3.
4.	4. Wait for A
5. If (maybe) Wait for B	

How can we make sure to avoid deadlock?

Deadlock Dynamics

- Safe state:
  - For any possible sequence of future resource requests, it is possible to eventually grant all requests
  - May require waiting even when resources are available!
- Unsafe state:
  - Some sequence of resource requests can result in deadlock
- Doomed state:
  - All possible computations lead to deadlock

Possible System States



Question

- What are the doomed states for Dining Lawyers?

- What are the unsafe states?

- What are the safe states?

Communal Dining Lawyers

- n chopsticks in middle of table
- n lawyers, each can take one chopstick at a time
- What are the safe states?
- What are the unsafe states?
- What are the doomed states?

Communal Mutant Dining Lawyers

- N chopsticks in the middle of the table
- N lawyers, each takes one chopstick at a time
- Lawyers need k chopsticks to eat, $k > 1$

- What are the safe states?
- What are the unsafe states?
- What are the doomed states?

Communal Mutant Absent-Minded Dining Lawyers

- N chopsticks in the middle of the table
- N lawyers, each takes one chopstick at a time
- Lawyers need k chopsticks to eat, k > 1
  - k larger if lawyer is talking on his/her cellphone

- What are the safe states?
- What are the unsafe states?
- What are the doomed states?

Predict the Future

- Banker's algorithm
  - State maximum resource needs in advance
  - Allocate resources dynamically when resource is needed -- wait if granting request would lead to deadlock
  - Request can be granted if some sequential ordering of threads is deadlock free

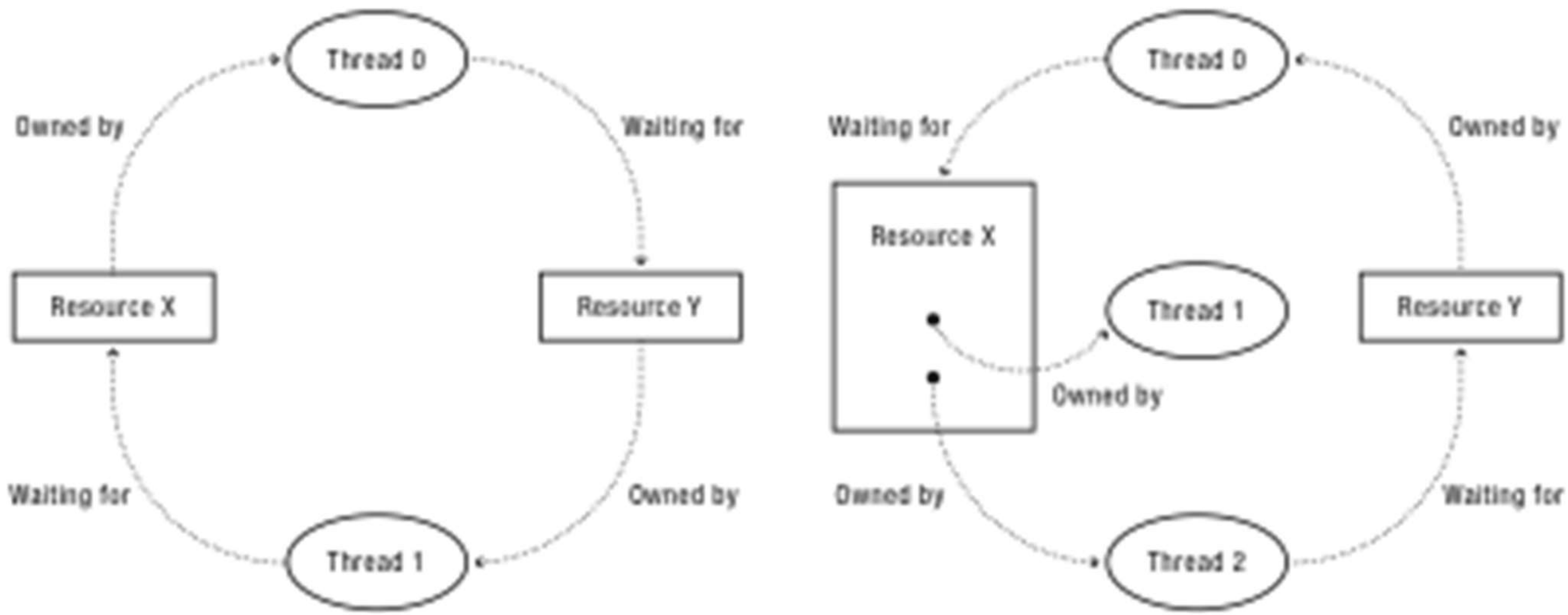
Banker's Algorithm

- Grant request iff result is a safe state
- Sum of maximum resource needs of current threads can be greater than the total resources
  - Provided there is some way for all the threads to finish without getting into deadlock
- Example: proceed iff
  - total available resources - # allocated >= max remaining that might be needed by this thread in order to finish
  - Guarantees this thread can finish

Detect and Repair

- Algorithm
  - Scan wait for graph
  - Detect cycles
  - Fix cycles
- Proceed without the resource
  - Requires robust exception handling code
- Roll back and retry
  - Transaction: all operations are provisional until have all required resources to complete operation

Detecting Deadlock



Non-Blocking Synchronization

- Goal: data structures that can be read/modified without acquiring a lock
  - No lock contention!
  - No deadlock!
- General method using compareAndSwap
  - Create copy of data structure
  - Modify copy
  - Swap in new version iff no one else has
  - Restart if pointer has changed

Lock-Free Bounded Buffer

```
tryget() {
  do {
    copy = ConsistentCopy(p);
    if (copy->front == copy->tail)
      return NULL;
    else {
      item = copy->buf[copy->front % MAX];
      copy->front++;
  } while (compareAndSwap(&p, p, copy));
  return item;
}
```