Concurrent Systems
8L for Part IB

Handout 1

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Recommended Reading

- "*Operating Systems, Concurrent and Distributed Software Design*", Jean Bacon and Tim Harris, Addison-Wesley 2003
  - or "*Concurrent Systems*", (2nd Ed), Jean Bacon, Addison-Wesley 1997
- "*Modern Operating Systems*", (3rd Ed), Andrew Tannenbaum, Prentice-Hall 2007
- "*Java Concurrency in Practice*", Brian Goetz and others, Addison-Wesley 2006

What is Concurrency?

- Computers can appear to do many things at once
  - e.g. running multiple programs on your laptop
  - e.g. writing back data buffered in memory to the hard disk while the program(s) continue to execute
- In the first case, this may actually be an **illusion**
  - e.g. processes time-sharing a single CPU
- In the second, there is **true parallelism**
  - e.g. DMA engine transfers data from memory and writes to disk at the same time as the CPU executes code
- In both cases, we have a **concurrency**
  - many things are occurring "at the same time"

In this course we will

- Investigate the ways in which concurrency can occur in a computer system;
  - processes, threads, interrupts, hardware
- Consider how to control concurrency;
  - mutual exclusion (locks, semaphores), condition synchronization, lock-free programming
- Learn about how to handle deadlock; and
  - prevention, avoidance, detection, recovery
- See how abstraction can provide support for correct & fault-tolerant concurrent execution
  - transactions, serializability, concurrency control

Recap: Processes and Threads

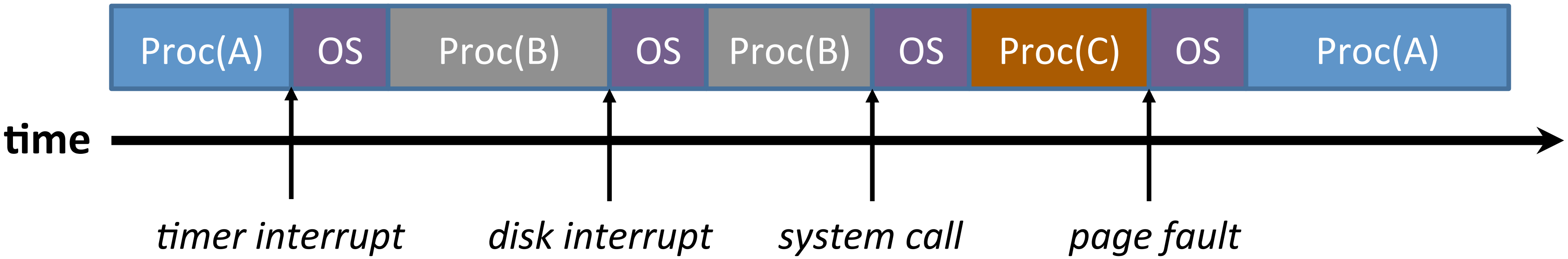
- A process is a program in execution
  - Unit of protection & resource allocation
  - Has an associated virtual address space (VAS); and one or more **threads**
- A thread is an entity managed by the scheduler
  - Represents an individual execution context
  - Managed by a thread control block (TCB) which holds the saved context (registers), scheduler info, etc
- Threads run in the VAS of their containing process
  - (or within the kernel address space)

Concurrency with a single CPU

- Process / OS Concurrency
  - Process X runs for a while (until blocks or **interrupted**)
  - OS runs for a while (e.g. does some TCP processing)
  - Process X resumes where it left off…
- Inter-Process Concurrency
  - Process X runs for a while; then OS; then Process Y; then OS; then Process Z; etc
- Intra-Process Concurrency
  - Process X has multiple threads X1, X2, X3, …
  - X1 runs for a while; then X3; then X1; then X2; then …

