Operating Systems

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U of T

Announcement

- Check discussion board for announcements
- A1 is posted

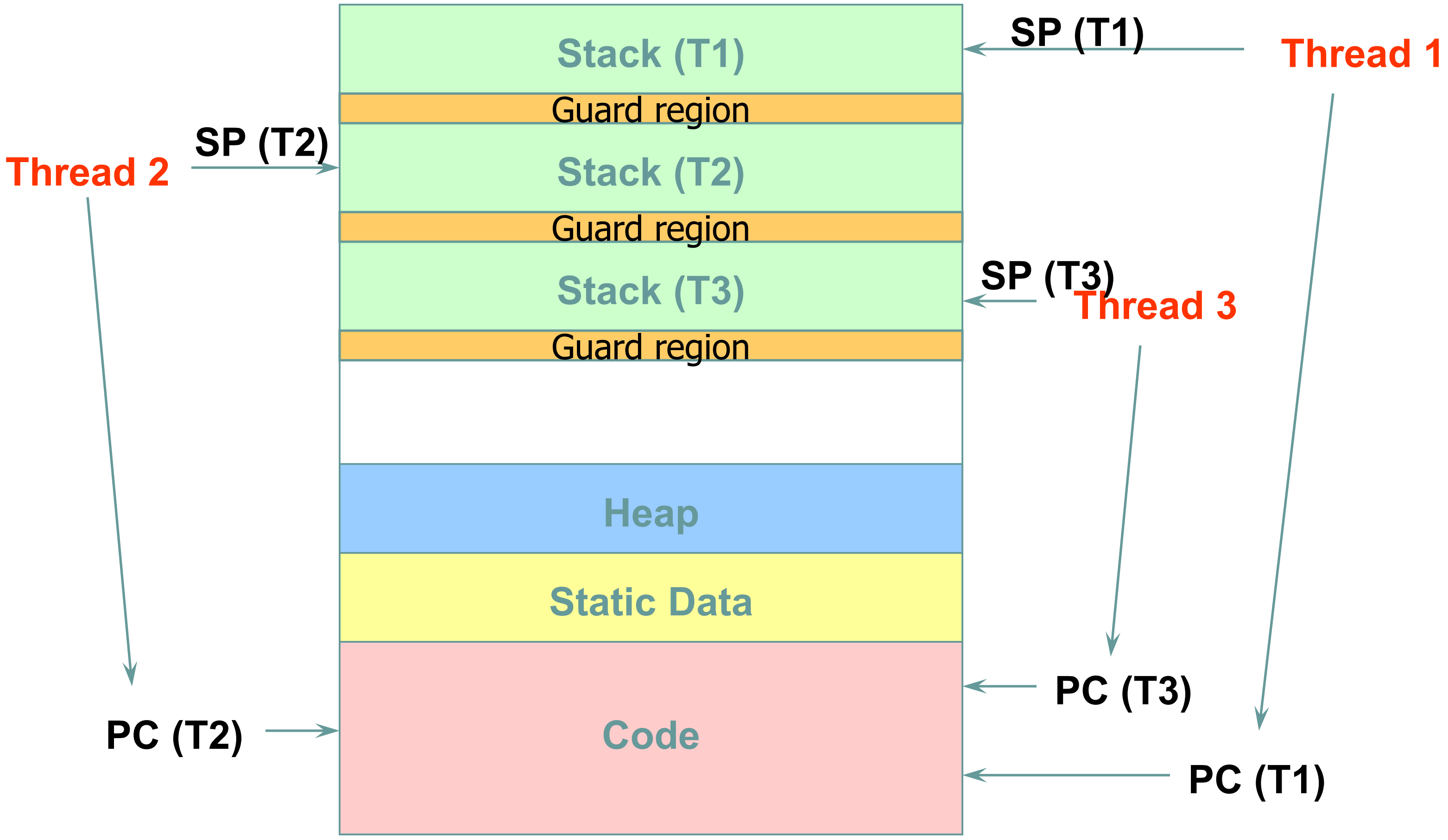
Recap: Process Creation: Unix

- In Unix, processes are created using fork()

```
int fork()
```

- fork()
  - Creates a new address space
  - Initializes the address space with a **copy** of the entire contents of the address space of the parent
  - Initializes the kernel resources to point to the resources used by parent (e.g., open files)

Recap: Threads



TODAY:

- System Calls
- Intro to Synchronization

Bootstrapping

- Hardware stores small program in non-volatile memory
  - BIOS – Basic Input Output System
  - Knows how to access simple hardware devices
    - Disk, keyboard, display
- When power is first supplied, this program executes
- What does it do?
  - Checks that RAM, keyboard, and basic devices are installed and functioning correctly
  - Scans buses to detect attached devices and configures new ones
  - Determines boot device (tries list of devices in order)
  - Reads first sector from boot device and executes it (bootloader)
  - Bootloader reads partition table, finds active partition, reads secondary bootloader

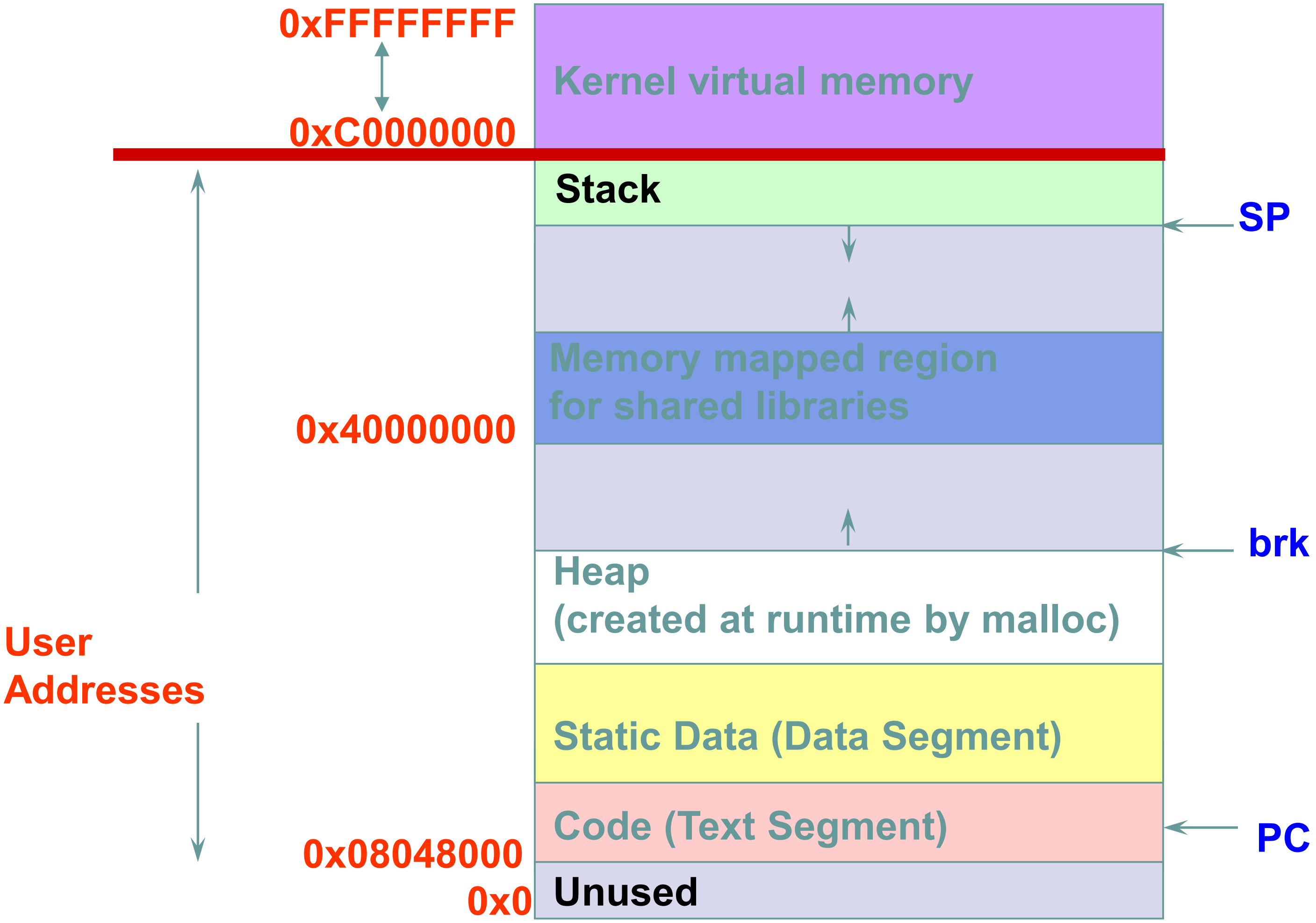
    active partition where OS resides
  - Secondary bootloader reads OS into memory and executes it

