CS 422/522 Design & Implementation
of Operating Systems

Lectures 6-8: Synchronization

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Independent vs. cooperating threads

- Independent threads
  - **no state shared with other threads**
  - deterministic --- input state determines result
  - reproducible
  - scheduling order does not matter
  - still not fully isolated (may share files)
- Cooperating threads
  - **shared state**
  - non-deterministic
  - non-reproducible

Non-reproducibility and non-determinism means that bugs can be intermittent. This makes debugging really hard!

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Example: two threads, one counter

- A web site gets millions of hits a day. Uses multiple threads (on multiple processors) to speed things up.
- Simple shared state error: each thread increments a shared counter to track the number of hits today:

```
...
hits = hits + 1;
...
```

- What happens when two threads execute this code concurrently?

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Problem with shared counters

- One possible result: lost update!

hits = 0

time

T1

read hits (0)

hits = 0 + 1

T2

read hits (0)

hits = 0 + 1

hits = 1

- **One other possible result: everything works.**
  - Bugs are frequently intermittent. Makes debugging hard.
  - This is called “race condition”

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Race conditions

- Race condition: timing dependent error involving shared state.
  - whether it happens depends on how threads scheduled
- *Hard* because:
  - ***must make sure all possible schedules are safe***. Number of possible schedules permutations is huge.

```
if(n == stack_size)  /* A */
        return full;   /* B */
stack[n] = v;          /* C */
n = n + 1;             /* D */
```

    * Some bad schedules aaccdd, acadcd, … (how many?)
  - they are intermittent. Timing dependent = small changes (adding a print stmt, different machine) can hide bug.

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More race condition example:

Thread a:
```
i = 0;
while(i < 10)
i = i + 1;
print "A won!";
```

Thread b:
```
i = 0;
while(i > -10)
    i = i - 1;
print "B won!";
```

• Who wins?
• Guaranteed that someone wins?
• What if both threads on its own identical speed CPU executing in parallel? will it go on forever?

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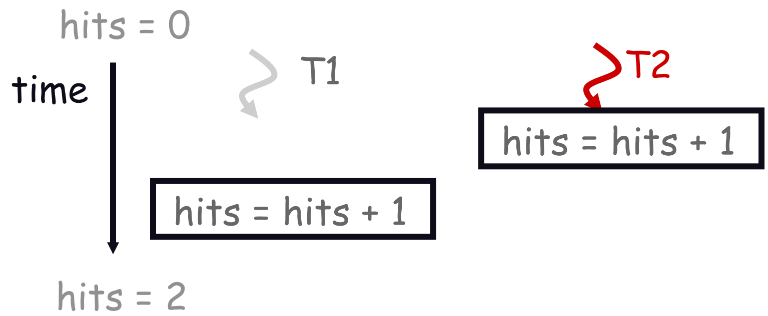
Preventing race conditions: atomicity

- atomic unit = instruction sequence guaranteed to execute indivisibly (also, a "critical section").
  - * If two threads execute the same atomic unit at the same time, one thread will execute the whole sequence before the other begins.



- How to make multiple inst's seem like one atomic one?

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Synchronization motivation

- When threads concurrently read/write shared memory, program behavior is undefined → race conditions
  - Two threads write to the same variable; which one should win?
- Thread schedule is non-deterministic
  - Behavior changes when re-run program
- Compiler/hardware instruction reordering
- Multi-word operations are not atomic

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Question: can this panic?

Thread 1	Thread 2

p = someComputation();
pInitialized = true;
	while (!pInitialized)
	    ;
	q = someFunction(p);
	if (q != someFunction(p))
	    panic

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Why reordering?

- Why do compilers reorder instructions?
  - Efficient code generation requires analyzing control/data dependency
  - If variables can spontaneously change, most compiler optimizations become impossible
- Why do CPUs reorder instructions?
  - Write buffering: allow next instruction to execute while write is being completed

Fix: **memory barrier**
  - Instruction to compiler/CPU
  - All ops before barrier complete before barrier returns
  - No op after barrier starts until barrier returns

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Example: the Too-Much-Milk problem

	Person A	Person B
3:00	Look in fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away
		Oh no !

Goal: 1. never more than one person buys
2. someone buys if needed

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Too much milk: solution #1

- Basic idea:
  - leave a note (kind of like "lock")
  - remove note (kind of like "unlock")
  - don't buy if there is a note (wait)

```
if (noMilk) {
  if (noNote) {
      leave Note;
      buy milk;
      remove Note
  }
}
```

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Why solution #1 does not work ?

	Thread A	Thread B
3:00	if (noMilk) {	
3:05	if (noNote) {	
3:10		if (noMilk) {
3:15		if (noNote) {
3:20	leave Note;	leave Note;
3:25	buy milk;	buy milk;
3:30	remove Note} }	remove Note } }

Threads can get context-switched at any time !