Concurrency with a single CPU

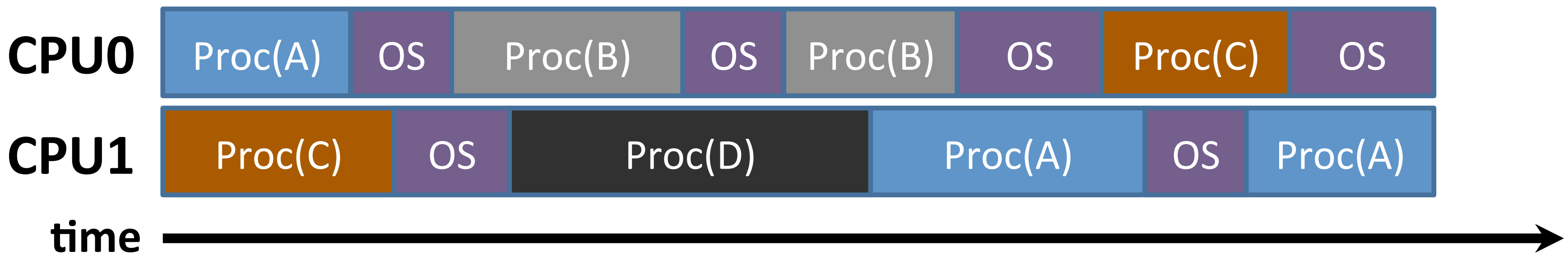
- With just one CPU, can think of concurrency as **interleaving** of different executions, e.g.



- Exactly where execution is interrupted and resumed is not usually known in advance…
  - this makes concurrency challenging!
- Generally should assume worst case behavior

Concurrency with multiple processors

- Many modern systems have multiple CPUs
  - And even if don't, have other processing elements
- Hence things can occur in parallel, e.g.



- Notice that the OS runs on both CPUs: tricky!
- More generally can have different threads of the same process executing on different CPUs too

Threading Models

- Threads can be user-level or kernel-level
- User-level threads
  - OS schedules a single process (e.g. JVM)
  - User-code (or a user-mode library) implements threading calls, a scheduler, and context switching code
- Advantages include:
  - lightweight creation/termination and context switch; application-specific scheduling; OS independence
- Disadvantages:
  - awkward to implement preemption, or to handle blocking system calls or page faults; and cannot use multiple CPUs
- Examples: Java greenthreads, stackless Python, Haskell

Threading Models

- Kernel-level threads
  - OS aware of both processes and threads
  - By default, a process has one main thread…
  - … but can create more via system call interface
  - Kernel schedules threads (and performs context switching)
- Advantages:
  - Easy to handle preemption or blocking system calls
  - Relatively straightforward to utilize multiple CPUs
- Disadvantages:
  - Higher overhead (trap to kernel); less flexible; less portable
- Examples: Windows NT, modern Linux, Mac OS X, FreeBSD

Hybrid Threading Models

- Ideally would like the best of both worlds
  - i.e. advantages of user- and kernel-level threads
- Various hybrid solutions proposed (first-class threads, scheduler activations, Solaris LWP, FreeBSD KSE)
  - OS and user-space co-operate in scheduling
  - User-space registers an activation handler
  - OS either resumes a context, or "upcalls" the handler
  - The former provides transparent kernel-thread scheduling; the latter, notifications of blocking events
  - On an upcall, handler can switch to another thread
- Mostly experimental or even deprecated (why?) in OSes, widely used in VMMs
  - Reappearing in work distribution frameworks e.g., Grand Central Dispatch (GCD)

Advantages of Concurrency

- Allows us to overlap computation and I/O on a single machine
- Can simplify code structuring and/or improve responsiveness
  - e.g. one thread redraws the GUI, another handles user input, and another computes game logic
  - e.g. one thread per HTTP request
  - e.g. background GC thread in JVM/CLR
- Enables the seamless (?!) use of multiple CPUs

Concurrent Systems

- In general, have some number of processes…
  - … each with some number of threads …
  - … running on some number of computers…
  - … each with some number of CPUs.
- For this half of the course we'll focus on a single computer running a multi-threaded process
  - most problems & solutions generalize to multiple processes, CPUs, and machines, but more complex
  - (we'll look at distributed systems in Lent term)
- Challenge: threads share the address space

Example: Housemates Buying Beer

- 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!
- Obviously more worrying if "look in fridge" is "check reactor", and "buy beer" is "toggle safety system" ;-)

Solution #1: Leave a Note

- Thread 1 (person 1)
  1. Look in fridge
  2. If no beer & no note
     1. Leave note on fridge
     2. Go buy beer
     3. Put beer in fridge
     4. Remove note
- Thread 2 (person 2)
  1. Look in fridge
  2. If no beer & no note
     1. Leave note on fridge
     2. Go buy beer
     3. Put beer in fridge
     4. Remove note
- Probably works for human beings…
  - But computers are stooopid!
- Can you see the problem?

