# CPSC 213

## Introduction to Computer Systems

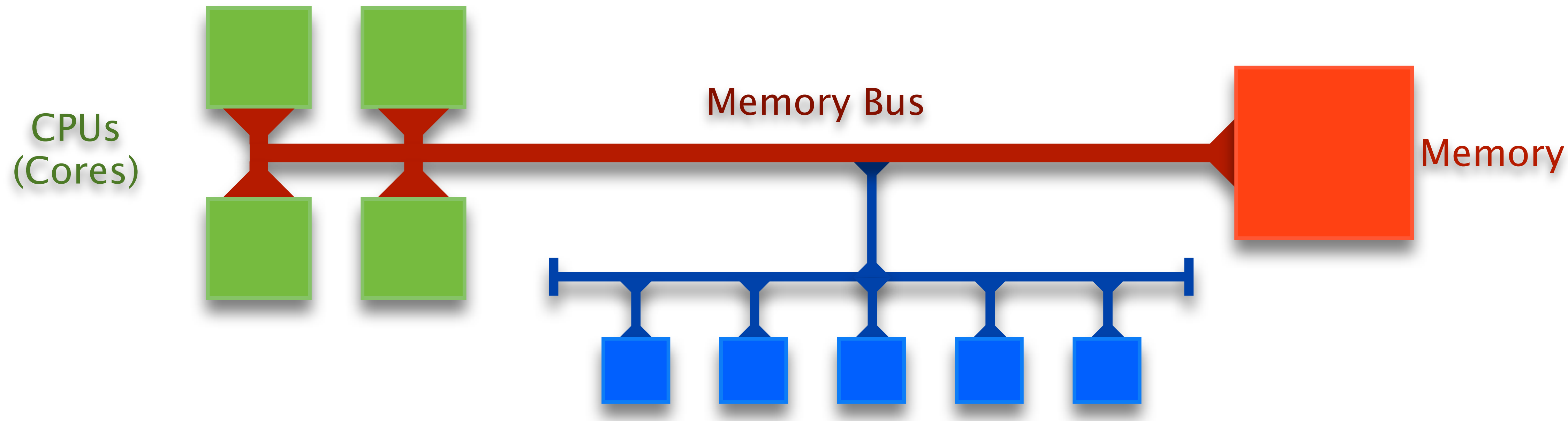
*Unit 2c*

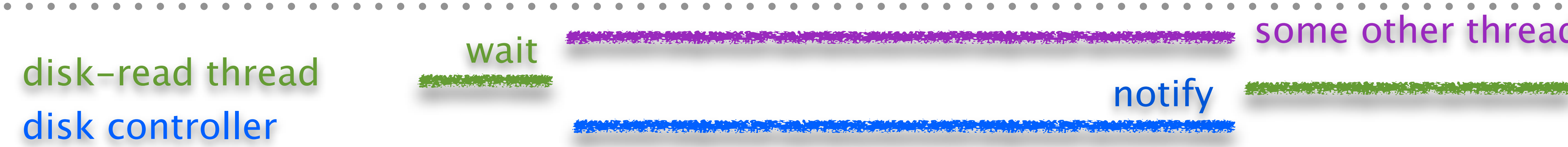
***Synchronization***

# Reading

- Companion
  - 6 *(Synchronization)*
- Text
  - *Shared Variables in a Threaded Program, Synchronizing Threads with Semaphores, Using Threads for Parallelism, Other Concurrency Issues*
  - 2ed: 12.4-12.6, parts of 12.7
  - 1ed: 13.4-13.5, (no equivalent to 12.6), parts of 13.7

# Synchronization




- We invented Threads to
  - **exploit parallelism** do things at the same time on different processors
  - **manage asynchrony** do something else while waiting for I/O Controller
- But, we now have two problems
  - coordinating access to memory (variables) shared by multiple threads
  - control flow transfers among threads (wait until notified by another thread)
- Synchronization is the mechanism threads use to
  - ensure ***mutual exclusion*** of critical sections
  - wait for and notify of the occurrence of events

# The Importance of Mutual Exclusion

- Shared data
  - data structure that could be accessed by multiple threads
  - typically concurrent access to shared data is a bug
- Critical Sections
  - sections of code that access shared data
- Race Condition
  - simultaneous access to critical section section by multiple threads
  - conflicting operations on shared data structure are arbitrarily interleaved
  - unpredictable (non-deterministic) program behaviour — usually a bug (a serious bug)
- Mutual Exclusion
  - a mechanism implemented in software (with some special hardware support)
  - to ensure critical sections are executed by one thread at a time
  - though reading and writing should be handled differently (more later)
- For example
  - consider the implementation of a shared stack by a linked list ...

# Stack implementation

```
void push_st (struct SE* e) {
  e->next = top;
  top     = e;
}
```

```
struct SE {
  struct SE* next;
};
struct SE *top=0;
```

```
struct SE* pop_st () {
  struct SE* e = top;
  top = (top)? top->next: 0;
  return e;
}
```

# Sequential test works

```
void push_driver (long int n) {
  struct SE* e;
  while (n--)
    push ((struct SE*) malloc (...));
}
```

```
push_driver (n);
pop_driver  (n);
assert      (top==0);
```

```
void pop_driver (long int n) {
  struct SE* e;
  while (n--) {
    do {
      e = pop ();
    } while (!e);
    free (e);
  }
}
```

- concurrent test doesn't always work

```
et = uthread_create ((void* (*)(void*)) push_driver, (void*) n);
dt = uthread_create ((void* (*)(void*)) pop_driver,  (void*) n);
uthread_join (et);
uthread_join (dt);
assert (top==0);
```

**malloc: *** error for object 0x1022a8fa0: pointer being freed was not allocated**

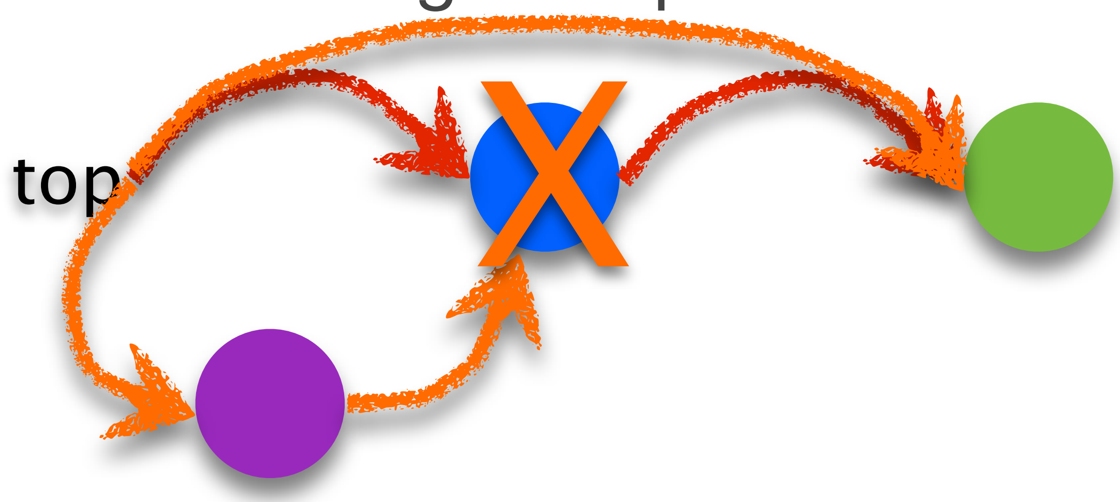
- what is wrong?

```
void push_st (struct SE* e) {
  e->next = top;
  top     = e;
}
```

```
struct SE* pop_st () {
  struct SE* e = top;
  top = (top)? top->next: 0;
  return e;
}
```