creates process for OS, brings OS from hard disk to memory
since OS is in a process. OS has its own pcb, heap, stack, …

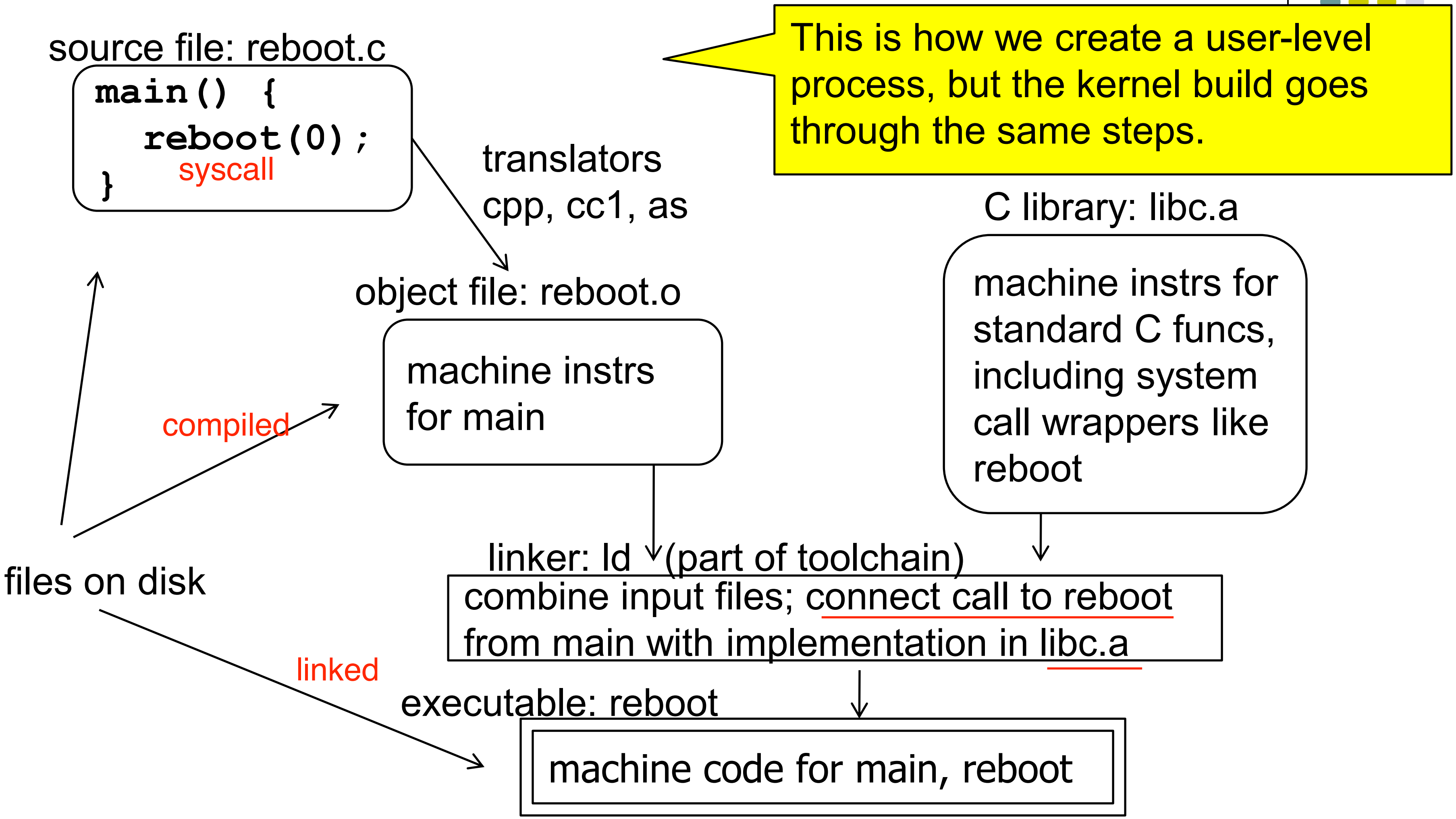
Operating System Startup

- Machine starts in system mode, so kernel code can execute immediately
- OS initialization:
  - Initialize internal data structures
    - Machine dependent operations are typically done first
  - Create first process
  - Switch mode to user and start running first process
    when login occurs
  - Wait for something to happen
    - OS is entirely driven by external events

Memory Layout (Linux, x86)



From Program to Process… 1



This is how we create a user-level process, but the kernel build goes through the same steps.

source file: reboot.c

```
main() {
   reboot(0);
}
```

syscall

translators
cpp, cc1, as

object file: reboot.o

machine instrs for main

compiled

C library: libc.a

machine instrs for standard C funcs, including system call wrappers like reboot

files on disk

linker: ld (part of toolchain)

combine input files; connect call to reboot from main with implementation in libc.a

linked

executable: reboot

machine code for main, reboot

Unix Shells

syscall
+ execution mode will change from user to kernel mode
+ hence permission matters here

```
while (1) {
  char *cmd = read_command();
  int child_pid = fork();
  if (child_pid == 0) {
   exec(cmd); //cmd=executable name(reboot)
  } else {
     wait(child_pid);
  }
}
```

will likely give permission error

Process Creation: Unix (2)

- Wait a sec ... How do we actually start a new program?

