Thread Coordination: Basic Lock Implementation

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CS162 – Operating Systems and Systems Programming

Lecture 9

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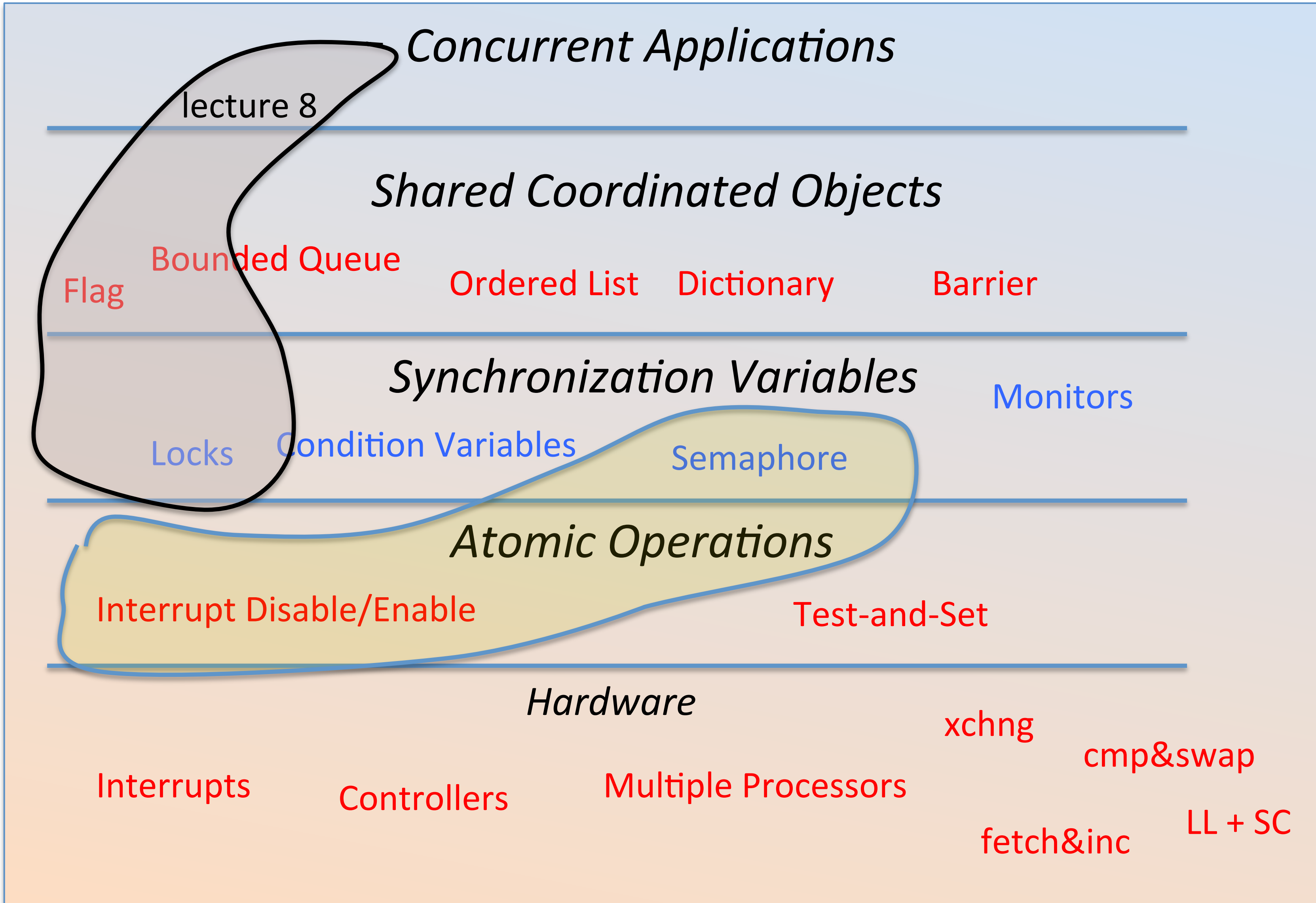
Reading: A&D 5.7-5.9
HW 2 out
Proj 1 out: CP1