Non-Solution #1: Leave a Note

```
// thread 1
beer = checkFridge();
if(!beer) {
  if(!note) {
     note = 1;
     buyBeer();
     note = 0;
  }
}
```

```
// thread 2
beer = checkFridge();
if(!beer) {
  if(!note) {
     note = 1;
     buyBeer();
     note = 0;
  }
}
```

- Easier to see with pseudo-code…

Non-Solution #1: Leave a Note

```
// thread 1
beer = checkFridge();
if(!beer) {
  if(!note) {
```

context switch

```
// thread 2
beer = checkFridge();
if(!beer) {
  if(!note) {
     note = 1;
     buyBeer();
     note = 0;
```

context switch

```
     note = 1;
     buyBeer();
     note = 0;
  }
}
```

```
  }
}
```

- Easier to see with pseudo-code…

Non-Solution #1: Leave a Note

- Of course this won't happen all the time
  – Need threads to interleave in the just the right way (or just the wrong way ;-)
- Unfortunately code that is 'mostly correct' is much worse than code that is 'mostly wrong'!
  – Difficult to catch in testing, as occurs rarely
  – May even go away when running under debugger
    - e.g. only context switches threads when they block
    - (such bugs are sometimes called "Heisenbugs")

Critical Sections & Mutual Exclusion

- The high-level problem here is that we have two threads trying to solve the same problem
  - Both execute buyBeer() concurrently
  - Ideally want only one thread doing that at a time
- We call this code a **critical section**
  - a piece of code which should never be concurrently executed by more than one thread
- Ensuring this involves **mutual exclusion**
  - If one thread is executing within a critical section, all other threads are prohibited from entering it

Achieving Mutual Exclusion

- One way is to let only one thread ever execute a particular critical section – e.g. a nominated beer buyer – but this restricts concurrency
- Alternatively our (broken) solution #1 was ***trying*** to provide mutual exclusion via the note
  - Leaving a note means "I'm in the critical section";
  - Removing the note means "I'm done"
  - But, as we saw, it didn't work ;-)
- This was since we could experience a context switch between reading 'note', and setting it

Non-Solution #1: Leave a Note

```
// thread 1
beer = checkFridge();
if(!beer) {
  if(!note) {
```

We decide to enter the critical section here…

context switch

But only mark the fact here …

```
      note = 1;
      buyBeer();
      note = 0;
  }
}
```

```
// thread 2
beer = checkFridge();
if(!beer) {
  if(!note) {
      note = 1;
      buyBeer();
      note = 0;
  }
}
```

context switch

Atomicity

- What we want is for the checking of note and the (conditional) setting of note to happen without any other thread being involved
  - We don't care if another thread reads it after we're done; or sets it before we start our check
  - But once we start our check, we want to continue without any interruption
- If a sequence of operations (e.g. read-and-set) occur as if one operation, we call them **atomic**
  - Since indivisible from the point of view of the program
- An atomic "read-and-set" operation is sufficient for us to implement a correct beer program

Solution #2: Atomic Note

```
// thread 1
beer = checkFridge();
if(!beer) {
  if(read-and-set(note)) {
     buyBeer();
     note = 0;
  }
}
```

```
// thread 2
beer = checkFridge();
if(!beer) {
  if(read-and-set(note)) {
     buyBeer();
     note = 0;
  }
}
```

- read-and-set(&address) **atomically** checks the value in memory and iff it is zero, sets it to one
  - returns 1 iff the value was changed from 0 -> 1
- This prevents the behavior we saw before, and is sufficient to implement a correct program...
  - although this is not that program :-)

Non-Solution #2: Atomic Note

```
// thread 1
beer = checkFridge();
if(!beer) {
```

context switch

```
// thread 2
beer = checkFridge();
if(!beer) {
  if(read-and-set(note)) {
     buyBeer();
     note = 0;
```

context switch

```
  if(read-and-set(note)) {
     buyBeer();
     note = 0;
  }
}
```

```
  }
}
```

- Our critical section doesn't cover enough!

