Concurrent systems

Lecture 4: CCR, monitors, and concurrency in practice.

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(Thanks to Dr Robert N. M. Watson)

Reminder from last time

- Implementing **mutual exclusion**: hardware support for **atomicity** and **inter-processor interrupts**
- Semaphores for mutual exclusion, **condition synchronisation**, and **resource allocation**
- Two-party and generalised **producer-consumer** relationships
- **Invariants** and **locks**

From last time: Semaphores summary

- Powerful abstraction for implementing concurrency control:
  - mutual exclusion & condition synchronization
- Better than read-and-set()… **but** correct use requires considerable care
  - e.g. forget to wait(), can corrupt data
  - e.g. forget to signal(), can lead to infinite delay
  - generally get more complex as add more semaphores
- Used internally in some OSes and libraries, but generally deprecated for other mechanisms…

Semaphores are a low-level implementation primitive – they say **what to do**, rather than describing **programming goals**

This time

- **Multi-Reader Single-Writer** (MRSW) locks
  - **Starvation** and **fairness**
- 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

Multiple-Readers Single-Writer (MRSW)

- Another common synchronisation paradigm is MRSW
  - Shared resource accessed by a set of threads
    - e.g. cached set of DNS results
  - Safe for many threads to read simultaneously, but a writer (updating) must have exclusive access
  - MRSW locks have **read lock** and **write lock** operations
  - Mutual exclusion vs. **data stability**
- Simple implementation uses two semaphores
- **First semaphore** is a mutual exclusion lock (**mutex**)
  - Any writer must wait to acquire this
- **Second semaphore** protects a **reader count**
  - Reader count incremented whenever a reader enters
  - Reader count decremented when a reader exits
  - First reader acquires mutex; last reader releases mutex.

Simplest MRSW solution

```
int nr = 0;                      // number of readers
rSem   = new Semaphore(1);  // protects access to nr
wSem   = new Semaphore(1);  // protects writes to data
```

```
// a writer thread
wait(wSem);
.. perform update to data
signal(wSem);
```

Code for writer is simple…

```
// a reader thread
wait(rSem);
nr = nr + 1;
if (nr == 1)  // first in
  wait(wSem);
signal(rSem);
.. read data
wait(rSem);
nr = nr - 1;
if (nr == 0) // last out
  signal(wSem);
signal(rSem);
```

.. but reader case more complex: must track number of readers, and acquire or release overall lock as appropriate

Simplest MRSW solution

- Solution on previous slide is “correct”
  - Only one writer will be able to access data structure, but – providing there is no writer – any number of readers can access it
- However writers can **starve**
  - If readers continue to arrive, a writer might wait forever (since readers will not release wSem)
  - Would be fairer if a writer only had to wait for all current readers to exit…
  - Can implement this with an additional semaphore.

A fairer MRSW solution

```
int nr = 0;                    // number of readers
rSem   = new Semaphore(1);  // protects access to nr
wSem   = new Semaphore(1);  // protects writes to data
turn   = new Semaphore(1);  // write is awaiting a turn
```

Once a writer tries to enter, it will acquire turn…

… which prevents any further readers from entering

```
// a writer thread
wait(turn);
wait(wSem);
.. perform update to data
signal(turn);
signal(wSem);
```

```
// a reader thread
wait(turn);
signal(turn);
wait(rSem);
nr = nr + 1;
if (nr == 1)  // first in
  wait(wSem);
signal(rSem);
.. read data
wait(rSem);
nr = nr - 1;
if (nr == 0) // last out
  signal(wSem);
signal(rSem);
```

Conditional Critical Regions

- Implementing synchronisation with locks is difficult
  - Only the developer knows what data is protected by which locks
- One early (1970s) effort to address this problem was CCRs
  - Variables can be explicitly declared as ‘shared’
  - Code can be tagged as using those variables, e.g.

```
shared int A, B, C;
region A, B {
    await( /* arbitrary condition */);
    // critical code using A and B
}
```

- Compiler automatically declares and manages underlying primitives for mutual exclusion or synchronization
  - e.g. wait/signal, read/await/advance, …
- Easier for programmer (c/f previous implementations).