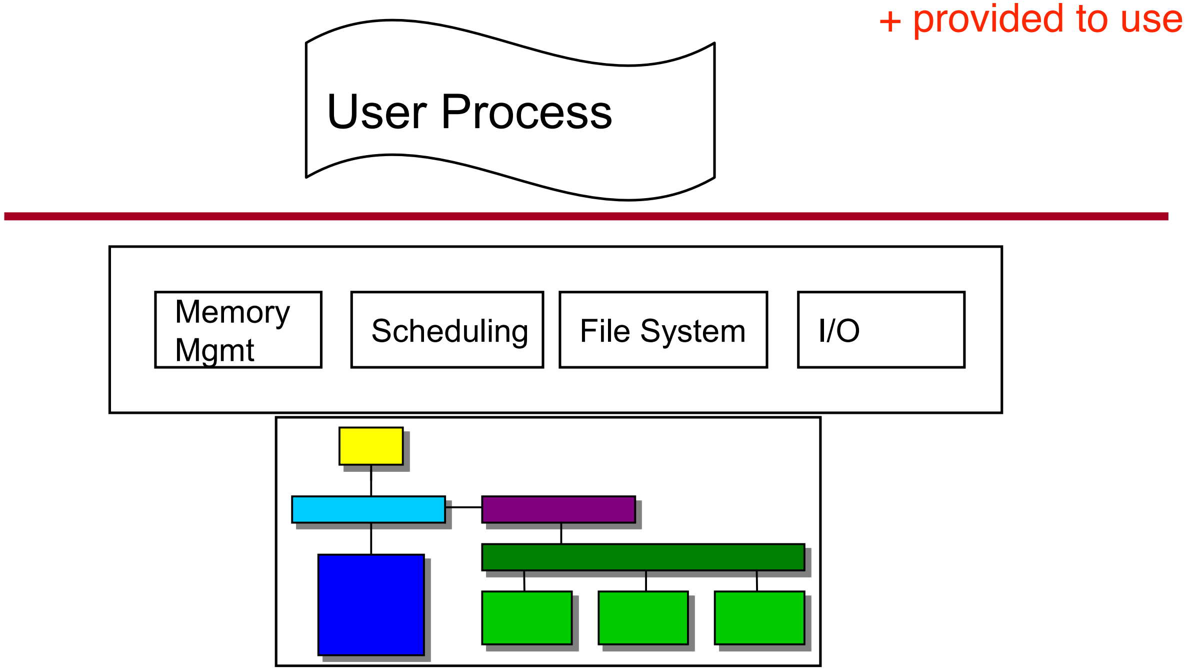
```
int exec(char *prog, char *argv[])
```

- exec()
  - Stops the current process only the CODE portion replaced
  - Loads the program "prog" into the process' address space
  - Initializes hardware context and args for the new program
  - Places the PCB onto the ready queue
  - Note: It **does not** create a new process

Requesting OS Services

- Operating System and user programs are isolated from each other
- But OS provides service to user programs…
- So, how do they communicate?

communicate
1. syscall
+ provided to user



Boundary Crossings

- Getting to kernel mode
  - Boot time (not really a crossing, starts in kernel)
  - Explicit system call – request for service by application
  - Hardware interrupt
  - Software trap or exception i.e. division by 0, invalid mem access
  - Hardware has table of "Interrupt service routines"

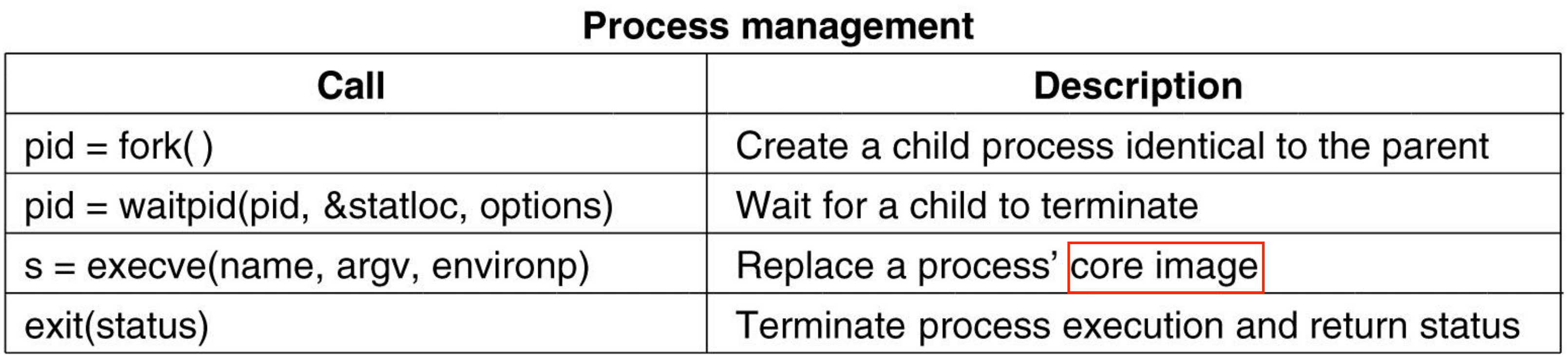
table contains map from syscall name to function

- Kernel to user
  - Jumps to next application instruction

return from successful syscall

a software routine that hardware invokes in response to an interrupt. ISRs examine an interrupt and determine how to handle it.

System Calls for Process Management

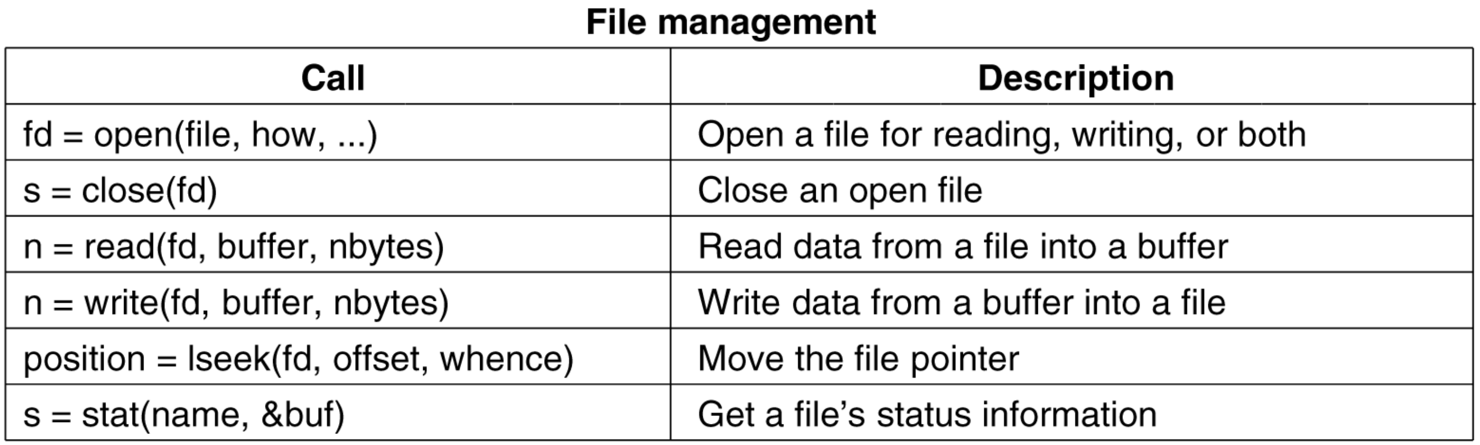


Process management

Call	Description
pid = fork( )	Create a child process identical to the parent
pid = waitpid(pid, &statloc, options)	Wait for a child to terminate
s = execve(name, argv, environp)	Replace a process' core image
exit(status)	Terminate process execution and return status

Some of the major system calls.

