Lecture 19: Threads and Concurrency

CS 105 Spring 2025

Why Concurrent Programs?

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Program Structure: expressing logically concurrent programs

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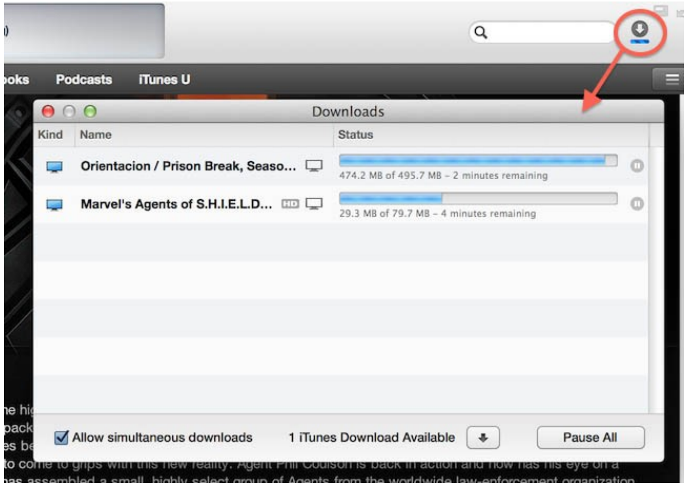

Responsiveness: shifting work to run in the background

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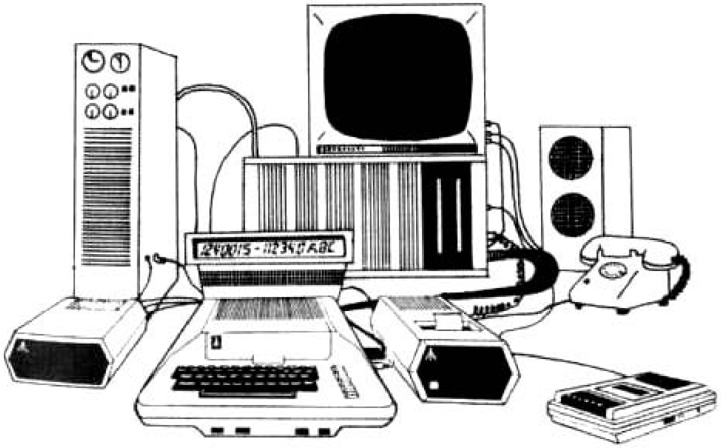
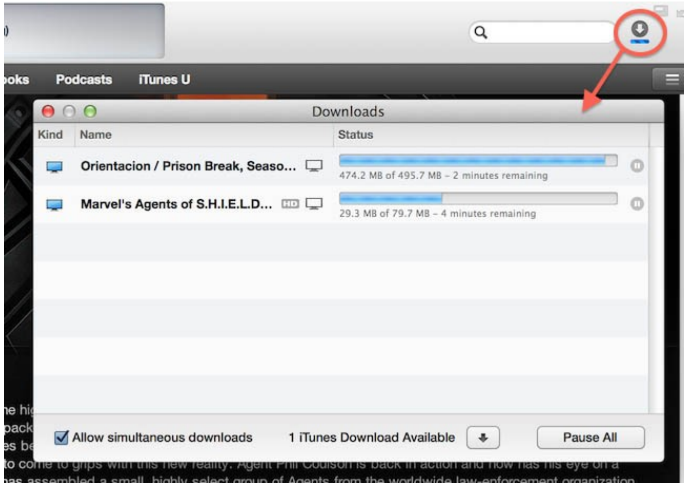


