Concurrent systems

Lecture 3: Mutual exclusion, semaphores, and producer-consumer relationships

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(Thanks to Dr Robert N. M. Watson)

Reminder from last time

- Automata models of concurrent systems
- Concurrency hardware mechanisms

- Challenge: concurrent access to shared resources
- Mutual exclusion, race conditions, and atomicity
- Mutual exclusion locks (mutexes)

From first lecture

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

We spotted **race conditions** in obvious concurrent implementations.
Ad hoc solutions (e.g., leaving a note) failed.
Even naïve application of atomic operations failed.
Mutexes provide a general mechanism for mutual exclusion.

This time

- Implementing **mutual exclusion**
- Semaphores for mutual exclusion, condition synchronisation, and **resource allocation**
- Two-party and generalised **producer-consumer** relationships

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;
}
```

Semaphores

- Despite with atomic ops, busy waiting remains inefficient…
  - Lock contention with **spinning**-based solution wastes CPU cycles.
  - 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!)
- Can be used for **mutual exclusion** with sleeping
- Can also be used for **condition synchronisation**
  - Wake up another waiting thread on a **condition** or event
  - E.g., “There is an item available for processing in a queue”

Semaphore implementation

- Implemented as an integer and a queue

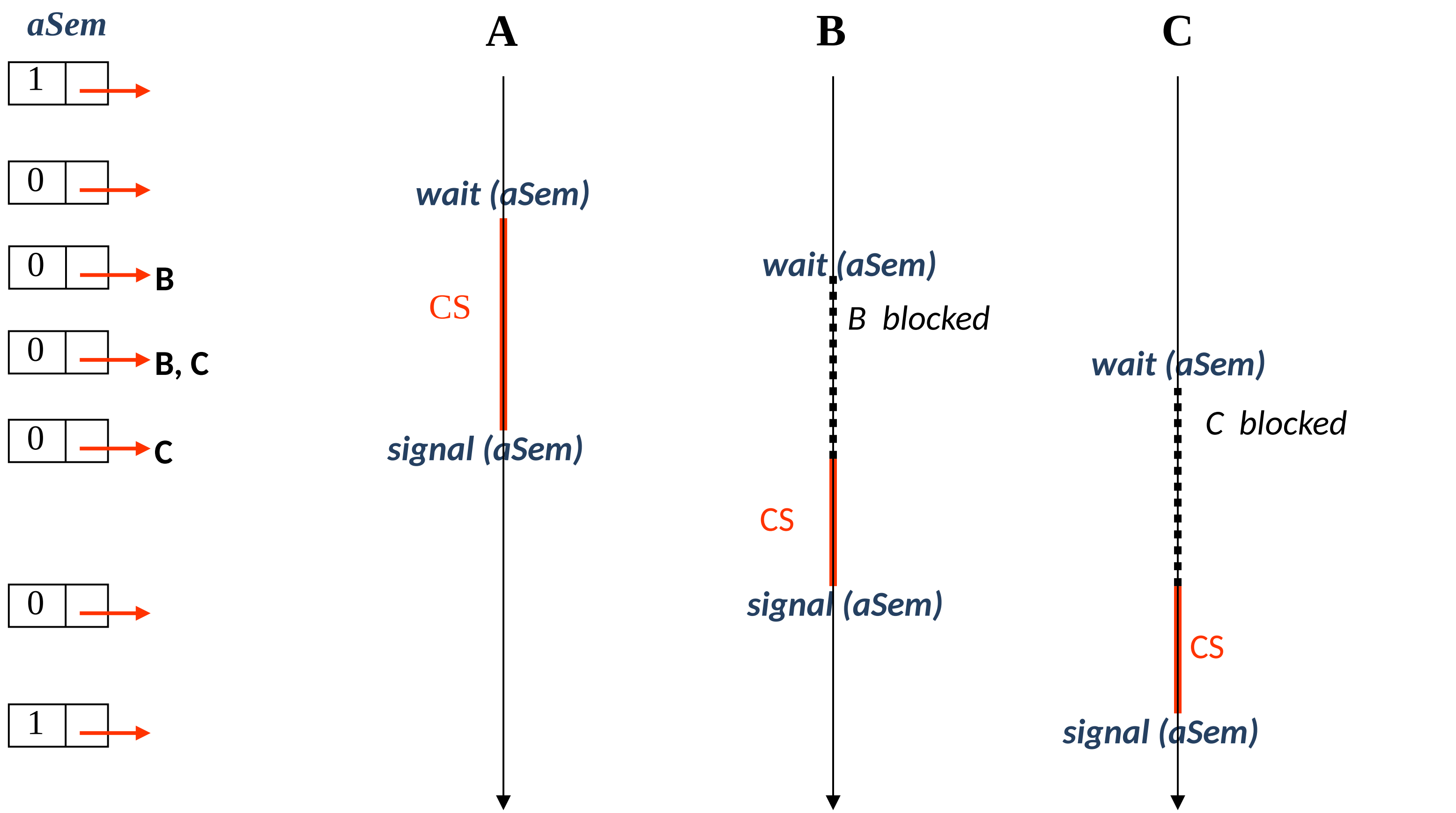
```
wait(sem) {
  if(sem > 0) {
     sem = sem - 1;
   } else suspend caller & add thread to queue for sem
}

