

Operating Systems

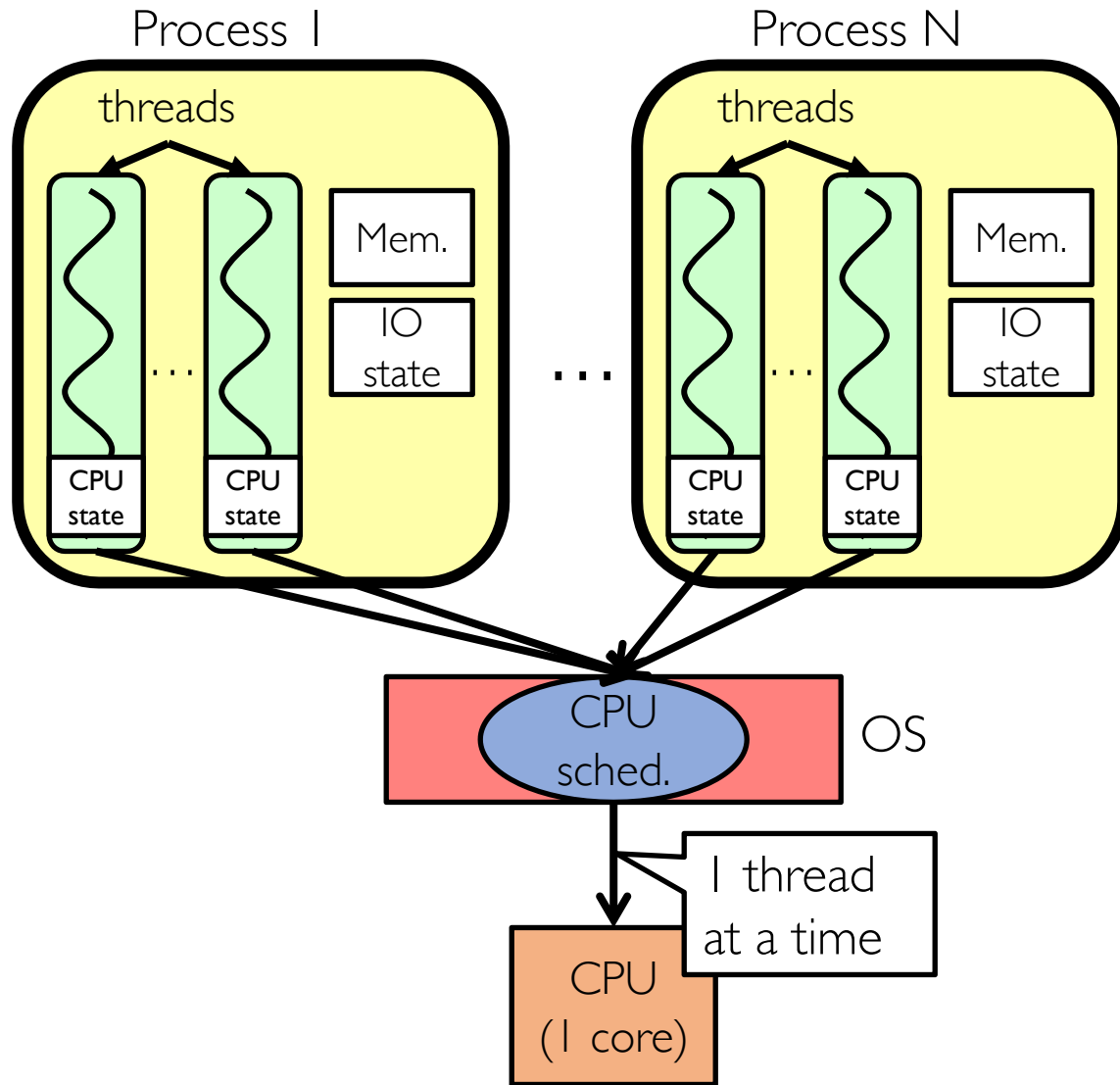
Lecture 10

lock and conditional variable design

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Much of the contents are from Prof. Ion Stoica (cs162@Berkeley)