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Too much milk: solution #2

Thread A

```
leave NoteA
if (noNoteB) {
      if (noMilk)
           buy milk
 }
 remove NoteA
```

Thread B

```
leave NoteB
if (noNoteA) {
      if (noMilk)
           buy milk
 }
 remove NoteB
```

Problem: neither thread to buy milk --- think other is going to buy --- ***starvation !***

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Too much milk: solution #3

Thread A	Thread B
leave NoteA	leave NoteB
while (NoteB) // X	if (noNoteA) { // Y
do nothing;	if (noMilk)
if (noMilk)	buy milk;
buy milk;	}
remove NoteA	remove NoteB

Either safe for me to buy or others will buy !

It works but:

- **it is too complex**
- **A's code different from B's (what if lots of threads ?)**
- **A busy-waits --- consumes CPU !**

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A better solution

- Have hardware provide better primitives than atomic load and store.
- Build higher-level programming abstractions on this new hardware support.
- Example: using locks as an atomic building block

Acquire --- wait until lock is free, then grabs it
Release --- unlock, waking up a waiter if any

These must be atomic operations --- if two threads are waiting for the lock, and both see it is free, only one grabs it!

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Too much milk: using a lock

- It is really easy !

```
lock -> Acquire();
if (nomilk)
    buy milk;
lock -> Release();
```

- What makes a good solution?
  - Only one process inside a critical section
  - No assumption about CPU speeds
  - Processes outside of critical section should not block other processes
  - No one waits forever
  - Works for multiprocessors
- Future topics:
  - hardware support for synchronization
  - high-level synchronization primitives & programming abstraction
  - how to use them to write correct concurrent programs?

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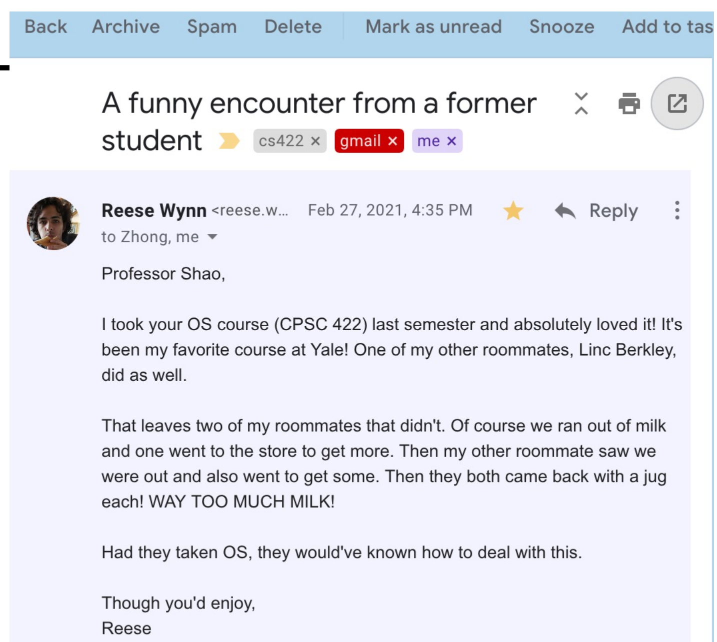
An ancedote



Professor Shao,

I took your OS course (CPSC 422) last semester and absolutely loved it! It's been my favorite course at Yale! One of my other roommates, Linc Berkley, did as well.

That leaves two of my roommates that didn't. Of course we ran out of milk and one went to the store to get more. Then my other roommate saw we were out and also went to get some. Then they both came back with a jug each! WAY TOO MUCH MILK!

Had they taken OS, they would've known how to deal with this.

Though you'd enjoy,
Reese

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A few definitions

- **Sychronization:**
  - using atomic operations to ensure cooperation between threads
- **Mutual exclusion:**
  - ensuring that only one thread does a particular thing at a time. One thread doing it excludes the other, and vice versa.
- **Critical section:**
  - piece of code that only one thread can execute at once. Only one thread at a time will get into the section of code.
- **Lock:** prevents someone from doing something
  - lock before entering critical section, before accessing shared data
  - unlock when leaving, after done accessing shared data
  - wait if locked

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A quick recap

- We talked about critical section

```
Acquire(lock);
if (noMilk)
  buy milk;
Release(lock);
```

Critical section

- We also talked about what is a good solution
  - Only one process inside a critical section
  - No assumption about CPU speeds
  - Processes outside of critical section should not block other processes
  - No one waits forever
  - Works for multiprocessors

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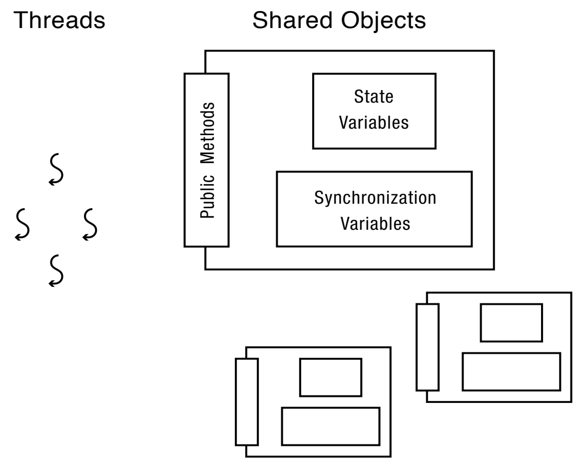
How to write concurrent programs?