## The bug

- push and pop are critical sections on the shared stack
- they run in parallel so their operations are arbitrarily interleaved
- sometimes, this interleaving corrupts the data structure




```
void push_st (struct SE* e) {
  e->next = top;
  top     = e;
}
```

```
struct SE* pop_st () {
  struct SE* e = top;
  top = (top)? top->next: 0;
  return e;
}
```

1. e->next = top

2. e = top
3. top = top->next
4. return e
5. free e

6. top = e

# Mutual Exclusion using Locks

- lock semantics
  - a lock is either *held* by a thread or *available*
  - at most one thread can hold a lock at a time
  - a thread attempting to acquire a lock that is already held is forced to wait
- lock primitives
  - **lock** acquire lock, wait if necessary
  - **unlock** release lock, allowing another thread to acquire if waiting
- using locks for the shared stack

```
void push_cs (struct SE* e) {
  lock (&aLock);
  push_st (e);
  unlock (&aLock);
}
```

```
struct SE* pop_cs () {
  struct SE* e;
  lock (&aLock);
  e = pop_st ();
  unlock (&aLock);

  return e;
}
```

# Implementing Simple Locks

- Here's a first cut
  - use a shared global variable for synchronization
  - **lock** loops until the variable is 0 and then sets it to 1
  - **unlock** sets the variable to 0

```
int lock = 0;
```

```
void lock (int* lock) {
  while (*lock==1) {}
  *lock = 1;
}
```

```
void unlock (int* lock) {
  *lock = 0;
}
```

  - why doesn't this work?

- We now have a race in the lock code

**Thread A**

```
void lock (int* lock) {
  while (*lock==1) {}
  *lock = 1;
}
```

1. read *lock==0, exit loop

3. *lock = 1
4. return with lock held

**Thread B**

```
void lock (int* lock) {
  while (*lock==1) {}
  *lock = 1;
}
```

2. read *lock==0, exit loop

5. *lock = 1, return
6. return with lock held

Both threads think they hold the lock ...

## The race exists even at the machine-code level

- two instructions acquire lock: one to read it free, one to set it held
- but read by another thread and interpose between these two

```
      ld $lock, r1
      ld $1,    r2

loop: ld  (r1), r0
      beq r0, free
      br  loop

free: st  r2, (r1)
```

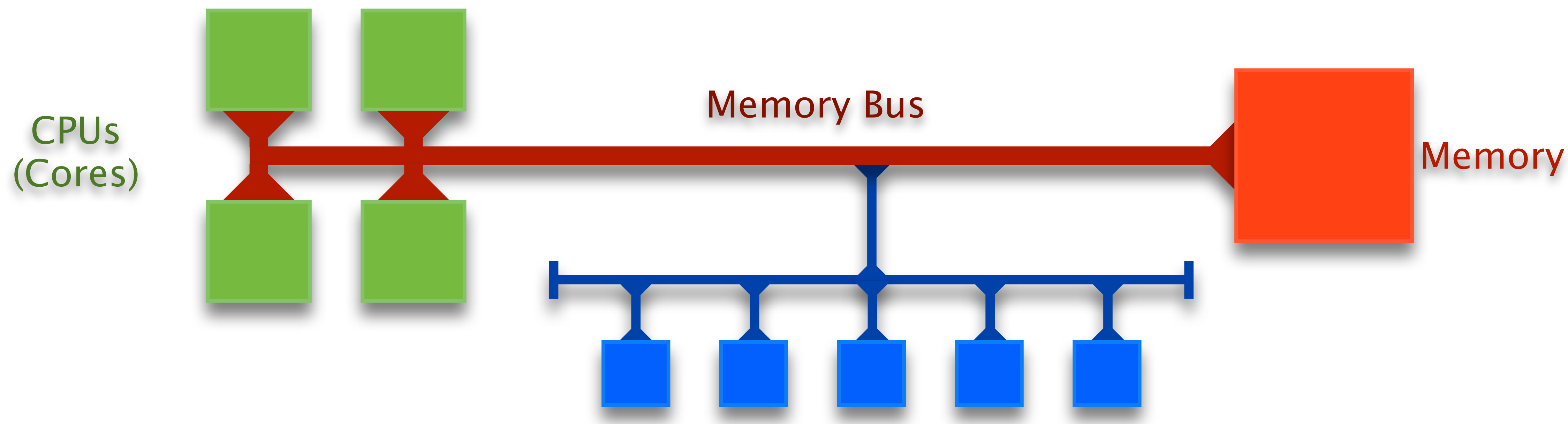

| Thread A | Thread B |
|---|---|
| ld (r1), r0 | |
| | ld (r1), r0 |
| st r2, (r1) | |
| | st r2, (r1) |

# Atomic Memory Exchange Instruction

- We need a new instruction
  - to ***atomically*** read **and** write a memory location
  - with no intervening access to that memory location from any other thread allowed
- Atomicity
  - is a general property in systems
  - where a group of operations are performed as a single, indivisible unit
- The Atomic Memory Exchange
  - one type of atomic memory instruction (there are other types)
  - group a load and store together atomically
  - exchanging the value of a register and a memory location

| Name | Semantics | Assembly |
|---|---|---|
| *atomic exchange* | r[v] ← m[r[a]]<br>m[r[a]] ← r[v] | xchg (ra), rv |

# Implementing Atomic Exchange




- Can not be implemented just by CPU
  - must synchronize across multiple CPUs
  - accessing the same memory location at the same time
- Implemented by Memory Bus
  - memory bus synchronizes every CPUs access to memory
  - the two parts of the exchange (read + write) are coupled on bus
  - bus ensures that no other memory transaction can intervene
  - this instruction is **much slower**, higher overhead than normal read or write