CCR example: Producer-Consumer

```
shared int buffer[N];
shared int in = 0; shared int out = 0;
```

```
// producer thread
while(true) {
  item = produce();
  region in, out, buffer {
    await((in–out) < N);
    buffer[in % N] = item;
    in = in + 1;
  }
}
```

```
// consumer thread
while(true) {
  region in, out, buffer {
    await((in-out) > 0);
    item = buffer[out % N];
    out  = out + 1;
  }
  consume(item);
}
```

- Explicit (scoped) declaration of critical sections
  - automatically acquire mutual exclusion lock on region entry
- Powerful **await**(): any evaluable predicate.

CCR pros and cons

- On the surface seems like a definite step up
  - Programmer focuses on **variables** to be protected, compiler generates appropriate semaphores (etc)
  - Compiler can also check that shared variables are never accessed outside a CCR
  - (still rely on programmer annotating correctly ?)
- But **await**(<expr>) is problematic…
  - What to do if the (arbitrary) <expr> is not true?
  - very difficult to work out when it becomes true?
  - Solution was to leave region & try to re-enter: this is busy waiting (aka spinning), which is very inefficient…

Monitors

- **Monitors** are similar to CCRs (implicit mutual exclusion), but modify them in two ways
  - Waiting is limited to explicit **condition variables**
  - All related routines are combined together, along with initialization code, in a single construct
- Idea is that only one thread can ever be executing 'within' the monitor
  - If a thread calls a monitor method, it will block (enqueue) if another thread is holding the monitor
  - Hence all methods within the monitor can proceed on the basis that mutual exclusion has been ensured
- Java's **synchronized** primitive implements monitors.

Example Monitor syntax

```
monitor <foo> {

 // declarations of shared variables

 // set of procedures (or methods)
 procedure P1(...) { ... }
 procedure P2(...) { ... }
 ...
 procedure PN(...) { ... }

 {
   /* monitor initialization code */
 }

}
```

All related data and methods kept together

Shared variables only accessible from within monitor methods

Invoking any procedure causes an [implicit] mutual exclusion lock to be taken

Shared variables can be initialized here

Condition Variables (Queues)

- Mutual exclusion not always sufficient
  - **Condition synchronization** -- e.g., wait for a condition to occur
- Monitors allow **condition variables** (aka condition queues)
  - Explicitly declared and managed by programmer
  - NB: No integrated counter – not a stateful semaphore!
  - Support three operations:

```
wait(cv) {
   suspend thread and add it to the queue for CV,
   release monitor lock;
}
signal(cv) {
   if any threads queued on CV, wake one thread;
}
broadcast(cv) {
   wake all threads queued on CV;
}
```

Monitor Producer-Consumer solution?

```
monitor ProducerConsumer {
 int in, out, buffer[N];
 condition notfull = TRUE, notempty = FALSE;

 procedure produce(item) {
   if ((in-out) == N) wait(notfull);
   buffer[in % N] = item;
   if ((in-out) == 0) signal(notempty);
   in = in + 1;
 }
 procedure int consume() {
   if ((in-out) == 0) wait(notempty);
   item = buffer[out % N];
   if ((in-out) == N) signal(notfull);
   out = out + 1;
   return(item);
 }
 /* init */ { in = out = 0; }
}
```

If buffer is full, **wait** for consumer

If buffer was empty, **signal** the consumer

If buffer is empty, **wait** for producer

If buffer was full, **signal** the producer

Does this work?

- Depends on implementation of **wait**() & **signal**()
- Imagine two threads, **T1** and **T2**
  - **T1** enters the monitor and calls **wait**(**C**) – this suspends **T1**, places it on the queue for **C**, and unlocks the monitor
  - Next **T2** enters the monitor, and invokes **signal**(**C**)
  - Now **T1** is unblocked (i.e. capable of running again)…
  - … but can only have one thread active inside a monitor!
- If we let **T2** continue (**signal-and-continue**), **T1** must queue for re-entry to the monitor
  - And no guarantee it will be *next* to enter
- Otherwise **T2** must be suspended (**signal-and-wait**), allowing **T1** to continue…

Note: C is either of our two condition variables.

Signal-and-Wait ("Hoare Monitors")

- Consider the queue **E** to enter the monitor
  - If monitor is occupied, threads are added to **E**
  - May not be FIFO, but should be fair.
- If thread **T1** waits on **C**, added to queue **C**
- If **T2** enters monitor & signals, waking **T1**
  - **T2** is added to a new queue **S** "in front of" **E**
  - **T1** continues and eventually exits (or re-waits)
- Some thread on **S** chosen to resume
  - Only admit a thread from **E** when **S** is empty.