Use shared objects (aka concurrent objects) --- always encapsulate (hide) its shared state



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The big picture

Concurrent Applications

Shared Objects

Bounded Buffer   Barrier

Synchronization Variables

Semaphores   Locks   Condition Variables

Atomic Instructions

Interrupt Disable   Test-and-Set

Hardware

Multiple Processors   Hardware Interrupts

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The big picture (cont'd)

- Shared object layer: all shared objects appear to have the same interface as those for a single-threaded program
- Synchronization variable layer: a synchronization variable is a data structure used for coordinating concurrent access to shared state
- Atomic instruction layer: atomic processor-specific instructions

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Locks

- Lock::acquire
  - wait until lock is free, then take it
- Lock::release
  - release lock, waking up anyone waiting for it

1. At most one lock holder at a time (safety)
2. If no one holding, acquire gets lock (progress)
3. If all lock holders finish and no higher priority waiters, waiter eventually gets lock (progress)

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Question: why only Acquire/Release

- Suppose we add a method to a lock, to ask if the lock is free. Suppose it returns true. Is the lock:
  - Free?
  - Busy?
  - Don't know?

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Lock example: malloc/free

```
char *malloc (n) {
    heaplock.acquire();
    p = allocate memory
    heaplock.release();
    return p;
}
```

```
void free(char *p) {
    heaplock.acquire();
    put p back on free list
    heaplock.release();
}
```

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Rules for using locks

- Lock is initially free
- Always acquire before accessing shared data structure
  - Beginning of procedure!
- Always release after finishing with shared data
  - End of procedure!
  - Only the lock holder can release
  - DO NOT throw lock for someone else to release
- Never access shared data without lock
  - Danger!

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Will this code work?

```
if (p == NULL) {
    lock.acquire();
    if (p == NULL) {
        p = newP();
    }
    lock.release();
}
use p->field1
```

```
newP() {
    p = malloc(sizeof(p));
    p->field1 = …
    p->field2 = …
    return p;
}
```

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Example: thread-safe bounded queue

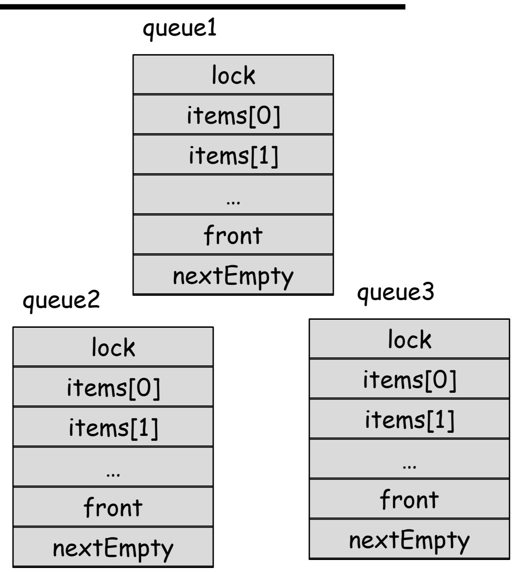
```
// Thread-safe queue interface

const int MAX = 10;

class TSQueue {
  // Synchronization variables
    Lock lock;

  // State variables
    int items[MAX];
    int front;
    int nextEmpty;

  public:
    TSQueue();
    ~TSQueue(){};
    bool tryInsert(int item);
    bool tryRemove(int *item);
};
```



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Example: thread-safe bounded queue

```
// Initialize the queue to empty
// and the lock to free.
TSQueue::TSQueue() {
   front = nextEmpty = 0;
}

// Try to insert an item.
// If the queue is full, return false;
// otherwise return true.

bool TSQueue::tryInsert(int item) {
   bool success = false;

   lock.acquire();
   if ((nextEmpty - front) < MAX) {
      items[nextEmpty % MAX] = item;
      nextEmpty++;
      success = true;
   }
   lock.release();
   return success;
}
```

```
// Try to remove an item. If the queue
// is empty, return false;
// otherwise return true.

bool TSQueue::tryRemove(int *item) {
   bool success = false;

   lock.acquire();
   if (front < nextEmpty) {
      *item = items[front % MAX];
      front++;
      success = true;
   }
   lock.release();
   return success;
}
```

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Example: thread-safe bounded queue

The lock holder always maintain the following invariants when releasing the lock:

- The total number of items ever inserted in the queue is nextEmpty.
- The total number of items ever removed from the queue is front.
- front <= nextEmpty
- The current number of items in the queue is nextEmpty – front
- nextEmpty – front <= MAX

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Example: thread-safe bounded queue

```
// TSQueueMain.cc
//   Test code for TSQueue.
int main(int argc, char **argv) {
    TSQueue *queues[3];
    sthread_t workers[3];
    int i, j;

    // Start worker threads to insert.
    for (i = 0; i < 3; i++) {
        queues[i] = new TSQueue();
        thread_create(&workers[i],
                putSome, queues[i]);
    }

    // Wait for some items to be put.
    thread_join(workers[0]);

    // Remove 20 items from each queue.
    for (i = 0; i < 3; i++) {
        printf("Queue %d:\n", i);
        testRemoval(&queues[i]);
    }
}
```

```
// Insert 50 items into a queue.
void *putSome(void *p) {
    TSQueue *queue = (TSQueue *)p;
    int i;

    for (i = 0; i < 50; i++) {
        queue->tryInsert(i);
    }
    return NULL;
}

// Remove 20 items from a queue.
void testRemoval(TSQueue *queue) {
    int i, item;

    for (i = 0; i < 20; j++) {
        if (queue->tryRemove(&item))
          printf("Removed %d\n", item);
        else
          printf("Nothing there.\n");
        }
    }
}
```

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How to use the lock ?

- The lock provides mutual exclusion to the shared data
- Rules for using a lock:
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock is initially free.
- Simple example: a synchronized queue

```
bool tryInsert()
{
   lock.Acquire();          // lock before use
   … put item on queue;     // ok to access
   lock.Release();          // unlock after done
   return success;
}
```

```
bool tryRemove()
{  …
   lock.Acquire();
   if something on queue          // can we wait?
        remove it;
   lock->Release();
   return success;
}
```

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Condition variables

- How to make tryRemove wait until something is on the queue?
  - can't sleep while holding the lock
  - Key idea: make it possible to go to sleep inside critical section, by atomically releasing lock at same time we go to sleep.
- **Condition variable**: *a queue of threads waiting for something inside a critical section.*
  - **Wait()** --- Release lock, go to sleep, re-acquire lock
    - release lock and going to sleep is atomic
  - **Signal()** --- Wake up a waiter, if any
  - **Broadcast()** --- Wake up all waiters

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Synchronized queue using condition variables

- **Rule:** must hold lock when doing condition variable operations

```
AddToQueue()
{
   lock.acquire();

   put item on queue;
   condition.signal();

   lock.release();
}
```

```
RemoveFromQueue()
{
   lock.acquire();

   while nothing on queue
     condition.wait(&lock);
               // release lock; got to
               // sleep; reacquire lock

   remove item from queue;
   lock.release();
   return item;
}
```

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Condition variable design pattern

```
methodThatWaits() {
   lock.acquire();

   // Read/write shared state

   while (!testSharedState()) {
       cv.wait(&lock);
   }

   // Read/write shared state

   lock.release();
}
```

```
methodThatSignals() {
   lock.acquire();

   // Read/write shared state

   // If testSharedState is now true
   cv.signal(&lock);

   // Read/write shared state

   lock.release();
}
```

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Example: blocking bounded queue

```
// Thread-safe blocking queue.

const int MAX = 10;

class BBQ{
  // Synchronization variables
    Lock lock;
    CV itemAdded;
    CV itemRemoved;

  // State variables
    int items[MAX];
    int front;
    int nextEmpty;

  public:
    BBQ();
    ~BBQ() {};
    void insert(int item);
    int remove();
};
```

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Example: blocking bounded queue

```
//Wait until there is room and
// then insert an item.

void BBQ::insert(int item) {

   lock.acquire();
    while ((nextEmpty - front) == MAX) {
        itemRemoved.wait(&lock);
    }

    items[nextEmpty % MAX] = item;
    nextEmpty++;
    itemAdded.signal();

    lock.release();
}
```

```
// Wait until there is an item and
// then remove an item.
int BBQ::remove() {
    int item;

    lock.acquire();
    while (front == nextEmpty) {
        itemAdded.wait(&lock);
    }
    item = items[front % MAX];
    front++;
    itemRemoved.signal();
    lock.release();
    return item;
}

// Initialize the queue to empty,
// the lock to free, and the
// condition variables to empty.
BBQ::BBQ() {
    front = nextEmpty = 0;
}
```

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Pre/Post conditions & invariants

- What is state of the blocking bounded queue at lock acquire?
  - front <= nextEmpty
  - front + MAX >= nextEmpty
- These are also true on return from wait
- And at lock release
- Allows for proof of correctness