System Calls for File Management

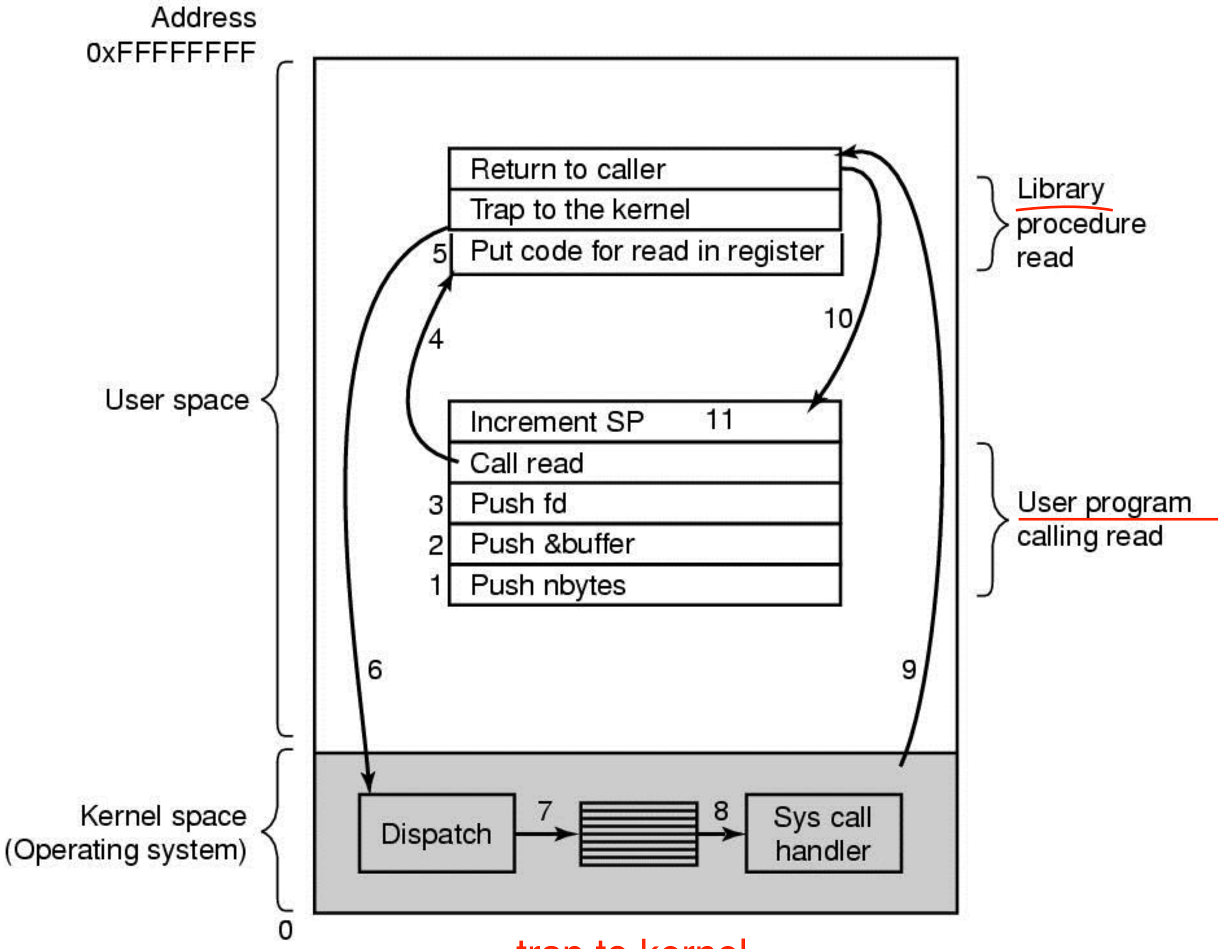


File management

Call	Description
fd = open(file, how, ...)	Open a file for reading, writing, or both
s = close(fd)	Close an open file
n = read(fd, buffer, nbytes)	Read data from a file into a buffer
n = write(fd, buffer, nbytes)	Write data from a buffer into a file
position = lseek(fd, offset, whence)	Move the file pointer
s = stat(name, &buf)	Get a file’s status information

Some of the major system calls.

System Calls



Read(fd, buffer, nbytes).

trap to kernel
+ Uses a hashtable which maps from syscall name to address of function

System Call Interface

- User program calls C library function with arguments
- C library function arranges to pass arguments to OS, including a system call identifier
- Executes special instruction to trap to system mode
  - Interrupt/trap vector transfers control to a system call handling routine
- Syscall handler figures out which system call is needed and calls a routine for that operation
- How does this differ from a normal C language function call? Why is it done this way?
  - Extra level of indirection through system call handler, rather than direct control flow to called function
  - Hardware support is needed to enforce separation of userspace and kernel

System Call Operation

- Kernel must verify arguments that it is passed
  - Why?
- A fixed number of arguments can be passed in registers

hence data not passed directly but address to which data will be stored

  - Often pass the address of a user buffer containing data (e.g., for write())
  - Kernel must copy data from user space into its own buffers
- Result of system call is returned in register

Intro to Synchronization

Cooperating Processes

- A process is *independent* if it cannot affect or be affected by the other processes executing in the system
- No data sharing ⇒ process is independent
- A process is *cooperating* if it is not independent
- Cooperating processes must be able to communicate with each other and to synchronize their actions

Interprocess Communication

- Cooperating processes need to exchange information, using either
  - Shared memory (e.g. fork())
  - Message passing
- Message passing models
  - Send(P, msg) – send msg to process P
  - Receive(Q, msg) – receive msg from process Q

Motivating Example

- Suppose we write functions to handle withdrawals and deposits to a bank account:

update and return the balance to shared account on > 1 processes/threads

```
Withdraw(acct, amt) {
    balance = get_balance(acct);
    balance = balance - amt;
    put_balance(acct,balance);
    return balance;
}
```

```
Deposit(account, amount) {
    balance = get_balance(acct);
    balance = balance + amt;
    put_balance(acct,balance);
    return balance;
}
```

shared: each account may be accessed by more than one instance5

- Idea: Create separate threads for each action, which may run at the bank's central server

- What's wrong with this implementation?
  - Think about potential schedules for these two threads

Motivating Example

- Suppose we write functions to handle withdrawals and deposits to a bank account:

```
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```

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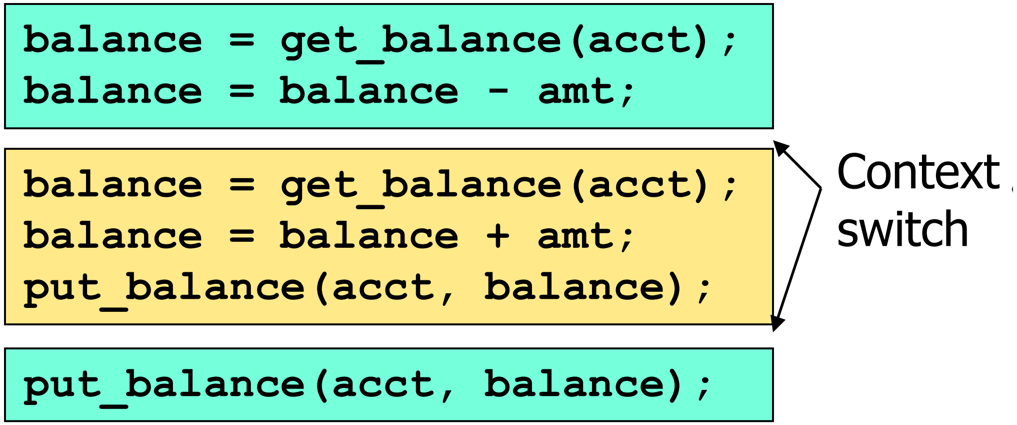
    balance = get_balance(acct);
    balance = balance + amt;
    put_balance(acct,balance);
    return balance;
}
```

