Part 2: Processes & Threads

Part 1: Processes & Scheduling

Processes and threads

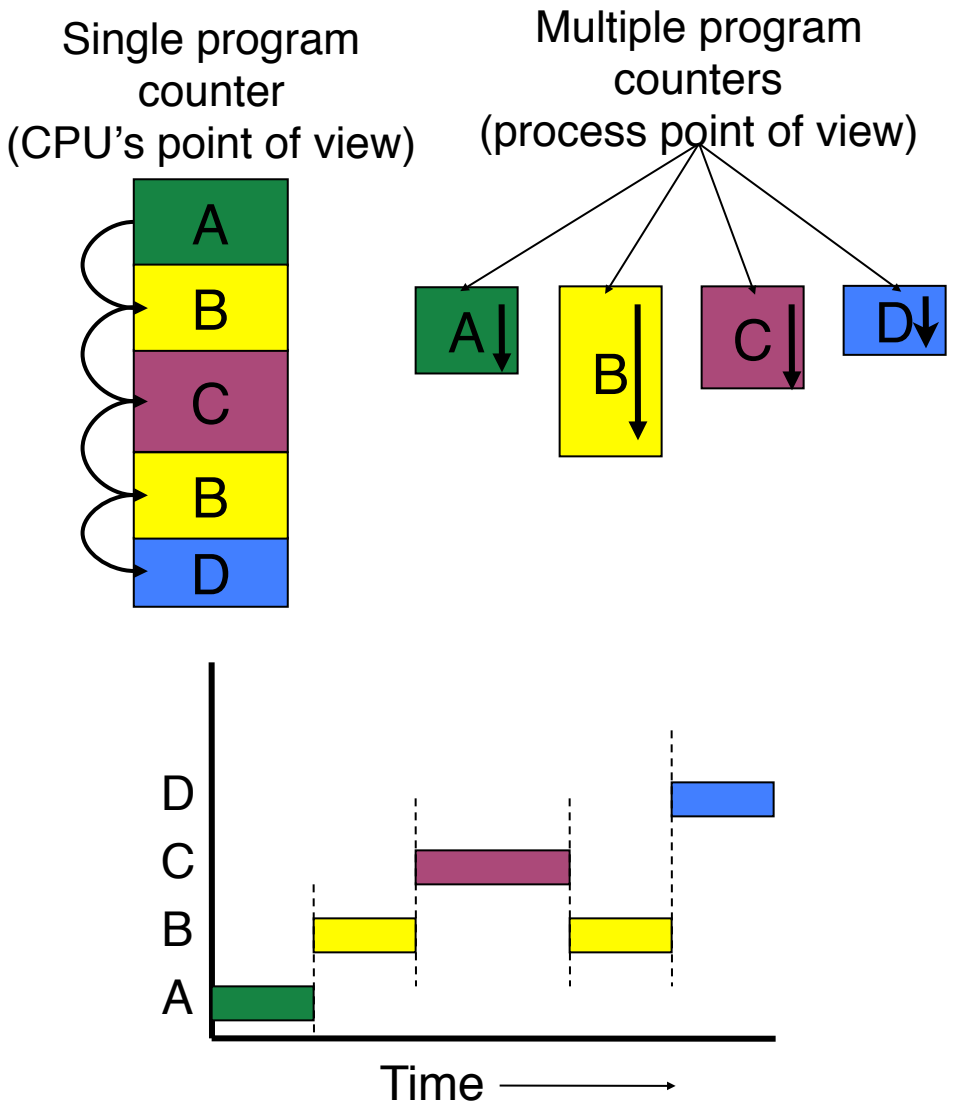
- Processes
- Threads
- Scheduling
- Interprocess communication
- Classical IPC problems

What is a process?

- Code, data, and stack
  - Usually (but not always) has its own address space
- Program state
  - CPU registers
  - Program counter (current location in the code)
  - Stack pointer
- Only one process can be running in the CPU at any given time!

The process model

- Multiprogramming of four programs
- Conceptual model
  - 4 independent processes
  - Processes run sequentially
- Only one program active at any instant!
  - That instant can be very short…
  - Only applies if there's a single CPU in the system



When is a process created?

