Implementing Threads 2

Time Slicing

- **Periodically**
  - current thread forced to do a thread yield

```
void ClockInterrupt(int sig) {
  thread_yield();
}
```

- **Implement ClockInterrupt with VTALRM signal**

Invoking the Signal Handler

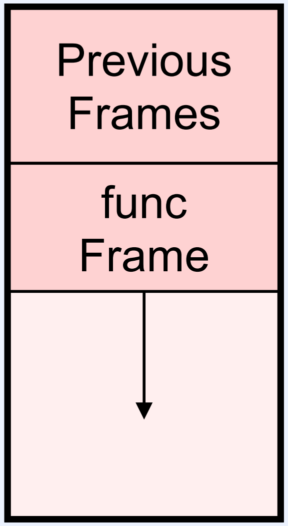
- Basic idea is to set up the user stack so that the handler is called as a subroutine and so that when it returns, normal execution of the thread may continue
- Complications:
  - – saving and restoring registers
  - – signal mask

Invoking the Signal Handler (1)

Main Line

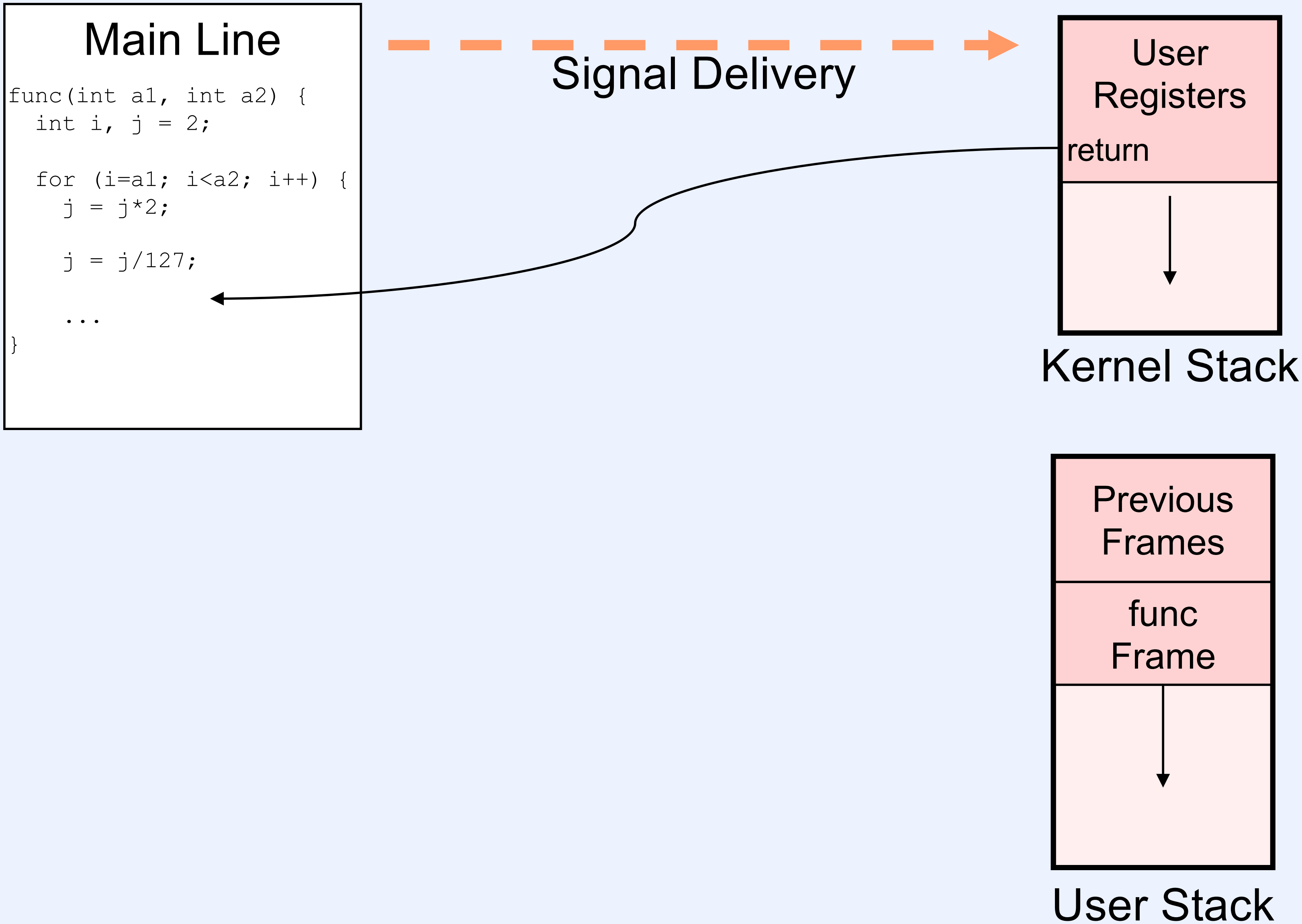
```
func(int a1, int a2) {
  int i, j = 2;

  for (i=a1; i<a2; i++) {
    j = j*2;

    j = j/127;

    ...
}
```

