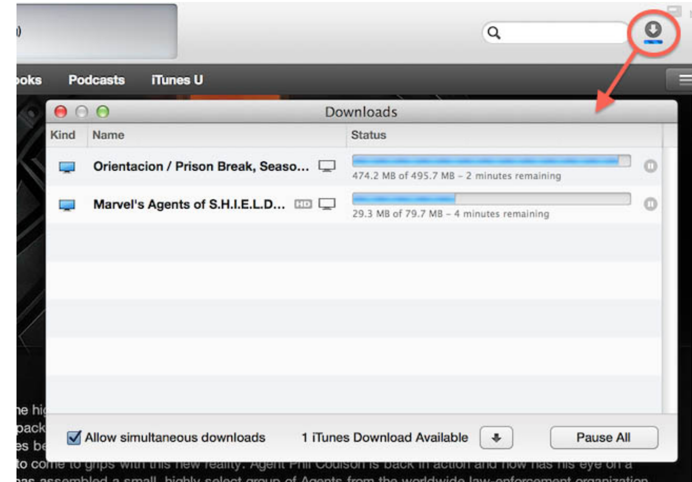
Lecture 21: Concurrency

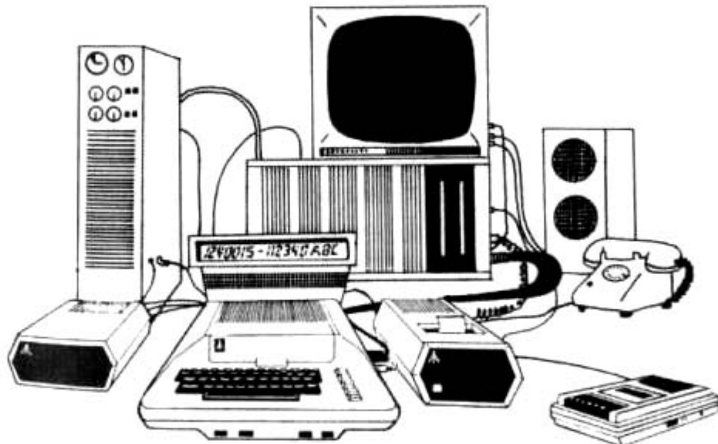
CS 105

Why Concurrent Programs?

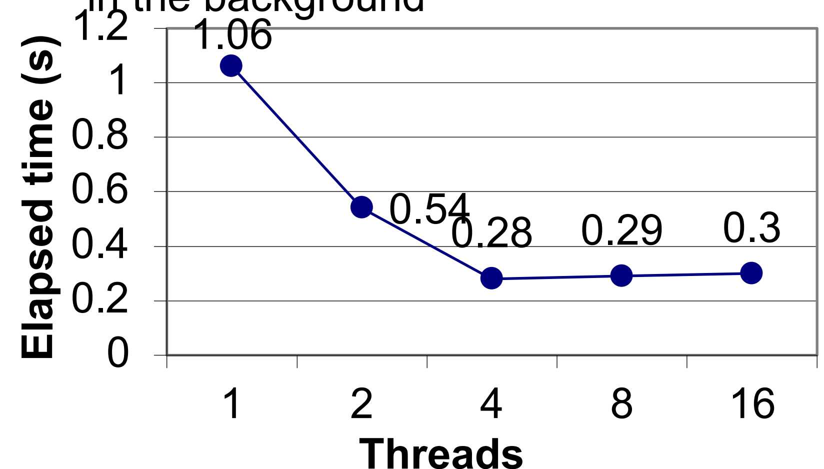
Program Structure: expressing logically concurrent programs