OS Conceptual Framework

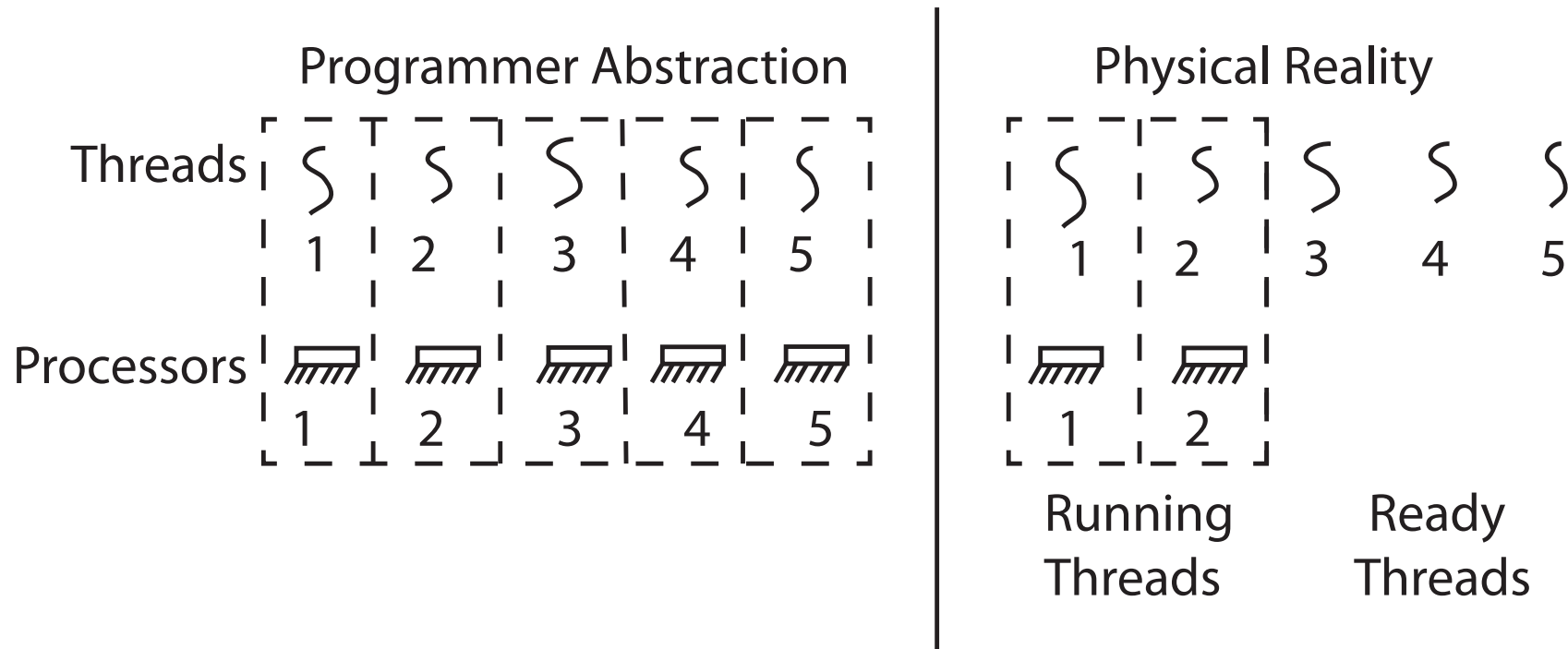


- Physical addresses shared
 - **So:** Processes and Address Translation
- CPU must be Shared
 - **So:** Threads
- Processes aren't trusted
 - **So:** Kernel/Userspace Split
- Threads might not cooperate
 - **So:** Use timer interrupts to context switch ("preemption")

Goals for Today

- Motivating synchronization: why it's difficult
- Locks
- Condition variables
- Semaphores

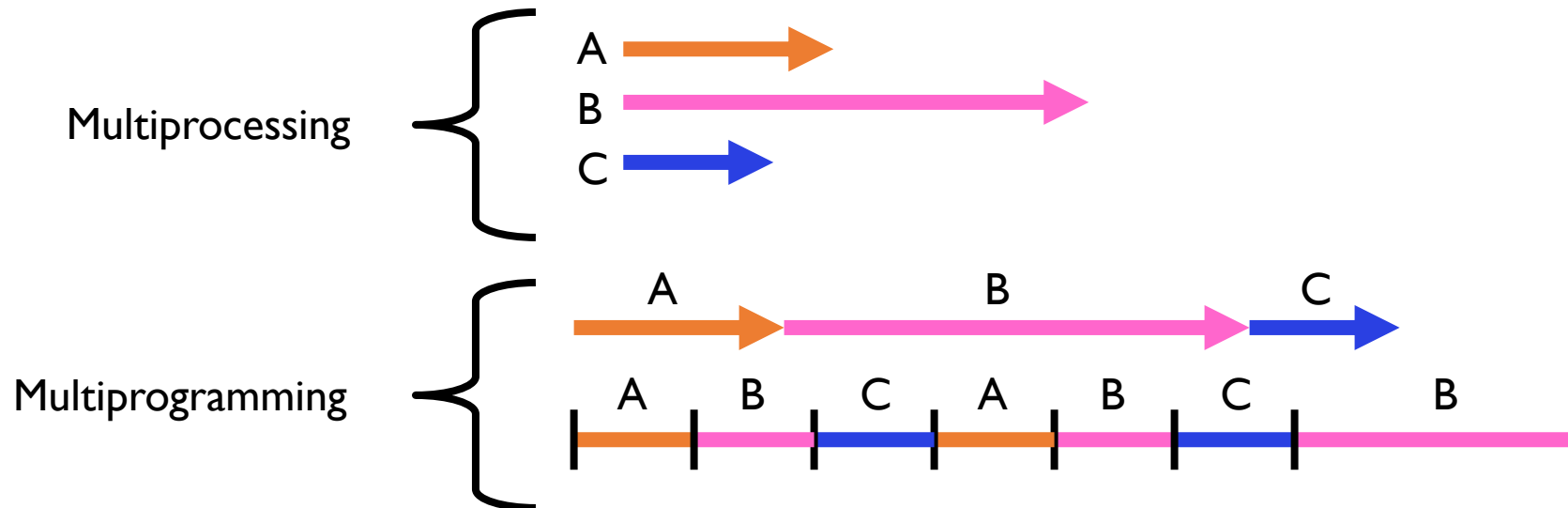
Recall: Thread Abstraction



- Infinite number of processors
- Threads execute with variable speed
 - Programs must be designed to work with any schedule

Multiprocessing vs Multiprogramming

- Remember Definitions:
 - Multiprocessing \equiv Multiple CPUs or cores or hyperthreads (HW per-instruction interleaving)
 - Multiprogramming \equiv Multiple Jobs or Processes
 - Multithreading \equiv Multiple threads per Process
- What does it mean to run two threads “concurrently”?
 - Scheduler is free to run threads in any order and interleaving: FIFO, Random, ...



Why Allow Cooperating Threads?