- Processes can be created in two ways
  - System initialization: one or more processes created when the OS starts up
  - Execution of a process creation system call: something explicitly asks for a new process
- System calls can come from
  - User request to create a new process (system call executed from user shell)
  - Already running processes
    - User programs
    - System daemons

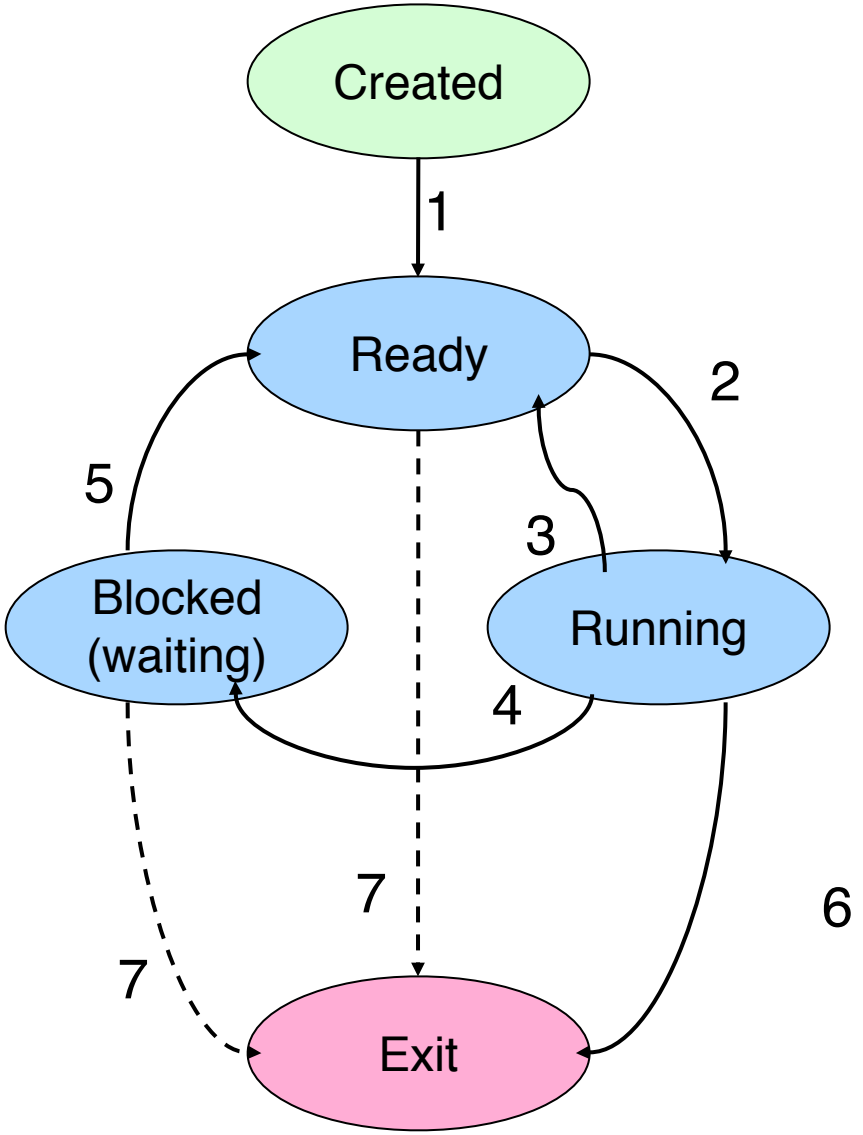
When do processes end?

- Conditions that terminate processes can be
  - Voluntary
  - Involuntary
- Voluntary
  - Normal exit
  - Error exit
- Involuntary
  - Fatal error (only sort of involuntary)
  - Killed by another process

Process hierarchies

- Parent creates a child process
  - Child processes can create their own children
- Forms a hierarchy
  - UNIX calls this a "process group"
  - If a process terminates, its children are "inherited" by the terminating process's parent
- Windows has process groups
  - Multiple processes grouped together
  - One process is the "group leader"