Responsiveness: shifting work to run in the background



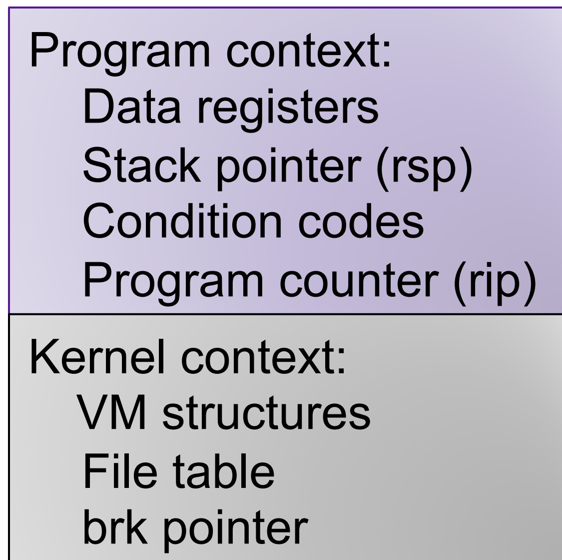
Responsiveness: managing I/O devices

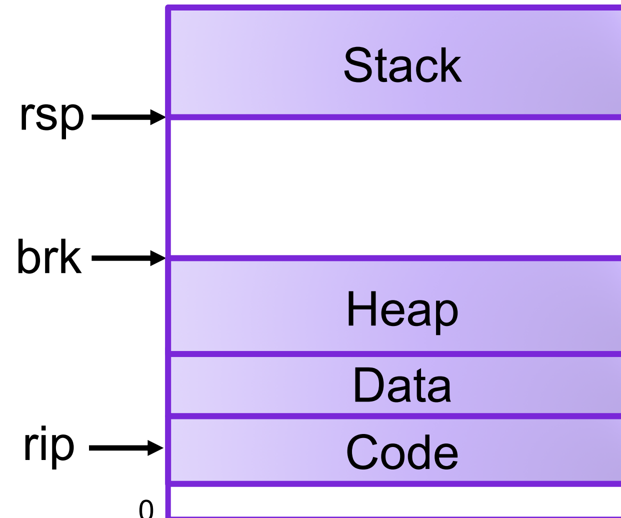


Performance: exploiting multiprocessors

Traditional View of a Process

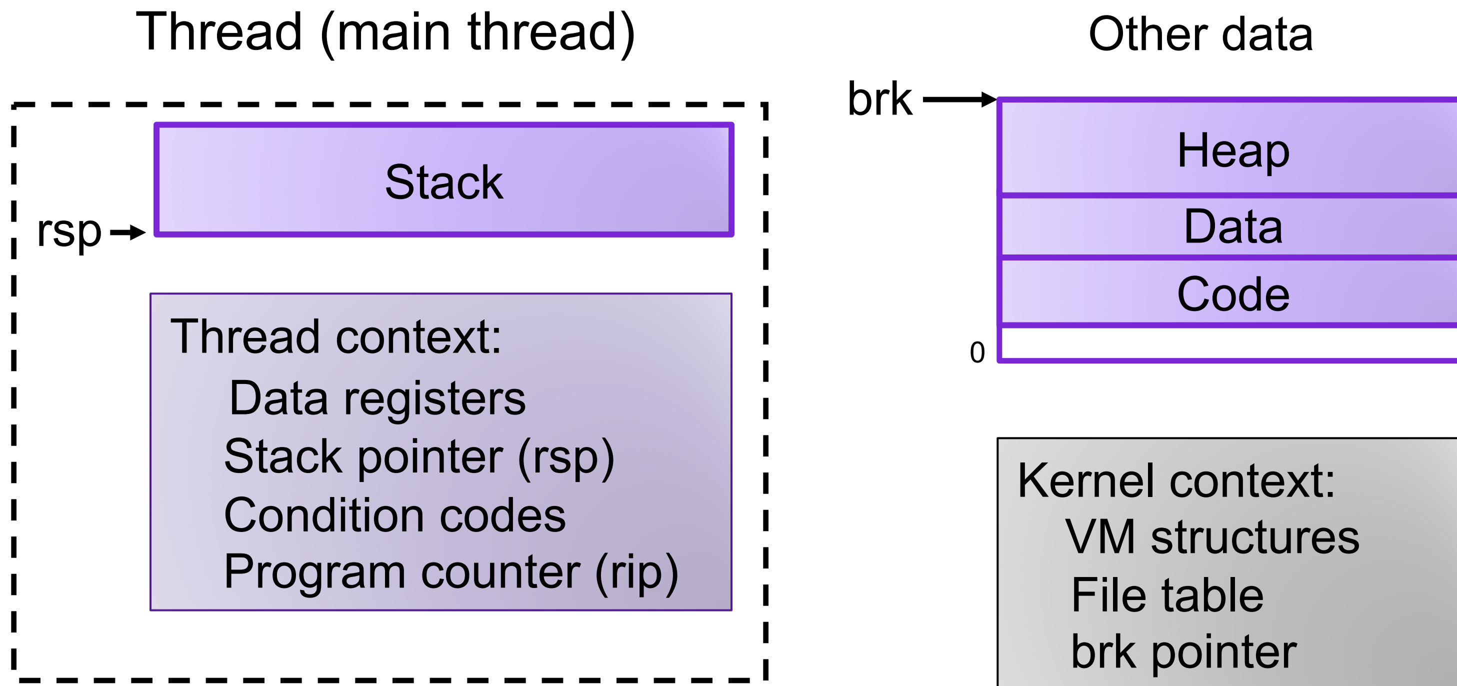
- Process = process context + (virtual) memory state





