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

- Speedup = Time on one CPU/Time on N CPUs
- A program with lots of concurrent threads can have poor speedup, because:
  - Lock contention: only one thread at a time holding 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

Question

- Suppose a critical section is 5% of the total work per request (on a single CPU)
- What is maximum possible speedup from running each request in its own thread?

- Suppose CPU is 5x slower when executing in critical section due to cache effects
- What is maximum possible speedup?

A Simple Test of Cache Behavior

- An array of locks, each protects a counter
  - Critical section: increment counter
  - Multiple cores
- 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

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
  - Check out item, modify, check back in
- Staged architecture
  - Divide and conquer

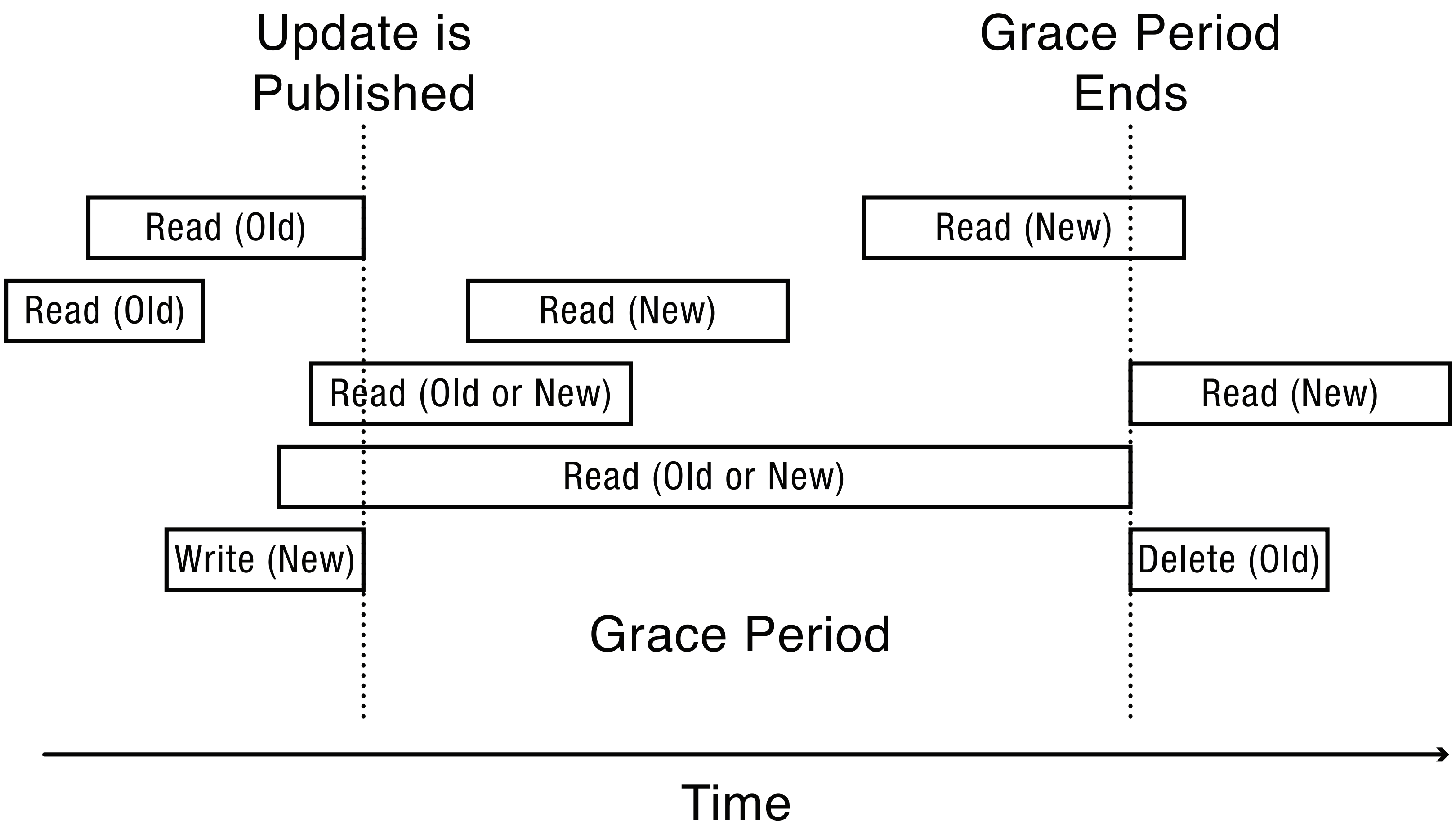
What If Locks are Still Busy?