IP

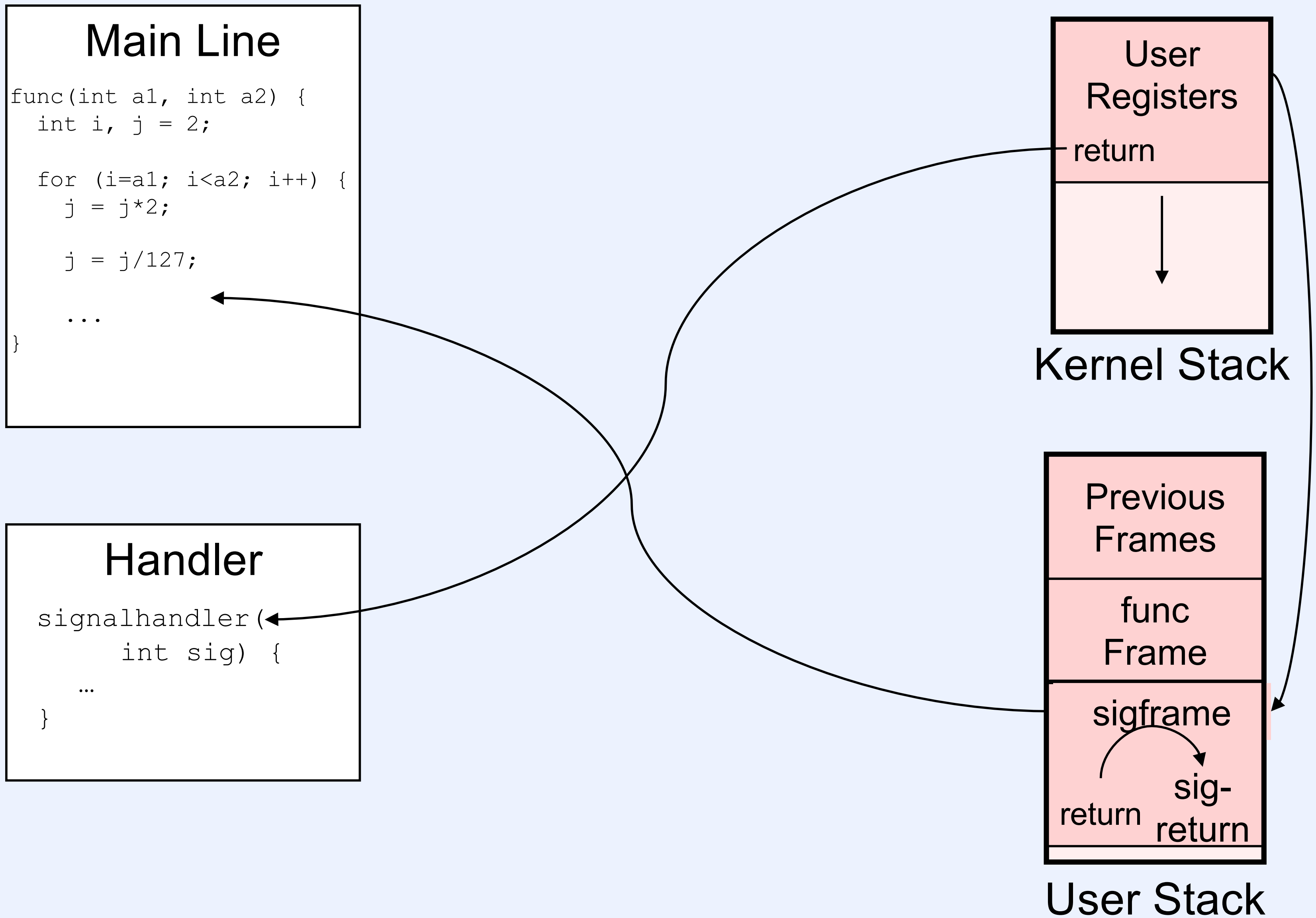


User Stack

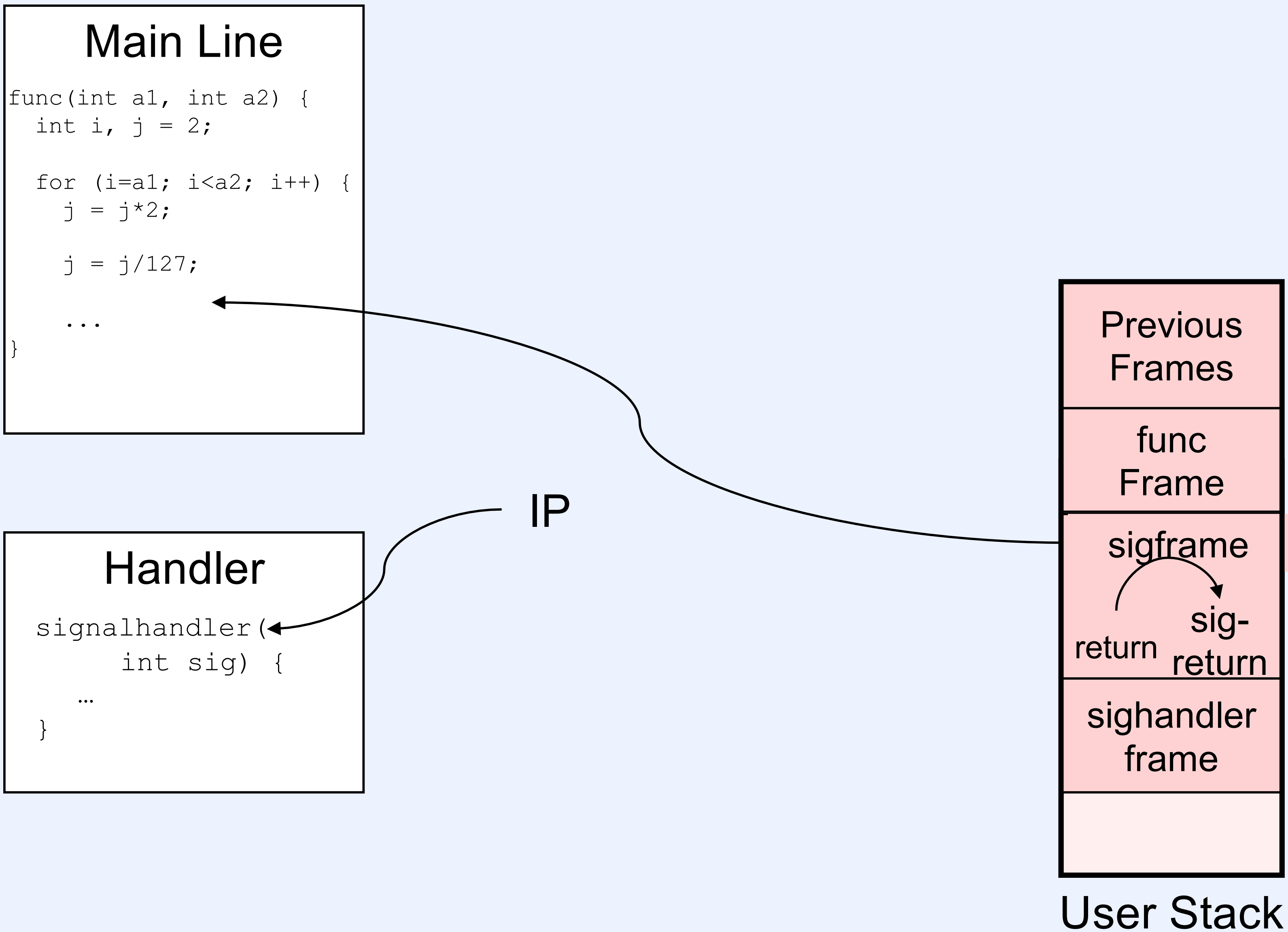