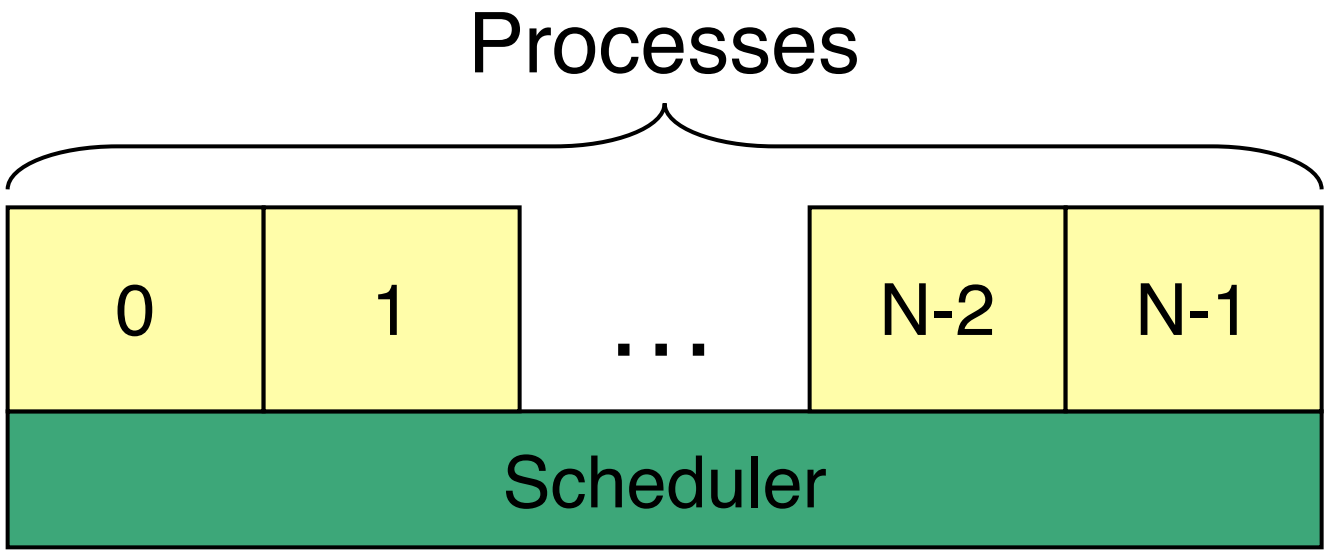
Process states



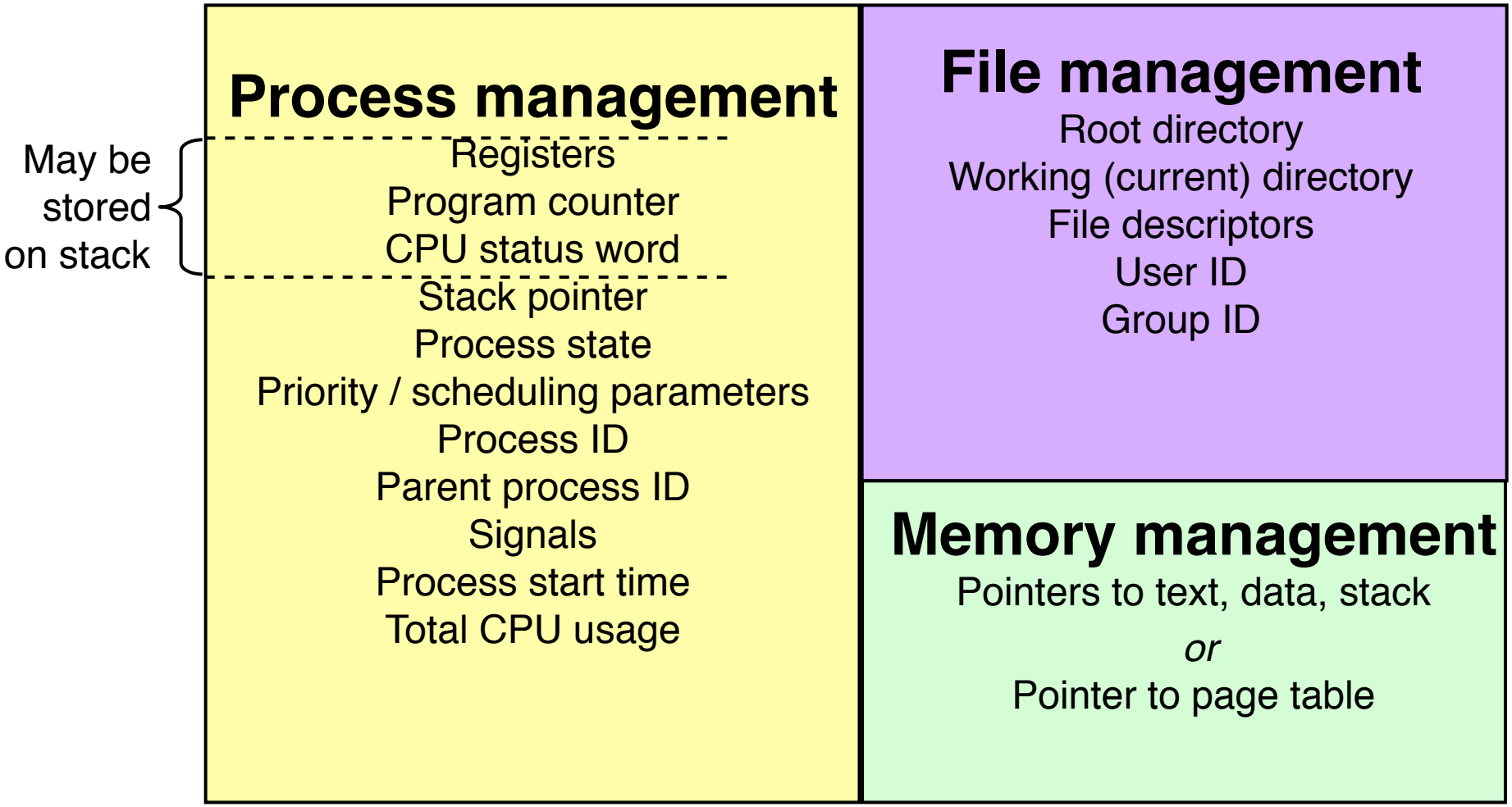
- Process in one of 5 states
  - Created
  - Ready
  - Running
  - Blocked
  - Exit
- Transitions between states
  - Process enters ready queue
  - Scheduler picks this process
  - Scheduler picks a different process
  - Process waits for event (such as I/O)
  - Event occurs
  - Process exits
  - Process ended by another process