Objectives

- Demonstrate a structured way to approach concurrent programming (of threads)
  - Synchronized shared objects (in C!)
- Introduce the challenge of concurrent programming
- Develop understanding of a family of mechanisms
  - Flags, Locks, Condition Variables & semaphores
- Understand how these mechanisms can be implemented

Concurrency Coordination Landscape



Recall

- Two key aspects of coordination
  - Mutually exclusive access to shared objects so that they can be manipulated correctly
  - Conveying precedence from one computational entity to another
- Atomic: sequence of actions that is indivisible (from a certain perspective)
- Critical section: segment of computation that is performed under exclusive control
  - While locking others out

Illustration: "Too much milk"

Went to buy milk

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: using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We'll show that is hard to build anything useful with only reads and writes
- Critical Section: piece of code that only one thread can execute at once
- Mutual Exclusion: ensuring that only one thread executes critical section
  - One thread *excludes* the other while doing its task
  - Critical section and mutual exclusion are two ways of describing the same thing

Too Much Milk: non-Solution

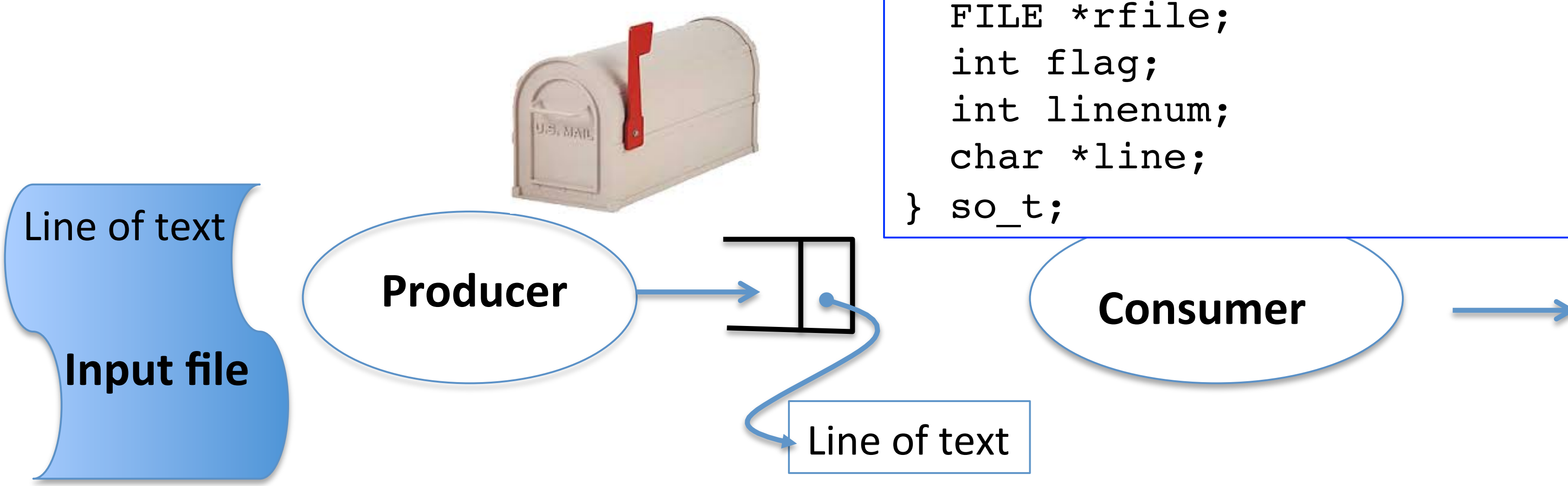
- Still too much milk but only occasionally!

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

- Thread can get context switched after checking milk and note but before leaving note!
- Solution makes problem worse since fails intermittently
  - Makes it really hard to debug…
  - Must work despite what the thread dispatcher does!