Invoking the Signal Handler (2)



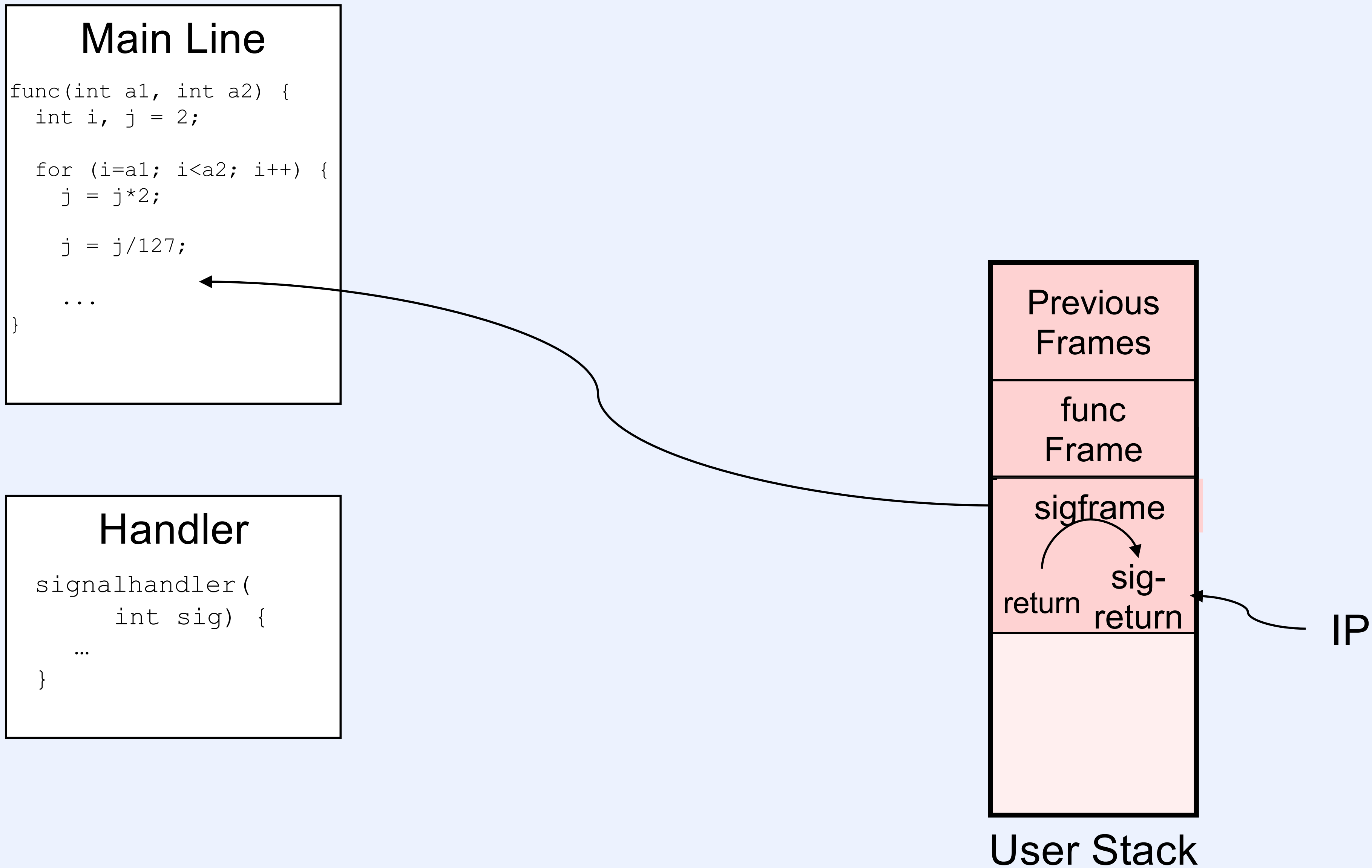
Invoking the Signal Handler (3)



