Concurrent systems

Lecture 2: More mutual exclusion, semaphores, producer-consumer, and MRSW

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Reminder from last time

- Definition of a concurrent system
- Origins of concurrency within a computer
- Processes and threads
- Challenge: concurrent access to shared resources
- Mutual exclusion, race conditions, and atomicity
- Mutual exclusion locks (mutexes)

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From last time: beer-buying example

- Thread 1 (person 1)
  1. Look in fridge
  2. If no beer, go buy beer
  3. Put beer in fridge
- Thread 2 (person 2)
  1. Look in fridge
  2. If no beer, go buy beer
  3. Put beer in fridge
- In most cases, this works just fine…
- But if both people look (step 1) before either refills the fridge (step 3)… we'll end up with too much beer!

We spotted race conditions in obvious concurrent implementations
Ad hoc solutions (e.g., leaving a note) failed
Even naïve application of atomic operations failed
What we want is a general solution for mutual exclusion

This time

- Implementing **mutual exclusion**
- Hardware support for **atomicity**, **condition synchronisation**
- Semaphores for mutual exclusion, condition synchronisation, and **resource allocation**
- Two-party and generalised **producer-consumer** relationships
- **Multi-Reader Single-Writer** (MRSW) locks

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From last lecture

Implementing mutual exclusion

- Associate a mutual exclusion lock with each critical section, e.g. a variable **L**
  - (must ensure use correct lock variable!)

  ENTER_CS() = "LOCK(L)"
  LEAVE_CS() = "UNLOCK(L)"
- Can implement LOCK() using read-and-set():

```
LOCK(L) {
  while(!read-and-set(L))
    ; // do nothing
}
```

```
UNLOCK(L) {
  L = 0;
}
```

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Hardware foundations for atomicity

- How can we implement atomic read-and-set?
- Simple pair of load and store instructions fail the atomicity test (obviously divisible!)
- Need a ISA primitive for protection against parallel access to memory from another CPU
- Two common flavours:
  - Atomic **Compare and Swap** (CAS)
  - **Load Linked, Store Conditional** (LL/SC)

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Atomic Compare and Swap (CAS)

- Found on CISC systems such as x86
- Atomic **Test and Set** (TAS) another variation
- Caller provides previous value as argument
- If memory contents match, assignment occurs
- Return value can be tested to trigger loop

```
        mov             %edx, 1             # New value
spin:
        mov             foo_lock, %eax      # Load old value
        test            %eax, %eax          # If non-zero (owned),
        jnz             spin                #   loop
        lock cmpxchg    %edx, foo_lock      # If foo_lock == %eax,
        test            %eax, %eax          #   swap in value from
        jnz             spin                #   %edx; else loop
```

Load Linked-Store Conditional (LL/SC)

- Found on RISC systems (MIPS, Alpha, ARM, …)
  - Load value from memory location with **LL**
  - Manipulate value in register
  - **SC** fails if memory location modified since **LL**
  - Return value can be checked; loop on failure
- Foundation for a more general technique seeing early deployment: **Software Transactional Memory** (STM)

```
spin:
        lld     $t0, 0($a0)         # Load old value
        bnez    $t0, spin           # If non-zero (owned), loop
        dli     $t0, 1              # New value (branch-delay slot)
        scd     $t0, 0($a0)         # Conditional store to $a0
        beqz    $t0, spin           # If failed ($t0 zero), loop
        nop                         # Branch-delay slot
```

Locks and invariants

- One important goal of locking is to avoid exposing **inconsistent intermediate states** to other threads
- This suggests a more general invariants strategy:
  - Invariants hold when lock is acquired
  - Invariants may be violated while lock is held
  - Invariants must be restored before lock is released
- E.g., deletion from a doubly linked list
  - Invariant: an entry is in the list, or not in the list
  - Individually non-atomic updates of forward and backward pointers around a deleted object are fine as long as the lock isn't released in between the two pointer writes

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Semaphores

- Even with atomic operations, busy waiting for a lock is inefficient…
  - Better to sleep until resource available
- Dijkstra (THE, 1968) proposed **semaphores**
  - New type of variable
  - Initialized once to an integer value (default 0)
- Supports two operations: **wait()** and **signal()**
  - Sometimes called **down()** and **up()**
  - (and originally called **P()** and **V()** … blurk!)