- Advantage 1: Share resources
 - One computer, many users
 - One bank balance, many ATMs
 - ❑ What if ATMs were only updated at night?
 - Embedded systems (robot control: coordinate arm & hand)
- Advantage 2: Speedup
 - Overlap I/O and computation
 - ❑ Many different file systems do read-ahead
 - Multiprocessors – chop up program into parallel pieces
- Advantage 3: Modularity
 - More important than you might think
 - Chop large problem up into simpler pieces
 - ❑ To compile, for instance, **gcc** calls **cpp** | **cc1** | **cc2** | **as** | **ld**
 - ❑ Makes system easier to extend

Correctness for Systems with Concurrency

- If dispatcher can schedule threads in any way, programs must work under all circumstances
 - Can you test for this?
 - How can you know if your program works?
- Independent Threads:
 - No state shared with other threads
 - Deterministic \Rightarrow Input state determines results
 - Reproducible \Rightarrow Can recreate Starting Conditions, I/O
 - Scheduling order doesn't matter (if **switch()** works!!!)
- Cooperating Threads:
 - Shared State between multiple threads
 - Non-deterministic
 - Non-reproducible
- Non-deterministic and Non-reproducible means that bugs can be intermittent
 - Sometimes called “Heisenbugs”

Interactions Complicate Debugging

- Is any program truly independent?
 - Every process shares the file system, OS resources, network, etc.
 - Extreme example: buggy device driver causes thread A to crash “independent thread” B
- Non-deterministic errors are really difficult to find
 - Example: Memory layout of kernel+user programs
 - ❑ Depends on scheduling, which depends on timer/other things
 - ❑ Original UNIX had a bunch of non-deterministic errors
 - Example: Something which does interesting I/O
 - ❑ User typing of letters used to help generate secure keys

Problem is at the Lowest Level

- Most of the time, threads are working on separate data, so scheduling doesn't matter:

Thread A

$x = 1;$

Thread B

$y = 2;$

- However, what about (Initially, $y = 1$):

Thread A

$x = 1;$

Thread B

$x = 2;$

- x could be 1 or 2 (non-deterministic!)
- Could even be 3 for serial processors:
 - Thread A writes 0001, B writes 0010 → scheduling order ABABABBA yields 3!

Problem is at the Lowest Level

- A more complex case (Initially, $x = 0$):

Thread A

$x = x + 1;$

```
load r1, x
add r2, r1, 1
store x, r2
```

Thread B

$x = x + 2;$

```
load r1, x
add r2, r1, 2
store x, r2
```

- What are the possible outputs?

Problem is at the Lowest Level

- A more complex case (Initially, $x = 0$):

Thread A

$x = x + 1;$

Thread B

$x = x + 2;$

```
load r1, x
add r2, r1, 1
store x, r2
```

```
load r1, x
add r2, r1, 2
store x, r2
```

Final: $x = 3$

```
load r1, x
add r2, r1, 1
store x, r2
load r1, x
add r2, r1, 2
store x, r2
```

Final: $x = 2$

```
load r1, x
add r2, r1, 1
store x, r2
load r1, x
add r2, r1, 2
store x, r2
```

Final: $x = 1$

What's Worse: Reordered Instructions by Compiler



- Compilers could reorder the instructions to maximize the instruction level parallelism.
 - Yet, it only ensures the dependency correctness within a thread, not across threads.
 - pInialized could be set to true before funcA().

Thread A

```
p = funcA();  
pInialized = true;
```

Thread B

```
y = 2;  
while(!pInialized); // wait  
q = funcB(p)
```

Atomic Operations

- To understand a concurrent program, we need to know what the underlying indivisible operations are!
- Atomic Operation (原子操作): an operation that always runs to completion or not at all
 - It is *indivisible*: it cannot be stopped in the middle and state cannot be modified by someone else in the middle
 - Fundamental building block – if no atomic operations, then have no way for threads to work together
- On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
 - Consequently – weird example that produces “3” on previous slide can’t happen
- Many instructions are not atomic
 - Double-precision floating point store often not atomic
 - VAX and IBM 360 had an instruction to copy a whole array

Motivation: “Too Much Milk”

- Great thing about OS's – analogy between problems in OS and problems in real life
 - Help you understand real life problems better
 - But, computers are much stupider than people
- Example: People need to coordinate:



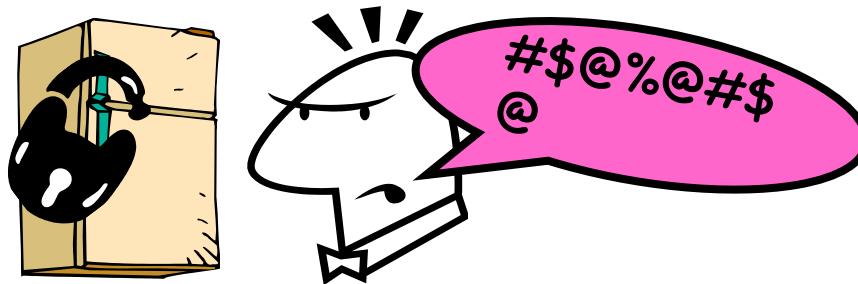
Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

Definitions

- **Synchronization (同步)**: using atomic operations to ensure cooperation between threads
 - For now, only loads and stores are atomic
 - We are going to show that its hard to build anything useful with only reads and writes
- **Mutual Exclusion (互斥)**: ensuring that only one thread does a particular thing at a time
 - One thread *excludes* the other while doing its task
- **Critical Section (临界区)**: piece of code that only one thread can execute at once.
 - Critical section is the result of mutual exclusion
 - Critical section and mutual exclusion are two ways of describing the same thing

Definitions

- **Lock**: prevents someone from doing something
 - Lock before entering critical section and before accessing shared data
 - Unlock when leaving, after accessing shared data
 - Wait if locked
- Important idea: all synchronization involves waiting
- For example: fix the milk problem by putting a key on the refrigerator
 - Lock it and take key if you are going to go buy milk
 - Fixes too much: roommate angry if only wants orange