Responsiveness: managing I/O devices



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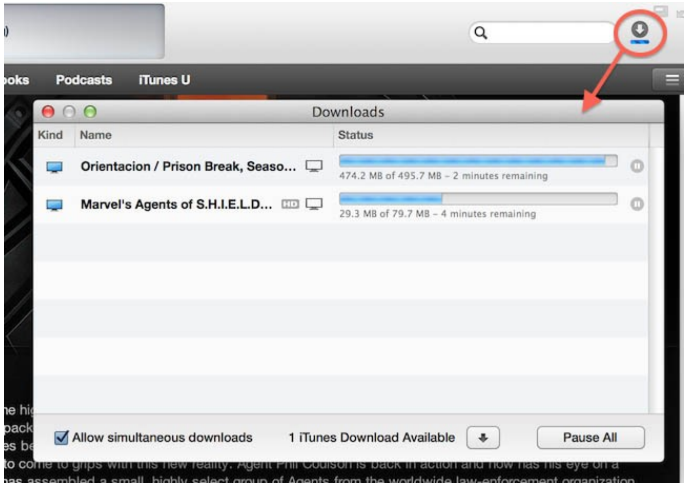

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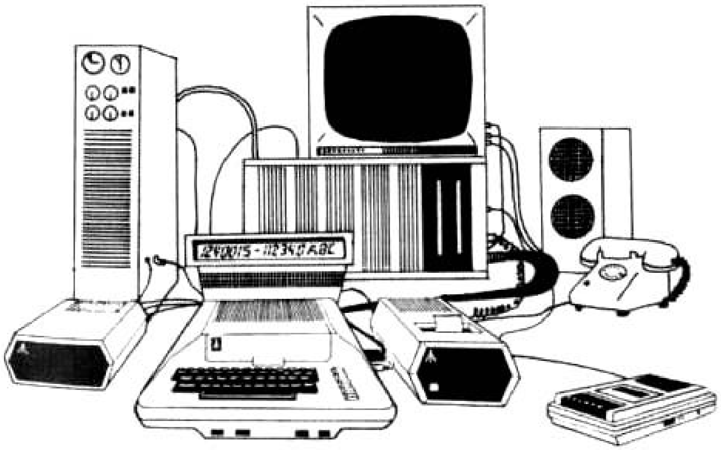

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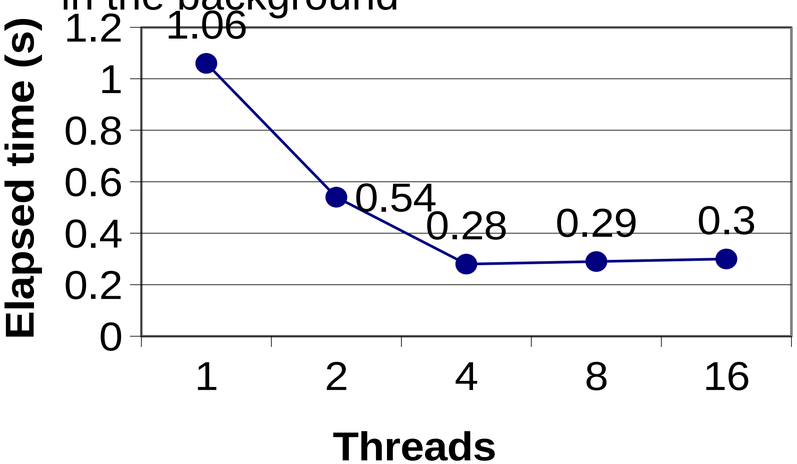


Performance: exploiting multiprocessors

Traditional View of a Process

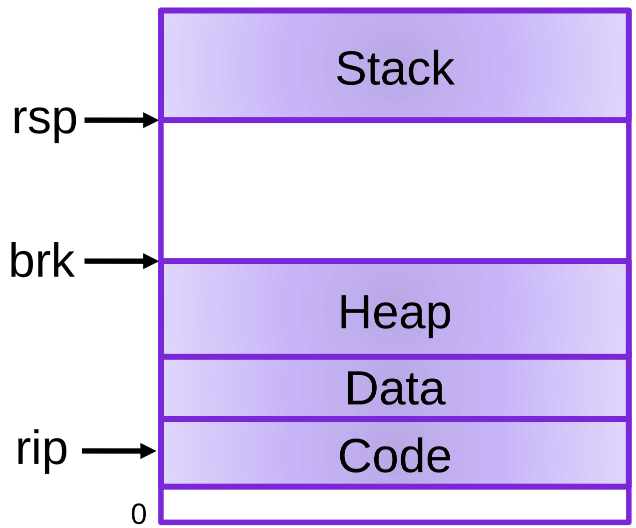
- Process = process context + (virtual) memory state