Recall: Simplest synchronization

```
typedef struct sharedobject {
  FILE *rfile;
  int flag;
  int linenum;
  char *line;
} so_t;
```



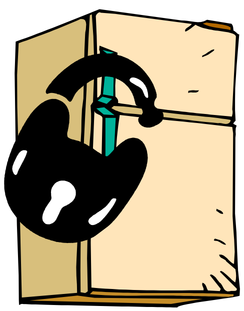
- Alternating protocol of a single producer and a single consumer can be coordinated by a simple flag
- Integrated with the shared object

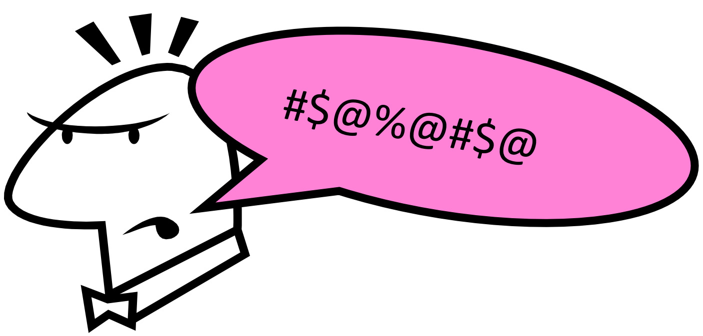
```
int markfull(so_t *so) {
  so->flag = 1;
  while (so->flag) {}
  return 1;
}
```

```
int markempty(so_t *so) {
  so->flag = 0;
  while (!so->flag) {}
  return 1;
}
```

More 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
- Example: fix the milk problem by putting a lock on refrigerator
  - Lock it and take key if you are going to go buy milk
  - Fixes too much (coarse granularity): roommate angry if only wants orange juice





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

Too Much Milk: Solution

- Suppose we have some sort of implementation of a lock (more in a moment)
  - `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, 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"

How to Implement Lock?

- Lock: prevents someone from accessing something
  – Lock before entering critical section (e.g., before accessing shared data)
  – Unlock when leaving, after accessing shared data
  – Wait if locked
    - Important idea: all synchronization involves waiting
    - Should sleep if waiting for long time

- Hardware lock instructions ?
  – Is this a good idea?
    - We will see various atomic read-modify-write instructions
  – What about putting a task to sleep?
    - How do handle interface between hardware and scheduler?
  – Complexity?
    - Each feature makes hardware more complex and slower