- Of Course – We don't know how to make a lock yet

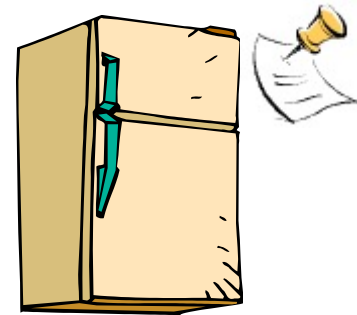
Too Much Milk: Correctness Properties

- Need to be careful about correctness of concurrent programs, since non-deterministic
 - Impulse is to start coding first, then when it doesn't work, pull hair out
 - Instead, think first, then code
 - Always write down behavior first
- What are the correctness properties for the “Too much milk” problem???
 - Never more than one person buys
 - Someone buys if needed
- Restrict ourselves to use only atomic load and store operations as building blocks

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
 - Leave a note before buying (kind of “lock”)
 - Remove note after buying (kind of “unlock”)
 - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

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



Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
 - Leave a note before buying (kind of “lock”)
 - Remove note after buying (kind of “unlock”)
 - Don’t buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

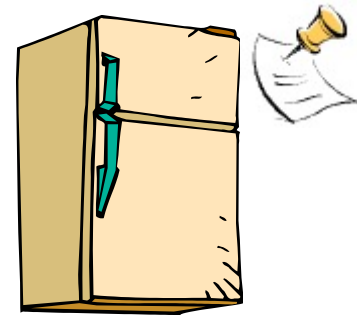
```
Thread A  
if (noMilk) {  
  
    if (noNote) {  
        leave Note;  
        buy Milk;  
        remove Note;  
    }  
}
```

```
Thread B  
if (noMilk) {  
    if (noNote) {  
  
        leave Note;  
        buy Milk;  
        remove Note;  
    }  
}
```

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
 - Leave a note before buying (kind of “lock”)
 - Remove note after buying (kind of “unlock”)
 - Don’t buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

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



- Result?
 - Still too much milk **but only occasionally!**
 - Thread can get context switched after checking milk and note but before buying milk!
- Solution makes problem worse since fails **intermittently**
 - Makes it really hard to debug...
 - Must work despite what the dispatcher does!

Too Much Milk: Solution #1 ½

- Clearly the Note is not quite blocking enough
 - Let's try to fix this by placing note first
- Another try at previous solution:

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

- What happens here?
 - Well, with human, probably nothing bad
 - With computer: no one ever buys milk

Too Much Milk Solution #2

- How about labeled notes?
 - Now we can leave note before checking
- Algorithm looks like this:

Thread A

```
leave note A;  
if (noNote B) {  
    if (noMilk) {  
        buy Milk;  
    }  
}  
remove note A;
```

Thread B

```
leave note B;  
if (noNoteA) {  
    if (noMilk) {  
        buy Milk;  
    }  
}  
remove note B;
```

- Does this work?

Too Much Milk Solution #2

- How about labeled notes?
 - Now we can leave note before checking
- Algorithm looks like this:

Thread A

```
leave note A;
if (noNote B) {
    if (noMilk) {
        buy Milk;
    }
}
remove note A;
```

Thread B

```
leave note B;
if (noNoteA) {
    if (noMilk) {
        buy Milk;
    }
}
remove note B;
```

- Does this work?
- Possible for neither thread to buy milk
 - Context switches at exactly the wrong times can lead each to think that the other is going to buy
- Really insidious:
 - **Extremely unlikely** this would happen, but will at worse possible time
 - Probably something like this in UNIX

Too Much Milk Solution #3

- Here is a possible two-note solution:

Thread A

```
leave note A;
while (note B) {\X
    do nothing;
}
if (noMilk) {
    buy milk;
}
remove note A;
```

Thread B

```
leave note B;
if (noNote A) {\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

- Does this work?

Too Much Milk Solution #3

- Here is a possible two-note solution:

```
Thread A
leave note A;
while (note B) { \\X
    do nothing;
}
if (noMilk) {
    buy milk;
}
remove note A;
```

```
Thread B
leave note B;
if (noNote A) { \\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

- Does this work? **Yes**. Both can guarantee that:
 - It is safe to buy, or
 - Other will buy, ok to quit
- At **X**:
 - If no note B, safe for A to buy,
 - Otherwise wait to find out what will happen
- At **Y**:
 - If no note A, safe for B to buy
 - Otherwise, A is either buying or waiting for B to quit

Case I

- “leave note A” happens before “if (noNote A)”

```
leave note A;  
while (note B) {\X  
    do nothing;  
};
```

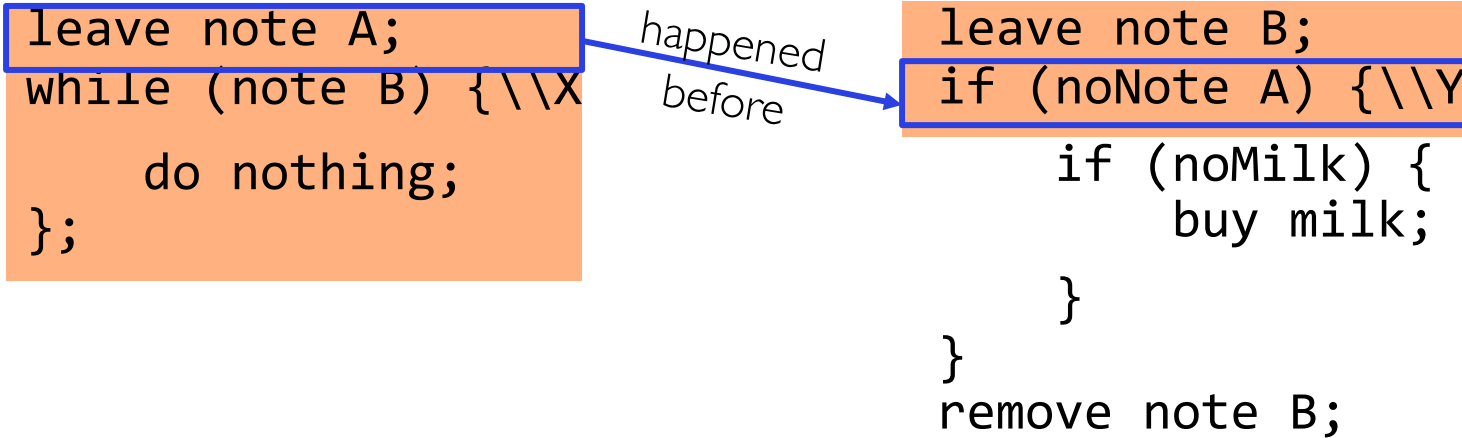
*happened
before*

```
leave note B;  
if (noNote A) {\Y  
    if (noMilk) {  
        buy milk;  
    }  
}  
remove note B;
```

```
if (noMilk) {  
    buy milk;}  
}  
remove note A;
```