# Spinlock

- A Spinlock is
  - a lock where waiter *spins* on looping memory reads until lock is acquired
  - also called "busy waiting" lock
- Simple implementation using Atomic Exchange
  - spin on atomic memory operation
  - that attempts to acquire lock while
  - atomically reading its old value

```
      ld   $lock, r1
      ld   $1, r0
loop: xchg (r1), r0
      beq  r0, held
      br   loop
held:
```

  - but there is a problem: atomic-exchange is an expensive instruction

# Implementing Spinlocks Efficiently

- Spin first on fast normal read, then try slow atomic exchange
  - use normal read in loop until lock appears free
  - when lock appears free use exchange to try to grab it
  - if exchange fails then go back to normal read

```
      ld   $lock, %r1
loop: ld   (%r1), %r0
      beq  %r0, try
      br   loop
try:  ld   $1, %r0
      xchg (%r1), %r0
      beq  %r0, held
      br   loop
held:
```

- Busy-waiting pros and cons
  - Spinlocks are necessary and okay if spinner only waits a short time
  - But, using a spinlock to wait for a long time, wastes CPU cycles

# Blocking Locks

- If a thread may wait a long time
  - it should block so that other threads can run
  - it will then unblock when it becomes runnable (lock available or event notification)
- Blocking locks for mutual exclusion
  - if lock is held, locker puts itself on waiter queue and blocks
  - when lock is unlocked, unlocker restarts one thread on waiter queue
- Blocking locks for event notification
  - waiting thread puts itself on a a waiter queue and blocks
  - notifying thread restarts one thread on waiter queue (or perhaps all)
- Implementing blocking locks presents a problem
  - lock data structure includes a waiter queue and a few other things
  - data structure is shared by multiple threads; lock operations are critical sections
  - mutual exclusion can be provided by blocking locks (they aren't implemented yet)
  - and so, we need to use spinlocks to implement blocking locks (this gets tricky)

# Implementing a Blocking Lock

```
void lock (struct blocking_lock l) {
  spinlock_lock (&l->spinlock);
    while (l->held) {
      enqueue        (&waiter_queue, uthread_self ());
      spinlock_unlock (&l->spinlock);
      uthread_switch  (ready_queue_dequeue (), TS_BLOCKED);
      spinlock_lock   (&l->spinlock);
    }
    l->held = 1;
  spinlock_unlock (&l->spinlock);
}
```

```
void unlock (struct blocking_lock l) {
  uthread_t* waiter_thread;

  spinlock_lock (&l->spinlock);
  l->held = 0;
  waiter_thread = dequeue (&l->waiter_queue);
  spinlock_unlock (&->spinlock);
  if (waiter_thread) {
     waiter_thread->state = TS_RUNNABLE;
     ready_queue_enqueue (waiter_thread);
  }
}
```

```
struct blocking_lock {
  spinlock_t          spinlock;
  int                 held;
  uthread_queue_t  waiter_queue;
};
```

- Spinlock guard
  - on for critical sections
  - off before thread blocks

# Blocking Lock Example Scenario

## Thread A

1. calls lock()
2. grabs spinlock
5. grabs blocking lock
6. releases spinlock
7. returns from lock()
12. calls unlock()
13. grabs spinlock
14. releases lock
15. restarts Thread B
16. releases spinlock
17. returns from unlock()

## Thread B

3. calls lock()
4. tries to grab spinlock, but spins
8. grabs spinlock
9. queues itself on waiter list
10. releases spinlock
11. blocks
18. scheduled
19. grabs spinlock
20. grabs blocking lock
21. releases spinlock
22. returns from lock()

thread running
spinlock held
blocking lock held

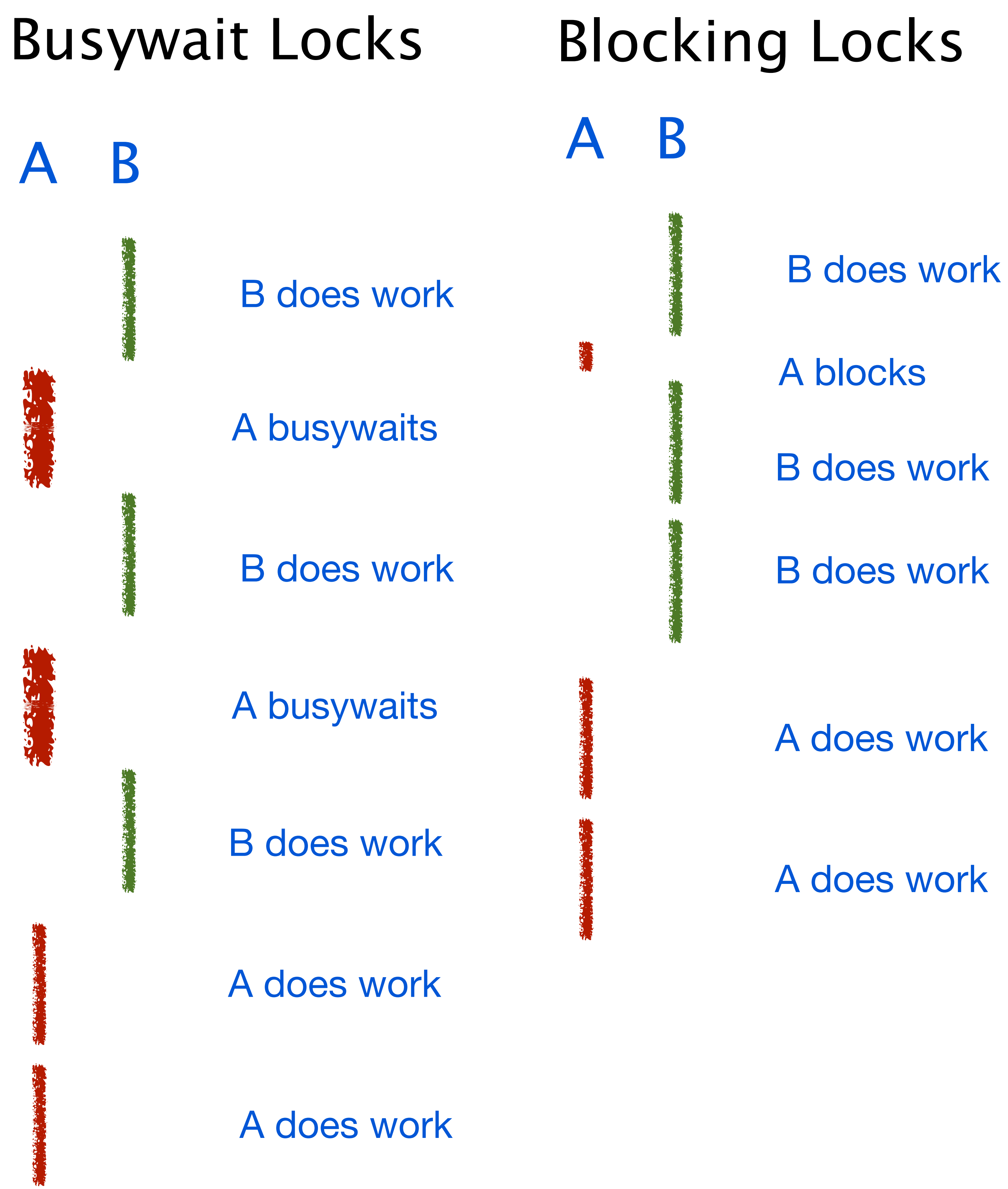
# Blocking vs Busy Waiting

- Spinlocks
  - Pros and Cons
    - uncontended locking has low overhead
    - contending for lock has high cost
  - Use when
    - critical section is small
    - contention is expected to be minimal
    - event wait is expected to be very short
    - when implementing Blocking locks