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

- Method bodies are implemented **atomically**
- Think of “sem” as count of the number of available “items”
- “suspend” and “wake” invoke threading APIs

Hardware support for wakeups: IPIs

- CAS/LLSC/… support atomicity via shared memory
- But what about "**wake up thread**"?
  - E.g., notify waiter of resources now free, work now waiting, …
  - Generally known as **condition synchronisation**
  - 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)** **(aka Inter-Core Interrupt ICI)**
  - Mark thread as "runnable"
  - Send an interrupt to the target CPU
  - IPI handler runs thread scheduler, preempts running thread, triggers context switch
- Together, shared memory and IPIs support **atomicity** and **condition synchronisation** between processors

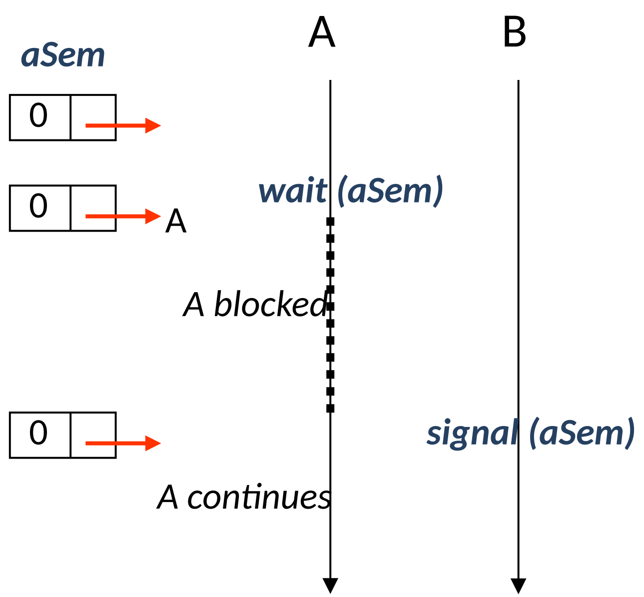
Mutual exclusion with a semaphore



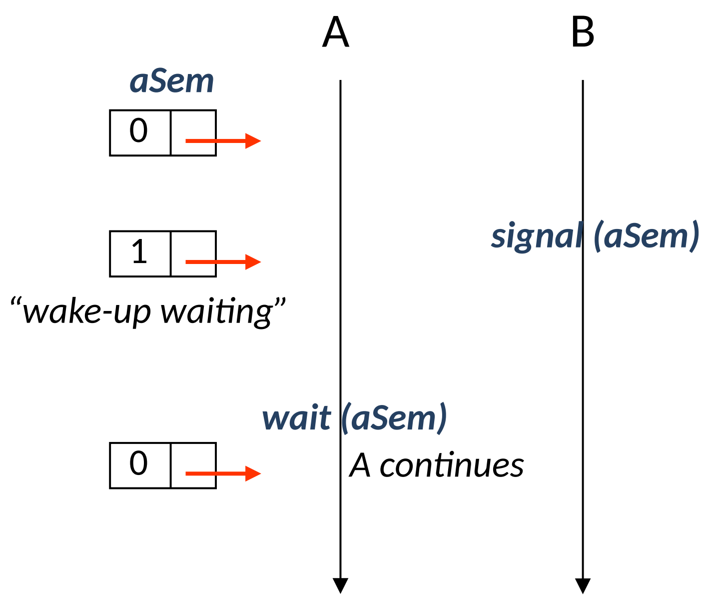
- Initialize semaphore to 1; **wait()** is lock(), **signal()** is unlock()

Condition synchronisation

wait before signal



signal before wait



- 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**
  - Any job wanting printer does **wait**(sem)
  - After **N** jobs get a printer, next will sleep
  - To release resource, **signal**(sem)
    - Will wake some job if any job is waiting.
- Will typically also require mutual exclusion
  - E.g. to decide which printers are free