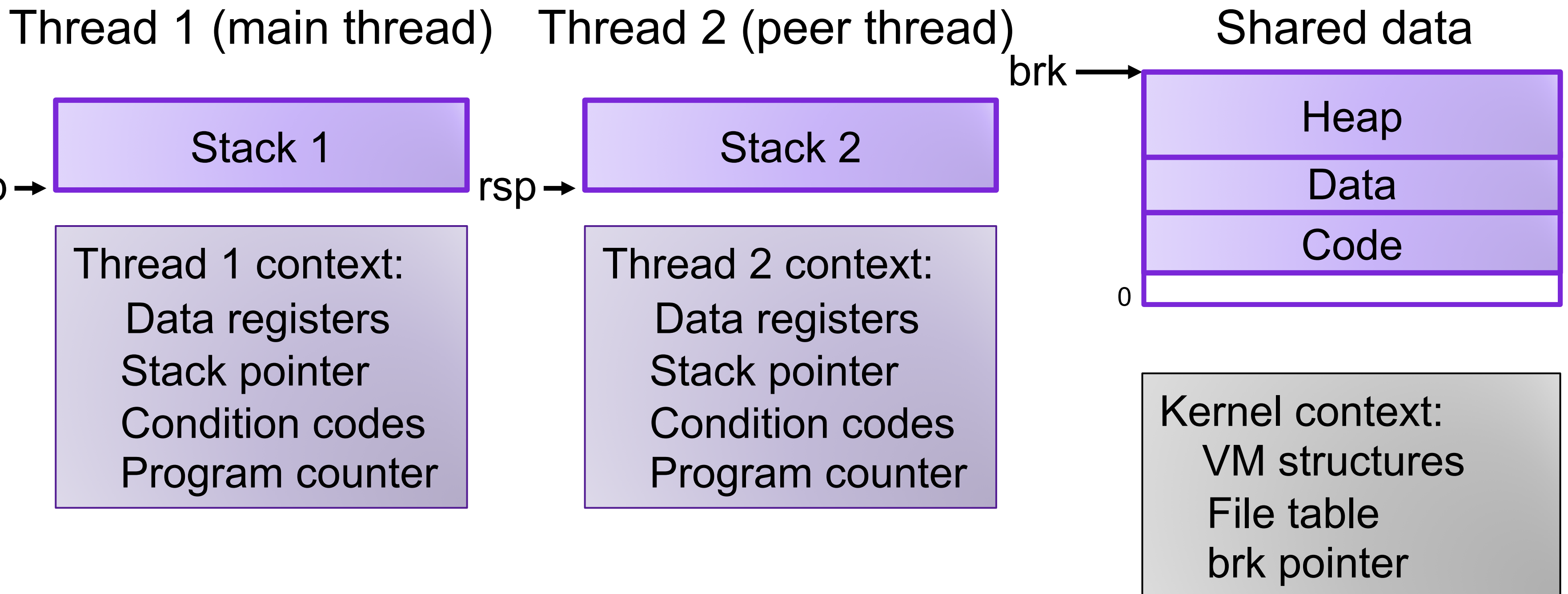
Alternate View of a Process

- 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

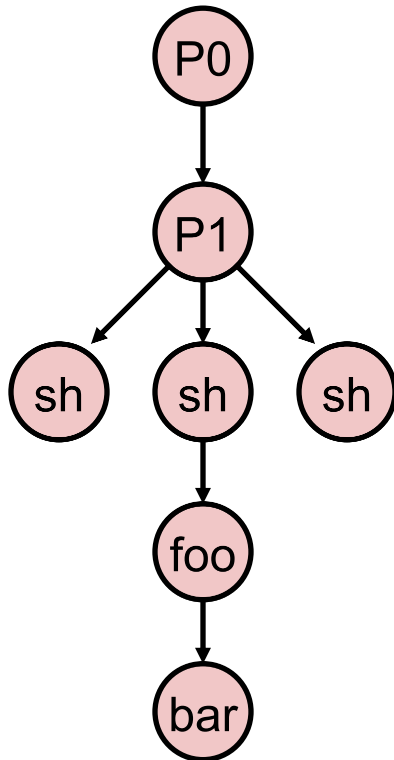


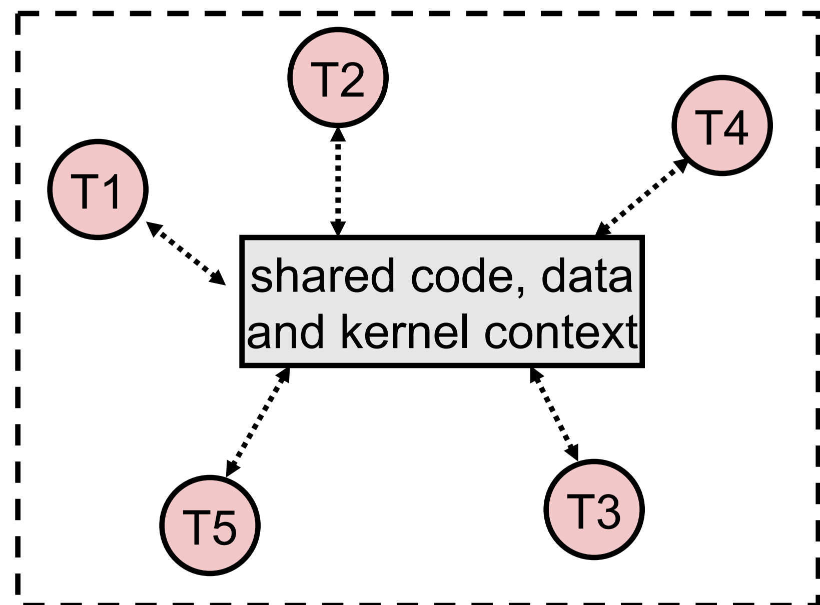
Threads vs. Processes

- 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





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

```c
/*
 * 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

```c
void *thread(void *vargp) /* thread routine */
{
    printf("Hello, world!\n");
    return NULL;
}
```

hello.c

Thread ID

Thread attributes (usually NULL)

Thread routine

Thread arguments (void *p)

Return value (void **p)

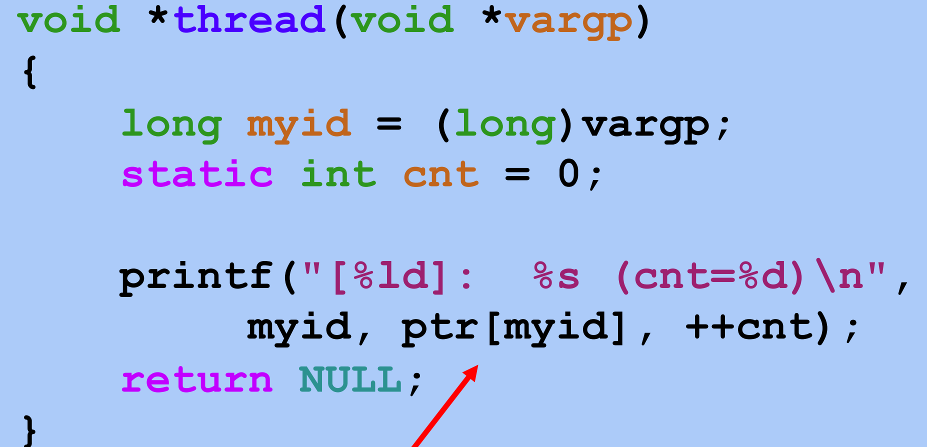
Example Program to Illustrate Sharing

```c
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



```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);
}
```

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

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

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`.

Variable instance	*Referenced by main thread?*	*Referenced by peer thread 0?*	*Referenced by peer thread 1?*
`ptr`	yes	yes	yes
`cnt`	no	yes	yes
`i.main`	yes	no	no
`msgs.main`	yes	yes	yes
`myid.thread0`	no	yes	no
`myid.thread1`	no	no	yes

- **`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,
        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;
  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

```
    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:
```

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…

- 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
  }
}
```

Safety violation: you've introduced a Heisenbug!

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
```

Liveness violation: No one buys milk

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