Case I

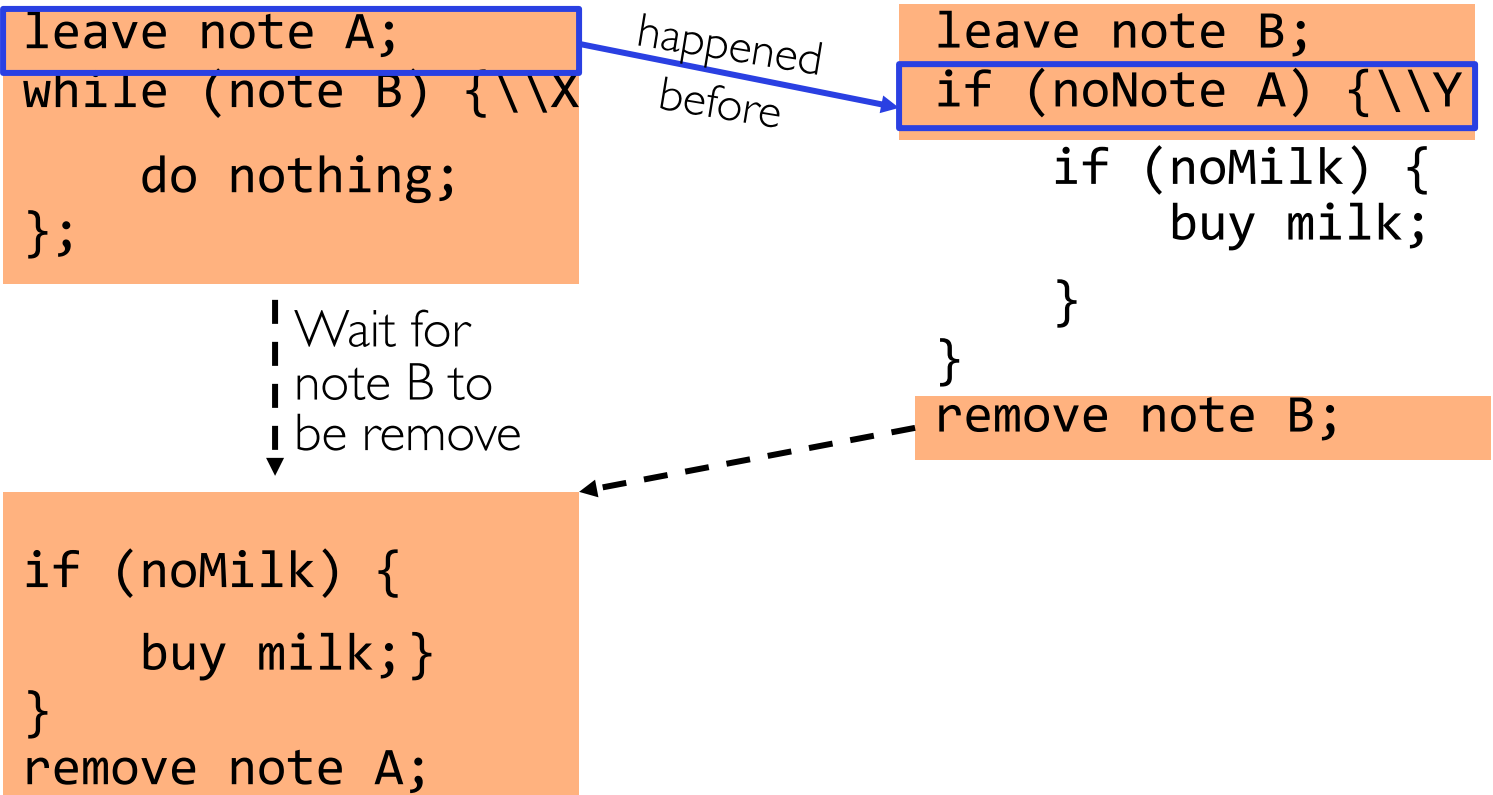
- “leave note A” happens before “if (noNote A)”



```
if (noMilk) {
    buy milk;}
}
remove note A;
```

Case I

- “leave note A” happens before “if (noNote A)”



Case 2

- “if (noNote A)” happens before “leave note A”

```
leave note A;  
while (note B) {\X  
    do nothing;  
};
```

happened
before

```
leave note B;  
if (noNote A) {\Y  
    if (noMilk) {  
        buy milk;  
    }  
}  
remove note B;
```

```
if (noMilk) {  
    buy milk;  
}  
remove note A;
```

Case 2

- “if (noNote A)” happens before “leave note A”

```
leave note A;  
while (note B) {\X  
    do nothing;  
};
```