Naïve use of Interrupt Enable/Disable

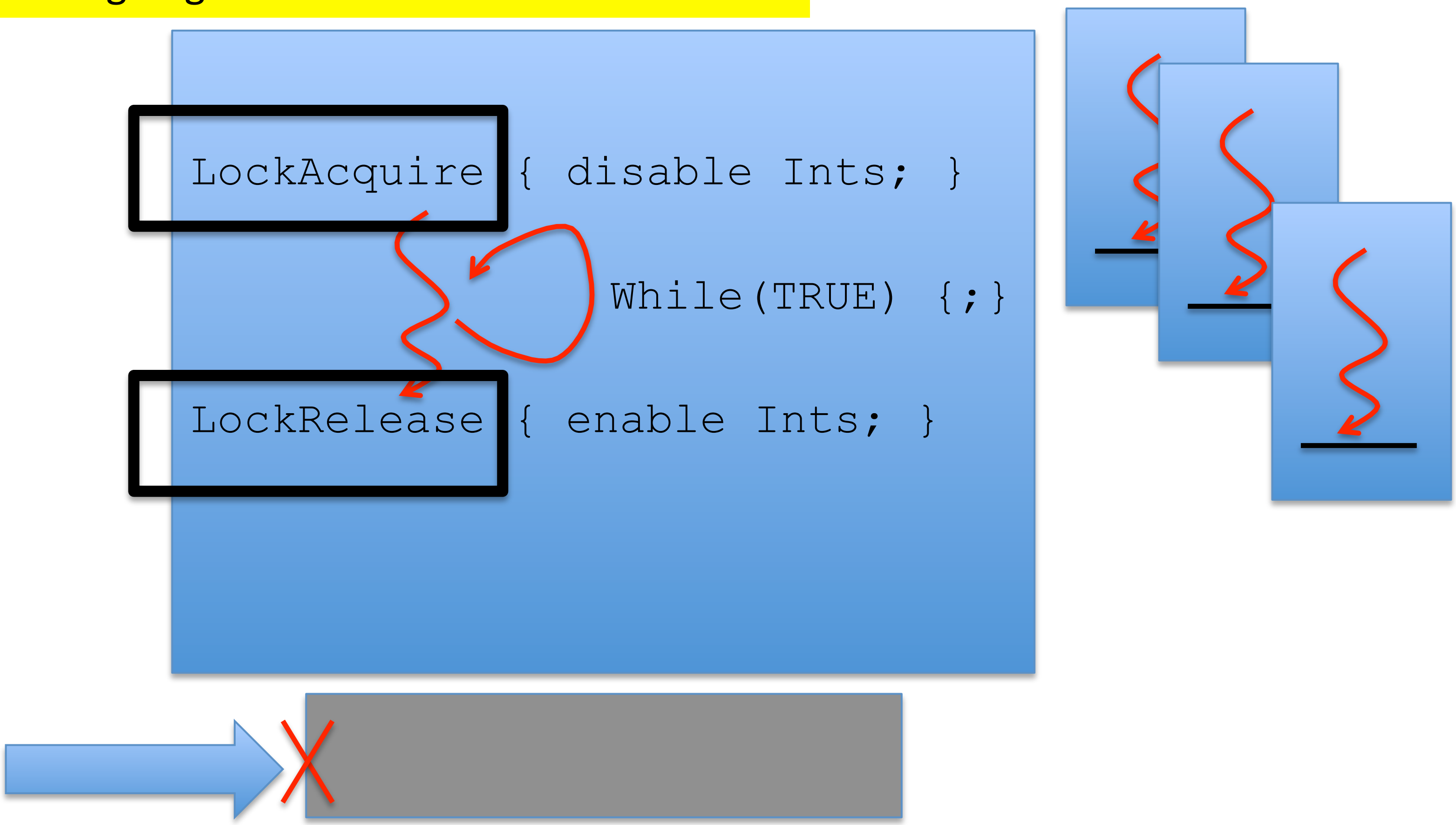
- How can we build multi-instruction atomic operations?
  - Recall: dispatcher gets control in two ways.
    - Internal: Thread does something to relinquish the CPU
    - External: Interrupts cause dispatcher to take CPU
  - On a uniprocessor, can avoid context-switching by:
    - Avoiding internal events (although virtual memory tricky)
    - Preventing external events by disabling interrupts

- Consequently, naïve Implementation of locks:

```
LockAcquire { disable Ints; }
LockRelease { enable Ints; }
```

Lock vs Disable

Only disable for the implementation of the lock itself
Not what you are going to do under it!



An OS Implementation of Locks

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

Checking and Setting are indivisible
- otherwise two thread could see !BUSY

```
int value = FREE;
```

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

```
Release() {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Put at front of ready queue
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

Critical Section

Locks

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
Acquire() {
  disable interrupts;
}
```

```
Release() {
  enable interrupts;
}
```

```
int value = 0;
Acquire() {
  disable interrupts;
  if (value == 1) {
    put thread on wait-queue;
    go to sleep() //??
  } else {
    value = 1;
    enable interrupts;
  }
}
```

```
Release() {
 disable interrupts;
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  enable interrupts;
}
```

If one thread in critical section, no other activity (including OS) can run!

Interrupt re-enable in going to sleep

- What about re-enabling ints when going to sleep?