Processes in the OS

- Two "layers" for processes
- Lowest layer of process-structured OS handles interrupts, scheduling
- Above that layer are sequential processes
  - Processes tracked in the process table
  - Each process has a process table entry



What's in a process table entry?

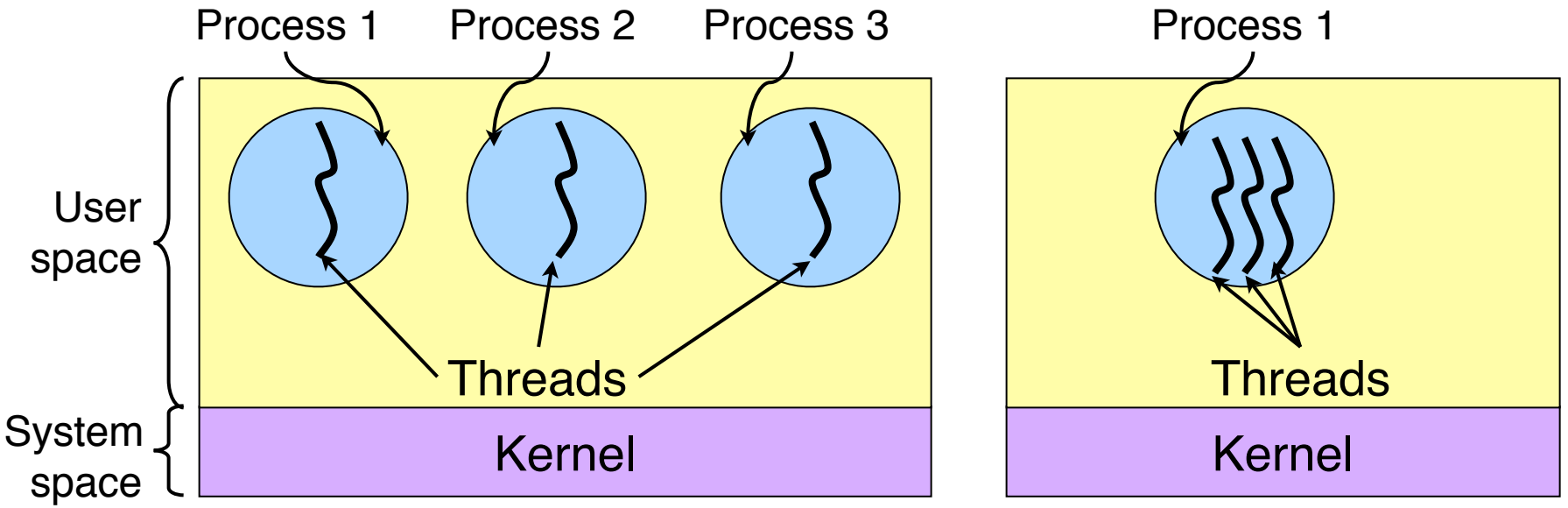


What happens on a trap/ interrupt?