Note: C is one of our two condition queues (aka condition variables).

Note: E is the thread entry queue associated with the mutex present in all monitors.

Note: S is a further entry queue for this form of monitor.

Signal-and-Wait pros and cons

- We call **signal**() exactly when condition is true, then directly transfer control to waking thread
  - Hence condition will still be true!
- But more difficult to implement…
- And can be complex to reason about (a call to signal *may or may not* result in a context switch)
  - Hence we must ensure that any invariants are maintained at time we invoke **signal**()
- With these semantics, our example is broken:
  - We **signal**() before incrementing in/out.

Same code as slide 15

Monitor Producer-Consumer solution?

```
monitor ProducerConsumer {
 int in, out, buf[N];
 condition notfull,notempty;

 procedure produce(item) {
   if ((in-out) == N) wait(notfull);
   buffer[in % N] = item;
   if ((in-out) == 0) signal(notempty);
   in = in + 1;
 }
 procedure int consume() {
   if ((in-out) == 0) wait(notempty);
   item = buffer[out % N];
   if ((in-out) == N) signal(notfull);
   out = out + 1;
   return(item);
 }
 /* init */ { in = out = 0; }
}
```

Race

Race

If buffer is full, **wait** for consumer

If buffer was empty, **signal** the consumer

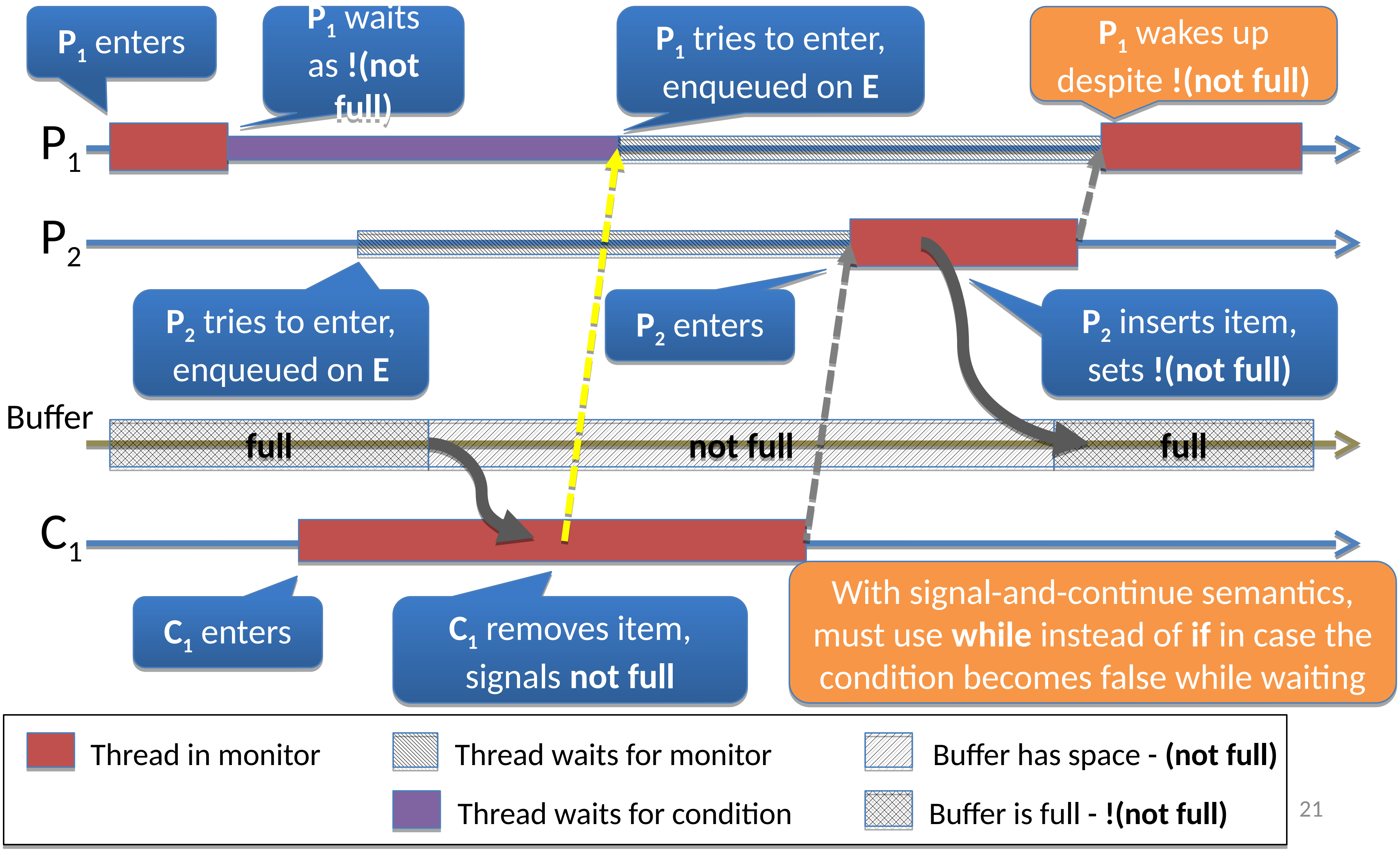
If buffer is empty, **wait** for producer