Enable Position
Enable Position
Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
```

- Before putting thread on the wait queue?
  – Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  – Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  – Misses wakeup and still holds lock (deadlock!)
- Want to put it after sleep(). But, how?

How to Re-enable After Sleep()?

- Since ints are disabled when you call sleep:
  - Responsibility of the next thread to re-enable ints
  - When the sleeping thread wakes up, returns to acquire and re-enables interrupts

<u>Thread A</u> | <u>Thread B</u>

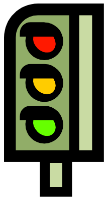
```
   Thread A                          Thread B
      .
      .
 disable ints
    sleep       --context switch-->
                                   yield return
                                   enable ints
                                        .
                                        .
                                        .
                                   disable int
                <--context switch-- yield
 sleep return
 enable ints
      .
      .
```

Administrative Break

- hmmm
- HW2: experience with sockets&fork
  - experience with threads as separate exercise
- Proj 1:
  - think, read, think, design, simple start, think, write
  - then code code code

Semaphores

- Semaphores are a kind of generalized locks
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX



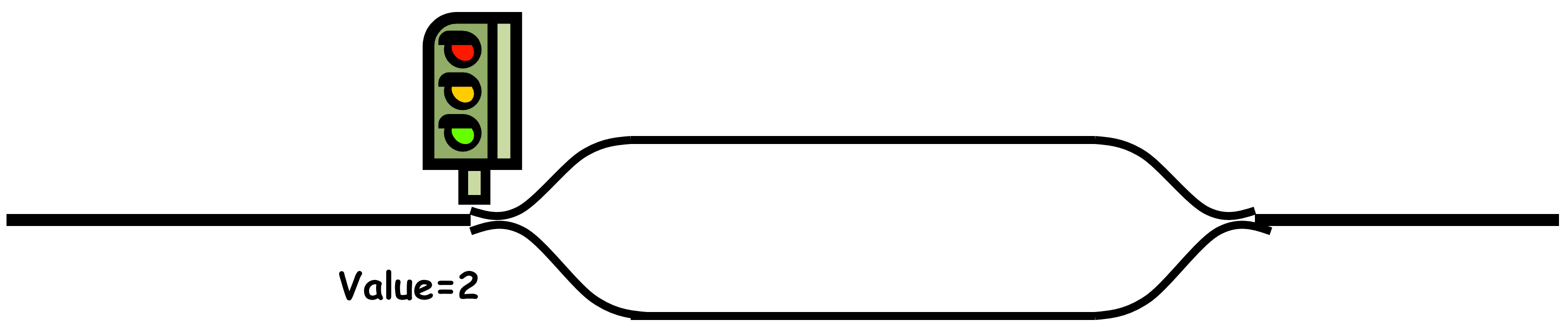