```

Liveness violation: You've introduced deadlock

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

Rewind…

- What problem are we actually trying to solve?

Algorithm 1:

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

- We want to limit the possible schedules so that checking for milk and buying milk act as a single **atomic** operation

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)
```

Correct!

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

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

```c
/* 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);
}
```

```c
/* 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

Problem 1: Locks are Hard

```
philosopher_thread(i){
  while(True){
    think();

    pickup_fork(i);
    pickup_fork(i+1%n);

    eat();

    putdown_fork(i);
    putdown_fork(i+1%n);
  }
}
```

Problem 2: Locks are Slow

- threads that fail to acquire a lock on the first attempt must "spin", which wastes CPU cycles
  - replace no-op with yield()
- threads get scheduled and de-scheduled while the lock is still locked
  - need a better synchronization primitive

Better Synchronization Primitives

- Semaphores
  - stateful synchronization primitive

- Condition variables
  - event-based synchronization primitive

Exercise 3: Feedback

1. Rate how well you think this recorded lecture worked
   1. Better than an in-person class
   2. About as well as an in-person class
   3. Less well than an in-person class, but you still learned something
   4. Total waste of time, you didn't learn anything
2. How much time did you spend on this video (including exercises)?
3. Do you have any particular questions you'd like me to address in this week's problem session?
4. Do you have any other comments or feedback?