

# Lecture 19: Threads and Concurrency

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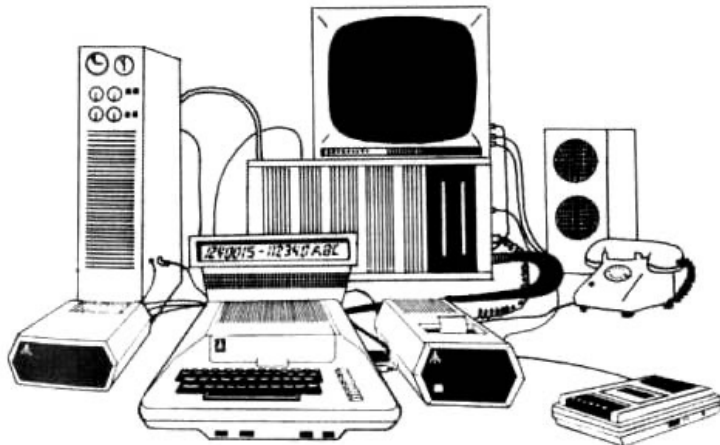
CS 105

Spring 2023

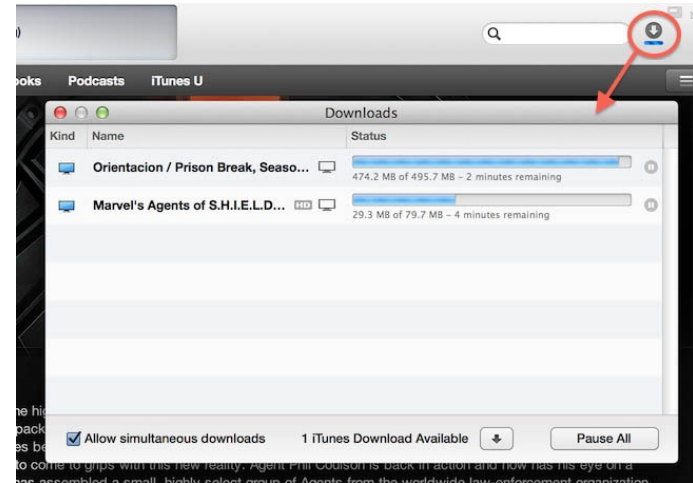
# Why Concurrent Programs?



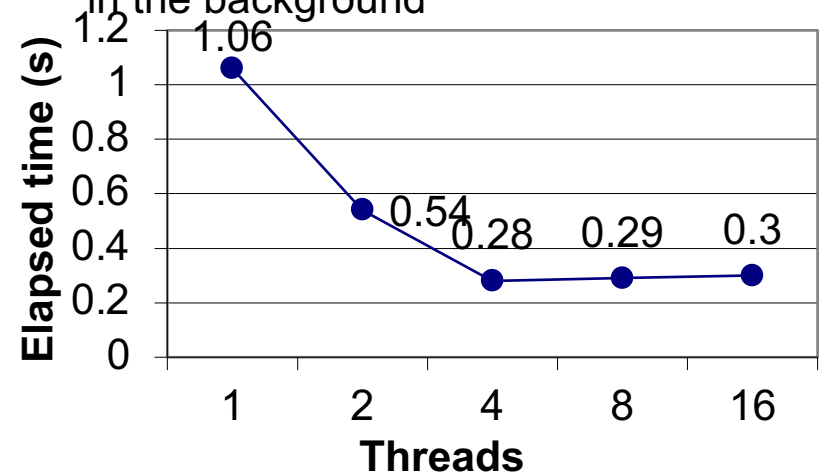
Program Structure: expressing logically concurrent programs