- Blocking Locks
  - Pros and Cons
    - uncontended locking has higher overhead
    - contending for lock has no cost
  - Use when
    - lock may be held for some time
    - when contention is high
    - when event wait may be long

# Busywaiting vs Blocking

- Using spinlocks to busywait for long time wastes CPU cycles
  - use for short things
    - including within implementation of blocking locks
- Using blocking locks has high overhead
  - use for long things
- Common mistake
  - assume that CPU is busywaiting during blocking locks
    - thread does not run again until after blocking lock is released



# Locks and Loops Common Mistakes

- Confusion about spinlocks inside blocking locks
  - use spinlocks in the implementation of blocking locks
  - two separate levels of lock!
    - holding spinlock guarding variable read/write
    - holding actual blocking lock
- Confusion about when spinlocks needed
  - must turn on to guard access to shared variables
  - must turn off before finishing or blocking
- Confusion about loop function
  - busywait
    - only inside spinlock
  - thread blocked inside loop body, **not** busywaiting
    - yield for blocking lock
    - re-check for desired condition: is lock available?

# Synchronization Abstractions

- Monitors and condition variables
  - monitor guarantees mutual exclusion with blocking locks
  - condition variable provides control transfer among threads with wait/notify
  - abstraction supports explicit locking
- Semaphores
  - blocking atomic counter, stop thread if counter would go negative
  - introduced to coordinate asynchronous resource use
  - abstraction implicitly supports mutex, no need for explicit locking by user
  - use to implement monitors, barriers (and condition variables, sort of)

# Monitors and Conditions

- Mutual exclusion plus inter-thread synchronization
  - introduced by Tony Hoare and Per Brinch Hansen circa 1974
  - abstraction supporting explicit locking
    - basis for synchronization primitives in Java etc.
- Monitor
  - monitor guarantees mutual exclusion with blocking locks
  - primitives are enter (lock) and exit (unlock)
- Condition Variable
  - allows threads to synchronize with each other (provides control transfer between threads):
  - **wait** blocks until a subsequent signal operation on the variable
  - **notify** unblocks waiter, but continues to hold monitor (Hansen)
  - **notify_all** unblocks all waiters and continues to hold monitor
  - can only be accessed from inside of a monitor (i.e, with monitor lock held)

# Monitors

- Provides mutual exclusion with blocking lock
  - **enter** lock
  - **exit** unlock

```
void doSomething (uthread_monitor_t* mon) {
  uthread_monitor_enter (mon);
    touchSharedMemory();
  uthread_monitor_exit (mon);
}
```

- Standard case: assume all threads could overwrite shared memory.
  - mutex: only allows access one at a time
- Special case: distinguish read-only access (readers) from threads that change shared memory values (writers).
  - mutex: allow multiple readers but only one writer

# Condition Variables

- Mechanism to transfer control back and forth between threads
  - uses monitors: CV can only be accessed when monitor lock is held
- Primitives
  - **wait** blocks until a subsequent **notify** operation on the variable
  - **notify** unblocks one waiter, continues to hold monitor
  - **notify_all** unblocks all waiters (broadcast), continues to hold monitor
- Each CV associated with a monitor
- Multiple CVs can be associated with same monitor
  - independent conditions, but guarded by same mutex lock

```
uthread_monitor_t* beer = uthread_monitor_create ();
```

```
uthread_cv_t* not_empty = uthread_cv_create (beer);
uthread_cv_t* warm      = uthread_cv_create (beer);
```

# Using Conditions

- Basic formulation
  - one thread enters monitor and may wait for a condition to be established

```
monitor {
  while (!x)
    wait ();
}
```

  - another thread enters monitor, establishes condition and signals waiter

```
monitor {
  x = true;
  notify ();
}
```

- **wait** exits the monitor and blocks thread
  - before waiter blocks, it exits monitor to allow other threads to enter
  - when wait unblocks, it re-enters monitor, waiting/blocking to enter if necessary
  - note: other threads may have been in monitor between wait call and return

- **notify** awakens one thread
  - does not release monitor
  - waiter does not run until notifier exits monitor
  - a third thread could intervene and enter monitor before waiter
  - waiter must thus re-check wait condition

```
monitor {
  x = true;
  notify ();
}
```

```
monitor {
  while (!x)
    wait ();
}
```

And not

```
monitor {
  if (!x)
    wait ();
}
```

- **notify_all** awakens all threads
  - may wake up too many
  - okay since threads re-check wait condition and re-wait if necessary

```
monitor {
  x += n;
  notify_all ();
}
```

```
monitor {
  while (!x)
    wait ();
}
```

# Drinking Beer Example

- Beer pitcher is shared data structure with these operations
  - **pour** from pitcher into glass
  - **refill** pitcher
- Implementation goal
  - synchronize access to the shared pitcher
  - pouring from an empty pitcher requires waiting for it to be filled
  - filling pitcher releases waiters

```
void pour () {
  monitor {
    while (glasses==0)
      wait ();
    glasses--;
  }}
```

```
void refill (int n) {
  monitor {
    for (int i=0; i<n; i++) {
      glasses++;
      notify ();
    }}}
```

or

```
monitor {
  glasses+=n;
  notify_all ();
}
```

# Wait and Notify Semantics

- Monitor automatically exited before block on wait
  - before waiter blocks, it exits monitor to allow other threads to enter
- Monitor automatically re-entered before return from wait
  - when trying to return from wait after notify, thread may block again until monitor can be entered (if monitor lock held by another thread)
- Monitor stays locked after notify: does not block
- Implication: cannot assume desired condition holds after return from blocking wait
  - other threads may have been in monitor between wait call and return
    - must explicitly re-check: usually enclose wait in while loop with condition check
    - same idea as blocking lock implementation with spinlocks!

```
void pour () {
  monitor {
    while (glasses==0)
      wait;
    glasses--;
  }}
```

```
void refill (int n) {
  monitor {
    for (int i=0; i<n; i++) {
      glasses++;
      notify;
    }}}
```