If buffer was full, **signal** the producer

Signal-and-Continue

- Alternative semantics introduced by Mesa programming language (Xerox PARC).
- An invocation of **signal**() moves a thread from the condition queue **C** to the entry queue **E**
  – Invoking threads continues until exits (or waits).
- Simpler to build… but now not guaranteed that condition holds (is true) when resume!
  – Other threads may have executed after the signal, but before you continue.

Signal-and-Continue example (1)



Signal-and-Continue example (2)

- Consider multiple producer-consumer threads
  1. **P1** enters. Buffer is full so blocks on queue for **C**
  2. **C1** enters.
  3. **P2** tries to enter; occupied, so queues on **E**
  4. **C1** continues, consumes, and signals **C** (“notfull”)
  5. **P1** unblocks; monitor occupied, so queues on **E**
  6. **C1** exits, allowing **P2** to enter
  7. **P2** fills buffer, and exits monitor
  8. **P1** resumes and tries to add item – BUG!
- Hence must *re-test condition*:

  i.e. while((in - out) == N) wait(not full);

if() replaced with while() for conditions

Monitor Producer-Consumer solution?

```
monitor ProducerConsumer {
 int in, out, buf[N];
 condition notfull, notempty;

 procedure produce(item) {
  while ((in-out) == N) wait(notfull);
  buf[in % N] = item;
  if ((in-out) == 0) signal(notempty);
  in = in + 1;
 }
 procedure int consume() {
  while ((in-out) == 0) wait(notempty);
  item = buf[out % N];
  if ((in-out) == N) signal(notfull);
  out = out + 1;
  return(item);
 }
 /* init */ { in = out = 0; }
}
```

While buffer is full, **wait** for consumer

If buffer was empty, **signal** the consumer

While buffer is empty, **wait** for producer

If buffer was full, **signal** the producer

With signal-and-continue semantics, increment after signal does not race.

Monitors: summary

- Structured concurrency control
  - groups together shared data and methods
  - (today we'd call this object-oriented)
- Considerably simpler than semaphores, but still perilous in places
- May be overly conservative sometimes:
  - e.g. for MRSW cannot have >1 reader in monitor
  - Typically must work around with entry and exit methods (**BeginRead**(), **EndRead**(), **BeginWrite**(), etc)
- Exercise: sketch a working MRSW monitor implementation.

Concurrency in practice

- Seen a number of abstractions for concurrency control
  - Mutual exclusion and condition synchronization
- Next let's look at some concrete examples:
  - POSIX pthreads (C/C++ API)
  - FreeBSD kernels
  - Java.

Example: pthreads (1)

- Standard (POSIX) threading API for C, C++, etc
  - mutexes, condition variables, and barriers
- Mutexes are essentially binary semaphores:

```
int pthread_mutex_init(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);
```

- A thread calling **lock**() blocks if the mutex is held
  - **trylock**() is a non-blocking variant: returns immediately; returns 0 if lock acquired, or non-zero if not.

Example: pthreads (2)

- Condition variables are Mesa-style:

```
int pthread_cond_init(pthread_cond_t *cond, ...);
int pthread_cond_wait(pthread_cond_t *cond,
     pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

- No proper monitors: must manually code e.g.