Responsiveness: managing I/O devices



Responsiveness: shifting work to run in the background

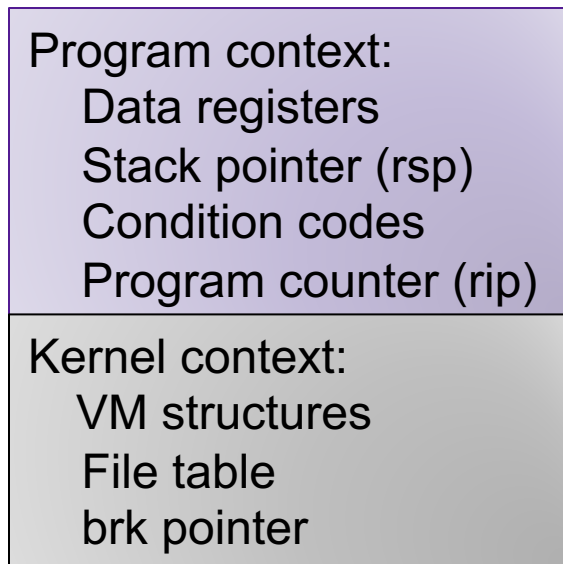


Performance: exploiting multiprocessors

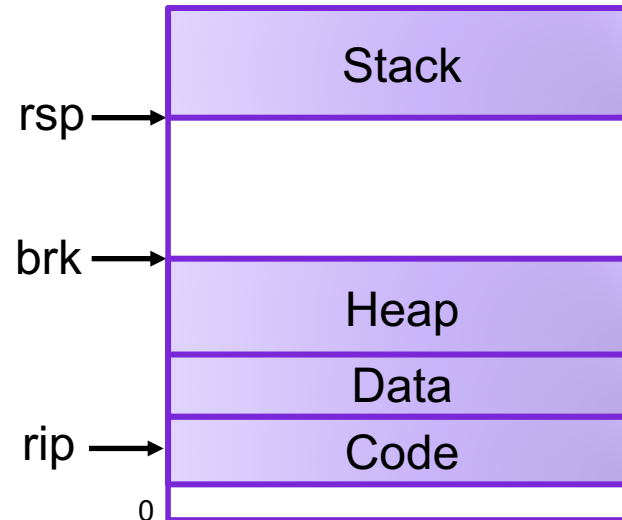
# Traditional View of a Process

- Process = process context + (virtual) memory state

Process Control Block

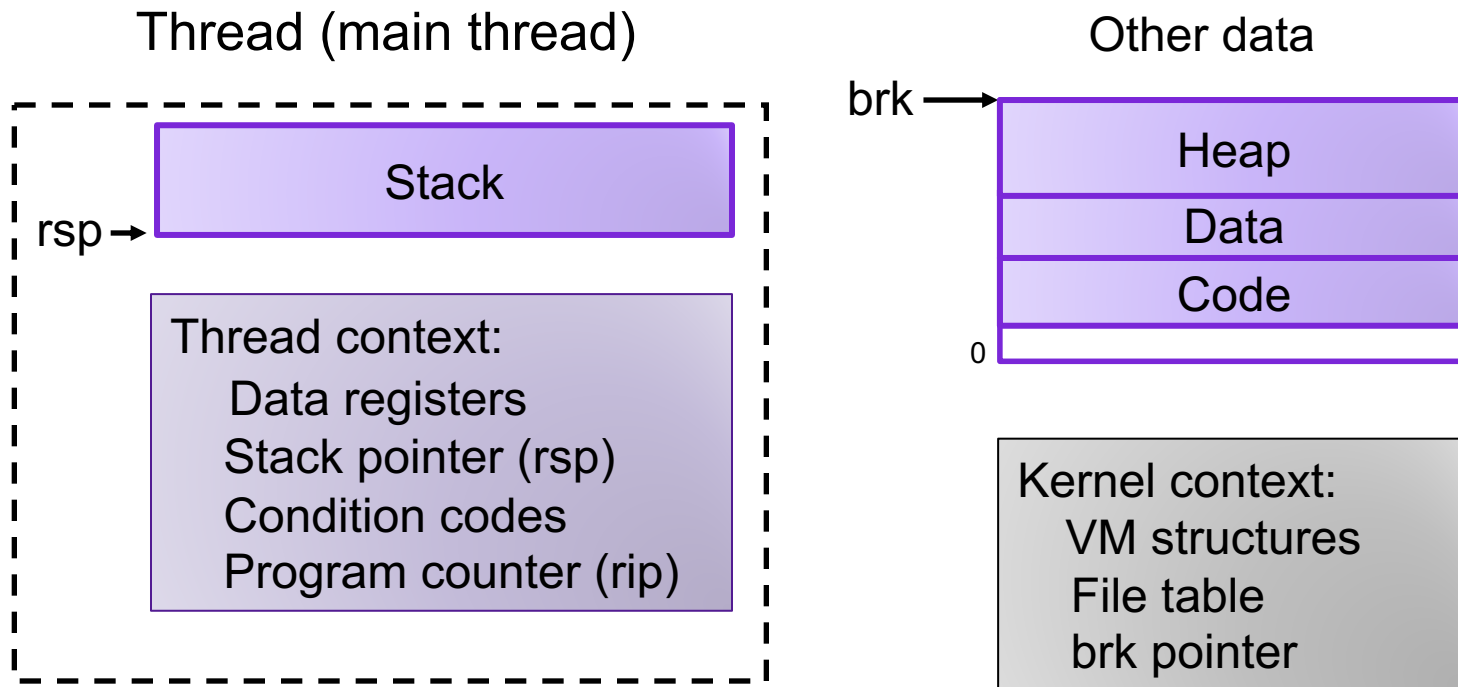


Virtual Memory



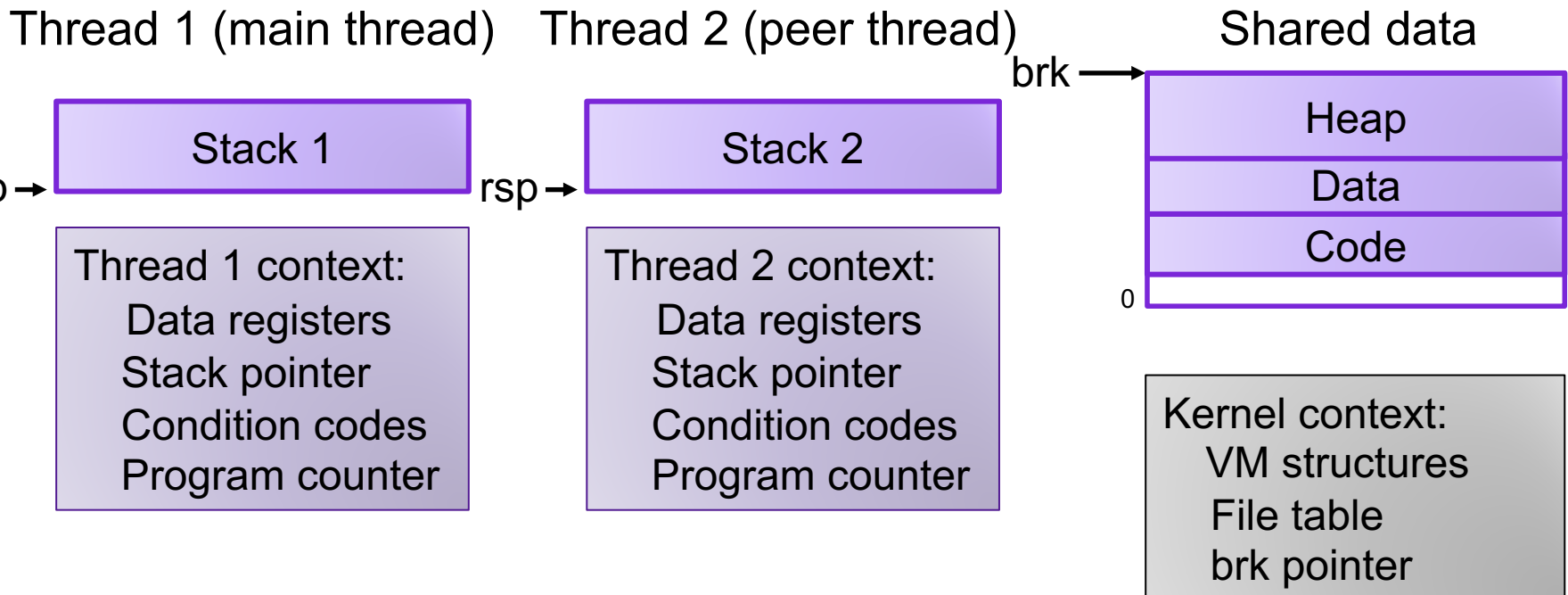
# Alternate View of a Process

- Process = thread + other state



# A Process With Multiple Threads

- Multiple threads can be associated with a process