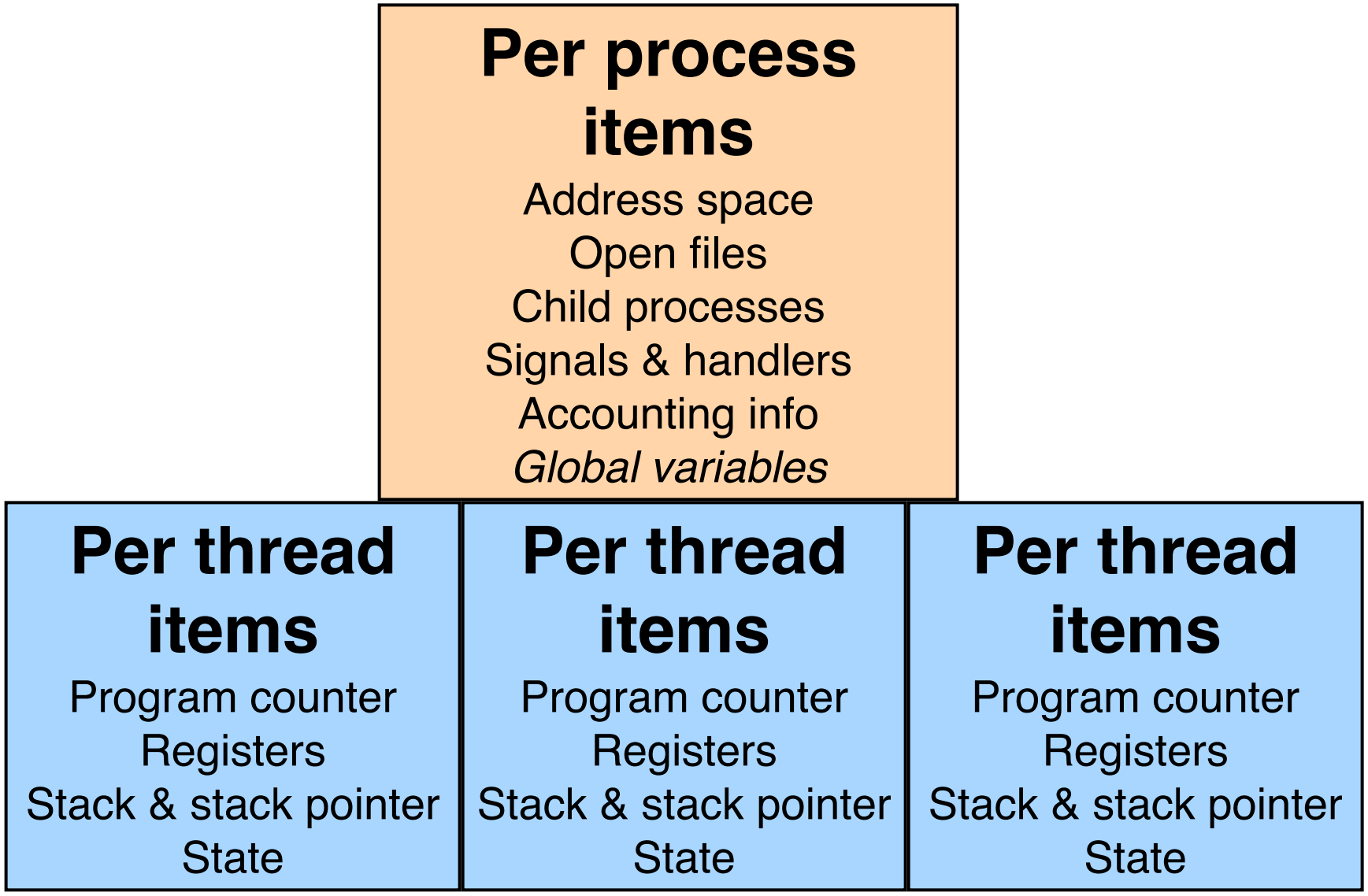
1. Hardware saves program counter (on stack or in a special register)
2. Hardware loads new PC, identifies interrupt
3. Assembly language routine saves registers
4. Assembly language routine sets up stack
5. Assembly language calls C to run service routine
6. Service routine calls scheduler
7. Scheduler selects a process to run next (might be the one interrupted…)
8. Assembly language routine loads PC & registers for the selected process