- Suppose you share this account with someone and the balance is $1000
- You each go to separate ATM machines - you withdraw $100 and your S.O. deposits $100

Interleaved Schedules

- The problem is that the execution of the two processes can be interleaved:

Schedule A



```
balance = get_balance(acct);
balance = balance - amt;
```

```
balance = get_balance(acct);
balance = balance + amt;
put_balance(acct, balance);
```

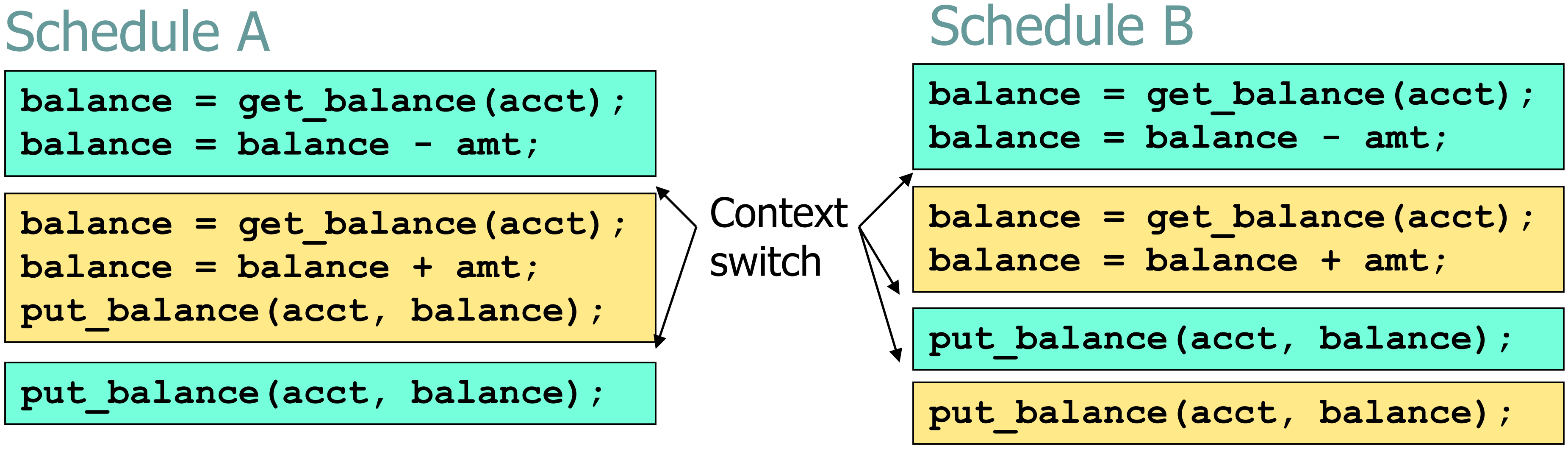
```
put_balance(acct, balance);
```

900

- What is the account balance now?
- Is the bank happy with our implementation?
  - Are you?

Interleaved Schedules

- The problem is that the execution of the two processes can be interleaved:



Schedule A

```
balance = get_balance(acct);
balance = balance - amt;
```

```
balance = get_balance(acct);
balance = balance + amt;
put_balance(acct, balance);
```

```
put_balance(acct, balance);
```

Context switch

Schedule B

```
balance = get_balance(acct);
balance = balance - amt;
```

```
balance = get_balance(acct);
balance = balance + amt;
```

```
put_balance(acct, balance);
```

```
put_balance(acct, balance);
```

900

1100

- What is the account balance now?
- Is the bank happy with our implementation?
  - Are you?

What Went Wrong

- Two concurrent threads manipulated a *shared resource* (the account) without any synchronization
  - Outcome depends on the order in which accesses take place
    - This is called a *race condition*

result depends on execution order

- We need to ensure that only one thread at a time can manipulate the shared resource
  - So that we can reason about program behavior

→ We need *synchronization*

Example continued …

- Could the same problem occur with a simple shared variable:
  - T_1 and T_2 share variable X
  - T_1 increments X (X := X+1)
  - T_2 decrements X (X := X-1)
  - At the machine level, we have:

changing value of a
variable take multiple steps.

```
T1:     LOAD  X
        INCR
        STORE  X
```

```
T2:     LOAD  X
        DECR
        STORE  X
```

- Same problem of interleaving can occur!

atomic operation: execute or cannot execute at all,
i.e. CPU guarantees to finish execution

Mutual Exclusion

- Given:
  - A set of *n* threads, T_0, T_1, …, T_n
  - A set of resources shared between threads
  - A segment of code which accesses the shared resources, called the *critical section, CS*

```
Withdraw(acct, amt) {
     balance = get_balance(acct);
     balance = balance - amt;
     put_balance(acct,balance);
     return balance;
}
```

CS

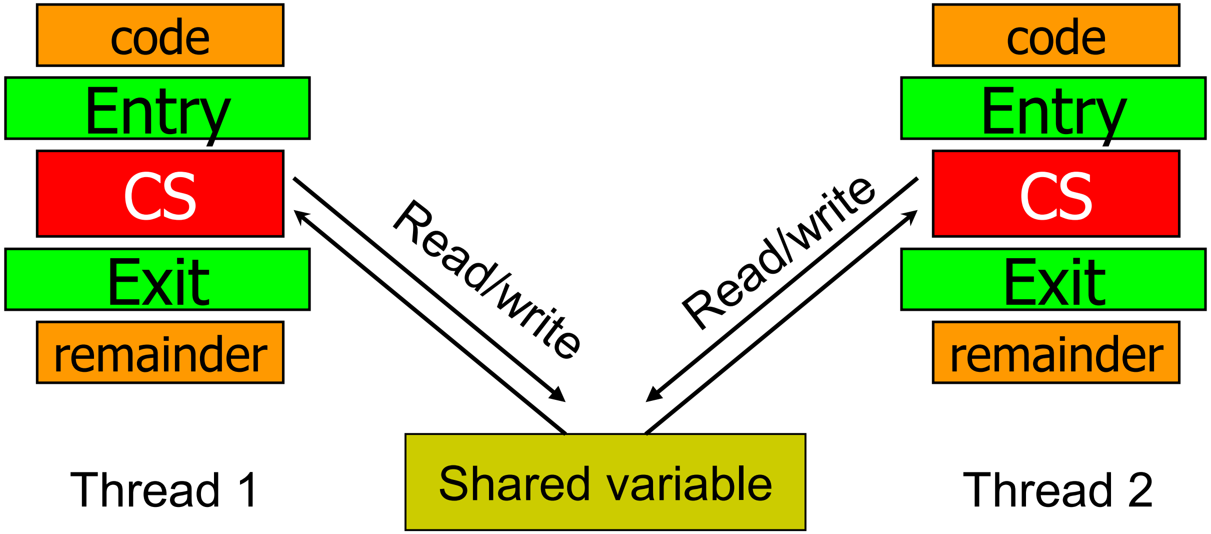
- We want to ensure that:
  - Only one thread at a time can execute in the critical section
  - All other threads are forced to wait on entry
  - When a thread leaves the CS, another can enter

Aside: What program data is shared between threads?