- 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

Read-Copy-Update

- 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
  - OK if write is slow

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
  - OK to garbage collect

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

```
buffer1.put(data);
buffer1.put(data);

buffer2.get();
buffer2.get();
```

Thread B

```
buffer2.put(data);
buffer2.put(data);

buffer1.get();
buffer1.get();
```

Two locks and a condition variable

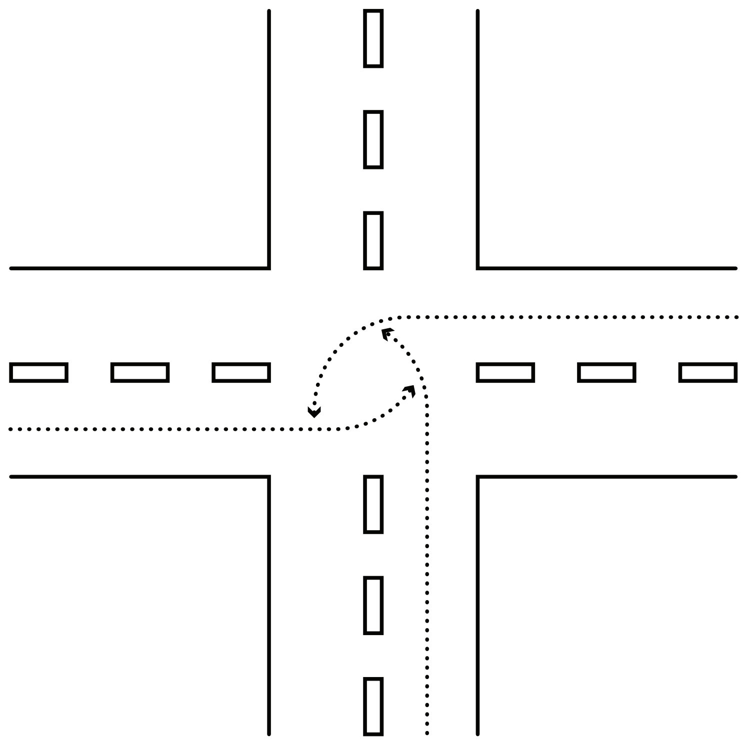
Thread A