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Pre/Post conditions & invariants

```
methodThatWaits() {
   lock.acquire();
   // Pre-condition: State is consistent

   // Read/write shared state

   while (!testSharedState()) {
       cv.wait(&lock);
    }
   // WARNING: shared state may
   // have changed!  But
  // testSharedState is TRUE
  // and pre-condition is true

  // Read/write shared state
   lock.release();
}
```

```
methodThatSignals() {
   lock.acquire();
   // Pre-condition: State is consistent

   // Read/write shared state

   // If testSharedState is now true
   cv.signal(&lock);

   // NO WARNING: signal keeps lock

   // Read/write shared state
   lock.release();
}
```

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Condition variables

- ALWAYS hold lock when calling wait, signal, broadcast
  - Condition variable is sync FOR shared state
  - ALWAYS hold lock when accessing shared state
- Condition variable is memoryless
  - If signal when no one is waiting, no op
  - If wait before signal, waiter wakes up
- Wait atomically releases lock
  - What if wait, then release?
  - What if release, then wait?

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Question 1: wait replaced by unlock + sleep?

```
methodThatWaits() {
   lock.acquire();

   // Read/write shared state

   while (!testSharedState()) {
       lock.release()
       cv.sleep(&lock);
    }

   // Read/write shared state

   lock.release();
}
```

```
methodThatSignals() {
   lock.acquire();

   // Read/write shared state

   // If testSharedState is now true
   cv.signal(&lock);

   // Read/write shared state

   lock.release();
}
```

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Question 2: wait does not acquire lock?

```
methodThatWaits() {
   lock.acquire();

   // Read/write shared state

   while (!testSharedState()) {
       cv.wait (&lock);
       lock.acquire();
    }

   // Read/write shared state

   lock.release();
}
```

```
methodThatSignals() {
   lock.acquire();

   // Read/write shared state

   // If testSharedState is now true
   cv.signal(&lock);

   // Read/write shared state

   lock.release();
}
```

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Condition variables, cont'd

- When a thread is woken up from wait, it may not run immediately
  - Signal/broadcast put thread on ready list
  - When lock is released, anyone might acquire it
- Wait MUST be in a loop

```
while (needToWait()) {
     condition.Wait(lock);
}
```

- Simplifies implementation
  - Of condition variables and locks
  - Of code that uses condition variables and locks

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Structured synchronization

- Identify objects or data structures that can be accessed by multiple threads concurrently
- Add locks to object/module
  - Grab lock on start to every method/procedure
  - Release lock on finish
- If need to wait
  - while(needToWait()) { condition.Wait(lock); }
  - Do not assume when you wake up, signaller just ran
- If do something that might wake someone up
  - Signal or Broadcast
- Always leave shared state variables in a consistent state
  - When lock is released, or when waiting

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Monitors and condition variables

- Monitor definition:
  - *a lock and zero or more condition variables for managing concurrent access to shared data*
- Monitors make things easier:
  - "locks" for mutual exclusion
  - "condition variables" for scheduling constraints

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Monitors embedded in prog. languages (1)

- High-level data abstraction that unifies handling of:
  - Shared data, operations on it, synch and scheduling
    * All operations on data structure have single (implicit) lock
    * An operation can relinquish control and wait on condition

```
// only one process at time can update instance of Q
class Q {
        int head, tail;  // shared data
        void enq(v) { locked access to Q instance }
        int deq() { locked access to Q instance }
}
```

  - Java from Sun; Mesa/Cedar from Xerox PARC
- Monitors easier and safer than semaphores
  - Compiler can check, lock implicit (cannot be forgotten)

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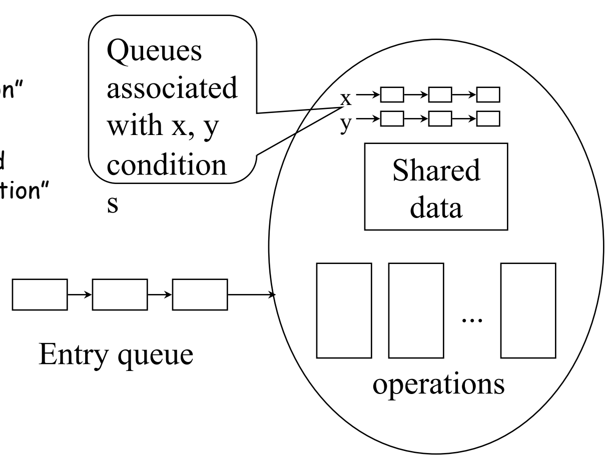
Monitors embedded in prog. languages (2)

- Wait()
  - Block on "condition"
- Signal()
  - Wakeup a blocked process on "condition"



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Java language manual

When waiting upon a Condition, a “spurious wakeup” is permitted to occur, in general, as a concession to the underlying platform semantics. This has little practical impact on most application programs as a Condition should always be waited upon in a loop, testing the state predicate that is being waited for.