Process Control Block

Program context:
- Data registers
- Stack pointer (rsp)
- Condition codes
- Program counter (rip)

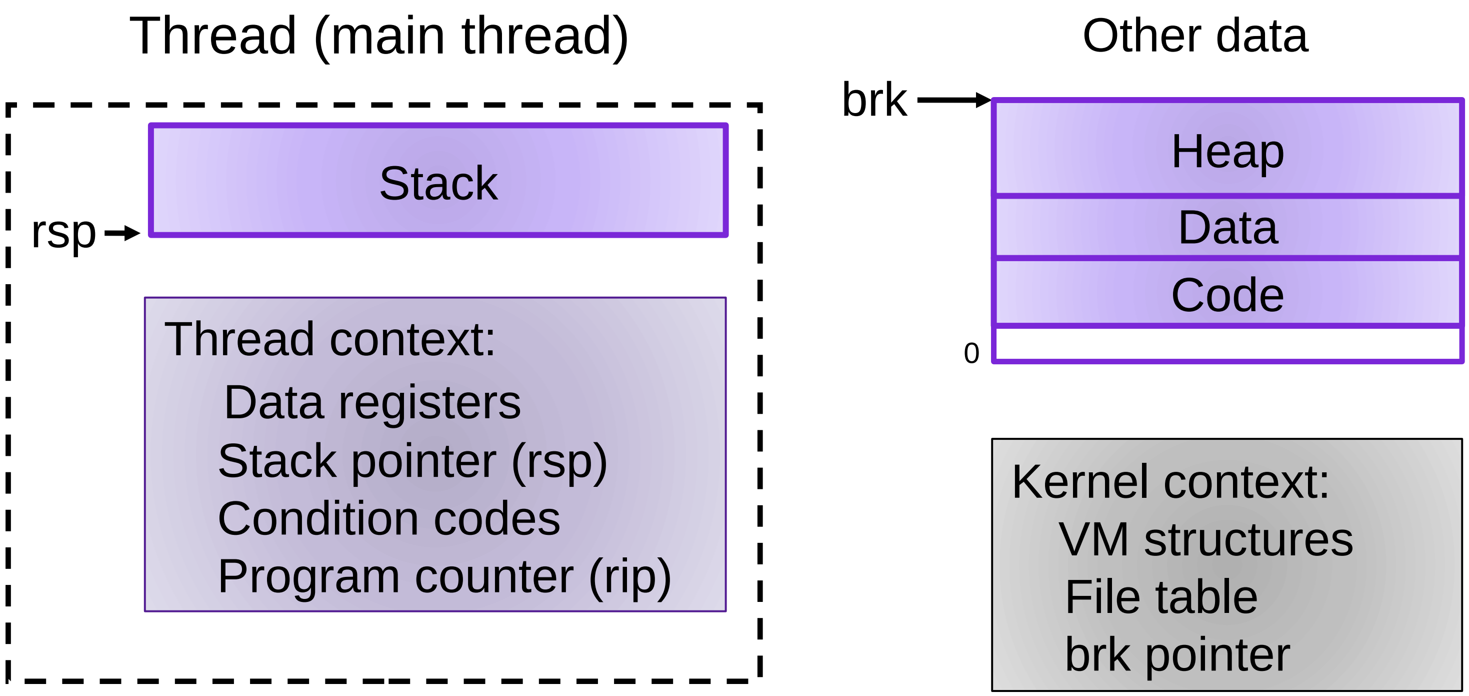
Kernel context:
- VM structures
- File table
- brk pointer