  - Each thread has its own logical control flow
  - Each thread has its own stack for local variables
  - Each thread has its own thread id (TID)
  - Each thread shares the same code, data, and kernel context



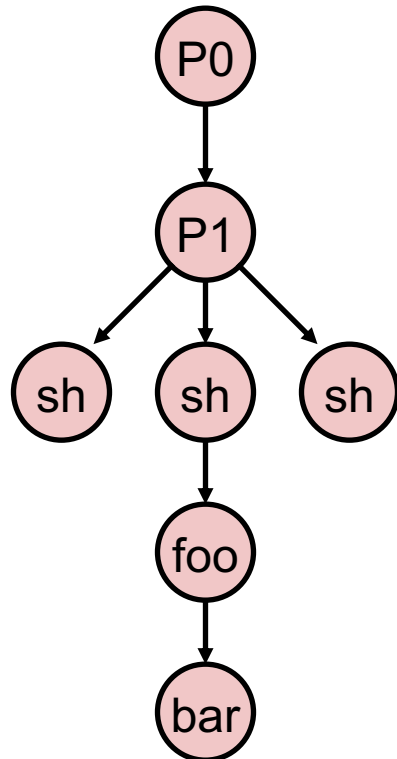
# Threads vs. Processes

- How threads and processes are similar
  - Each has its own logical control flow
  - Each can run concurrently with others (possibly on different cores)
  - Each is scheduled and context switched
- How threads and processes are different