- Local variables are not shared (*private*)
  - Each thread has its own stack
  - Local vars are allocated on this private stack
- Global variables and static objects are *shared*
  - Stored in the static data segment, accessible by any thread
- Dynamic objects and other heap objs are *shared*
  - Allocated from heap with malloc/free or new/delete

The Critical Section Problem

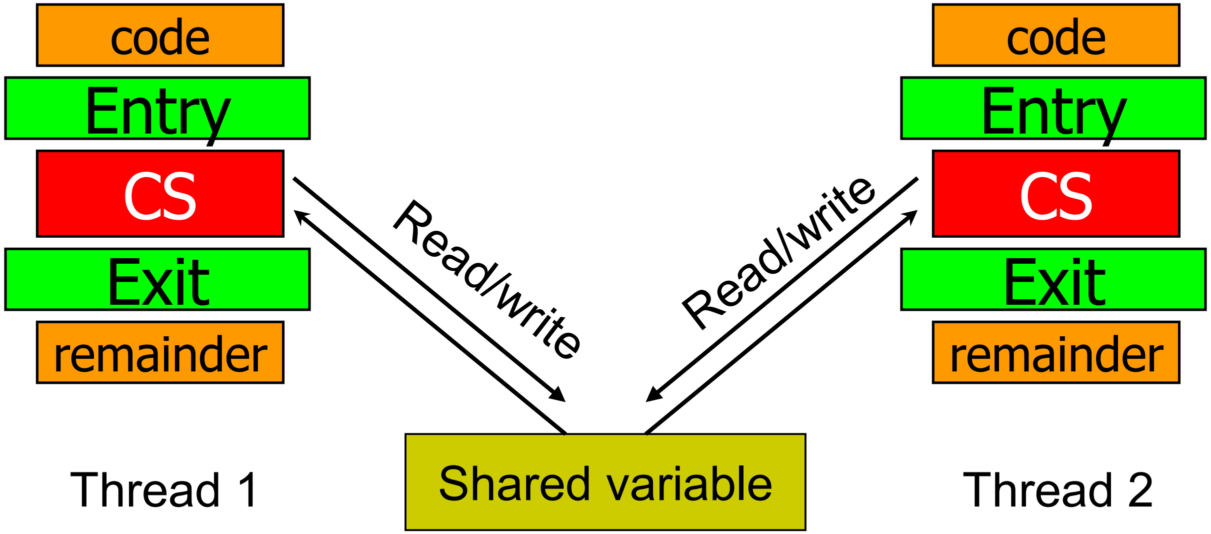
- Design a protocol that threads can use to cooperate



- Each thread must request permission to enter its CS, in its *entry* section
- CS may be followed by an *exit* section
- Remaining code is the *remainder* section

Critical Section Requirements (1)

- Design a protocol that threads can use to cooperate

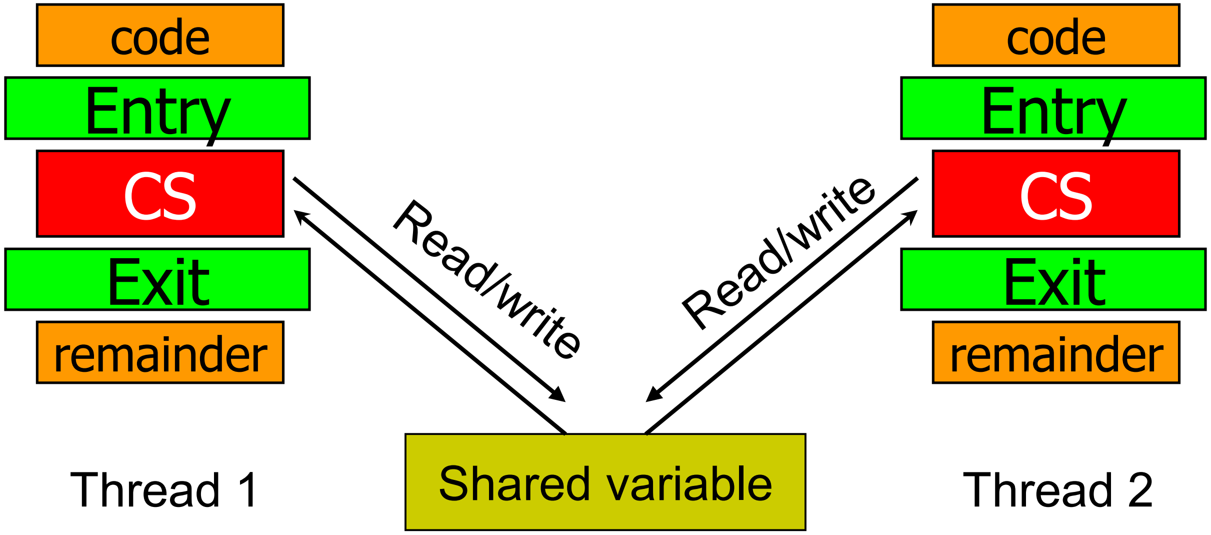


1) Mutual Exclusion

- If one thread is in the CS, then no other is

Critical Section Requirements (2)

- Design a protocol that threads can use to cooperate

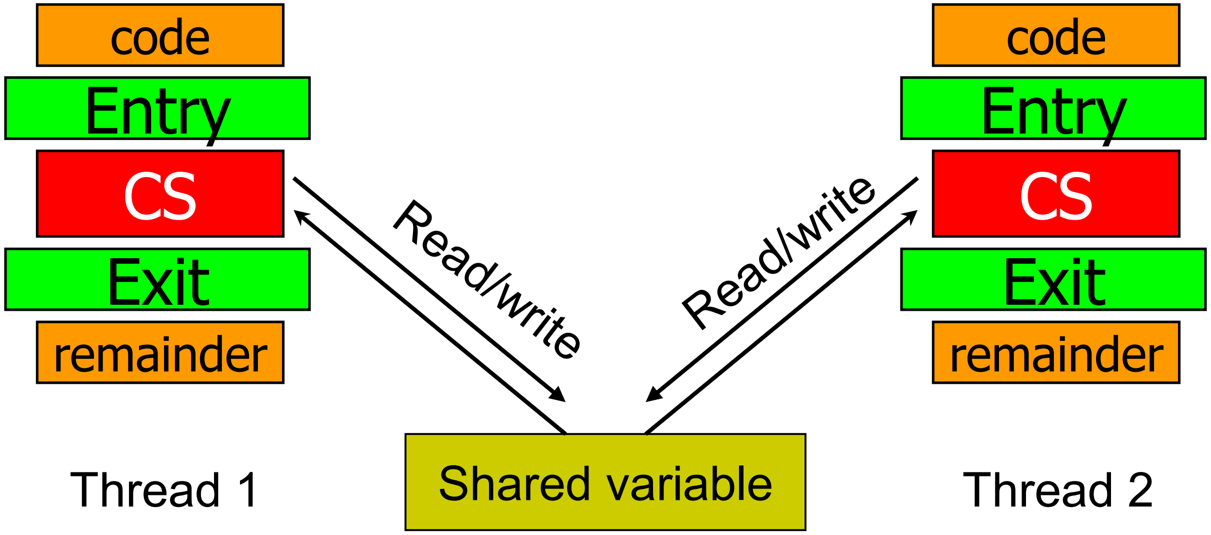


2) Progress

- If no thread is in the CS, and some threads want to enter CS, it should be able to enter in definite time