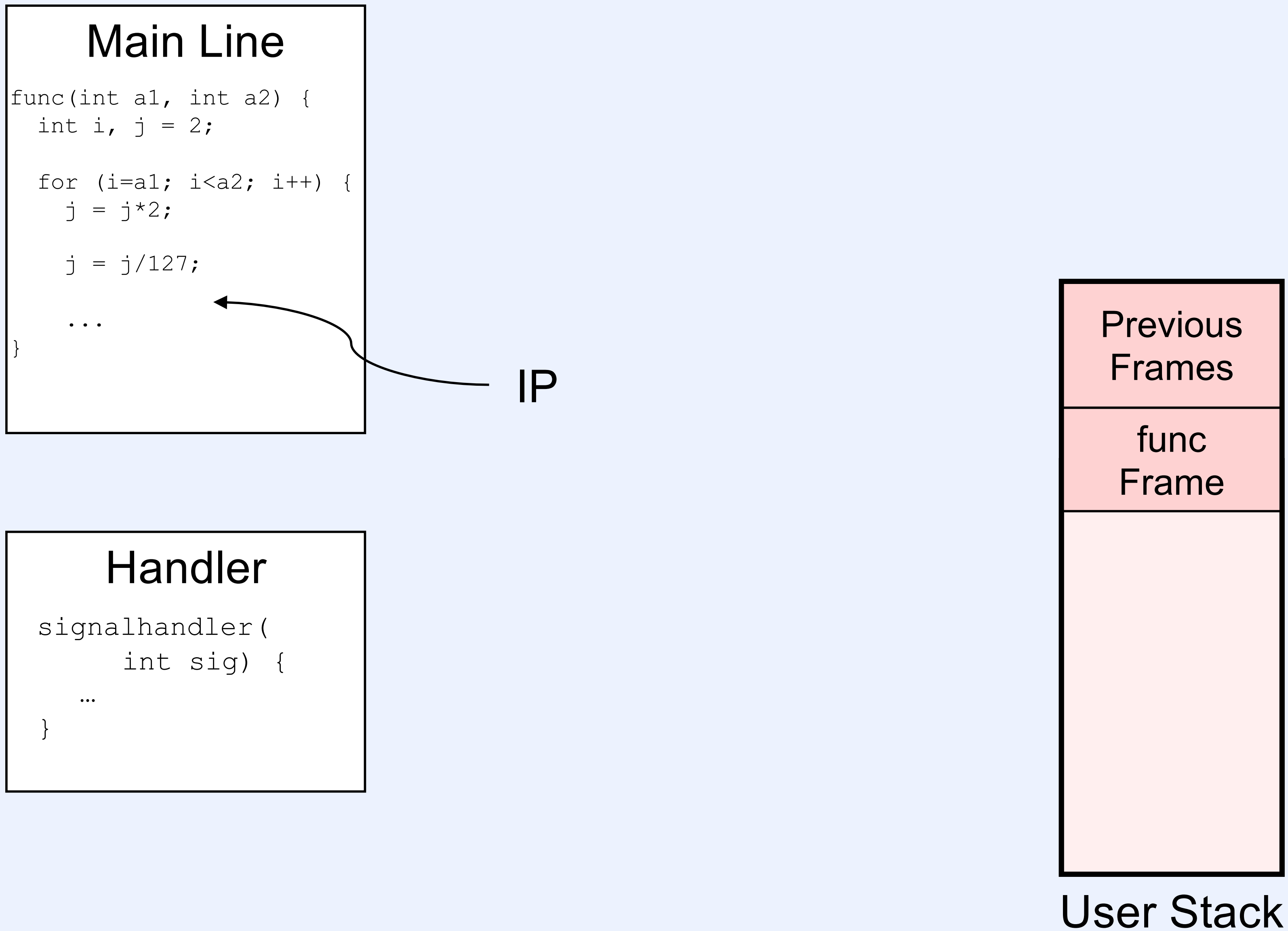
Invoking the Signal Handler (4)



Invoking the Signal Handler (5)



Invoking the Signal Handler (6)



Quiz 1

The description of invoking the signal handler:

a) works fine

b) is susceptible to buffer-overflow attacks

c) is rendered useless because of an approach for making such attacks more difficult (by turning off execute permission on some memory)

d) doesn’t work, period

Time Slicing

- **Periodically**
  - **current thread forced to do a thread yield**

```c
void ClockInterrupt(int sig) {
  // SIGVTALRM is now masked
  sigprocmask(SIG_UNBLOCK, &VTALRMmask, 0);
  // SIGVTALRM is now unmasked
  uthread_yield();
  // thread resumes here
}
```