# Monitors and Condition Variables

- Programs can have multiple independent monitors
  - so a monitor implemented as a "variable" (a struct really)

```
uthread_monitor_t* beer = uthread_monitor_create ();
```

- Monitors may have multiple independent conditions
  - so a condition is also a variable, connected to its monitor

```
uthread_cv_t* not_empty = uthread_cv_create (beer);
uthread_cv_t* warm      = uthread_cv_create (beer);
```

```
void pour (int isEnglish) {
  uthread_monitor_enter (beer);
    while (glasses==0 || (isEnglish && temp<15)) {
      if (glasses==0)
        uthread_cv_wait (not_empty);
      if (isEnglish && temp < 15)
        uthread_cv_wait (warm);
    }
  glasses--;
  uthread_monitor_exit (beer);
}
```

# Using Condition Variables for Disk Read

- Blocking read
  - call async read as before
  - but now block on condition variable that is given to completion routine

```
void read (char* buf, int bufSize, int blockNo) {
  uthread_monitor_t* mon = uthread_monitor_create ();
  uthread_cv_t*      cv  = uthread_cv_create (mon);
  uthread_monitor_enter (mon);
    asyncRead (buf, bufSize, readComplete, mon, cv);
    uthread_cv_wait (cv);
  uthread_monitor_exit (mon);
}
```

- Read completion
  - called by disk ISR as before
  - but now notify the condition variable, restarting the blocked read cal

```
void readComplete (uthread_monitor_t* mon, uthread_cv_t* cv) {
  uthread_monitor_enter (mon);
    uthread_cv_notify (cv);
  uthread_monitor_exit (mon);
}
```

# Shared Queue Example

- Unsynchronized Code

```
void enqueue (uthread_queue_t* queue, uthread_t* thread) {
  thread->next = 0;
  if (queue->tail)
    queue->tail->next = thread;
  queue->tail = thread;
  if (queue->head==0)
    queue->head = queue->tail;
}

uthread_t* dequeue (uthread_queue_t* queue) {
  uthread_t* thread;
  if (queue->head) {
    thread = queue->head;
    queue->head = queue->head->next;
    if (queue->head==0)
      queue->tail=0;
  } else
    thread=0;
  return thread;
}
```

# Adding Mutual Exclusion

```
void enqueue (uthread_queue_t* queue, uthread_t* thread) {
  uthread_monitor_enter (&queue->monitor);
    thread->next = 0;
    if (queue->tail)
      queue->tail->next = thread;
    queue->tail = thread;
    if (queue->head==0)
      queue->head = queue->tail;
  uthread_monitor_exit (&queue->monitor);
}

uthread_t* dequeue (uthread_queue_t* queue) {
  uthread_t* thread;
  uthread_monitor_enter (&queue->monitor);
    if (queue->head) {
      thread = queue->head;
      queue->head = queue->head->next;
      if (queue->head==0)
        queue->tail=0;
    } else
      thread=0;
  uthread_monitor_exit (&queue->monitor);
  return thread;
}
```

# Now have dequeue wait for item if queue is empty

- classical producer-consumer model with each in different thread
  - e.g., producer enqueues video frames consumer thread dequeues them for display

```
void enqueue (uthread_queue_t* queue, uthread_t* thread) {
  uthread_monitor_enter (&queue->monitor);
    thread->next = 0;
    if (queue->tail)
      queue->tail->next = thread;
    queue->tail = thread;
    if (queue->head==0)
      queue->head = queue->tail;
    uthread_cv_notify (&queue->not_empty);
  uthread_monitor_exit (&queue->monitor);
}

uthread_t* dequeue (uthread_queue_t* queue) {
  uthread_t* thread;
  uthread_monitor_enter (&queue->monitor);
    while (queue->head==0)
      uthread_cv_wait (&queue->not_empty);
    thread = queue->head;
    queue->head = queue->head->next;
    if (queue->head==0)
      queue->tail=0;
  uthread_monitor_exit (&queue->monitor);
  return thread;
}
```

# Some Questions About Example

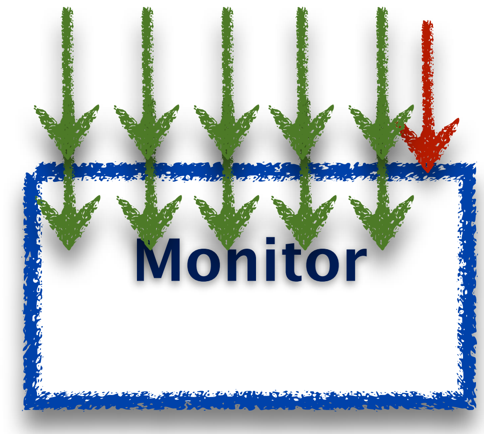
```
uthread_t* dequeue (uthread_queue_t* queue) {
 uthread_t* thread;
 uthread_monitor_enter (&queue->monitor);
  while (queue->head==0)
   uthread_cv_wait (&queue->not_empty);
  thread = queue->head;
  queue->head = queue->head->next;
  if (queue->head==0)
   queue->tail=0;
 uthread_monitor_exit (&queue->monitor);
 return thread;
}
```

- Why is does dequeue have a while loop to check for non-empty?
- Why must condition variable be associated with specific monitor?
- Why can't we use condition variable outside of monitor?
  - this is called a *naked* use of the condition variable
  - this is actually required sometimes ... can you think where (BONUS)?
    - Experience with Processes and Monitors with Mesa, Lampson and Redell, 1980

# Implementing Condition Variables

- Some key observations
  - wait, notify and notify_all are called while monitor is held
  - the monitor must be held when they return
  - wait must release monitor before locking and re-acquire before returning
- Implementation
  - in the lab
  - look carefully at the implementations of monitor enter and exit
  - understand how these are similar to wait and notify
  - use this code as a guide
  - you also have the code for semaphores, which you might also find helpful

# Reader-Writer Monitors




- If we classify critical sections as
  - **reader** if only reads the shared data
  - **writer** if updates the shared data
- Then we can weaken the mutual exclusion constraint
  - writers require exclusive access to the monitor
  - but, a group of readers can access monitor concurrently
- Reader-Writer Monitors
  - monitor state is one of
    - **free**, **held-for-reading**, or **held**
  - monitor_enter ()
    - waits for monitor to be **free** then sets its state to **held**
  - monitor_enter_read_only ()
    - waits for monitor to be **free** or **held-for-reading**, then sets is state to **head-for-reading**
    - **increment reader count**
  - monitor_exit ()
    - if **held**, then set state to **free**
    - if **held-for-reading**, then **decrement reader count** and set state to **free if reader count is 0**