Virtual Memory



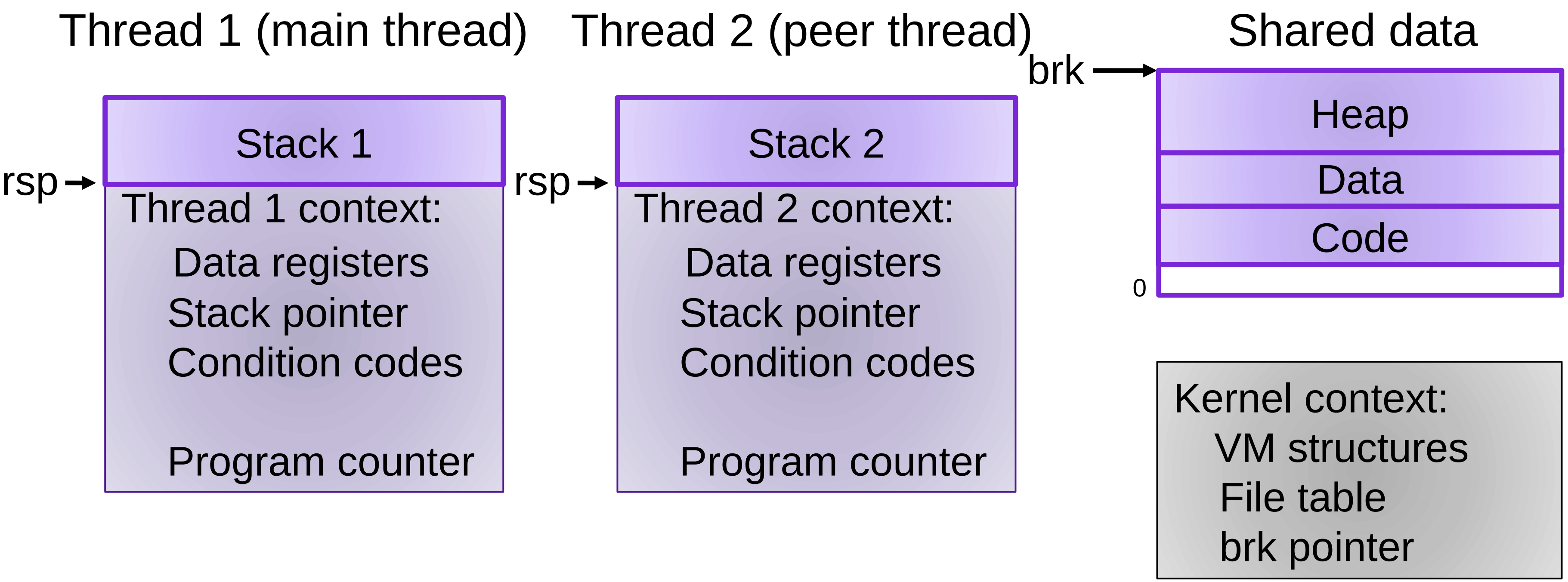
Alternate View of a Process

- 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

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)

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]

```c
/*

 * hello.c - Pthreads "hello, world" program

 */
#include "csapp.h"
void* thread(void* vargp);

int main(){

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

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

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

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int main(){

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```

Thread ID (points to `tid`)

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Thread ID

Thread attributes (usually NULL)

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Thread ID

Thread attributes (usually NULL)

Thread routine

Thread arguments (void* p)

Return value (void** p)

Example: Sharing with Threads

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

int main(){

  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,
                   fun, (void*) i);
  }
  pthread_exit(NULL);
}
```

```c
void* fun(void* vargp){

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

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

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

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- Global variables
  - *Def:* Variable declared outside of a function

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Exercise 1: Shared Variables

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int main(){

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                   "Hello from bar"};
  ptr = msgs;
  for (int i = 0; i < 2; i++){
    pthread_create(&tid, NULL,
                   fun, (void *)i);
  pthread_exit(NULL);
}
```

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

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

Which variables are shared (aka can be accessed by more than one thread)?