- **Implement ClockInterrupt with VTALRM signal**

Setting Up Time Slicing

```
struct sigaction timesliceact;
timesliceact.sa_handler = ClockInterrupt;
timesliceact.sa_mask = VTALRMmask;
timesliceact.sa_flags = SA_RESTART; // avoid EINTR
struct timeval interval = {0, 1};   // every microsecond
struct itimerval timerval;
timerval.it_value = interval;
timerval.it_interval = interval;
sigaction(SIGVTALRM, &timesliceact, 0);
setitimer(ITIMER_VIRTUAL, &timerval, 0);
    // time slicing is started!
```

Async-Signal Safety

- A function is asynchronous-signal safe if it may be used in the handler for an asynchronous signal (such as SIGVTALRM)
  - malloc and free
    - no
  - mutex_lock
    - no
  - read and write
    - yes

Achieving Async-Safety

- The problem: an action in the signal handler interferes with an action in the main-line code
  - while in malloc/free, a signal occurs and the handler calls malloc/free
  - while holding the lock on a mutex, a thread is interrupted and the handler attempts to lock the mutex
- The solution: mask signals while in malloc/free and when holding locks

Caution!

- *uthread_switch* is not async-signal safe
  - it's called from *uthread_yield*, which is called from the signal handler for SIGVTALRM
  - must mask signals before calling it (and unmask afterwards)

Masking/Unmasking Signals

```
sigset_t VTALRMmask;
…
sigemptyset(&VTALRMmask);
sigaddset(&VTALRMmask, SIGVTALRM);
…
sigprocmask(SIG_BLOCK, &VTALRMmask, 0);
…
sigprocmask(SIG_UNBLOCK, &VTALRMmask, 0);
```

Doing It Cheaply

```
void uthread_nopreempt_on() {
  uthread_no_preempt = 1;
}

void uthread_nopreempt_off() {
  uthread_no_preempt = 0;
}

void ClockInterrupt(int sig) {
  if (uthread_no_preempt)
    return;
  …
}
```

```
uthread_no_preempt_on();

uthread_switch();

uthread_no_preempt_off();
```

Nested Calls

```
void uthread_nopreempt_on() {
  uthread_no_preempt_count++;
}

void uthread_nopreempt_off() {
  uthread_no_preempt_count--;
}

void ClockInterrupt(int sig) {
  if (uthread_no_preempt_count > 0)
    return;
  …
}
```

Corrected Nested Calls

```
void uthread_nopreempt_on() {
  ut_curthr->uthread_no_preempt_count++;
}

void uthread_nopreempt_off() {
  ut_curthr->uthread_no_preempt_count--;
}

void ClockInterrupt(int sig) {
  if (ut_curthr->uthread_no_preempt_count > 0)
    return;
  …
}
```

Limitations of User Threads

- Threads are implemented strictly at user level
  - the OS kernel is unaware of their existence
- What happens if a user thread makes a blocking system call, e.g., *read*?

Quiz 2

```
void uthread_switch( ) {
   volatile int first = 1;
   getcontext(&CurrentThread->ctx);
   if (first) {
      first = 0;
      CurrentThread = dequeue(RunQueue);
      setcontext(&CurrentThread->ctx);
   }
   return;
}
```

Given the discussion so far, will RunQueue ever be empty (in a program that has no deadlocks)?

a) yes

b) no

Multiple Processors

```
void uthread_switch( ) {
   volatile int first = 1;
   getcontext(&CurrentThread->ctx);
   if (first) {
      first = 0;
      CurrentThread = dequeue(RunQueue);
      setcontext(&CurrentThread->ctx);
   }
   return;
}
```

- **How do we employ multiple processors?**
  - **code merely switches the caller's processor to another thread**
- **What if the RunQueue is empty?**
  - **it could be empty, particularly if we have multiple processors**

Solution Sketch

- Introduce “idle threads”, one for each processor
- Thread calling *uthread_switch* switches to idle thread for its current processor
- Idle thread then switches to first thread on *RunQueue*, if any
- If *RunQueue* is empty, idle thread repeatedly checks *RunQueue* until it’s not empty, then switches to first thread

Solution Details

```
void uthread_switch() {
  volatile int first = 1;
  getcontext(&CurrentThread[processor_ID]->context);
  if (!first)
    return;
  first = 0;
  setcontext(&IdleThread[processor_ID]->context);
}

void IdleThread_switch() {
  getcontext(&IdleThread[processor_ID]->context);
  while (1) {
    if (queue_empty(RunQueue))
        continue;
    CurrentThread[processor_ID] = dequeue(RunQueue);
    setcontext(&CurrentThread[processor_ID]->context);
  }
}
```

MThreads

- Idle threads are pthreads
  - called LWPs (lightweight processes), following standard usage
  - each LWP represents a processor (core)
    - a “virtual processor”
  - *lwp_switch* rather than *IdleThread_switch*
  - rather than “busy-wait” for a uthread to run, it calls *lwp_park* to wait for one (using a POSIX condition variable)

MP Mutual Exclusion

- Two sorts
  - spin locks
    - threads wait by repeatedly testing the lock
  - blocking locks
    - threads wait by sleeping, depending on some other thread to wake them up