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

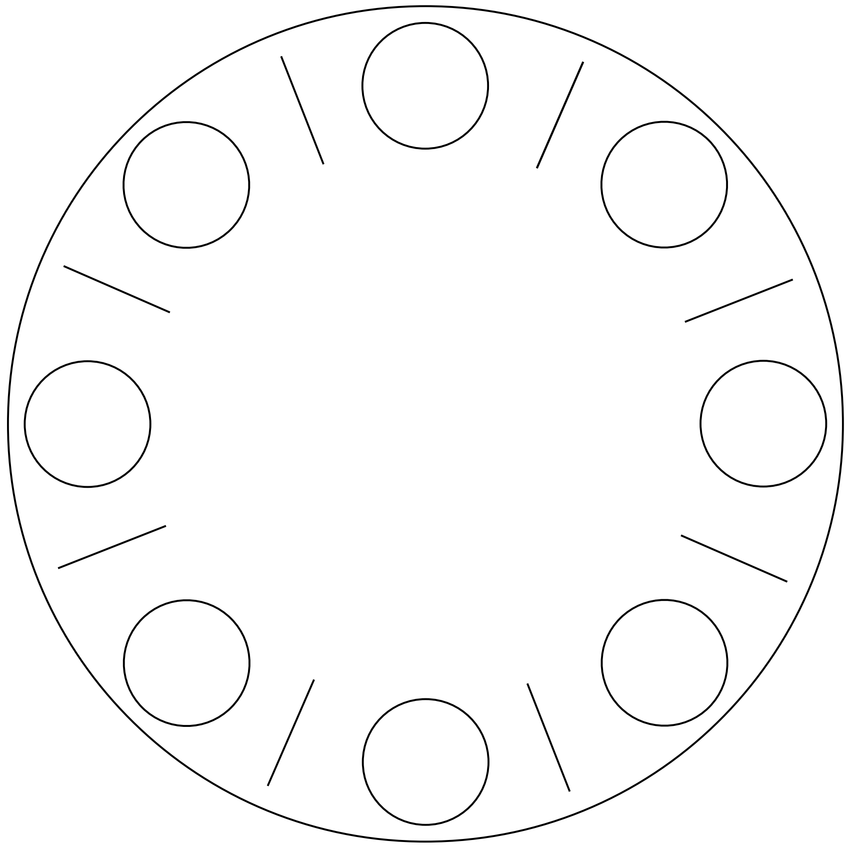
Thread B

```
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 system to prevent deadlock?

Example

Thread 1

1. Acquire A
2.
3. Acquire C
4.
5. Wait for B

Thread 2

1.
2. Acquire B
3.
4. Wait for A

How could we have avoided 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

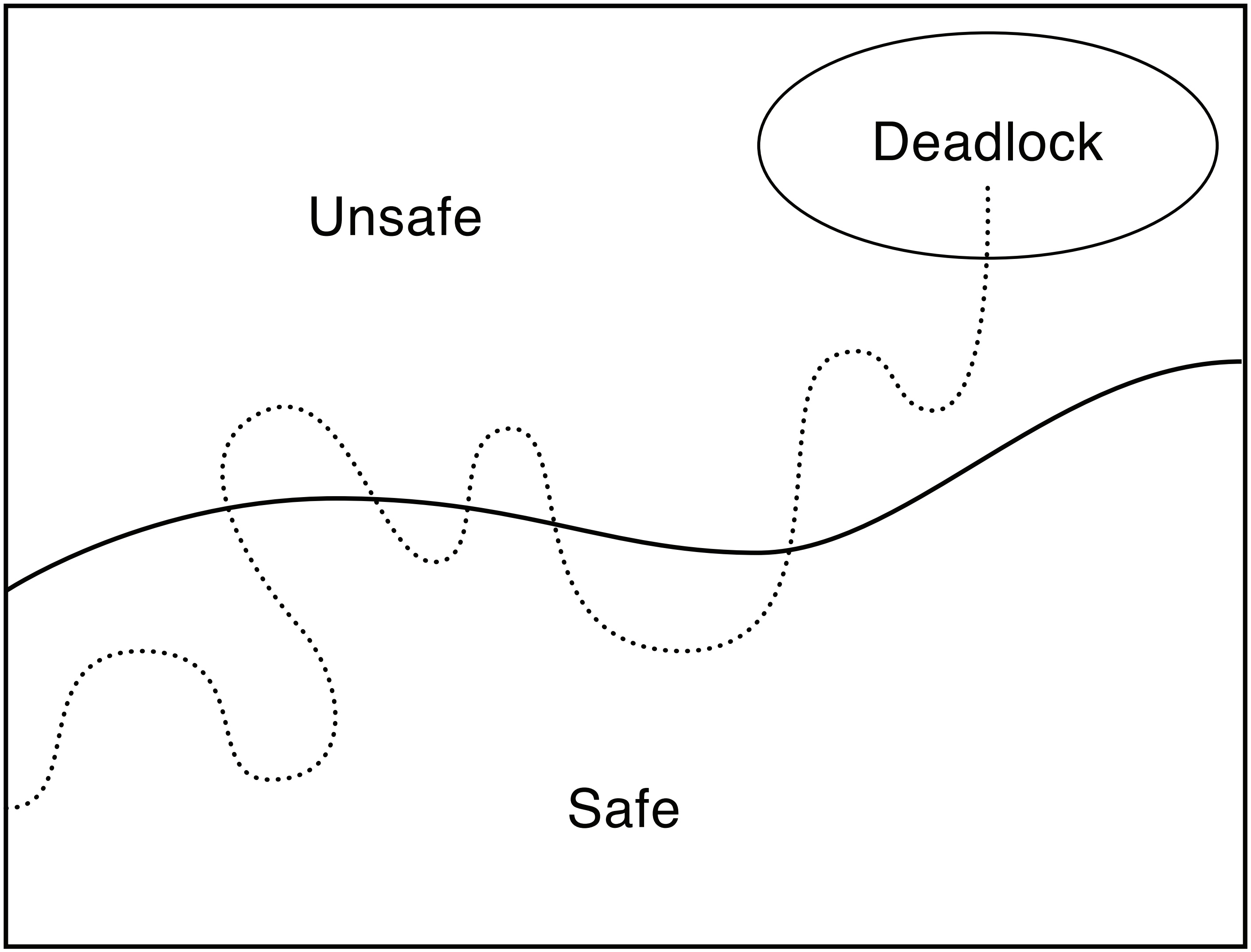
Exploit or Limit Behavior

- 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

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

Possible System States