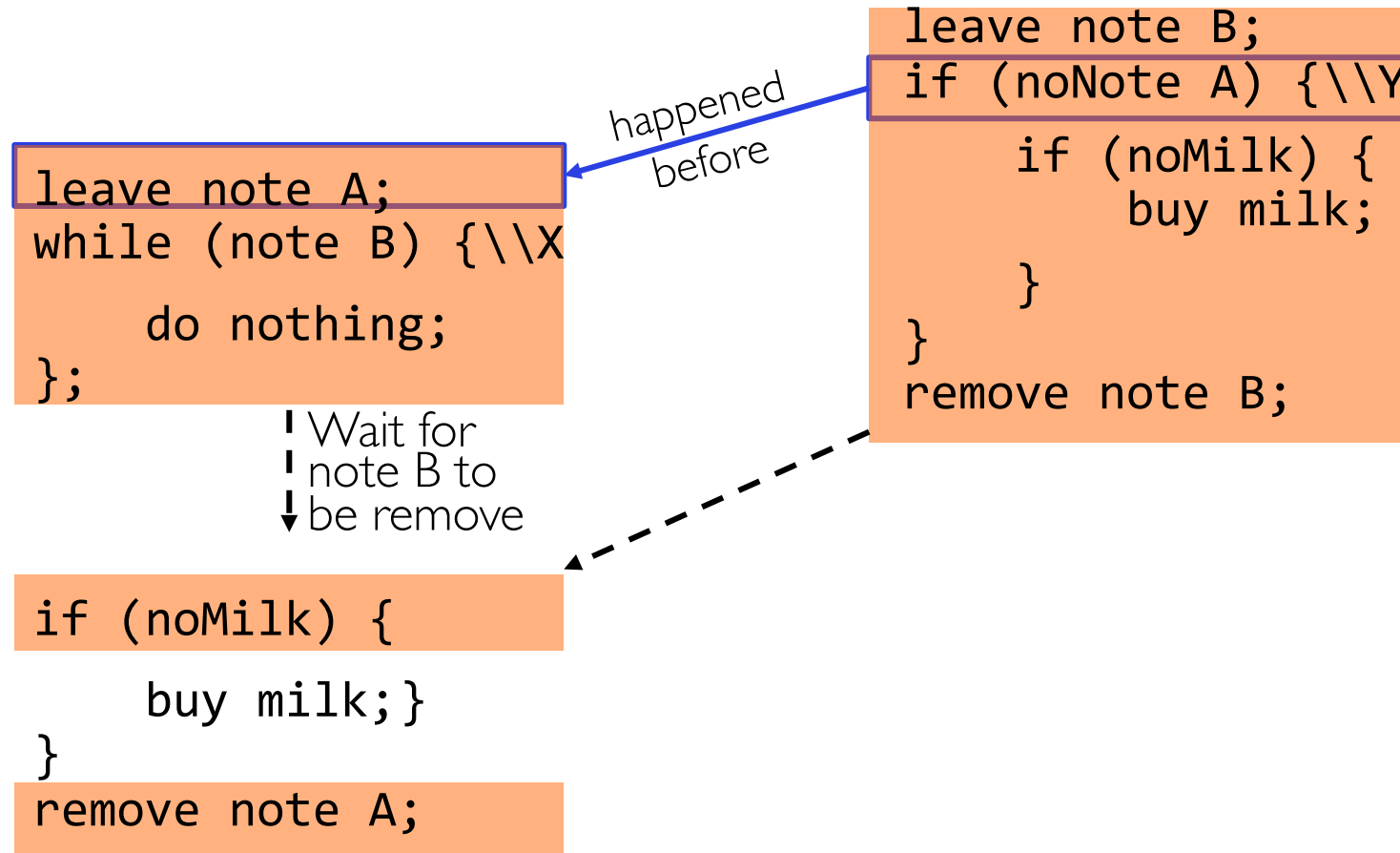
happened
before

```
leave note B;  
if (noNote A) {\Y  
    if (noMilk) {  
        buy milk;  
    }  
}  
remove note B;
```

```
if (noMilk) {  
    buy milk;  
}  
remove note A;
```

Case 2

- “if (noNote A)” happens before “leave note A”



Solution #3 Discussion

- Our solution protects a single “Critical-Section” piece of code for each thread:

```
if (noMilk) {  
    buy milk;  
}
```

- Solution #3 works, but it's really unsatisfactory
 - Really complex – even for this simple example
 - ❑ Hard to convince yourself that this really works
 - A's code is different from B's – what if lots of threads?
 - ❑ Code would have to be slightly different for each thread
 - While A is waiting, it is consuming CPU time
 - ❑ This is called “busy-waiting”
- There's a better way
 - Have hardware provide higher-level primitives than atomic load & store
 - Build even higher-level programming abstractions on this hardware support

Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock
 - `lock.Acquire()` – wait until lock is free, then grab
 - `lock.Release()` – Unlock, waking up anyone waiting
 - These must be atomic operations – if two threads are waiting for the lock and both see it's free, only one succeeds to grab the lock
- Then, our milk problem is easy:

```
milklock.Acquire();  
if (nomilk)  
    buy milk;  
milklock.Release();
```
- Once again, section of code between **Acquire()** and **Release()** called a “Critical Section”

Where are we going with synchronization?

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- We are going to implement various higher-level synchronization primitives using atomic operations
 - Everything is pretty painful if only atomic primitives are load and store
 - Need to provide primitives useful at user-level

Lock

- Suppose we have some sort of implementation of a lock
 - `lock.Acquire()` – wait until lock is free, then grab
 - `lock.Release()` – Unlock, waking up anyone waiting
 - These must be atomic operations – if two threads are waiting for the lock and both see it's free, only one succeeds to grab the lock
- 3 formal properties
 - **Mutual exclusion**: at most one thread holds the lock
 - **Progress**: if no thread holds the lock and any thread attempts to acquire the lock, then eventually some thread succeeds in acquiring the lock
 - **Bounded waiting**: if thread T attempts to acquire a lock, then there exists a bound on the number of times other threads can successfully acquire the lock before T does
 - ❑ Yet, it does not promise that waiting threads acquire the lock in FIFO order.