Hardware Support for Spin Locks

- **Compare and swap instruction**

```
int CAS(int *ptr, int old, int new) {
    int tmp = *ptr;
    if (*ptr == old)
        *ptr = new;
    return tmp;
}
```

Naive Spin Lock

```
void spin_lock(int *spin) {
   while(CAS(spin, 0, 1))
      ;
}

void spin_unlock(int *spin) {
   *spin = 0;
}
```


Better Spin Lock

```
void spin_lock(int *spin) {
   while (1) {
      if (*spin== 0) {
         // the mutex was at least momentarily unlocked
         if (!CAS(spin, 0, 1)
            break;  // we have locked the mutex
         // some other thread beat us to it, so try again
      }
   }
}
```


Spin Locks in MThreads

- Since LWPs represent virtual processors, we don’t want busy waiting
- Use POSIX mutexes instead

Blocking Locks

```
void blocking_lock(mutex_t *mut) {
  if (mut->holder != 0) {
    enqueue(mut->wait_queue,
        CurrentThread);
    uthread_switch();
  } else
    mut->holder = CurrentThread;
}
```

```
void blocking_unlock(mutex_t *mut) {
  if (queue_empty(mut->wait_queue))
    mut->holder = 0;
  else {
    mut->holder =
        dequeue(mut->wait_queue);
    enqueue(RunQueue, mut->holder);
  }
}
```

Does it work?

Working Blocking Locks (?)

```
void blocking_lock(mutex_t *mut) {
  spin_lock(&mut->spinlock);
  if (mut->holder != 0) {
    enqueue(mut->wait_queue,
          CurrentThread);
    spin_unlock(&mut->spinlock);
    uthread_switch();
  } else {
    mut->holder = CurrentThread;
    spin_unlock(&mut->spinlock);
  }
}
```

```
void blocking_unlock(mutex_t *mut) {
  spin_lock(&mut->spinlock);
  if (queue_empty(
        mut->wait_queue)) {
    mut->holder = 0;
  } else {
    mut->holder =
        dequeue(mut->wait_queue);
    enqueue(RunQueue,
        mut->holder);
  }
  spin_unlock(&mut->spinlock);
}
```

Quiz 3

This

a) **always works**
b) **sometimes doesn't work**
c) **never works**

Futexes

- Safe, *efficient* kernel conditional queueing in Linux
- All operations performed atomically
  - `futex_wait(futex_t *futex, int val)`
    - if `futex->val` is equal to `val`, then sleep
    - otherwise return
  - `futex_wake(futex_t *futex)`
    - wake up one thread from `futex`'s wait queue, if there are any waiting threads

Ancillary Functions

- `int atomic_inc(int *val)`
  - add 1 to `*val`, return its original value
- `int atomic_dec(int *val)`
  - subtract 1 from `*val`, return its original value

Attempt 1

```
void lock(futex_t *futex) {
  int c;
  while ((c = atomic_inc(&futex->val)) != 0)
    futex_wait(futex, c+1);
}

void unlock(futex_t *futex) {
  futex->val = 0;
  futex_wake(futex);
}
```


Attempt 2

```
void lock(futex_t *futex) {
  int c;
  if ((c = CAS(&futex->val, 0, 1) != 0)
    do {
      if (c == 2 || (CAS(&futex->val, 1, 2) != 0))
        futex_wait(futex, 2);
    while ((c = CAS(&futex->val, 0, 2)) != 0))
}

void unlock(futex_t *futex) {
  if (atomic_dec(&futex->val) != 1) {
    futex->val = 0;
    futex_wake(futex);
  }
}
```

Quiz 4
Does it work?

a) Yes
b) No

Blocking Locks in MThreads

- We could use futexes, but don’t
- *uthread_switch* gets an additional argument
  - a POSIX mutex (representing a spin lock)
  - unlock it after getting out of the context of the calling thread