```
pthread_mutex_lock(&M);
while (!condition)
    pthread_cond_wait(&C,&M);
// do stuff
if (condition)
    pthread_cond_broadcast(&C);
pthread_mutex_unlock(&M);
```

Notice: **while**() and not **if**() due to signal-and-continue semantics

Example: pthreads (3)

- **Barriers**: explicit synchronization mechanism
  - Wait until all threads reach some point
- E.g., in discrete event simulation, all parallel threads must complete one epoch before any begin on the next

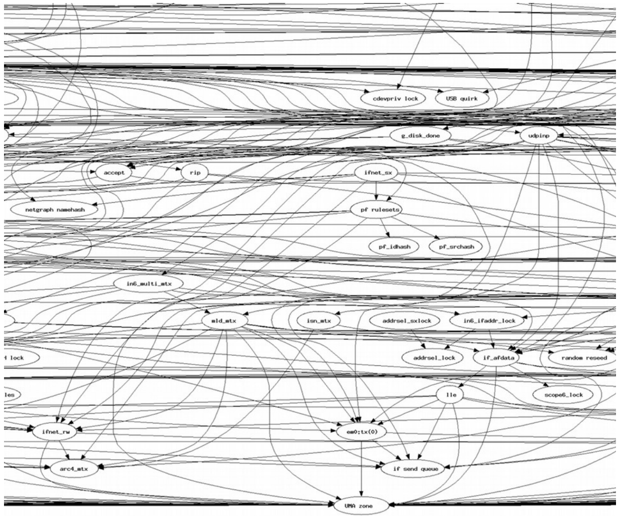
```
int pthread_barrier_init(pthread_barrier_t *b, ...,  N);
int pthread_barrier_wait(pthread_barrier_t *b);
```

```
pthread_barrier_init(&B, ..., NTHREADS);
for(i=0; i<NTHREADS; i++)
   pthread_create(..., worker, ...);

worker() {
   while(!done) {
      // do work for this round
      pthread_barrier_wait(&B);
   }
}
```

Example: FreeBSD kernel

- Kernel provides spin locks, mutexes, conditional variables, reader-writer + read-mostly locks
  - Semantics (roughly) modelled on POSIX threads
- A variety of **deferred work primitives**
- “Fully preemptive” and highly threaded
  - (e.g., interrupt processing in threads)
  - Interesting debugging tools
  - such as DTrace, **lock**
  - **contention measurement**,
- **lock-order checking**
- Further details are in last year’s lecture 8 …



Example: Java synchronization (1)

- Inspired by monitors – objects have **intrinsic locks**
- **Synchronized methods**:

```
public synchronized void myMethod() throws ...{
    // This code runs with the intrinsic lock held.
}
```

- **Synchronized statements**:

```
public void myMethod() throws ...{
    synchronized(this) {
        // This code runs with the intrinsic lock held.
}}
```

- Method return / statement exit release lock.
- Locks are **reentrant**: a single thread can reenter **synchronized** statements/methods without waiting.
- **synchronized**() can accept other objects than **this.**

Example: Java synchronization (2)

- Objects have **condition variables** for **guarded blocks**
- **wait**() puts the thread to sleep:

```
public synchronized void waitDone() {
    while (!done) {
        wait();
    }
}
```

- **notify**() and **notifyAll**() wake threads up:

```
public synchronized void notifyDone() {
    done = true;
    notifyAll();
}
```

- As with Mesa, **signal-and-continue semantics**
- As with locks, can name object (**thatObject.wait**())

Example: Java synchronization (3)

- Java also specifies **memory consistency** and **atomicity properties** that make some **lock-free** concurrent access safe – if used **very** carefully
  - We will consider lock-free structures later in the term
- **java.util.concurrent** (especially as of Java 8) includes many higher-level primitives –for example, **thread pools**, **concurrent collections**, **semaphores**, **cyclic barriers**, …
- Because Java is a type-safe, managed language, it is a much safer place to experiment with concurrent programming than (for example) C.

Concurrency Primitives: Summary

- Concurrent systems require means to ensure:
  - **Safety** (mutual exclusion in critical sections), and
  - **Progress** (condition synchronization)
- Spinlocks (busy wait); semaphores; MRSWs, CCRs, and monitors
  - Signal-and-Wait vs. Signal-and-Continue

- Many of these are used in practice
  - Subtle minor differences can be dangerous
  - Much care required to avoid bugs, especially where concurrency is a bolt-on to an existing imperative language.
  - E.g., failing to take out a lock or failing to release it,
  - E.g., “lost wakeups” – signal w/o waiter.

Summary + next 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

- Next time:
  - Problems with concurrency: deadlock, livelock, priorities
  - Resource allocation graphs; deadlock {prevention, detection, recovery}
  - Priority and scheduling; priority inversion; priority inheritance.