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - P(): an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - Think of this as the wait() operation

    down
  - V(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - This of this as the signal() operation

    up
  - Note that P() stands for "*proberen*" (to test) and V() stands for "*verhogen*" (to increment) in Dutch

Semaphores Like Integers Except

- 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:



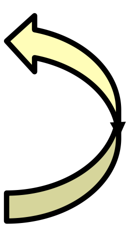
Two Uses of Semaphores

- 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 constrained is satisfied
  - Example: suppose you had to implement ThreadJoin which must wait for thread to terminate:

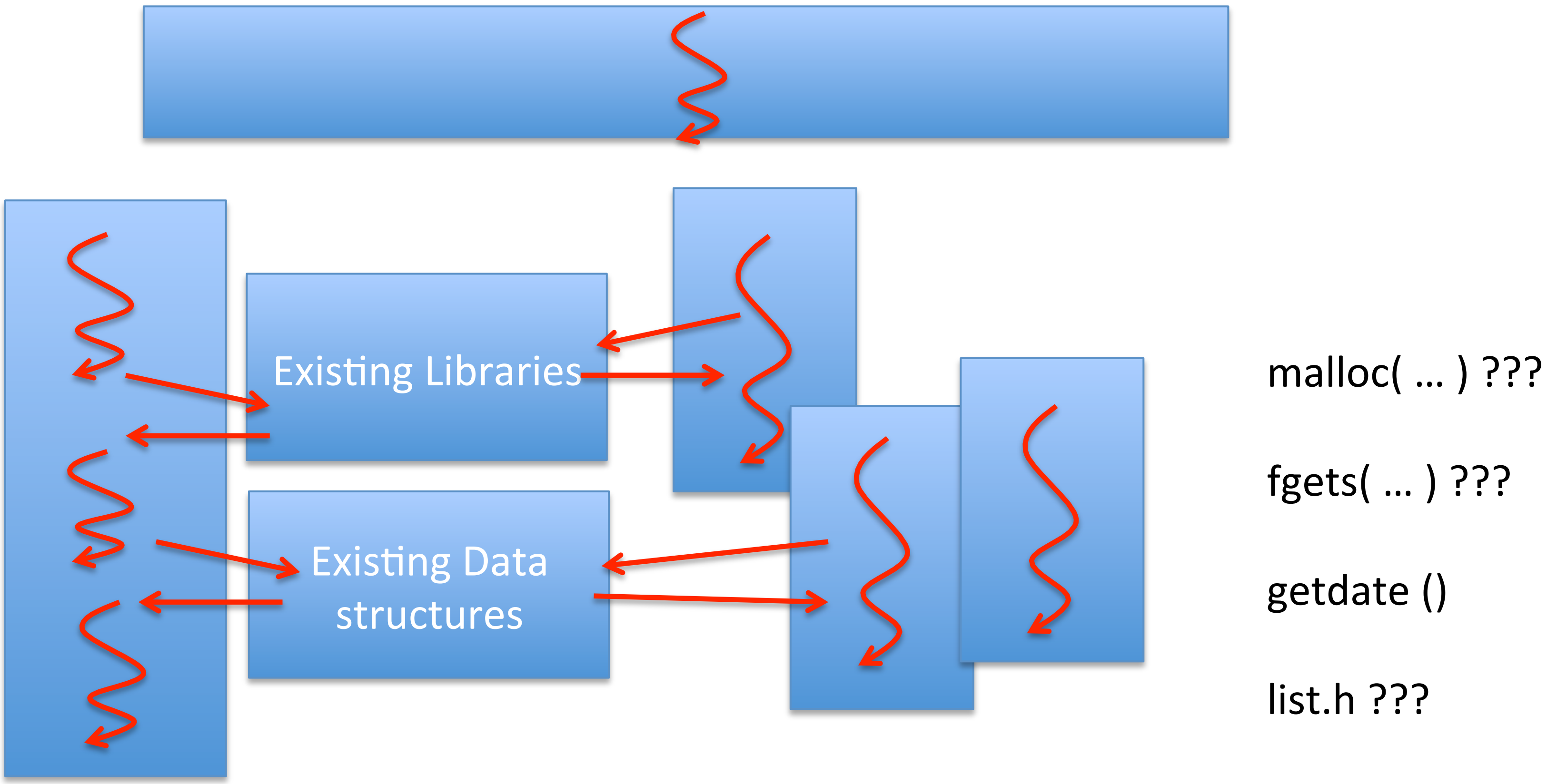
```
Initial value of semaphore = 0
ThreadJoin {
   semaphore.P();
}
ThreadFinish {
   semaphore.V();
}
```



Structured concurrent programming

- Use locks for mutual exclusion
  - Including manipulation of data structures
  - Locks more structured than semaphores
    - Ownership: acquirer must release
- Use Condition Variables (more soon) for Scheduling constraints
  - A => B. "stateless"
- Integrate these into concurrent objects
  - Synchronized methods effect the protocol
- But …

Thread Safe



- A thread-safe function is one that can be safely (i.e., it will deliver the same results regardless of whether it is) called from multiple threads at the same time.
  - http://man7.org/linux/man-pages/man7/pthreads.7.html

Legacy locks