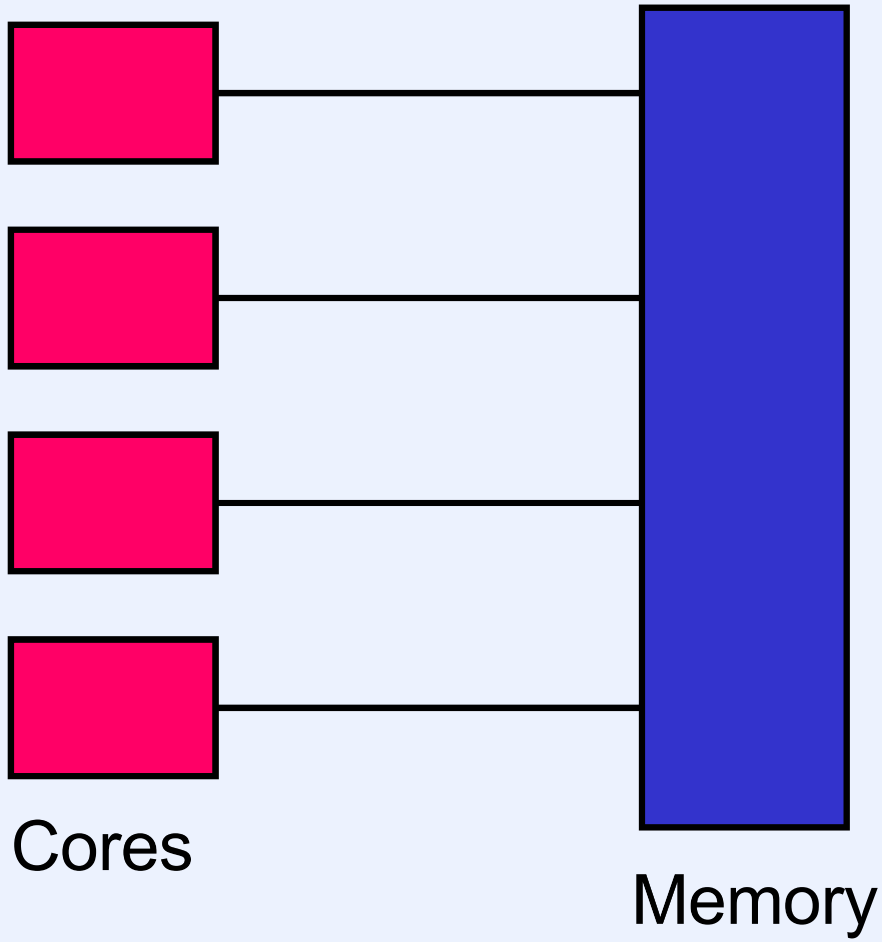
Actual Code

```
uthread_mtx_lock(uthread_mtx_t *mtx) {
    uthread_nopreempt_on();
    pthread_mutex_lock(&mtx->m_pmut);
    if (mtx->m_owner == NULL) {
        mtx->m_owner = ut_curthr;
        pthread_mutex_unlock(&mtx->m_pmut);
        uthread_nopreempt_off();
    } else {
        ut_curthr->ut_state = UT_WAIT;
        uthread_switch(&mtx->m_waiters, 0, &mtx->m_pmut);
        uthread_nopreempt_off();
    }
}
```

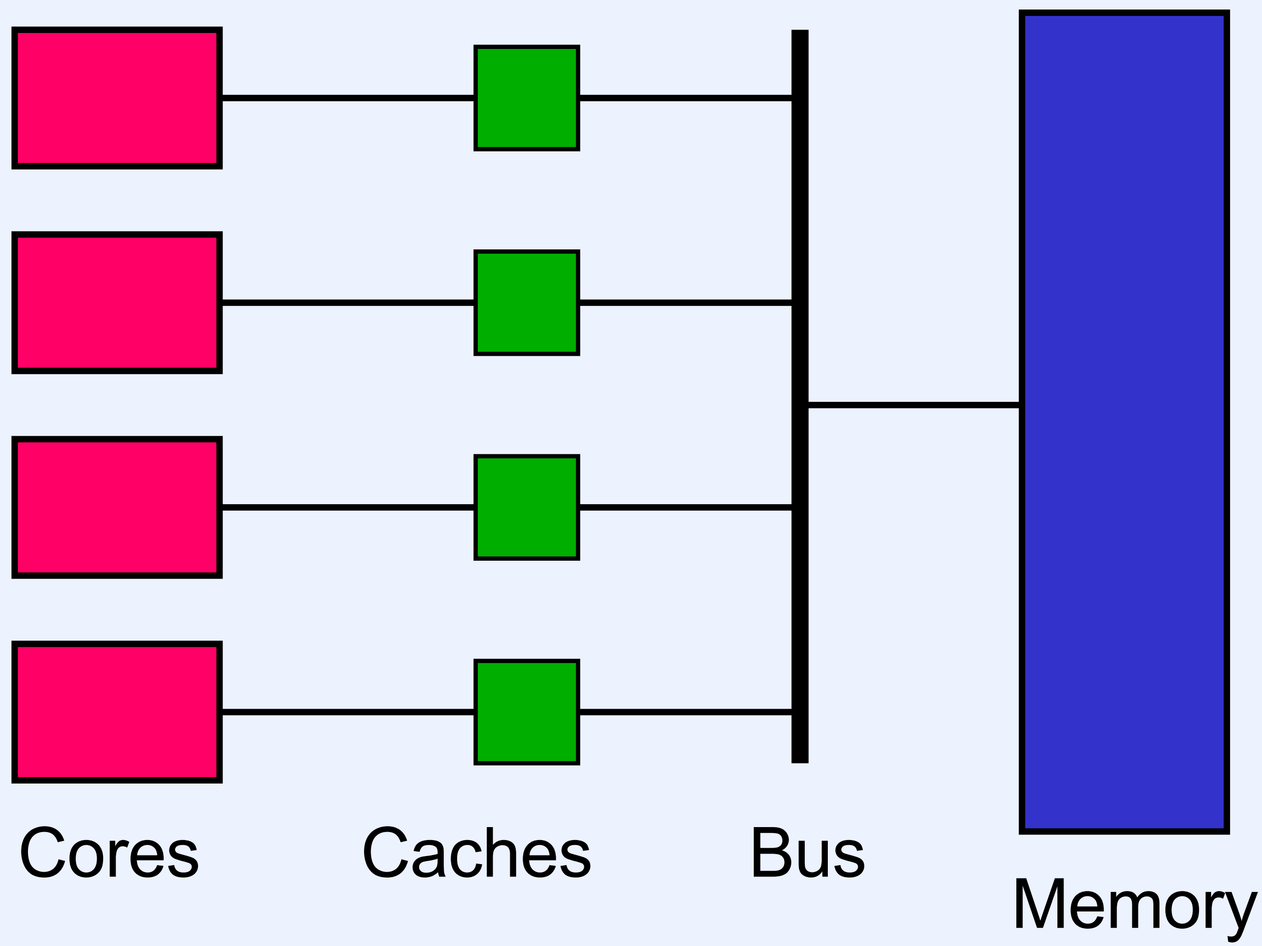
MP Memory Issues

- Naive view is that all processors in MP system see same memory contents at all times
  - they don’t

