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!

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?

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"

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.

More race condition example:

Thread a:

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

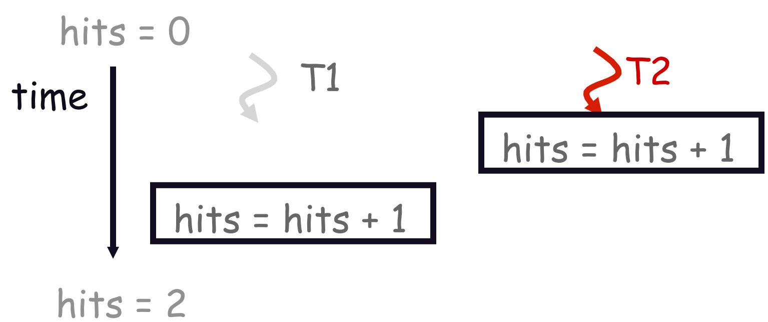
Thread b:

```
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?

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?

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

Question: can this panic?

Thread 1	Thread 2

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

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

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

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
  }
}
```

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 !

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 !***

Too much milk: solution #3

Thread A

```
leave NoteA
while (NoteB)        // X
     do nothing;
if (noMilk)
     buy milk;
 remove NoteA
```

Thread B

```
leave NoteB
if (noNoteA) {        // Y
     if (noMilk)
          buy milk;
}
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 !**

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!

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?

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

A quick recap

- We talked about critical section

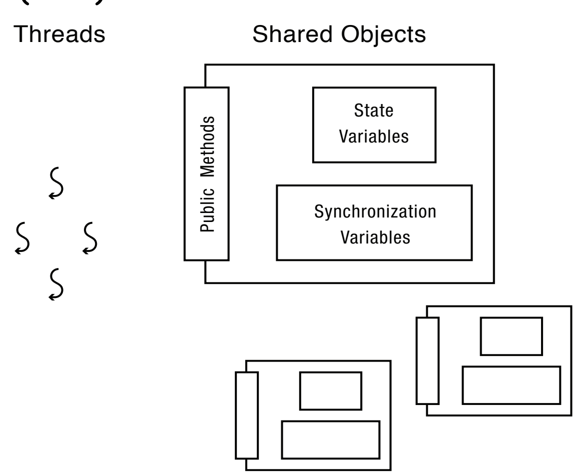
```
Acquire(lock);
if (noMilk)
  buy milk;
Release(lock);
```

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

How to write concurrent programs?

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



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

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)

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?

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();
}
```

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!

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;
}
```

Example: thread-safe bounded queue

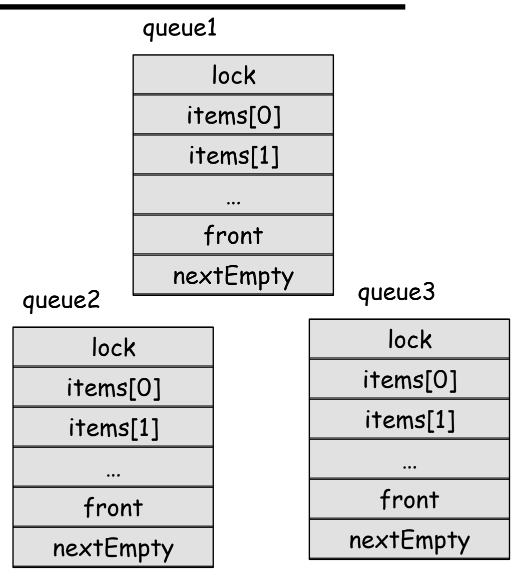
```
// Thread-safe queue interface

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);
};
```



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;
}
```

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

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");
   }
}
}
```

The big picture

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Semaphores   Locks   Condition Variables

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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;
}
```

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

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;
}
```

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();
}
```

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();
};
```

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;
}
```

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

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();
}
```

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?

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();
}
```

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();
}
```

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

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

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

Monitors embedded in prog. languages (1)

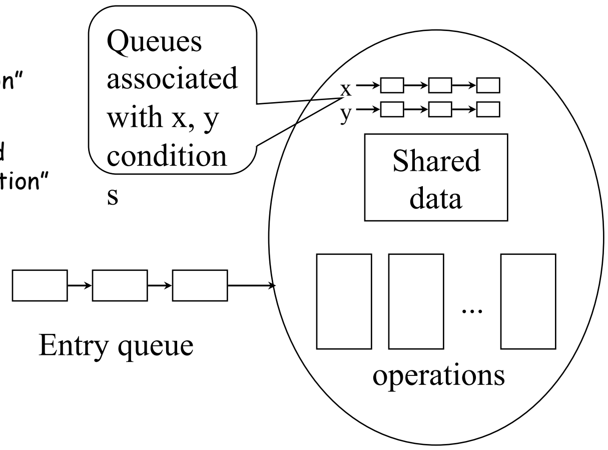
- High-level data abstraction that unifies handling of:
  - Shared data, operations on it, synch and scheduling
    - All operations on data structure have single (implicit) lock
    - An operation can relinquish control and wait on condition

```
// 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)

Monitors embedded in prog. languages (2)

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



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.

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()

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”

The big picture: more examples

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Semaphores Locks Condition Variables

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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();
}
```

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

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**

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();
}
```

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);
}
```

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;
}
```

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.

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);
   }

   maleCanGo = TRUE;
   maleToGo->Signal();
   numMale--;

   lock->Release()
}
```

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

   lock->Release()
}
```

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

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

   lock->Release()
}
```

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();

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();
}
```

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();
};
```

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;
}
```

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;
}
```

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();
}
```

Starvation-Free (FIFO) BBQ

- Bug 1: keeping destroyed CVs inside the removeQueue
  - Buffer size MAX=1, one producer and one consumer
  - Producer insets 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

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;
}
```