General Mutual Exclusion

- More generally, we would like the ability to define a region of code as a critical section e.g.

```
// thread 1
ENTER_CS();
beer = checkFridge();
if(!beer)
     buyBeer();
LEAVE_CS();
```

```
// thread 2
ENTER_CS();
beer = checkFridge();
if(!beer)
     buyBeer();
LEAVE_CS();
```

- This should work …
  - … providing that our implementation of ENTER_CS() / LEAVE_CS() is correct

Implementing Mutual Exclusion

- One option is to prevent context switches
  - e.g. disable interrupts (for kernel threads), or set an in-memory flag (for user threads)
- ENTER_CS() = "disable context switches"; LEAVE_CS() = "re-enable context switches"
- Can work but:
  - Rather brute force (stops all other threads, not just those who want to enter the critical section)
  - Potentially unsafe (if disable interrupts and then sleep waiting for a timer interrupt ;-)
  - And doesn't work across multiple CPUs

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;
}
```

Solution #3: Mutual Exclusion Locks

```
// thread 1
LOCK(fridgeLock);
beer = checkFridge();
if(!beer)
      buyBeer();
UNLOCK(fridgeLock);
```

```
// thread 2
LOCK(fridgeLock);
beer = checkFridge();
if(!beer)
      buyBeer();
UNLOCK(fridgeLock);
```

- This is – finally! – a correct program
- Still not perfect
  - Lock might be held for quite a long time (e.g. imagine another person wanting to get the milk!)
  - Waiting threads waste CPU time (or worse)

What if No Hardware Support?