Critical Section Requirements (3)

- Design a protocol that threads can use to cooperate



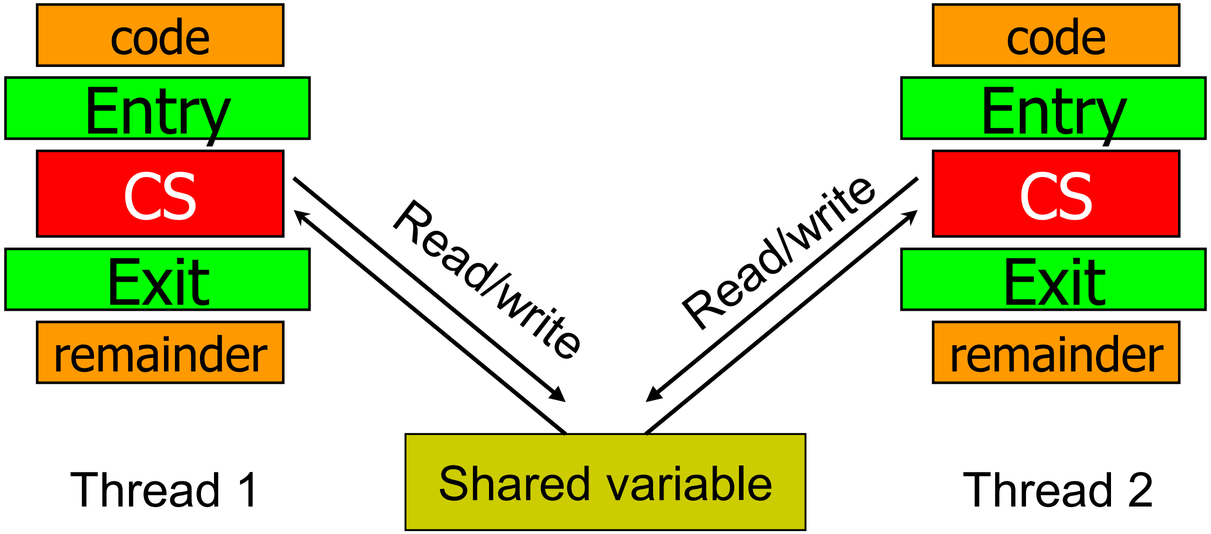
3) Bounded waiting (no starvation)

- If some thread T is waiting on the CS, then there is a limit on the number of times other threads can enter CS before this thread is granted access

hence waiting time is approx. uniform.

Critical Section Requirements (4)

- Design a protocol that threads can use to cooperate



4) Performance

- The overhead of entering and exiting the CS is small with respect to the work being done within it

Critical Section Requirements

1) Mutual Exclusion
   - If one thread is in the CS, then no other is
2) Progress
   - If no thread is in the CS, and some threads want to enter CS, it should be able to enter in definite time
3) Bounded waiting (no starvation)
   - If some thread T is waiting on the CS, then there is a limit on the number of times other threads can enter CS before this thread is granted access

- Performance
  - The overhead of entering and exiting the CS is small with respect to the work being done within it

Some Assumptions & Notation

- Assume no special hardware instructions, no restrictions on the # of processors (for now)
- Assume that basic machine language instructions (LOAD, STORE, etc.) are *atomic:*
  - If two such instructions are executed concurrently, the result is equivalent to their sequential execution in some unknown order
- If only two threads, we number them T_0 and T_1
  - Use T_i to refer to one thread, T_j for the other (j=1-i) when the exact numbering doesn't matter

to reflect that order is unknown

- Let's look at one solution…

2-Thread Solutions: 1st Try

- Let the threads share an integer variable *turn* initialized to 0 (or 1)
- If *turn=i* , thread T_i is allowed into its CS

```
My_work(id_t id) {  /* id_t can be 0 or 1 */
       ...
       while  (turn != id) ;/* entry section */
       /* critical section, access protected resource */
       turn = 1 - id;       /* exit section */
       ...                  /* remainder section */
}
```

✓ Only one thread at a time can be in its CS

✘ Progress is not satisfied strictly alternating. if T_i has a lot of task while T_j has one. Progress stagnate after one alteration.

- Requires strict alternation of threads in their CS: if *turn=0*, T_1 may not enter, even if T_0 is in the code section

2-Thread Solutions: 2nd Try

- First attempt does not have enough info about state of each process. It only remembers which process is allowed to enter its CS

  i.e. the value of Turn

- Replace turn with a shared flag for each thread
  - **boolean** `flag[2] = {false, false}`
  - Each thread may update its own flag, and read the other thread's flag
  - If `flag[i]` is true, T_i is ready to enter its CS

A Closer Look at 2nd Attempt

check the other thread

```
My_work(id_t id) {  /* id can be 0 or 1 */
      ...
      while (flag[1-id]) ;/* entry section */
      flag[id] = true;    /* indicate entering CS */
      /* critical section, access protected resource */
      flag[id] = false;   /* exit section */
      ...                 /* remainder section */
}
```

while loops indefinitely if any other thread is true;
and enter CS if other threads has flag=false.

- Mutual exclusion is not guaranteed
  - Each thread executes *while* statement, finds *flag* set to false

    at the same time. Context switching right after while check
  - Each thread sets own *flag* to *true* and enters CS
- Can’t fix this by changing order of testing and setting *flag* variables (leads to *deadlock*)

if flag both set to true. check other’s flag, true, hence both threads stay in while loop

problem arises since flag is a shared variable so require its own lock

2-Thread Solutions: 3rd Try

- Combine key ideas of first two attempts for a correct solution

turn is shared value

- The threads share the variables *turn* and *flag* (where *flag* is an array, as before)

```
Enter_region(id_t id) {     /* id can be 0 or 1 */

      flag[id] = true;      /* indicate entering CS */
      turn = id;                 turn <- intend to enter
      while (turn == id && flag[other] == true);
}                               loops if other is in CS…
```

```
Leave_region(id_t id) {     /* id can be 0 or 1 */

      flag[id] = false;
}
```

turn not set on exit, since turn reflects other threads' intention

2-Thread Solutions: 3rd Try

- Imagine two threads i and j execute `Enter_region()` at the same time:

Thread i

```
flag[i] = true;
turn = i;
while(turn==i && flag[j]==true);
```

Thread j

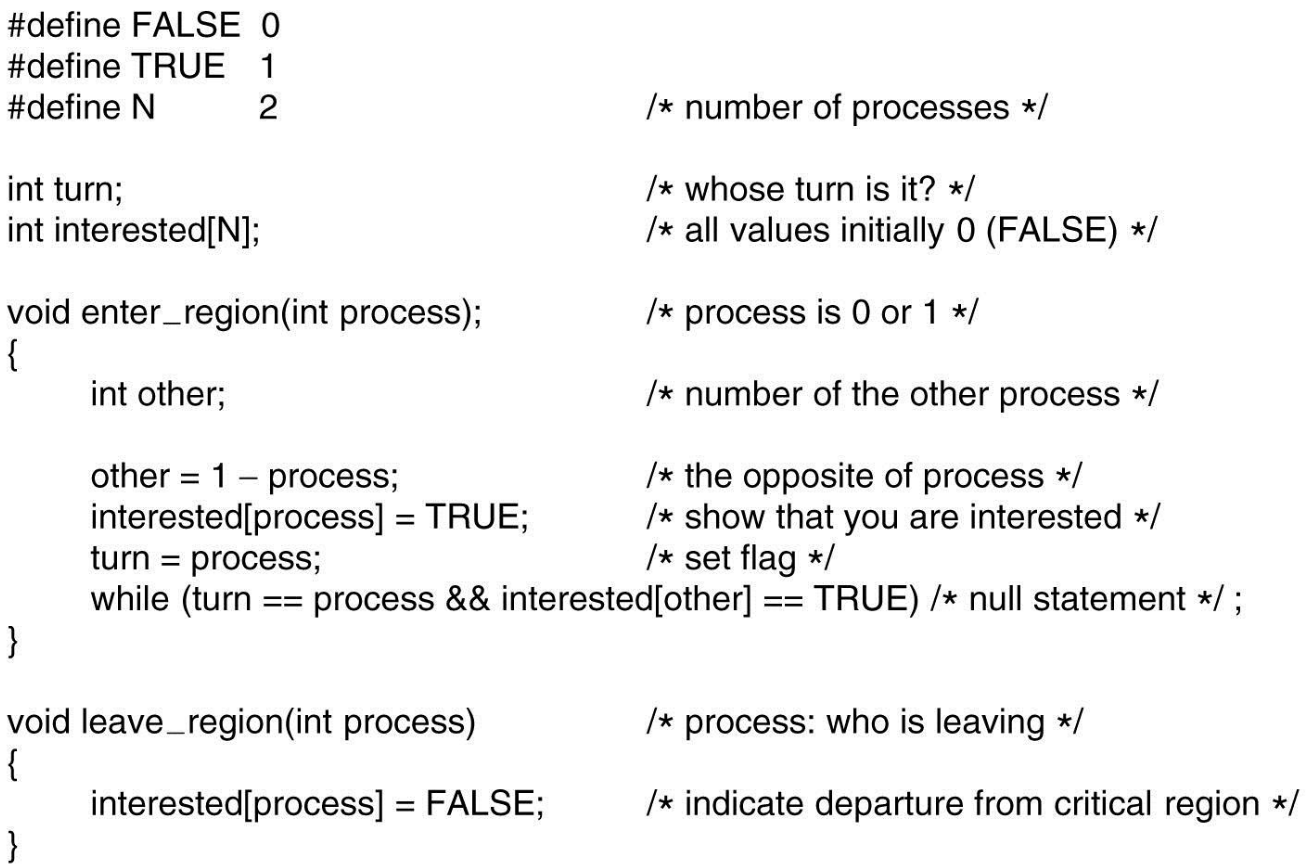
```
flag[j] = true;
turn = j;
while(turn==j && flag[i]==true);
```

- Basic idea: if both try to enter at the same time, *turn* will be set to both 0 and 1 at roughly the same time. Only one assignments will last. The final value of *turn* decides who gets to go first.

since turn holds 1 value at any time

- This is the basis of *Peterson’s Algorithm*

Peterson's Solution



```
#define FALSE  0
#define TRUE   1
#define N      2                        /* number of processes */

int turn;                               /* whose turn is it? */
int interested[N];                      /* all values initially 0 (FALSE) */

void enter_region(int process);         /* process is 0 or 1 */
{
     int other;                         /* number of the other process */

     other = 1 – process;               /* the opposite of process */
     interested[process] = TRUE;        /* show that you are interested */
     turn = process;                    /* set flag */
     while (turn == process && interested[other] == TRUE) /* null statement */ ;
}

void leave_region(int process)          /* process: who is leaving */
{
     interested[process] = FALSE;       /* indicate departure from critical region */
}
```

Peterson’s solution for achieving mutual exclusion.

Higher-level Abstractions for CS's

- Locks
  - Very primitive, minimal semantics
- Semaphores
  - Basic, easy to understand, hard to program with
- Monitors
  - High-level, ideally has language support (Java)
- Messages
  - Simple model for communication & synchronization
  - Direct application to distributed systems

Synchronization Hardware

- To build these higher-level abstractions, it is useful to have some help from the hardware
- On a uniprocessor:
  - Disable interrupts before entering critical section
  - Prevents context switches
  - Doesn’t work on multiprocessor
- Need some special atomic instructions

Atomic Instructions: Test-and-Set Lock (TSL)

- Test-and-set uses a *lock* variable
  - Lock == 0 => nobody is using the lock
  - Lock == 1 => lock is in use
  - In order to acquire lock, must change it's value from 0=>1

provided on single processor machine for implementing locks at hardware level

```
boolean test_and_set(boolean *lock)
{
      boolean old = *lock;
      *lock = True;
      return old;
}
```

Test if lock is available,
if lock is not available, returns false -> implies no function called before current
if lock is available, returns true -> implies no other function called before current
as sideeffect, lock always set to true

- Hardware executes this atomically!

Atomic Instructions: Test-and-Set

- The semantics of test-and-set are:
  - Record the old value of the variable
  - Set the variable to some non-zero value
  - Return the old value

```
boolean test_and_set(boolean *lock)
{
        boolean old = *lock;
        *lock = True;
        return old;
}
```

- *lock* is always *True* on exit from test-and-set
  - Either it was *True* (locked) already, and nothing changed
  - or it was *False* (available), but the caller now holds it
- Return value is either *True* if it was locked already, or *False* if it was previously available

A Lock Implementation

- There are two operations on locks: *acquire()* and *release()*

```
boolean lock;

void acquire(boolean *lock) {
        while(test_and_set(lock));
}  lock taken —> returns true -> while loop blocks
   lock not taken -> returns false -> while loop finishes

void release(boolean *lock) {
        *lock = false;
}
```

- This is a ***spinlock***
  - Uses *busy waiting* - thread continually executes *while* loop in *acquire()* , consumes CPU cycles

Using Locks

Function Definitions

```
Withdraw(acct, amt) {

    acquire(lock);
    balance = get_balance(acct);
    balance = balance - amt;
    put_balance(acct,balance);
    release(lock);
    return balance;
}
```

```
Deposit(account, amount) {

    acquire(lock);
    balance = get_balance(acct);
    balance = balance + amt;
    put_balance(acct,balance);
    release(lock);
    return balance;
}
```

Possible schedule

```
acquire(lock);
balance = get_balance(acct);
balance = balance - amt;
```

```
acquire(lock);
```

```
put_balance(acct, balance);
release(lock);
```

```
balance = get_balance(acct);
balance = balance + amt;
put_balance(acct, balance);
release(lock);
```

Next Week

- More on Synchronization

Announcement

- Check course website regularly
- Attend Tutorials