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Remember the rules

- Use consistent structure
- Always use locks and condition variables
- Always acquire lock at beginning of procedure, release at end
- Always hold lock when using a condition variable
- Always wait in while loop
- Never spin in sleep()

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Mesa vs. Hoare semantics

- Mesa
  - Signal puts waiter on ready list
  - Signaller keeps lock and processor
- Hoare
  - Signal gives processor and lock to waiter
  - When waiter finishes, processor/lock given back to signaller
  - Nested signals possible!

- For Mesa-semantics, you always need to check the condition after wait (use "while"). For Hoare-semantics you can change it to "if"

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The big picture: more examples

Concurrent Applications

Shared Objects

Bounded Buffer Barrier

Synchronization Variables

Semaphores Locks Condition Variables

Atomic Instructions

Interrupt Disable Test-and-Set

Hardware

Multiple Processors Hardware Interrupts

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Producer-consumer with monitors

```
Condition full;
Condition empty;
Lock lock;

Producer() {
   lock.Acquire();

   while (the buffer is full)
           full.wait(&lock);

   put 1 Coke in machine;

   if (the buffer was empty)
           empty.signal();
   lock.Release();
}
```

```
Consumer() {
   lock.Acquire();

   while (the buffer is empty)
           empty.wait(&lock);

   take 1 Coke;

   if (the buffer was full)
           full.signal();
   lock.Release();
}
```

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Example: the readers/writers problem

- Motivation
  - shared database (e.g., bank balances / airline seats)
  - Two classes of users:
    - * Readers --- never modify database
    - * Writers --- read and modify database
  - Using a single lock on the database would be overly restrictive
    - * want many readers at the same time
    - * only one writer at the same time
- Constraints
    - * Readers can access database when no writers (Condition okToRead)
    - * Writers can access database when no readers or writers (Condition okToWrite)
    - * Only one thread manipulates state variable at a time

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Design specification (readers/writers)

- Reader
  - wait until no writers
  - access database
  - check out - wake up waiting writer
- Writer
  - wait until no readers or writers
  - access data base
  - check out --- wake up waiting readers or writer
- State variables
  - # of active readers (AR); # of active writers (AW);
  - # of waiting readers (WR); # of waiting writers (WW);
- Lock and condition variables: **okToRead, okToWrite**

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Solving readers/writers

```
Reader() {
  // first check self into system
  lock.Acquire();
  while ((AW+WW) > 0) {
     WR ++;
     okToRead.Wait(&lock);
     WR --;
  }
  AR++;
  lock.Release();

   Access DB;

   // check self out of system
   lock.Acquire();
   AR--;
   if (AR == 0 && WW > 0)
         okToWrite.Signal(&lock);
   lock.Release();
}
```

```
Writer() {
  // first check self into system
  lock.Acquire();
  while ((AW+AR) > 0) {
     WW ++;
     okToWrite.Wait(&lock);
     WW --;
  }
  AW++;
  lock.Release();

   Access DB;

   // check self out of system
   lock.Acquire();
   AW--;
   if (WW > 0)  okToWrite.Signal(&lock);
     else if (WR > 0) okToRead.Broadcast(&lock);
   lock.Release();
}
```

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Example: the one-way-bridge problem

- Problem definition
  - a narrow light-duty bridge on a public highway
  - traffic cross in one direction at a time
  - at most 3 vehicles on the bridge at the same time (otherwise it will collapses)
- Each car is represented as one thread:

```
OneVechicle (int direc)
{
   ArriveBridge (direc);
   … crossing the bridge …;
   ExitBridge(direc);
}
```

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One-way bridge with condition variables

```
Lock lock;
Condition safe;          // safe to cross bridge
int currentNumber;    // # of cars on bridge
int currentDirec;       // current direction

ArriveBridge(int direc) {
  lock.Acquire();
  while (! safe-to-cross(direc)) {
     safe.wait(lock)
  }
  currentNumber++;
  currentDirec = direc;
  lock.Release();
}
```

```
ExitBridge(int direc) {
   lock.Acquire();
   currentNumber--;
   safe.signal(lock);
   lock.Release();
}

safe-to-cross(int direc) {
    if (currentNumber == 0)
       return TRUE;    // always safe if empty
    else if ( (currentNumber < 3) &&
             (currentDirec == direc) )
       return TRUE;
    else
       return FALSE;
}
```

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The mating-whales problem

- You have been hired by Greenpeace to help the environment. Because unscrupulous commercial interests have dangerously lowered the whale population, whales are having synchronization problems in finding a mate.
- To have children, **three whales** are needed, one male, one female, and one to play matchmaker --- literally, to push the other two whales together (I'm not making this up!).
- Write the three procedures:

```
void Male()
void Female()
void Matchmaker()
```

using **locks** and **Mesa-style condition variables**. Each whale is represented by a separate thread. A male whale calls `Male()` which waits until there is a waiting female and matchmaker; similarly, a female whale must wait until a male whale and a matchmaker are present. Once all three are present, all three return.