  - Threads share all code and data (except local stacks)
    - Processes (typically) do not
  - Threads are somewhat less expensive than processes
    - Thread control (creating and reaping) is half as expensive as process control
      - ~20K cycles to create and reap a process
      - ~10K cycles (or less) to create and reap a thread
    - Thread context switches are less expensive (e.g., don't flush TLB)

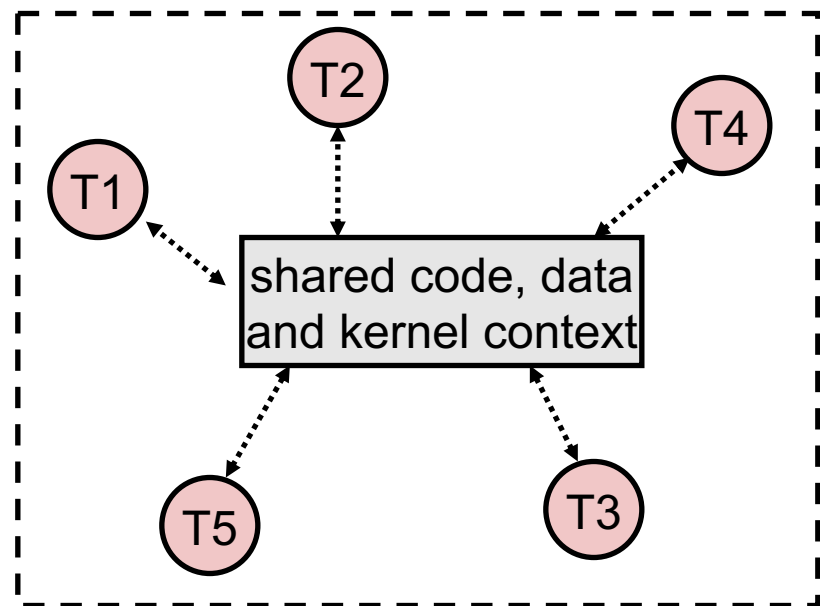
# Logical View of Threads

- Threads associated with process form a pool of peers
  - Unlike processes which form a tree hierarchy