- Policy question
  - monitor state is head-for-reading
  - thread A calls monitor_enter() and blocks waiting for monitor to be free
  - thread B calls monitor_enter_read_only(); what do we do?
- Disallowing new readers while writer is waiting
  - is the fair thing to do
  - thread A has been waiting longer than B, shouldn’t it get the monitor first?
- Allowing new readers while writer is waiting
  - may lead to faster programs by increasing concurrency
  - if readers must WAIT for old readers and writer to finish, less work is done
- What should we do
  - normally either provide a fair implementation
  - or allow programmer to choose (that’s what Java does)

# Semaphores

- Introduced by Edsger Dijkstra for the THE System circa 1968
  - recall that he also introduced the “process” (aka “thread”) for this system
  - was fearful of asynchrony, Semaphores synchronize interrupts
  - synchronization primitive provide by UNIX to applications
- A Semaphore is
  - an atomic counter that can never be less than 0
  - attempting to make counter negative blocks calling thread
- P (s)
  - try to decrement s (*prolaag* for *probeer te varlagen* in Dutch)
  - atomically blocks until s >0 then decrement s
- V (s)
  - increment s (*verhogen* in Dutch)
  - atomically increase s unblocking threads waiting in P as appropriate

# Using Semaphores to Drink Beer

- Explicit locking not required when using semaphores since atomicity built in
- Use semaphore to store glasses head by pitcher
  - set initial value of empty when creating it

```
uthread_semaphore_t* glasses = uthread_create_semaphore (0);
```

- Pouring and refilling don't require a monitor

```
void pour () {
  uthread_P (glasses);
}
```

```
void refill (int n) {
  for (int i=0; i<n; i++)
    uthread_V (glasses);
}
```

- Getting the beer warm, however, doesn't fit quite as nicely
  - need to keep track of the number of threads waiting for the warm beer
  - then call V that number of times
  - this is actually quite tricky

# Other ways to use Semaphores

- Asynchronous Operations
  - create ***outstanding_request*** semaphore
  - async_read: P (outstanding_request)
  - completion interrupt: V (outstanding_request)
- Rendezvous
  - two threads wait for each other before continuing
  - create a semaphore for each thread initialized to 0

```
void thread_a () {
  uthread_V (a);
  uthread_P (b);
}

void thread_b () {
  uthread_V (b);
  uthread_P (a);
}
```

What if you reversed order of V and P?

## Barrier (local)

- In a system of 1 parent thread and N children threads
- All threads must arrive at barrier before any can continue

```
void* add (void* arg) {
  struct arg_tuple* tuple = (struct arg_tuple*) arg;
  tuple->result = tuple->arg0 + tuple->arg1;
  uthread_V (tuple->barrier);
  return 0;
}
```

```
uthread_semaphore_t* barrier = uthread_semaphore_create (0);
struct arg_tuple a0 = {1,2,0,barrier};
struct arg_tuple a1 = {3,4,0,barrier};
uthread_init (1);
uthread_create (add, &a0);
uthread_create (add, &a1);
uthread_P (barrier);
uthread_P (barrier);
printf ("%d %d\n", a0.result, a1.result);
```

## Barrier (global)

- In a system of N threads with no parent
- All threads must arrive, before any can continue ... and should work repeatedly

- Implementing Monitors
  - initial value of semaphore is 1
  - lock is P()
  - unlock is V()
- Implementing Condition Variables
  - this is the warm beer problem
  - it took until 2003 before we actually got this right
  - for further reading
    - Andrew D. Birrell. “Implementing Condition Variables with Semaphores”, 2003.
    - Google “semaphores condition variables birrell”

# Using Semaphores

- good building block for implementing many other things
  - monitors
    - initial value of semaphore is 1
    - lock is P()
    - unlock is V()
  - condition variables (almost)
    - this is the warm beer problem
    - it took until 2003 before we actually got this right
    - for further reading
      - Andrew D. Birrell. “Implementing Condition Variables with Semaphores”, 2003.
      - Google “semaphores condition variables birrell”
  - rendezvous: two threads wait for each other before continuing
  - barriers: all threads must arrive at barrier before any can continue

# Synchronization in Java *(5)*

- Monitors using the Lock interface
  - a few variants allow interruptibility, just trying lock, ...

```
Lock l = ...;
l.lock ();
try {
  ...
} finally {
  l.unlock ();
}
```

```
Lock l = ...;
try {
  l.lockInterruptibly ();
  try {
    ...
  } finally {
    l.unlock ();
  }
} catch (InterruptedException ie) {}
```

  - multiple-reader single writer locks

```
ReadWriteLock l  = ...;
Lock          rl = l.readLock ();
Lock          wl = l.writeLock ();
```

# Condition variables

- **await** is wait (replaces Object wait)
- **signal** or **signalAll** is “notify” (replaces Object notify, notifyAll)

```
class Beer {
  Lock      l        = ...;
  Condition notEmpty = l.newCondition ();
  int       glasses  = 0;

  void pour () throws InterruptedException {
    l.lock ();
    try {
      while (glasses==0)
        notEmpty.await ();
      glasses--;
    } finaly {
      l.unlock ();
    }
  }

  void refill (int n) throws InterruptedException {
    l.lock ();
    try {
      glasses += n;
      notEmpty.signalAll ();
    } finaly {
      l.unlock ();
    }}}
```

## Semaphore class

- **acquire ()** or **acquire (n)** is P() or P(n)
- **release ()** or **release (n)** is V() or V(n)

```
class Beer {
  Semaphore glasses = new Semaphore (0);

  void pour () throws InterruptedException {
    glasses.acquire ();
  }

  void refill (int n) throws InterruptedException {
    glasses.release (n);
  }
}
```

## Lock-free Atomic Variables

- AtomicX where X in {Boolean, Integer, IntegerArray, Reference, ...}
- atomic operations such as getAndAdd(), compareAndSet(), ...
  - e.g., x.compareAndSet (y,z) atomically sets x=z iff x==y and returns true iff set occurred