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Step 1 --- two-way rendezvous

```
Lock*  lock;
Condition*  malePresent;
Condition*  maleToGo;
int numMale = 0;
bool maleCanGo = FALSE;

void Male() {
  lock->Acquire();
  numMale++;
  malePresent->Signal();

  while (! maleCanGo)  {
     maleToGo->Wait(lock);
  }
  maleCanGo = FALSE;
  lock->Release()
}
```

```
void MatchMaker() {
  lock->Acquire();

  while (numMale == 0) {
     malePresent->Wait(lock);
  }
  numMale--;

  maleCanGo = TRUE;
  maleToGo->Signal();

  lock->Release()
}
```

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Step 2 --- three-way rendezvous

```
Lock*  lock;
Condition*  malePresent;
Condition*  maleToGo;
int numMale = 0;
bool maleCanGo = FALSE;
```

```
Condition*  femalePresent;
Condition*  femaleToGo;
int numFemale = 0;
bool femaleCanGo = FALSE
```

```
void Male() {
   lock->Acquire();
   numMale++;
   malePresent->Signal();
   while (! maleCanGo)  {
       maleToGo->Wait(lock);
   }
   maleCanGo = FALSE;
   lock->Release()
}
```

```
void Female() {
   lock->Acquire();
   numFemale++;
   femalePresent->Signal();
   while (! femaleCanGo)  {
       femaleToGo->Wait(lock);
   }
   femaleCanGo = FALSE;
   lock->Release()
}
```

```
void MatchMaker() {
   lock->Acquire();

   while (numMale == 0) {
       malePresent->Wait(lock);
   }
   numMale--;
   while (numFemale == 0) {
       femalePresent->Wait(lock);
   }
   maleCanGo = TRUE;
   maleToGo->Signal();
   numFemale--;
   femaleCanGo = TRUE;
   femaleToGo->Signal();

   lock->Release()
}
```

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Step 3 --- a simplified version

```
Lock*  lock;

Condition*  malePresent;
Condition*  maleToGo;
int numMale = 0;

Condition*  femalePresent;
Condition*  femaleToGo;
int numFemale = 0;
```

```
void Male() {
   lock->Acquire();
   numMale++;
   malePresent->Signal();
   maleToGo->Wait(lock);
   lock->Release();
}

void Female() {
   lock->Acquire();
   numFemale++;
   femalePresent->Signal();
   femaleToGo->Wait(lock);
   lock->Release()
}
```

```
void MatchMaker() {
   lock->Acquire();

   while (numMale == 0) {
       malePresent->Wait(lock);
   }
   numMale--;
   while (numFemale == 0) {
       femalePresent->Wait(lock);
   }

   maleToGo->Signal();
   ~~numMale--;~~
   femaleToGo->Signal();
   numFemale--;

   lock->Release()
}
```

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Example: A MapReduce single-use barrier

```
// A single use synch barrier.
class Barrier{
  private:
    // Synchronization variables
    Lock lock;
    CV allCheckedIn;

    // State variables
    int numEntered;
    int numThreads;

  public:
    Barrier(int n);
    ~Barrier();
    void checkin();
};

Barrier::Barrier(int n) {
    numEntered = 0;
    numThreads = n;
}
```

```
// No one returns until all threads
// have called checkin.
void checkin() {
    lock.acquire();
    numEntered++;
    if (numEntered < numThreads) {
        while (numEntered < numThreads)
        allCheckedIn.wait(&lock);
    } else { // last thread to checkin
        allCheckedIn.broadcast();
    }
    lock.release();
}
```

Create n threads; Create barrier;

Each thread executes map operation;
barrier.checkin();

Each thread sends data to reducers;
barrier.checkin();

Each thread executes reduce operation;
barrier.checkin();

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Example: A reusable synch barrier

```
class Barrier{
  private:
    // Synchronization variables
    Lock lock;
    CV allCheckedIn;
    CV allLeaving;

    // State variables
    int numEntered;
    int numLeaving;
    int numThreads;

  public:
    Barrier(int n);
    ~Barrier();
    void checkin();
};
Barrier::Barrier(int n) {
    numEntered = 0;
    numLeaving = 0;
    numThreads = n;
}
```

```
// No one returns until all threads have called checkin.
void checkin() {
    lock.acquire();
    numEntered++;
    if (numEntered < numThreads) {
        while (numEntered < numThreads)
            allCheckedIn.wait(&lock);
    } else {
        // no threads in allLeaving.wait
        numLeaving = 0;
        allCheckedIn.broadcast();
    }
    numLeaving++;
    if (numLeaving < numThreads) {
        while (numLeaving < numThreads)
            allLeaving.wait(&lock);
    } else {
        // no threads in allCheckedIn.wait
        numEntered = 0;
        allLeaving.broadcast();
    }
    lock.release();
}
```