Process hierarchy



Threads associated with process foo



# Posix Threads Interface

## C (Pthreads)

- **Creating and reaping threads**
  - `pthread_create()`
  - `pthread_join()`
- **Determining your thread ID**
  - `pthread_self()`
- **Terminating threads**
  - `pthread_cancel()`
  - `pthread_exit()`
  - `exit()` [terminates all threads]
  - `RET` [terminates current thread]

## Python (threading)

- **Creating and reaping threads**
  - `Thread()`
  - `thread.join()`
- **Determining your thread ID**
  - `thread.get_ident()`
- **Terminating threads**
  - `thread.exit()`
  - `RET` [terminates current thread]



# The Pthreads "hello, world" Program

```
/*
 * hello.c - Pthreads "hello, world" program
 */
#include "csapp.h"
void *thread(void *vargp);

int main(){

    pthread_t tid;
    pthread_create(&tid, NULL, thread, NULL);
    pthread_join(tid, NULL);
    exit(0);
}
```

hello.c

Thread ID

Thread attributes  
(usually NULL)

Thread routine

Thread arguments  
(void \*p)

Return value  
(void \*\*p)

```
void *thread(void *vargp){ /* thread routine */

    printf("Hello, world!\n");
    return NULL;
}
```

hello.c

# Example: Sharing with Threads

```
char** ptr; /* global var */

int main(){

    long i;
    pthread_t tid;
    char* msgs[2] = {
        "Hello from foo",
        "Hello from bar"
    };

    ptr = msgs;
    for (i = 0; i < 2; i++)
        Pthread_create(&tid,
            NULL,
            thread,
            (void*) i);
    Pthread_exit(NULL);
}
```

sharing.c

```
void* thread(void* vargp){

    long myid = (long) vargp;
    static int cnt = 0;

    printf("[%ld]: %s (cnt=%d)\n",
        myid, ptr[myid], ++cnt);
    return NULL;
}
```

*Peer threads reference main thread's stack indirectly through global ptr variable*

# Mapping Variable Instances to Memory

- Global variables
  - *Def:* Variable declared outside of a function
  - **Virtual memory contains exactly one instance of any global variable**
- Local variables
  - *Def:* Variable declared inside function without `static` attribute
  - **Each thread stack contains one instance of each local variable**
- Local static variables
  - *Def:* Variable declared inside function with the `static` attribute
  - **Virtual memory contains exactly one instance of any local static variable.**

# Mapping Variable Instances to Memory

```
char **ptr; /* global var */

int main(){
    long i;
    pthread_t tid;
    char *msgs[2] = {"Hello from foo",
                    "Hello from bar"};

    ptr = msgs;
    for (int i = 0; i < 2; i++)
        Pthread_create(&tid, NULL,
                      thread, (void *)i);
    Pthread_exit(NULL);
}
```

*Global var:* 1 instance (ptr [data])

*Local vars:* 1 instance (i.m, msgs.m)

*Local var:* 2 instances (  
myid.p0 [peer thread 0's stack],  
myid.p1 [peer thread 1's stack]  
)

*Local static var:* 1 instance (cnt [data])

```
void *thread(void *vargp){
    long myid = (long)vargp;
    static int cnt = 0;

    printf("[%ld]: %s (cnt=%d)\n",
           myid, ptr[myid], ++cnt);
    return NULL;
}
```