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Semaphore implementation

- Implemented as an integer and a queue

```
wait(sem) {
  if(sem > 0) {
     sem = sem-1;
   } else suspend caller & add to queue for sem
}

signal(sem) {
  if no threads are waiting {
     sem = sem + 1;
  } else wake up some thread on queue
}
```

- Method bodies are implemented **atomically**
- "suspend" and "wake" invoke threading APIs

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Hardware support for wakeups

- CAS/LLSC/… support atomicity via shared memory
- But what about "**wake up thread**"?
  - On a single CPU, wakeup triggers context switch
  - How to wake up a thread on another CPU that is already busy doing something else?
- **Inter-Processor Interrupts** (IPIs)
  - Wakeup sends an interrupt to the target CPU
  - IPI handler runs thread scheduler, preempts running thread, triggers context switch
- Together, shared memory and IPIs provide **atomicity** and **condition synchronisation** between CPUs

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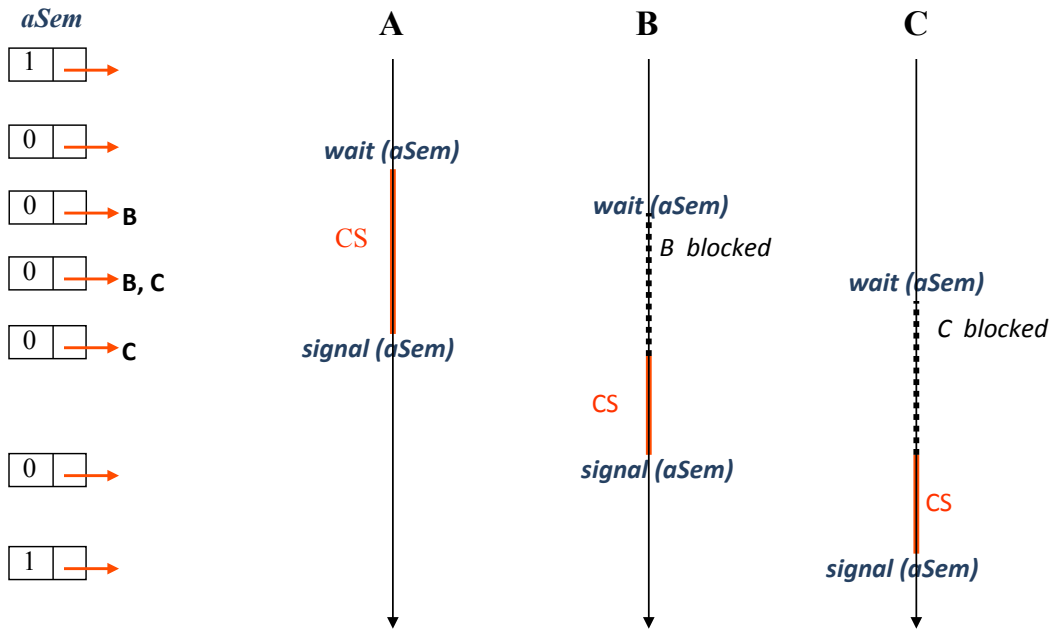
Mutual exclusion with a semaphore



- Initialize semaphore to 1; **wait()** is lock(), **signal()** is unlock()