Semaphore design patterns

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

Producer-consumer problem

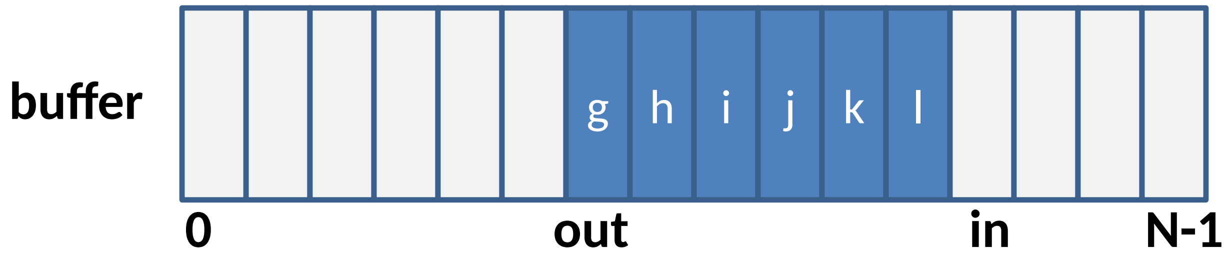
- General “pipe” concurrent programming paradigm
  - E.g. pipelines in Unix; staged servers; work stealing; download thread vs. rendering thread in web browser
- Shared buffer **B[]** with **N** slots, initially empty
- **Producer thread** wants to:
  - Produce an item
  - If there’s room, insert into next slot;
  - Otherwise, wait until there is room
- **Consumer thread** wants to:
  - If there’s anything in buffer, remove an item (+consume it)
  - Otherwise, wait until there is something
- Maintain order, use parallelism, avoid context switches

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);
}
```

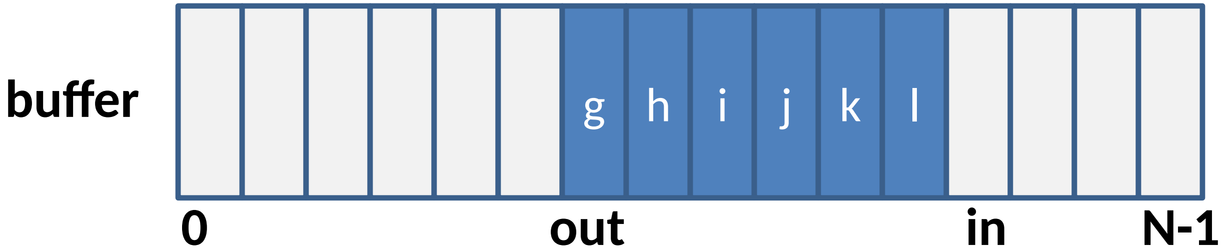


Producer-consumer solution

```
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**)
  - NB: **in** and **out** are each accessed solely in one of the producer (**in**) or consumer (**out**)

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
  - (Race conditions due to concurrent use of **in** and **out** precluded when just one thread on each end)
- 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);
}
```

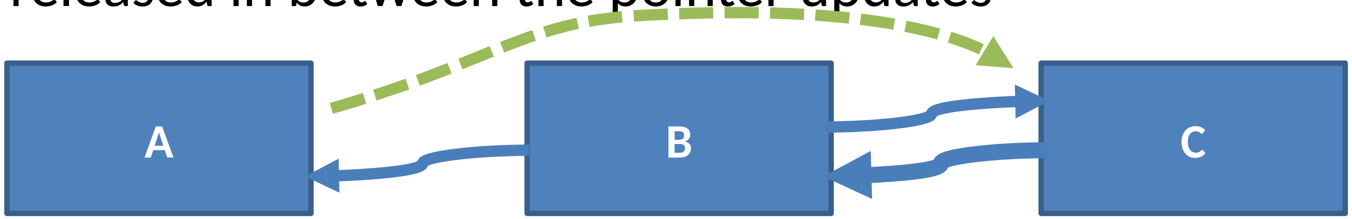
- Exercise: Can we modify this design to allow concurrent access by 1 producer and 1 consumer by adding one more semaphore?

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…

Mutual exclusion and invariants

- One important goal of locking is to avoid exposing **inconsistent intermediate states** to other threads
- This suggests an **invariants**-based strategy:
  - Invariants **hold** as mutex is acquired
  - Invariants **may be violated** while mutex is held
  - Invariants **must be restored** before mutex 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 pointer updates



Summary + next 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

- Next time:
  - Multi-Reader Single-Writer (MRSW) locks
  - Starvation and fairness
  - Alternatives to semaphores/locks
  - Concurrent primitives in practice