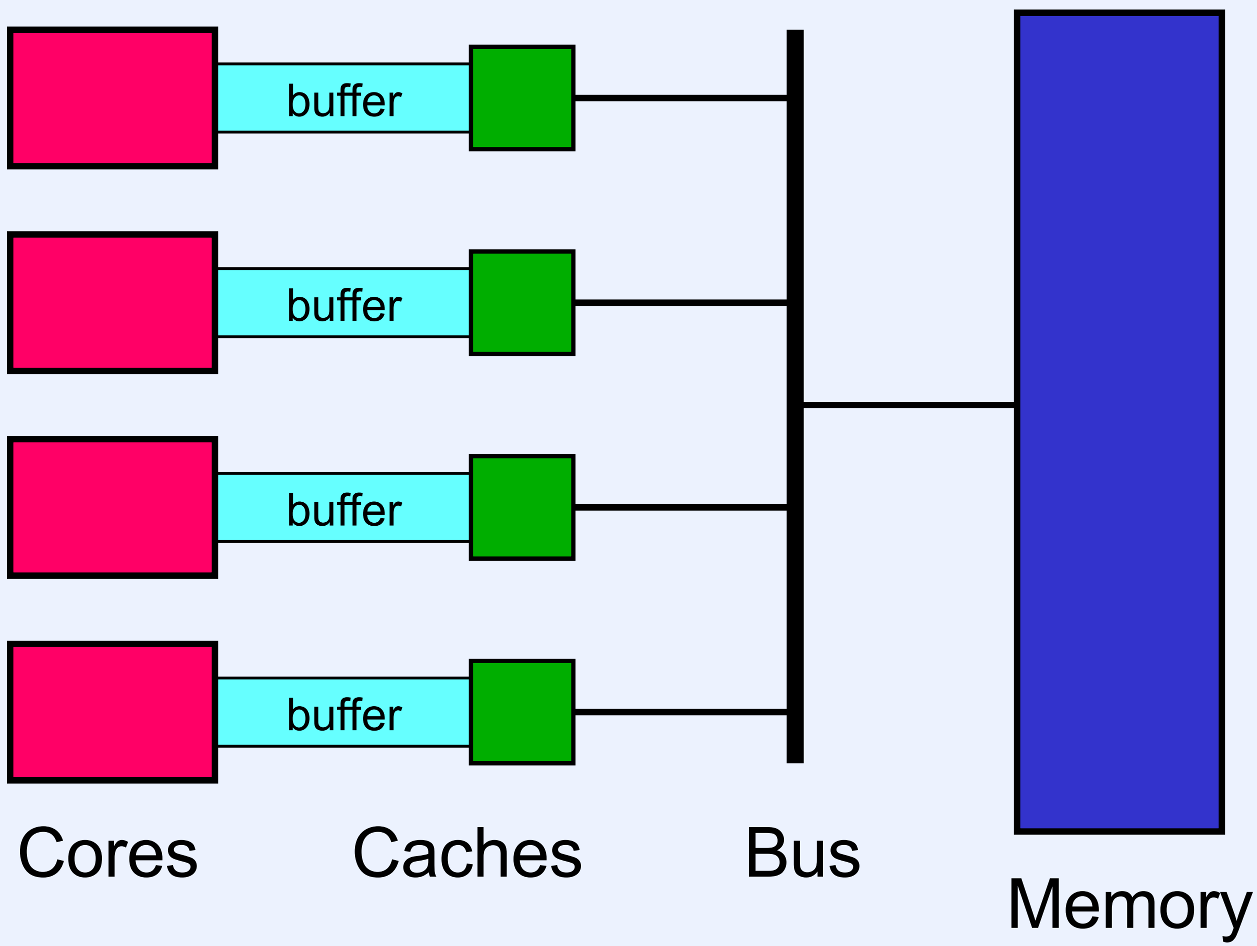
Multi-Core Processor: Simple View



Multi-Core Processor: More Realistic View



Multi-Core Processor: Even More Realistic



Concurrent Reading and Writing

Thread 1:

```
i = shared_counter;
```

Thread 2:

```
shared_counter++;
```

Mutual Exclusion w/o Mutexes

```
void peterson(long me) {
  static long loser;                          // shared
  static long active[2] = {0, 0};   // shared
  long other = 1 - me;                       // private
  active[me] = 1;
  loser = me;
  while (loser == me && active[other])
    ;
  // critical section
  active[me] = 0;
}
```


Busy-Waiting Producer/Consumer

```
void producer(char item) {

  while(in - out == BSIZE)
    ;

  buf[in%BSIZE] = item;

  in++;
}
```

```
char consumer( ) {
  char item;
  while(in - out == 0)
    ;

  item = buf[out%BSIZE];

  out++;

  return(item);
}
```

Coping

- Use what's available in the architecture to make sure all cores have the same view of memory (when necessary)
  – lock prefix on x86
  – mfence x86 instruction
- Use the synchronization primitives
  – presumably the implementers knew what they were doing