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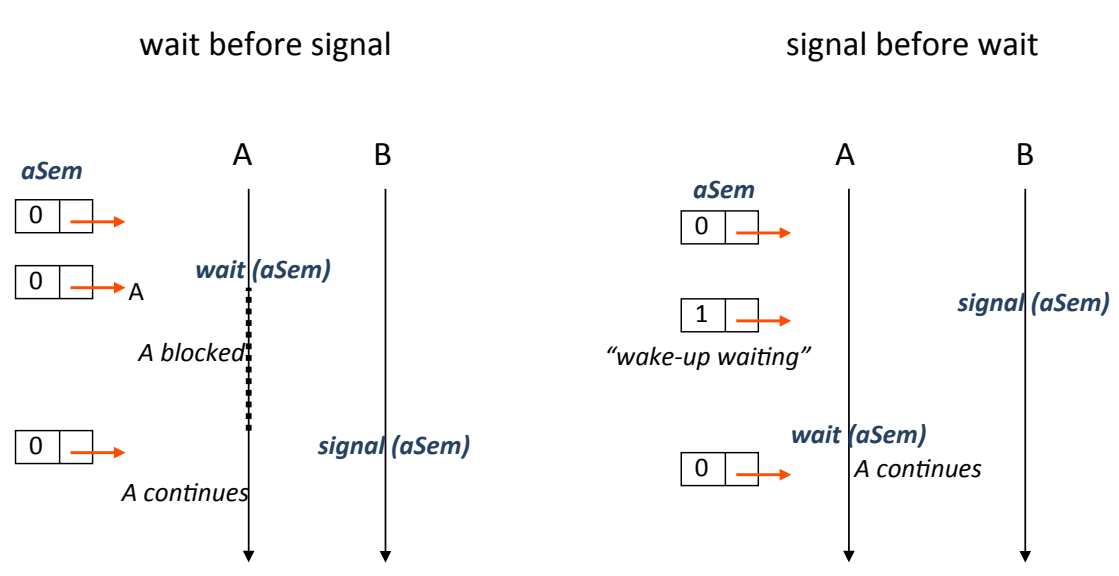
Two-process synchronization



- Initialize semaphore to 0; A proceeds only after B signals

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N-resource allocation

- Suppose there are N instances of a resource
  - e.g. N printers attached to a DTP system
- Can manage allocation with a semaphore sem, initialized to N
  - Anyone wanting printer does **wait**(sem)
  - After N people get a printer, next will sleep
  - To release resource, **signal**(sem)
    - Will wake someone if anyone is waiting
- Will typically also require mutual exclusion
  - e.g. to decide which printers are free

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Semaphore programming examples

- Semaphores are quite powerful
  - Can solve mutual exclusion…
  - Can also provide **condition synchronization**
    - Thread waits until some condition set by another thread becomes true
- Let's look at some examples:
  1. One producer thread, one consumer thread, with a N-slot shared memory buffer
  2. Any number of producer and consumer threads, again using an N-slot shared memory buffer
  3. Multiple reader, single writer synchronization

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Producer-consumer problem

- Shared buffer B[] with N slots, initially empty
- Producer thread wants to:
  - Produce an item
  - If there's room, insert into next slot;
  - Otherwise, wait until there is room
- Consumer thread wants to:
  - If there's anything in buffer, remove an item (and consume it)
  - Otherwise, wait until there is something
- General concurrent programming paradigm
  - e.g. pipelines in Unix; staged servers; work stealing

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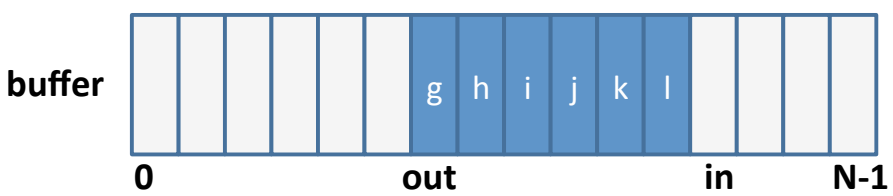
Producer-consumer solution

```
int buffer[N]; int in = 0, out = 0;
spaces = new Semaphore(N);
items  = new Semaphore(0);
```

```
// producer thread
while(true) {
  item = produce();
  if there is space {
     buffer[in] = item;
     in = (in + 1) % N;
  }
}
```

```
// consumer thread
while(true) {
  if there is an item {
     item = buffer[out];
     out  = (out + 1) % N;
  }
  consume(item);
}
```