- Solution #3 requires an atomic 'read-and-set' operation… but what if we don't have one?
- Option 1:
  - Fake atomic operation by disabling interrupts (or context switches) between read and set
  - But doesn't work across multiple CPUs
- Option 2:
  - Build a mutual exclusion scheme which only relies on atomic reads and writes!
  - Hot topic in the 1970s/80s; mostly irrelevant now
- In practice, we almost always build mutual exclusion on top of atomic instructions like CAS, TAS, LL/SC, ...

<< in case you're interested >>

- Examples for N-process mutual exclusion are:
  - Eisenberg M. A. and McGuire M. R., *Further comments on Dijkstra's concurrent programming control problem*, CACM 15(11), 1972
  - Lamport L, *A new solution to Dijkstra's concurrent programming problem*, CACM, 17(8), 1974 (this is his N-process **bakery algorithm**)
- These algorithms impose large overhead, and may not even be correct in modern CPUs

<< Solution – or Non-Solution? - #4 >>

```
// thread 1
flag1 = 1;
while(flag2 == 1)
  ; // do nothing
beer = checkFridge();
if(!beer)
     buyBeer();
flag1 = 0;
```

```
// thread 2
flag2 = 1;
if(!flag1) {
  beer = checkFridge();
  if(!beer)
      buyBeer();
}
flag2 = 0;
```

- Question: does this work?
- (And even if it does, would you want to have to write – or read – this kind of code??)

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 <u>originally</u> called **P()** and **V()** ... blurk!)

Semaphore Implementation

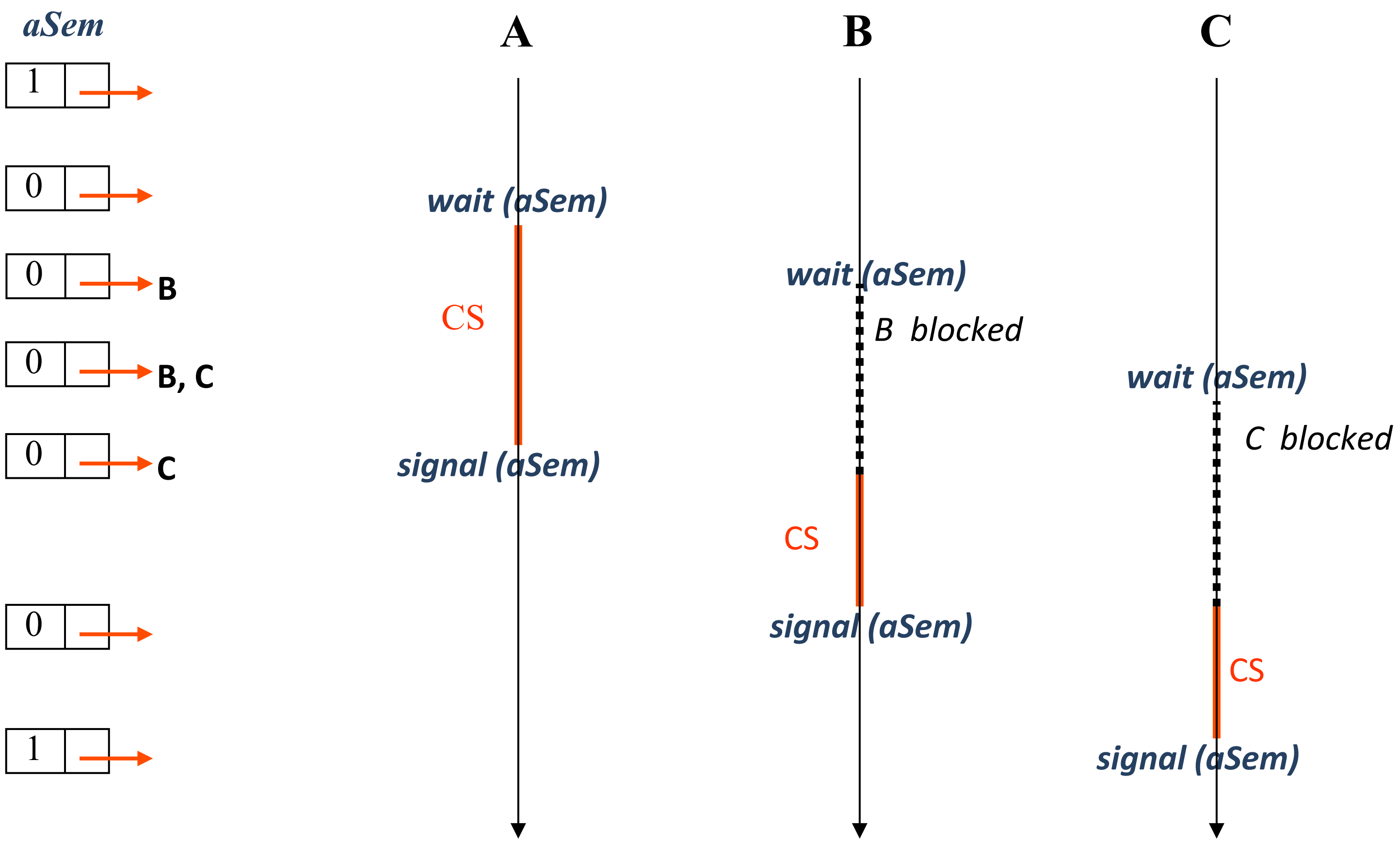
- Implemented as an integer and a queue