# Exercise 1: Shared Variables

```
char **ptr; /* global var */

int main(){
    long i;
    pthread_t tid;
    char *msgs[2] = {"Hello from foo",
                    "Hello from bar"};

    ptr = msgs;
    for (int i = 0; i < 2; i++)
        Pthread_create(&tid, NULL,
                      thread, (void *)i);
    Pthread_exit(NULL);
}
```

```
void *thread(void *vargp){
    long myid = (long)vargp;
    static int cnt = 0;

    printf("[%ld]: %s (cnt=%d)\n",
           myid, ptr[myid], ++cnt);
    return NULL;
}
```

Which variables are shared?

- ptr
- cnt
- i.main
- msgs.main
- myid.thread0
- myid.thread1

# Exercise 1: Shared Variables

- Which variables are shared?
  - A variable  $x$  is shared iff multiple threads reference at least one instance of  $x$ .

<i>Variable instance</i>	<i>Referenced by main thread?</i>	<i>Referenced by peer thread 0?</i>	<i>Referenced by peer thread 1?</i>
<code>ptr</code>			
<code>cnt</code>			
<code>i.main</code>			
<code>msgs.main</code>			
<code>myid.thread0</code>			
<code>myid.thread1</code>			

# Why not Concurrent Programs?

```
/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char** argv) {
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
        count_func, &niters);
    Pthread_create(&tid2, NULL,
        count_func, &niters);
    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    /* Check result */
    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}
```

```
/* Thread routine */
void* count_func(void* vargp) {
    long i, niters;
    niters = *((long*) vargp);

    for (i = 0; i < niters; i++) {
        cnt++;
    }

    return NULL;
}
```

```
linux> ./badcnt 10000
OK cnt=20000
linux> ./badcnt 10000
BOOM! cnt=13051
linux>
```

# Assembly Code for Counter Loop

C code for counter loop in thread  $i$

```
for (i = 0; i < niters; i++){  
    cnt++;  
}
```

*Asm code for thread  $i$*

<pre>movq  (%rdi), %rcx testq %rcx,%rcx jle   .L2 movl  \$0, %eax</pre>	}	$H_i$ : Head
<pre>.L3: movq  cnt(%rip), %rdx addq  \$1, %rdx movq  %rdx, cnt(%rip)</pre>		
<pre>addq  \$1, %rax cmpq  %rcx, %rax jne   .L3 .L2:</pre>	}	$T_i$ : Tail



# Race conditions

- A race condition is a timing-dependent error involving shared state
  - whether the error occurs depends on thread schedule
- program execution/schedule can be non-deterministic
- compilers and processors can re-order instructions

# A concrete example...

- You and your roommate share a refrigerator. Being good roommates, you both try to make sure that the refrigerator is always stocked with milk.
- **Liveness:** if you are out of milk, someone buys milk
- **Safety:** you never have more than one quart of milk



## Algorithm 1:

```
if (milk == 0) {           // no milk
    milk++;                 // buy milk
}
```

# A problematic schedule

You		Your Roommate	
3:00	Look in fridge; out of milk		
3:05	Leave for store		
3:10	Arrive at store	3:10	Look in fridge; out of milk
3:15	Buy milk	3:15	Leave for store
3:20	Arrive home; put milk in fridge	3:20	Arrive at store
		3:25	Buy milk
		3:30	Arrive home; put milk in fridge

**Safety violation:**  
You have too much milk and it spoils

# Solution 1: Leave a note

- You and your roommate share a refrigerator. Being good roommates, you both try to make sure that the refrigerator is always stocked with milk.



## Algorithm 2:

```
if (milk == 0) {           // no milk
    if (note == 0) {      // no note
        note = 1;         // leave note
        milk++;           // buy milk
        note = 0;         // remove note
    }
}
```

## Solution 2: Leave note before check note

- You and your roommate share a refrigerator. Being good roommates, you both try to make sure that the refrigerator is always stocked with milk.