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Example: blocking bounded queue [review]

```
// Thread-safe blocking queue.

const int MAX = 10;

class BBQ{
  // Synchronization variables
    Lock lock;
    CV itemAdded;
    CV itemRemoved;

  // State variables
    int items[MAX];
    int front;
    int nextEmpty;

  public:
    BBQ();
    ~BBQ() {};
    void insert(int item);
    int remove();
};
```

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Example: blocking bounded queue [review]

```
//Wait until there is room and
// then insert an item.

void BBQ::insert(int item) {

   lock.acquire();
    while ((nextEmpty - front) == MAX) {
        itemRemoved.wait(&lock);
    }

    items[nextEmpty % MAX] = item;
    nextEmpty++;
    itemAdded.signal();

    lock.release();
}
```

```
// Wait until there is an item and
// then remove an item.
int BBQ::remove() {
    int item;

    lock.acquire();
    while (front == nextEmpty) {
        itemAdded.wait(&lock);
    }
    item = items[front % MAX];
    front++;
    itemRemoved.signal();
    lock.release();
    return item;
}

// Initialize the queue to empty,
// the lock to free, and the
// condition variables to empty.
BBQ::BBQ() {
    front = nextEmpty = 0;
}
```

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Starvation-Free (FIFO) BBQ [Fig. 5.14 OSPP]

```
ConditionQueue insertQueue, removeQueue;
int numRemoveCalled = 0; // # of times remove has been called
int numInsertCalled = 0; // # of times insert has been called

int FIFOBBQ::remove() {
    int item, myPosition;
    CV *myCV, *nextWaiter;

    lock.acquire();
    myPosition = numRemoveCalled++;
    myCV = new CV;  // Create a new condition variable to wait on.
    removeQueue.append(myCV);

    // Even if I am woken up, wait until it is my turn.
    while (front < myPosition || front == nextEmpty) {
        myCV->Wait(&lock);
    }

    delete myCV;    // The condition variable is no longer needed.
    item = items[front % MAX];
    front++;

    // Wake up the next thread waiting in insertQueue, if any.
    nextWaiter = insertQueue.removeFromFront();
    if (nextWaiter != NULL)   nextWaiter->Signal(&lock);

    lock.release();
    return item;
}
```

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Starvation-Free (FIFO) BBQ (cont'd)

```
ConditionQueue insertQueue, removeQueue;
int numRemoveCalled = 0; // # of times remove has been called
int numInsertCalled = 0; // # of times insert has been called

void FIFOBBQ::insert(int item) {
   int myPostition;
   CV *myCV, nextWaiter;

   lock.acquire ();
   myPosition = numInsertCalled++;
   myCV = new CV;
   insertQueue.append(myCV);

   while (nextEmpty < myPosition || (nextEmpty - front) == MAX) {
         myCV->wait(&lock);
   }

   delete myCV;
   items[nextEmpty % MAX] = item;
   nextEmpty ++;

   nextWaiter = removeQueue.removeFromFront();
   if (nextWaiter != NULL) nextWaiter->Signal();
   lock.release();
}
```

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Starvation-Free (FIFO) BBQ

- Bug 1: keeping destroyed CVs inside the removeQueue
  - Buffer size MAX=1, one producer and one consumer
  - Producer inserts one item when the buffer is empty
  - Producer tries to insert again and sleep on a 2nd allocated CV
  - Consumer calls remove successfully and wakes up the first CV in the insertQueue; the CV is NULL, so Consumer moves on;
  - Consumer calls removes again but had to sleep because the buffer is empty.
- Bug 2: starvation when multiple CVs are waken up
  - Buffer size MAX=2; one producer and two consumers (C1,C2)
  - Two consumers run first and sleeps on empty buffer
  - Producer inserts one item and wakes up C1; P inserts another one and wakes up C2;
  - C2 is scheduled first; but (front < myPosition), so it is not C2's turn; so it goes to sleep; then C1 finishes; C2 will never wake up

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Starvation-Free (FIFO) BBQ [Bug Fixed]

```
int FIFOBBQ::remove () {
   int item,myPostition;
   CV *myCV,*nextWaiter;

   lock.acquire ();
   myPosition = numRemoveCalled++;
   myCV = new CV;
   removeQueue.append(myCV);

   while (front < myPosition || front == nextEmpty) {
      myCV->wait(&lock);
   }

   delete myCV;
   item = items[front % MAX];
   front ++;

   nextWaiter = insertQueue.peekFront();
   if (nextWaiter != NULL) nextWaiter->Signal();

   removeQueue.removeFromFront();   // the remover now responsible for removing itself from the removeQueue
   nextWaiter = removeQueue.peekFront(); // the remover responsible for waking up the next in the removeQueue
   if (nextWaiter != NULL) nextWaiter->Signal();

   lock.release();
   return item;
}
```

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