- `ptr`
- `cnt`
- `i`
- `msgs`
- `myid`

Exercise 1: Shared Variables

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

Variable instance	*Referenced by main thread?*	*Referenced by peer thread 0?*	*Referenced by peer thread 1?*
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`cnt`			
`i.main`			
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- **`ptr`, `cnt`, and `msgs` are shared**
- **`i` and `myid` are *not* shared**

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);
}
```

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

  return NULL;
}
```

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}
```

```c
  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++;
}
```

```
    movq  (%rdi), %rcx
    testq %rcx,%rcx
    jle   .L2
    movl  $0, %eax
.L3:
    movq  cnt(%rip),%rdx
    addq  $1, %rdx
    movq  %rdx, cnt(%rip)
    addq  $1, %rax
    cmpq  %rcx, %rax
    jne   .L3
.L2:
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.L2:
```

H_i : Head

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    cmpq  %rcx, %rax
    jne   .L3
.L2:
```

H_i : Head (movq (%rdi), %rcx … movl $0, %eax)

T_i : Tail (addq $1, %rax … .L2:)

Assembly Code for Counter Loop

C code for counter loop in thread i

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}
```

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    movq  %rdx, cnt(%rip)
    addq  $1, %rax
    cmpq  %rcx, %rax
    jne   .L3
.L2:
```

H_i : Head

L_i : Load `cnt`

U_i : Update `cnt`

S_i : Store `cnt`

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…

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- **Safety:** you never have more than one quart of milk

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- **Liveness:** if you are out of milk, someone buys milk
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Algorithm 1:

Look in fridge.
If out of milk:
    go to store,
    buy milk,
    go home
    put milk in fridge

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- **Liveness:** if you are out of milk, someone buys milk
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Algorithm 1:

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

A problematic schedule

You

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

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

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

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Algorithm 2:

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

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  }
}
```

Safety violation: you've introduced a Heisenbug!

Solution 2: Leave note before check note

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Algorithm 3:

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

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Algorithm 3:

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    milk++;         // buy milk
  }
}
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```

Liveness violation: No one buys milk

Solution 3: Keep checking for note

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- 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
  ;                      //   no note
}
if (milk == 0) {       // no milk
  milk++;              // buy milk
}
note1 = 0
```

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Liveness violation: You've introduced deadlock

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Algorithm 5:

```
note1 = 1
turn = 2
while (note2 == 1 and turn == 2){
  ;
}
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
```

(probably) correct, but complicated and inefficient

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

Atomic Operations

- Solution: hardware primitives to support synchronization
- A machine instruction that (atomically!) reads and updates

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- Solution: hardware primitives to support synchronization
- A machine instruction that (atomically!) reads and updates

- Example: `xchg` *src, dest*
  - one instruction
  - semantics: TEMP ← DEST; DEST ← SRC; SRC ← TEMP;

Spinlocks

```
acquire:
    mov  $1,   eax              ; Set EAX to 1
    xchg eax,  (rdi)            ; Atomically swap EAX w/ lock val
    test eax,  eax              ; check if EAX is 0 (lock unlocked)
    jnz  acquire                ; if was locked, loop
    ret                         ; lock has been acquired, return

release:
    mov  $0, eax                ; Set EAX to 0
    xchg eax,  (rdi)            ; Atomically swap EAX w/ lock val
    ret                         ; lock has been released, return
```

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.

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Algorithm 6:

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

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)
```

Correct!

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 aquire/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,
        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);
}
```

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




  return NULL;



}
```

- TODO: Modify this example to guarantee correctness

Problems with Locks

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

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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