Definitions

- 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

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

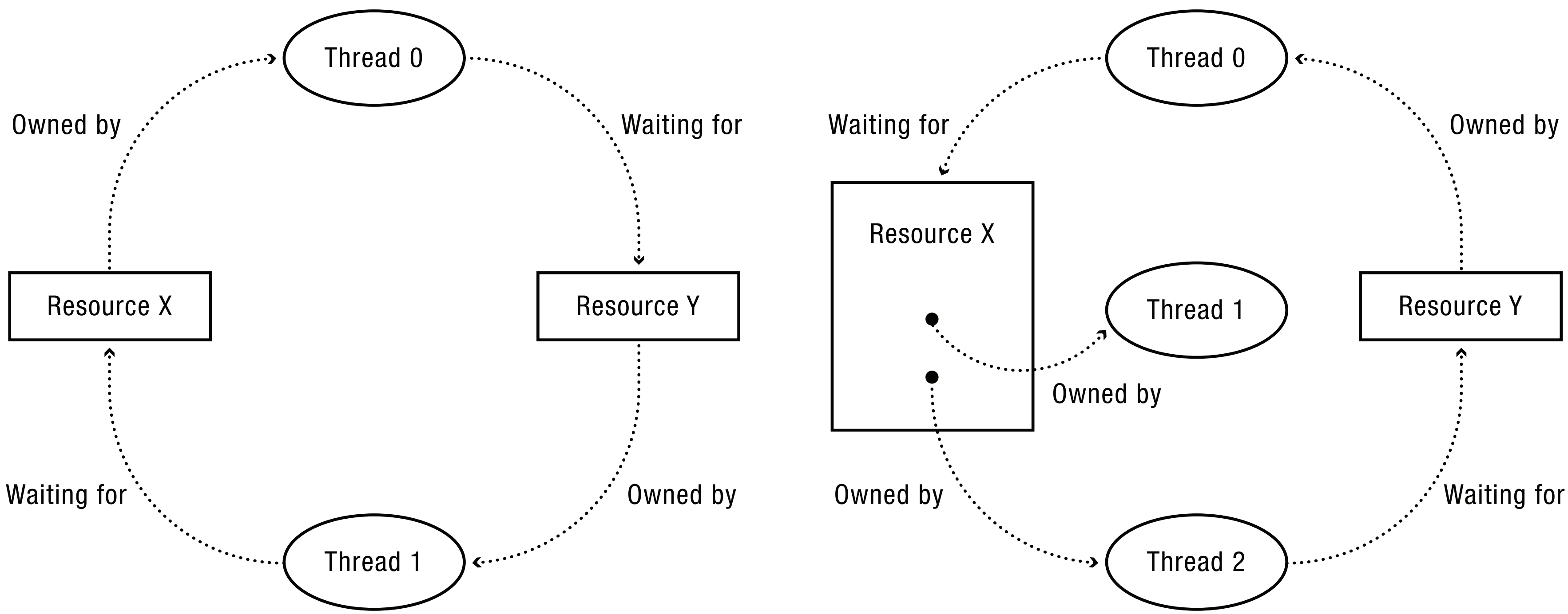
Example: Banker's Algorithm

- n chopsticks in middle of table
- n lawyers, each can take one chopstick at a time
- When is it ok for lawyer to take a chopstick?
- What if each lawyer needs k chopsticks?

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

- Compare and swap atomic instruction
  - 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 ((compare&swap(copy, p) != p);
    return item
}
```