What does a Lock Guarantee?

- A simple case of lock. x is shared among threads

```
int x = 0;
```

```
//T1: can we ensure  $x = 0$  here?
```

```
lock.acquire();
```

```
//T2: can we ensure  $x = 0$  here?
```

```
 $x = 1$ ;
```

```
//T3: can we ensure  $x = 1$  here?
```

```
lock.release();
```

```
//T4: can we ensure  $x = 1$  here?
```

```
 $x = 2$ ;
```

```
//T5: can we ensure  $x = 2$  here?
```

What does a Lock Guarantee?

- A simple case of lock. x is shared among threads

```
int x = 0;
```

```
//T1: can we ensure  $x = 0$  here?
```

```
lock.acquire();
```

```
//T2: can we ensure  $x = 0$  here?
```

```
 $x = 1$ ;
```

```
//T3: can we ensure  $x = 1$  here?
```

```
lock.release();
```

```
//T4: can we ensure  $x = 1$  here?
```

```
 $x = 2$ ;
```

```
//T5: can we ensure  $x = 2$  here?
```

- *If a lock is not held, nothing can be guaranteed*

Condition Variable

- Condition Variable (条件变量): a queue of threads waiting for something *inside* a critical section
 - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
- Operations:
 - **Wait(&lock)**: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
 - **Signal()**: Wake up one waiter, if any
 - **Broadcast()**: Wake up all waiters
 - Differentiate them from UNIX `wait` and `signal`

Condition Variable Example

- Condition Variable (条件变量): a queue of threads waiting for something *inside* a critical section
 - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
- A common pattern:

```
FuncA_wait() {  
    lock.acquire();  
    // read/write shared state here  
    while (!testOnSharedState())  
        cv.wait(&lock);  
    assert(testOnSharedState());  
    lock.release();  
}
```

```
FuncB_signal() {  
    lock.acquire();  
    // read/write shared state here  
    // If state has changed that allows  
    // another thread to make progress, call  
    // signal or broadcast  
    cv.signal();  
    lock.release();  
}
```

Condition Variable Example

- A concrete example of bounded queue implementation (or producer-consumer, 生产者消费者)

```
class bounded_queue {  
    Lock lock;  
    CV itemAdded;  
    CV itemRemoved;  
    void insert(int item);  
    int remove();  
}
```

```
void bounded_queue::insert(int item) {  
    lock.acquire();  
    while (queue.full()) {  
        itemRemoved.wait(&lock);  
    }  
    add_item(item);  
    itemAdded.signal();  
    lock.release();  
}
```

How to implement remove()?

Condition Variable Example

- A concrete example of bounded queue implementation (or producer-consumer, 生产者消费者)
- Two key principles
 - CV is always used with lock acquired
 - CV is put in a while loop. Why?

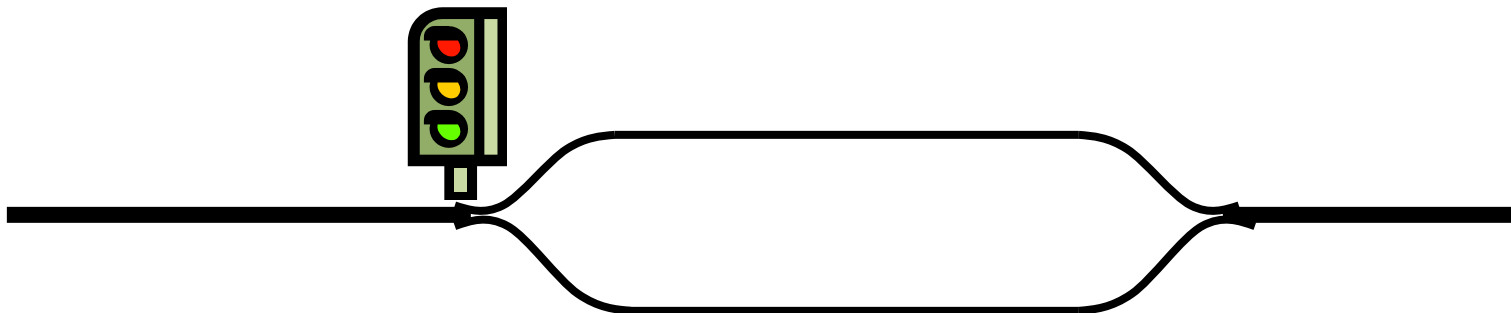
```
void bounded_queue::insert(int item) {  
    lock.acquire();  
    while (queue.full()) {  
        itemRemoved.wait(&lock);  
    }  
    add_item(item);  
    itemAdded.signal();  
    lock.release();  
}
```

Semaphores

- Semaphores (信号量) are a kind of generalized lock
 - First defined by Dijkstra in late 60s
 - Main synchronization primitive used in original UNIX
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
 - $P()$: an atomic operation that waits for semaphore to become positive, then decrements it by 1
 - Think of this as the `wait()` operation
 - $V()$: an atomic operation that increments the semaphore by 1, waking up a waiting P , if any
 - Think of this as the `signal()` operation
 - Note that $P()$ stands for “*proberen*” (to test) and $V()$ stands for “*verhogen*” (to increment) in Dutch

Semaphores vs. Integers

- Semaphores are like integers, except
 - No negative values
 - Only operations allowed are P and V – can't read or write value, except to set it initially
 - Operations must be atomic
 - ❑ Two P's together can't decrement value below zero
 - ❑ Similarly, thread going to sleep in P won't miss wakeup from V – even if they both happen at same time
- Semaphore from railway analogy
 - Here is a semaphore initialized to 2 for resource control:



Two Uses of Semaphores

Mutual Exclusion (initial value = 1)

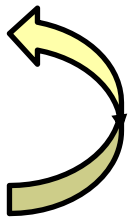
- Also called “Binary Semaphore”.
- Can be used for mutual exclusion:

```
semaphore.P();  
// Critical section goes here  
semaphore.V();
```

Scheduling Constraints (initial value = 0)

- Allow thread 1 to wait for a signal from thread 2, i.e., thread 2 **schedules** thread 1 when a given **event** occurs
- Example: suppose you had to implement ThreadJoin which must wait for thread to terminate:

```
Initial value of semaphore = 0  
ThreadJoin {  
    semaphore.P();  
}  
ThreadFinish {  
    semaphore.V();  
}
```

A yellow curved arrow points from the 'ThreadFinish' block to the 'ThreadJoin' block, indicating that the completion of ThreadFinish triggers the scheduling of ThreadJoin.