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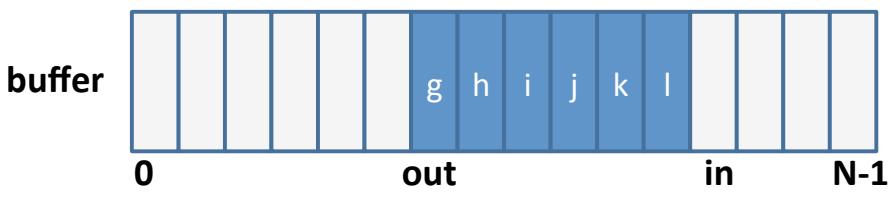
Producer-consumer solution

```
int buffer[N]; int in = 0, out = 0;
spaces = new Semaphore(N);
items  = new Semaphore(0);
```

```
// producer thread
while(true) {
  item = produce();
  wait(spaces);
     buffer[in] = item;
     in = (in + 1) % N;
  signal(items);
}
```

```
// consumer thread
while(true) {
  wait(items);
     item = buffer[out];
     out  = (out + 1) % N;
  signal(spaces);
  consume(item);
}
```



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Producer-consumer solution

- Use of semaphores for N-resource allocation
  - In this case, “resource” is a slot in the buffer
  - “spaces” allocates empty slots (for producer)
  - “items” allocates full slots (for consumer)
- No **explicit** mutual exclusion
  - Threads will never try to access the same slot at the same time; if “in == out” then either
    - buffer is empty (and consumer will sleep on ‘items’), or
    - buffer is full (and producer will sleep on ‘spaces’)

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Generalized producer-consumer

- Previously had exactly one producer thread, and exactly one consumer thread
- More generally might have many threads adding items, and many removing them
- If so, we **do** need explicit mutual exclusion
  - e.g. to prevent two consumers from trying to remove (and consume) the same item
- Can implement with one more semaphore…

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Generalized P-C solution

```
int buffer[N]; int in = 0, out = 0;
spaces = new Semaphore(N);
items  = new Semaphore(0);
guard  = new Semaphore(1);   // for mutual exclusion
```

```
// producer threads
while(true) {
  item = produce();
  wait(spaces);
  wait(guard);
     buffer[in] = item;
     in = (in + 1) % N;
  signal(guard);
  signal(items);
}
```

```
// consumer threads
while(true) {
  wait(items);
  wait(guard);
     item = buffer[out];
     out  = (out + 1) % N;
  signal(guard);
  signal(spaces);
  consume(item);
}
```

- Exercise: allow 1 producer and 1 consumer concurrent access

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Multiple-Readers Single-Writer (MRSW)

- Another common 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
  - Mutual exclusion vs. **data stability**
- Simplest solution uses a single semaphore as a mutual exclusion lock for write access
  - Any writer must wait to acquire this
  - First reader also acquires this; last reader releases it
  - Manage reader counts using another semaphore

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Simplest MRSW solution

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

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

```
// 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);
```

Code for writer is simple…

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

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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

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A fairer MRSW solution

```
int nr = 0;                  // number of readers
rSem   = new Semaphore(1);   // protects access to nr
wSem   = new Semaphore(1);   // protects access to data
turn   = new Semaphore(1);   // for more fairness!
```

Once a writer tries to enter he 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);
```

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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…

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Summary + next time

- Implementing **mutual exclusion**
- Hardware support for **atomicity**, **condition synchronisation**
- Semaphores for mutual exclusion, condition synchronisation, and **resource allocation**
- Two-party and generalised producer-consumer relationships
- Multi-Reader Single-Writer (MRSW) locks

- Next time:
  - Conditional critical regions (CCRs); Monitors
  - Condition variables; signal-and-wait vs. signal-and-continue
  - Concurrency in practice; concurrency primitives wrap-up

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