### Algorithm 3:

```
note1 = 1
if (note2 == 0) { // no note from
                    roommate
    if (milk == 0) { // no milk
        milk++;      // buy milk
    }
}
note1 = 0
```

# Solution 3: Keep checking for note

- You and your roommate share a refrigerator. Being good roommates, you both try to make sure that the refrigerator is always stocked with milk.



## Algorithm 4:

```
note1 = 1
while (note2 == 1) { // wait until
    ;                // no note
}
if (milk == 0) {    // no milk
    milk++;         // buy milk
}
note1 = 0
```

# Solution 4: Take turns

- You and your roommate share a refrigerator. Being good roommates, you both try to make sure that the refrigerator is always stocked with milk.



## Algorithm 5:

```
note1 = 1
turn = 2
while (note2 == 1 and turn == 2){
    ;
}
if (milk == 0) {           // no milk
    milk++;                // buy milk
}
note1 = 0
```

# Locks

- A **lock** (aka a mutex) is a synchronization primitive that provides mutual exclusion. When one thread holds a lock, no other thread can hold it.
  - a lock can be in one of two states: locked or unlocked
  - a lock is initially unlocked
- function `acquire(&lock)` waits until the lock is unlocked, then atomically sets it to locked
- function `release(&lock)` sets the lock to unlocked



# Solution 5: use a lock

- You and your roommate share a refrigerator. Being good roommates, you both try to make sure that the refrigerator is always stocked with milk.



## Algorithm 6:

```
acquire(&lock)
if (milk == 0) {           // no milk
    milk++;                // buy milk
}
release(&lock)
```

# Atomic Operations

- Solution: hardware primitives to support synchronization
- A machine instruction that (atomically!) reads and updates a memory location
- Example: `xchg src, dest`
  - one instruction
  - semantics:  $TEMP \leftarrow DEST; DEST \leftarrow SRC; SRC \leftarrow TEMP;$



# Programming with Locks

## C (pthreads)

- Defines lock type `pthread_mutex_t`
- functions to create/destroy locks:
  - `int pthread_mutex_init(&lock, attr);`
  - `int pthread_mutex_destroy(&lock);`
- functions to acquire/release lock:
  - `int pthread_mutex_lock(&lock);`
  - `int pthread_mutex_unlock(&lock);`

## Python (threading)

- Defines class `Lock`
- constructor to create locks:
  - `Lock()`
  - destroyed by garbage collector
- functions to acquire/release lock:
  - `lock.acquire()`
  - `lock.release()`

# Exercise 2: Locks

```
/* Global shared variable */
volatile long cnt = 0; /* Counter */

int main(int argc, char **argv)
{
    long niters;
    pthread_t tid1, tid2;

    niters = atoi(argv[1]);
    Pthread_create(&tid1, NULL,
                  thread, &niters);
    Pthread_create(&tid2, NULL,
                  thread, &niters);
    Pthread_join(tid1, NULL);
    Pthread_join(tid2, NULL);

    /* Check result */
    if (cnt != (2 * niters))
        printf("BOOM! cnt=%ld\n", cnt);
    else
        printf("OK cnt=%ld\n", cnt);
    exit(0);
}
```

```
/* Thread routine */
void *thread(void *vargp)
{
    long i, niters =
        *((long *)vargp);

    for (i = 0; i < niters; i++){
        cnt++;
    }

    return NULL;
}
```

- TODO: Modify this example to guarantee correctness

# Problems with Locks

## 1. Locks are slow

- threads that fail to acquire a lock on the first attempt must "spin", which wastes CPU cycles
- threads get scheduled and de-scheduled while the lock is still locked

## 2. Using locks correctly is hard

- hard to ensure all race conditions are eliminated
- easy to introduce synchronization bugs (deadlock, livelock)

# Better Synchronization Primitives

- Semaphores
  - stateful synchronization primitive
- Condition variables
  - event-based synchronization primitive