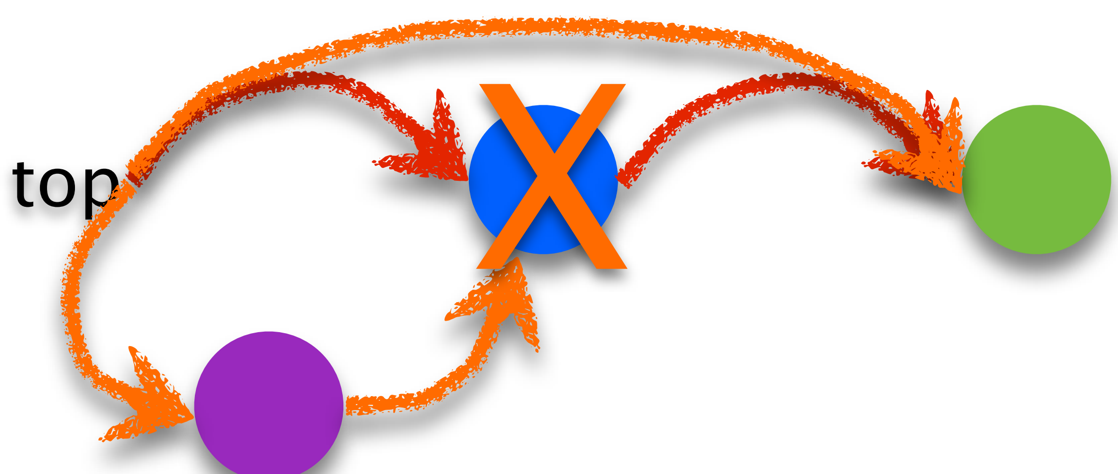
# Lock-Free Atomic Stack in Java

- Recall the problem with concurrent stack

```
void push_st (struct SE* e) {
  e->next = top;
  top     = e;
}
```

```
struct SE* pop_st () {
  struct SE* e = top;
  top = (top)? top->next: 0;
  return e;
}
```

  - a pop could intervene between two steps of push, corrupting linked list

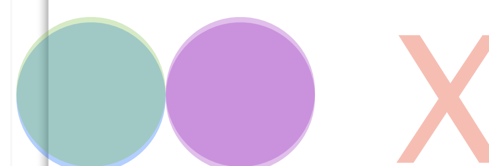


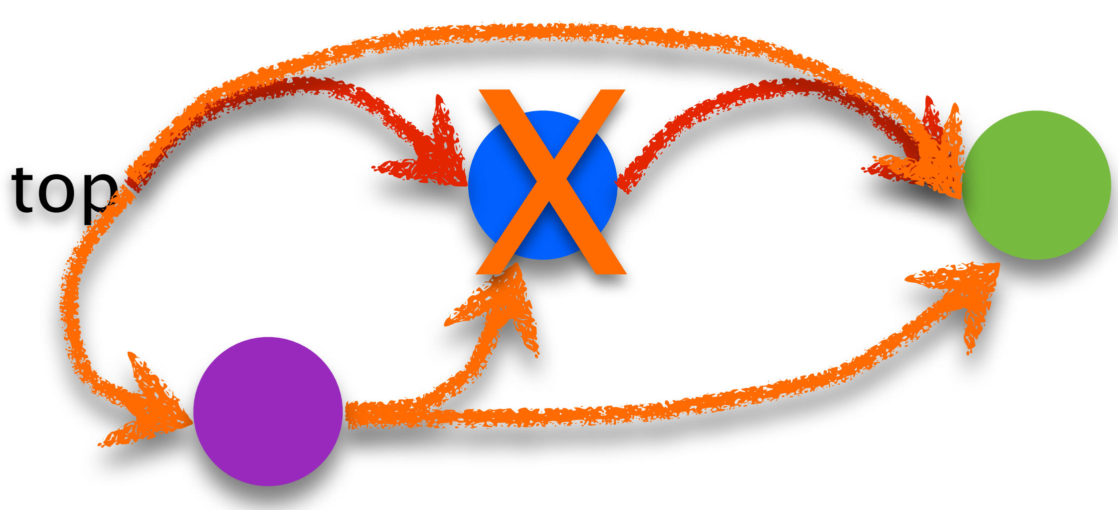

  - we solved this problem using locks to ensure mutual exclusion
  - now ... solve without locks, using **atomic compare-and-set** of top

```
class Element {
  Element* next;
}

class Stack {
  AtomcReference<Element> top;
  Stack () {
    top.set (NULL);
  }

  void push () {
    Element t;
    Element e = new Element ();
    do {
      t = top.get ();
      e.next = t;
    } while (!top.compareAndSet (t, e));
  }
}
```



# Problems with Concurrency

- Race Condition
  - competing, unsynchronized access to shared variable
    - from multiple threads
    - at least one of the threads is attempting to update the variable
  - solved with synchronization
    - guaranteeing mutual exclusion for competing accesses
    - **but the language does not help you see what data might be shared --- can be very hard**
- Deadlock
  - multiple competing actions wait for each other preventing any to complete
  - what can cause deadlock?
    - MONITORS
    - CONDITION VARIABLES
    - SEMAPHORES

# Recursive Monitor Entry

- What should we do for a program like this

```
void foo () {
  uthread_monitor_enter (mon);
    count--;
    if (count>0)
      foo();
  uthread_monitor_exit (mon);
}
```

- Here is implementation of lock, is this okay?

```
void lock (struct blocking_lock* l) {
  spinlock_lock (&l->spinlock);
    while (l->held) {
      enqueue        (&waiter_queue, uthread_self ());
      spinlock_unlock (&l->spinlock);
      uthread_switch  (ready_queue_dequeue (), TS_BLOCKED);
      spinlock_lock   (&l->spinlock);
    }
    l->held = 1;
  spinlock_unlock (&l->spinlock);
}
```

- if we try to lock the monitor again it is a *deadlock*
  - the thread will hold the monitor when it tries to enter
  - the thread will wait for itself, and thus never wake up
- allow a thread that holds the monitor to enter again

```
void uthread_monitor_enter (uthread_monitor_t* monitor) {
  spinlock_lock (&monitor->spinlock);
  while (monitor->holder && monitor->holder!=uthread_self()) {
    enqueue        (&monitor->waiter_queue, uthread_self ());
    spinlock_unlock (&monitor->spinlock);
    uthread_stop    (TS_BLOCKED);
    spinlock_lock   (&monitor->spinlock);
  }
  monitor->holder = uthread_self ();
  spinlock_unlock (&monitor->spinlock);
}
```

# Systems with multiple monitors

- We have already seen this with semaphores
- Consider a system with two monitors, a and b

```
void foo() {
  uthread_monitor_enter (a);
  uthread_monitor_exit   (a);
}
```

```
void bar() {
  uthread_monitor_enter (b);
  uthread_monitor_exit  (b);
}
```

```
void x() {
  uthread_monitor_enter (a);
    bar();
  uthread_monitor_exit  (a);
}
```