```
pthread_mutex_t mymalloclock;

void *my_malloc(size_t size) {
    void *res;
    pthread_mutex_lock(&mymalloclock);
    res = malloc(size);
    pthread_mutex_unlock(&mymalloclock);
    return res;
}

void my_free(void *ptr) {
 …
}
…
```

Thread <> Interrupt Handler

- Interrupt handlers are not threads
- Only threads can share locks
  - Ownership
- Yet in the kernel interrupt handlers and threads need to coordinate access to shared data structures

- The statefull aspect of semaphores makes the pending waiters work

eg. Pintos Locks (synch.c)

```
void lock_init (struct lock *lock) {
  ASSERT (lock != NULL);
  lock->holder = NULL;
  sema_init (&lock->semaphore, 1);
}

void lock_acquire (struct lock *lock) {
  ASSERT (lock != NULL); ASSERT (!intr_context ());
  ASSERT (!lock_held_by_current_thread (lock));

  sema_down (&lock->semaphore);
  lock->holder = thread_current ();
}
void
lock_release (struct lock *lock)
{
  ASSERT (lock != NULL);
  ASSERT (lock_held_by_current_thread (lock));

  lock->holder = NULL;
  sema_up (&lock->semaphore);
}
```

- Implements semaphores for synchronization and builds locks and CVs on top.

pintos semaphore (synch.{h,c})

see list.h

```
struct semaphore
  { unsigned value;        /* Current value. */
    struct list waiters; /* List of waiting threads.*/
  };
```

```
void sema_down (struct semaphore *sema) {
  enum intr_level old_level;

  ASSERT (sema != NULL);
  ASSERT (!intr_context ());

  old_level = intr_disable ();
  while (sema->value == 0)
    {
      list_push_back (&sema->waiters,
                      &thread_current ()->elem);
      thread_block ();
    }
  sema->value--;
  intr_set_level (old_level);
}
```

Critical section

Exclusive access while manipulating list

enter thread block with intrs disabled

atomic RMW on success

pintos semaphore -> thread

```
void sema_down (struct sem
  enum intr_level old_leve

  ASSERT (sema != NULL);
  ASSERT

  old_leve
  while (s
    {
      list

      thread_block ();
    }
  sema->value--;
  intr_set_level (old_level);
}
```

```
void thread_bloc
  ASSERT (!intr_
  ASSERT (intr_g

  thread_current()->status = THREAD_BLOCKED;
  schedule ();
}
```

```
static void schedule (void) {
  struct thread *cur = running_thread ();
  struct thread *next = next_thread_to_run ();
  struct thread *prev = NULL;

  ASSERT (intr_get_level () == INTR_OFF);
  ASSERT (cur->status != THREAD_RUNNING);
  ASSERT (is_thread (next));

  if (cur != next)
    prev = switch_threads (cur, next);
  thread_schedule_tail (prev);
}
```

pint

```
switch_threads:
    # Save caller's register state.
        pushl %ebx
        pushl %ebp
        pushl %esi
        pushl %edi
        # Get offsetof (struct thread, stack).
.globl thread_stack_ofs
        mov thread_stack_ofs, %edx

        # Save current stack pointer to old thread's stack, if any.
        movl SWITCH_CUR(%esp), %eax
        movl %esp, (%eax,%edx,1)

        # Restore stack pointer from new thread's stack.
        movl SWITCH_NEXT(%esp), %ecx
    movl (%ecx,%edx,1), %esp

        # Restore caller's register state.
        popl %edi
        popl %esi
        popl %ebp
        popl %ebx
    ret
.endfunc
```

```
void sema_d
  enum intr

  ASSERT (s
  ASSERT    v

  old_leve
  while (s
    {
      list
                }
      threa
    }
  sema->value--;
  intr_set_level (old_level);
}
```

pintos semaphores

```
void sema_up (struct semaphore *sema) {
  enum intr_level old_level;

  ASSERT (sema != NULL);

  old_level = intr_disable ();
  if (!list_empty (&sema->waiters))
    thread_unblock (list_entry (list_pop_front (&sema->waiters),
                                struct thread, elem));
  sema->value++;
  intr_set_level (old_level);
}
```

Concurrency Coordination Landscape