Producer-Consumer with a Bounded Buffer

- Problem Definition

- Producer puts things into a shared buffer
- Consumer takes them out
- Need synchronization to coordinate producer/consumer



- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them

- Need to synchronize access to this buffer
- Producer needs to wait if buffer is full
- Consumer needs to wait if buffer is empty

- Example 1: GCC compiler

- `cpp | cc1 | cc2 | as | ld`

- Example 2: Coke machine

- Producer can put limited number of Cokes in machine
- Consumer can't take Cokes out if machine is empty

Correctness constraints for solution

- Correctness Constraints:
 - Consumer must wait for producer to fill buffers, if none full (scheduling constraint)
 - Producer must wait for consumer to empty buffers, if all full (scheduling constraint)
 - Only one thread can manipulate buffer queue at a time (mutual exclusion)
- Remember why we need mutual exclusion
 - Because computers are stupid
 - Imagine if in real life: the delivery person is filling the machine and somebody comes up and tries to stick their money into the machine
- General rule of thumb:
Use a separate semaphore for each constraint
 - Semaphore fullSlots; // consumer's constraint
 - Semaphore emptySlots; // producer's constraint
 - Semaphore mutex; // mutual exclusion

Full Solution to Bounded Buffer

```
Semaphore fullSlots = ?;  
Semaphore emptySlots = ?;  
  
Semaphore mutex = 1;           // No one using machine  
  
Producer(item) {  
    emptySlots.P();           // Wait until space  
    mutex.P();                // Wait until machine free  
    Enqueue(item);  
    mutex.V();  
    fullSlots.V();           // Tell consumers there is  
                             // more coke  
}  
  
Consumer() {  
    fullSlots.P();           // Check if there's a coke  
    mutex.P();                // Wait until machine free  
    item = Dequeue();  
    mutex.V();  
    emptySlots.V();          // tell producer need more  
    return item;  
}
```

Full Solution to Bounded Buffer

```
Semaphore fullSlots = 0;    // Initially, no coke
Semaphore emptySlots = bufSize;
                               // Initially, num empty slots
Semaphore mutex = 1;        // No one using machine

Producer(item) {
    emptySlots.P();          // Wait until space
    mutex.P();              // Wait until machine free
    Enqueue(item);
    mutex.V();
    fullSlots.V();          // Tell consumers there is
                               // more coke
}

Consumer() {
    fullSlots.P();          // Check if there's a coke
    mutex.P();              // Wait until machine free
    item = Dequeue();
    mutex.V();
    emptySlots.V();         // tell producer need more
    return item;
}
```


Discussion about Solution

Why asymmetry?

- Producer does: `emptySlots.P()`
`fullSlots.V()`

Decrease # of
empty slots

Increase # of
occupied slots

- Consumer does: `fullSlots.P()` ,
`emptySlots.V()`

Increase # of
empty slots

Decrease # of
occupied slots

Discussion about Solution

Is order of P's important?

Is order of V's important?

What if we have 2 producers or 2 consumers?

```
Producer(item) {  
    mutex.P();  
    emptySlots.P();  
    Enqueue(item);  
    mutex.V();  
    fullSlots.V();  
}  
  
Consumer() {  
    fullSlots.P();  
    mutex.P();  
    item = Dequeue();  
    mutex.V();  
    emptySlots.V();  
    return item;  
}
```

Discussion about Solution

Is order of P's important?

- Yes! Can cause deadlock

Is order of V's important?

- No, except that it might affect scheduling efficiency

What if we have 2 producers or 2 consumers?

- Do we need to change anything?

```
Producer(item) {  
    mutex.P();  
    emptySlots.P();  
    Enqueue(item);  
    mutex.V();  
    fullSlots.V();  
}  
  
Consumer() {  
    fullSlots.P();  
    mutex.P();  
    item = Dequeue();  
    mutex.V();  
    emptySlots.V();  
    return item;  
}
```

Some Advices

- Always acquire the lock at the beginning of a method and release it right before the return
 - Consistent behavior makes it easier to program
 - Also makes it easier to read and debug

Some Advices

- Always acquire the lock at the beginning of a method and release it right before the return
 - Consistent behavior makes it easier to program
 - Also makes it easier to read and debug
- A case: double-checked locking

```
Singleton* Singleton::instance() {  
    if (pInstance == NULL) {  
        pInstance = new Instance();  
    }  
    return pInstance;  
}
```

An unsafe solution

```
Singleton* Singleton::instance() {  
    lock.acquire();  
    if (pInstance == NULL) {  
        pInstance = new Instance();  
    }  
    lock.release();  
    return pInstance;  
}
```

A safe solution

```
Singleton* Singleton::instance() {  
    if (pInstance == NULL) {  
        lock.acquire();  
        if (pInstance == NULL) {  
            pInstance = new Instance();  
        }  
        lock.release();  
    }  
    Return pInstance;  
}
```

An ``optimized'' solution.

Is it safe?

Homework

- Implement a thread-safe stack (with max size N) with locks and condition variable.
 - Use C++ or Java
 - Make it run, and test it with multi threads