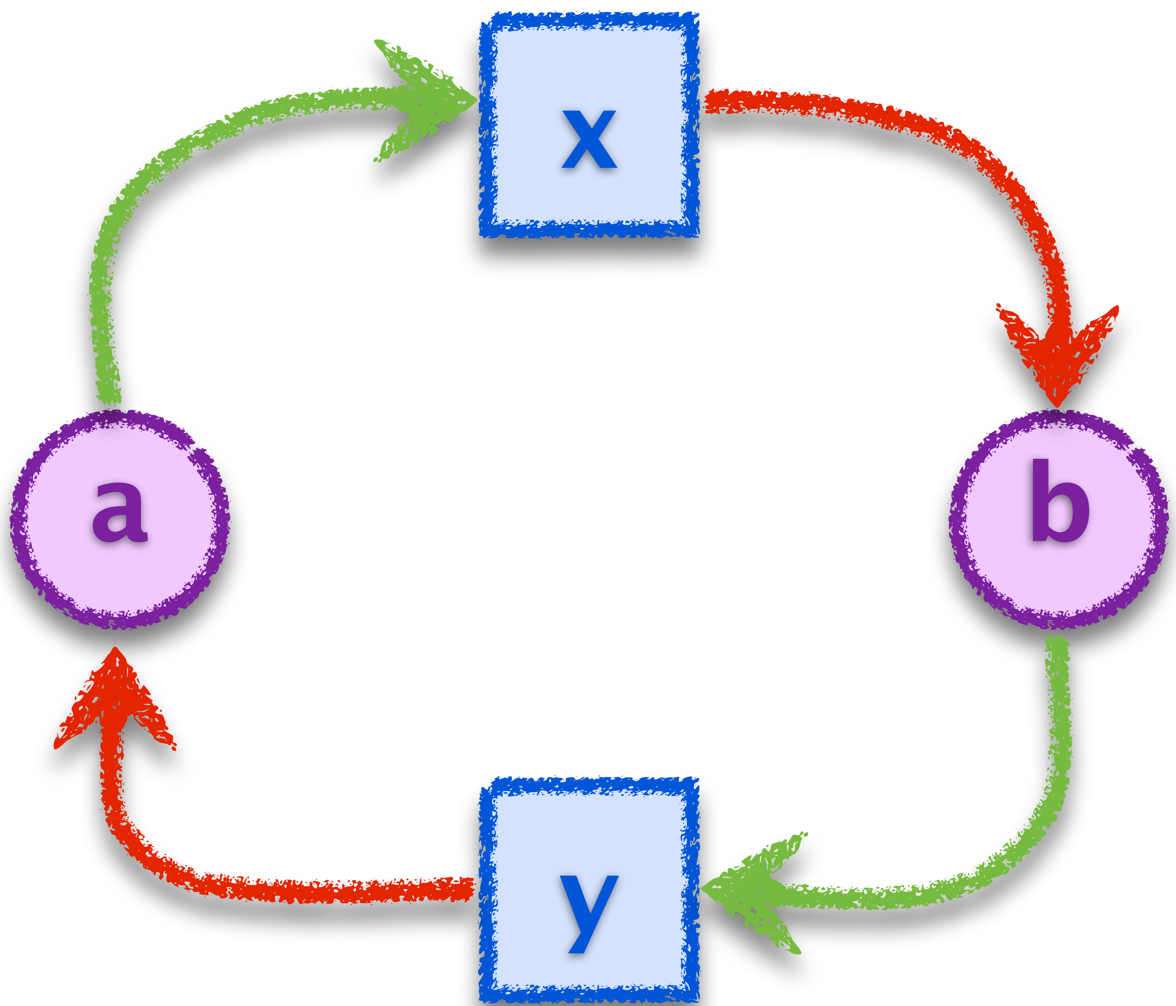
```
void y() {
  uthread_monitor_enter (b);
    foo();
  uthread_monitor_exit  (b);
}
```

Any problems so far?

What about now?

# Waiter Graph Can Show Deadlocks

- Waiter graph
  - edge from **lock** to thread if thread **HOLD**s lock
  - edge from **thread** to lock if thread **WANT**s lock
  - a cycle indicates deadlock




```
void foo() {
  uthread_monitor_enter (a);
  uthread_monitor_exit   (a);
}
```

```
void bar() {
  uthread_monitor_enter (b);
  uthread_monitor_exit  (b);
}
```

```
void x() {
  uthread_monitor_enter (a);
    bar();
  uthread_monitor_exit  (a);
}
```

```
void y() {
  uthread_monitor_enter (b);
    foo();
  uthread_monitor_exit  (b);
}
```

# The Dining Philosophers Problem

- Formulated by Edsger Dijkstra to explain deadlock (circa 1965)
  - 5 computers competed for access to 5 shared tape drives
- Re-told by Tony Hoare
  - 5 philosophers sit at a round table with fork placed in between each
    - fork to left and right of each philosopher and each can use only these 2 forks
  - they are either eating or thinking
    - while eating they are not thinking and while thinking they are not eating
    - they never speak to each other
  - large bowl of spaghetti at centre of table requires 2 forks to serve
    - dig in ...
  - deadlock
    - every philosopher holds fork to left waiting for fork to right (or vice versa)
    - how might you solve this problem?
  - starvation (aka *livelock*)
    - philosophers still starve (ever get both forks) due to timing problem, but avoid deadlock
    - for example:

# Avoiding Deadlock

- Don't use multiple threads
  - you'll have many idle CPU cores and write asynchronous code
- Don't use shared variables
  - if threads don't access shared data, no need for synchronization
- Use only one lock at a time
  - deadlock is not possible, unless thread forgets to unlock
- Organize locks into precedence hierarchy
  - each lock is assigned a unique precedence number
  - before thread *X* acquires a lock *i*, it must hold all higher precedence locks
  - ensures that any thread holding *i* can not be waiting for *X*
- Detect and destroy
  - if you can't avoid deadlock, detect when it has occurred
  - break deadlock by terminating threads (e.g., sending them an exception)

# Deadlock and Starvation

- Solved problem: race conditions
  - solved by synchronization abstractions: locks, monitors, semaphores
- Unsolved problems when using multiple locks
  - deadlock: nothing completes because multiple competing actions wait for each other
  - starvation: some actions never complete
  - no abstraction to simply solve problem, major concern intrinsic to synchronization
  - some ways to handle/avoid:
    - precedence hierarchy of locks
    - detect and destroy: notice deadlock and terminate threads

# Synchronization Summary

- Spinlock
  - one acquirer at a time, busy-wait until acquired
  - need atomic read-write memory operation, implemented in hardware
  - use for locks held for short periods (or when minimal lock contention)
- Monitors and Condition Variables
  - blocking locks, stop thread while it is waiting
  - monitor guarantees mutual exclusion
  - condition variables wait/notify provides control transfer among threads
- Semaphores
  - blocking atomic counter, stop thread if counter would go negative
  - introduced to coordinate asynchronous resource use
  - use to implement barriers or monitors
  - use to implement something like condition variables, but not quite
- Problems, problems, problems
  - race conditions to be avoided using synchronization
  - deadlock/livelock to be avoided using synchronization carefully