```
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
}
```

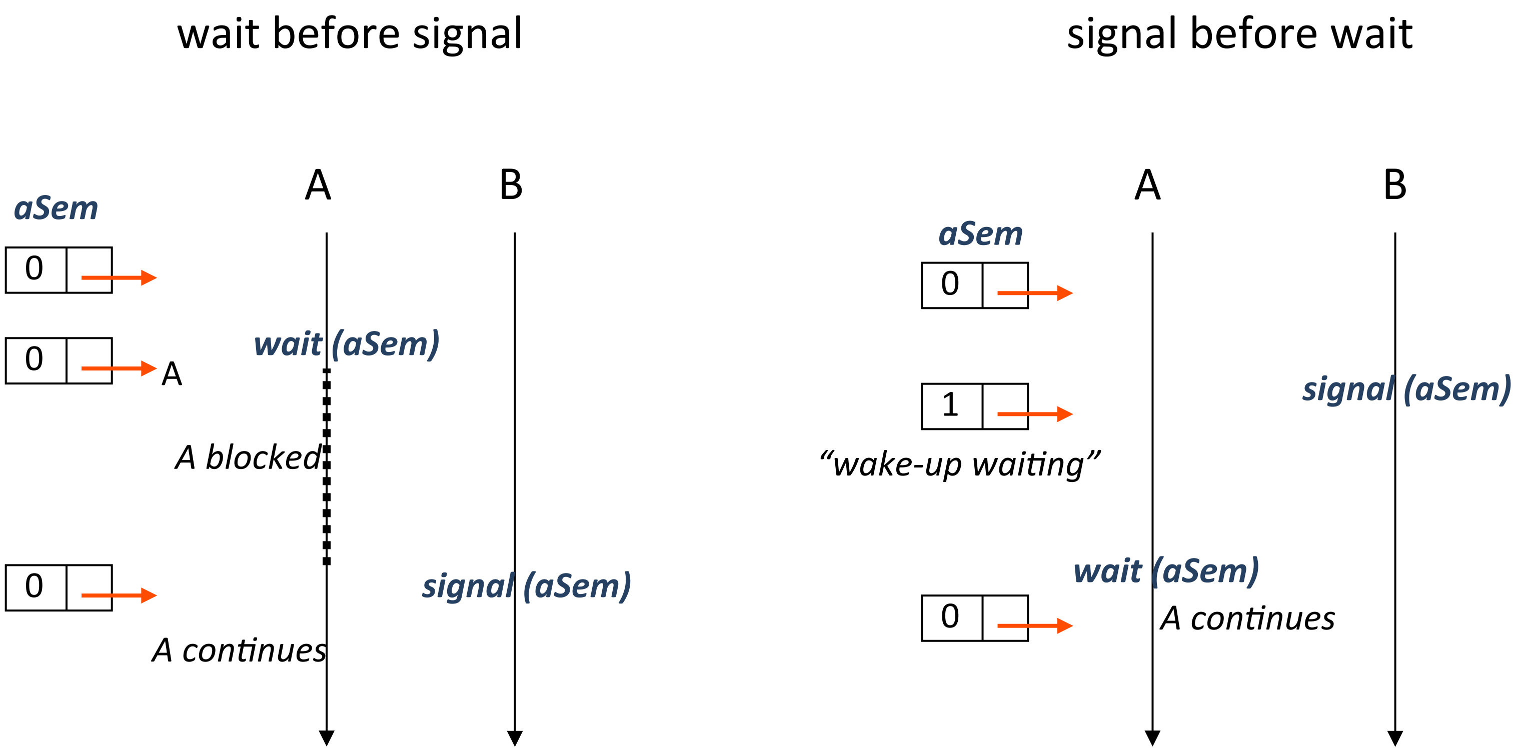
- Method bodies are implemented atomically
- “suspend” and “wake” invoke threading APIs

Mutual Exclusion with a Semaphore



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

Two Process Synchronization



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

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

Semaphore Programming Examples

- Semaphores are quite powerful
  - Can solve mutual exclusion…
  - Can also provide **condition synchronization**
    - Thread waits until some condition is 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

Producer-Consumer Problem

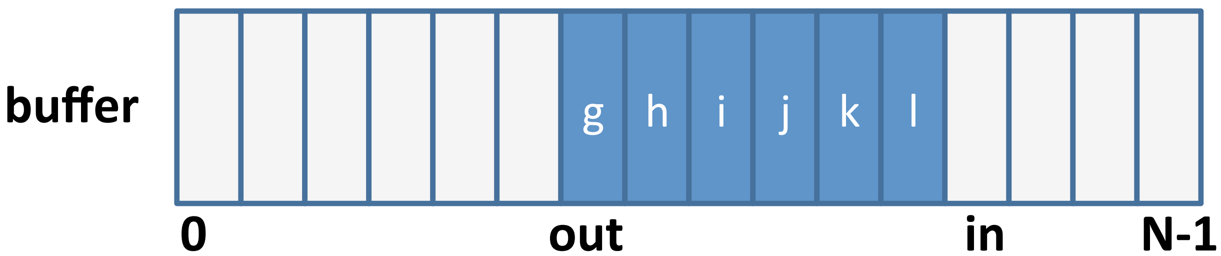
- Shared buffer B[] with N slots, initially empty
- Producer thread wants to:
  - Produce an item
  - If there's room, insert into next slot;
  - Otherwise, wait until there is room
- Consumer thread wants to:
  - If there's anything in buffer, remove an item (and consume it)
  - Otherwise, wait until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

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);
}
```

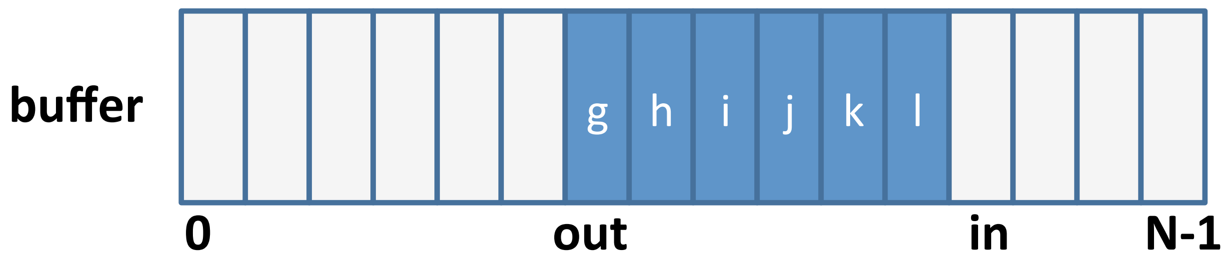


Producer-Consumer Solution

```
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);
}
```



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’)

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…

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

Multiple-Readers Single-Writer

- 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
- 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

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);
```

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 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);
```

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…