Threads: "processes" sharing memory

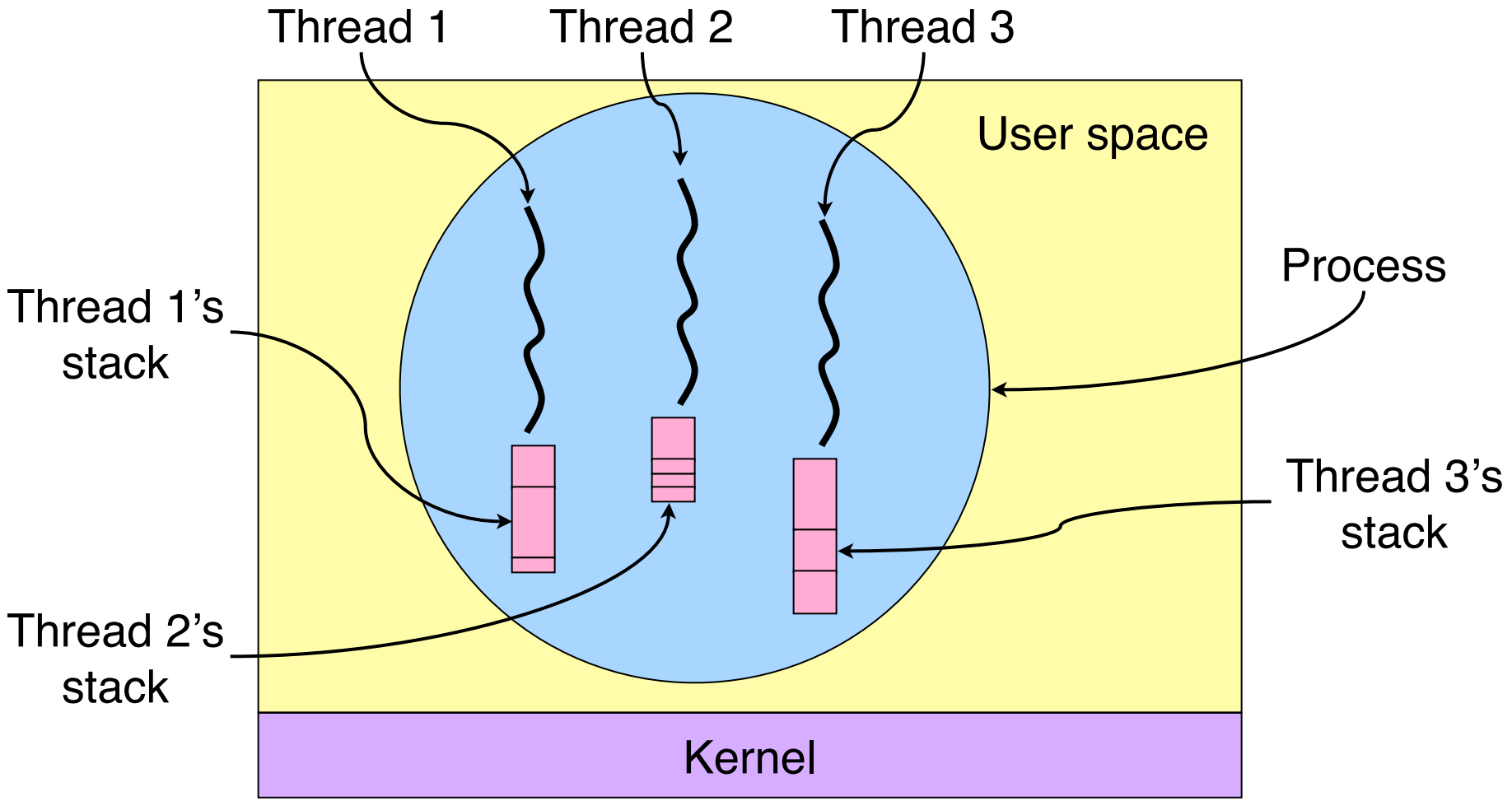
- Process == address space
- Thread == program counter / stream of instructions
- Two examples
  - Three processes, each with one thread
  - One process with three threads



Process & thread information



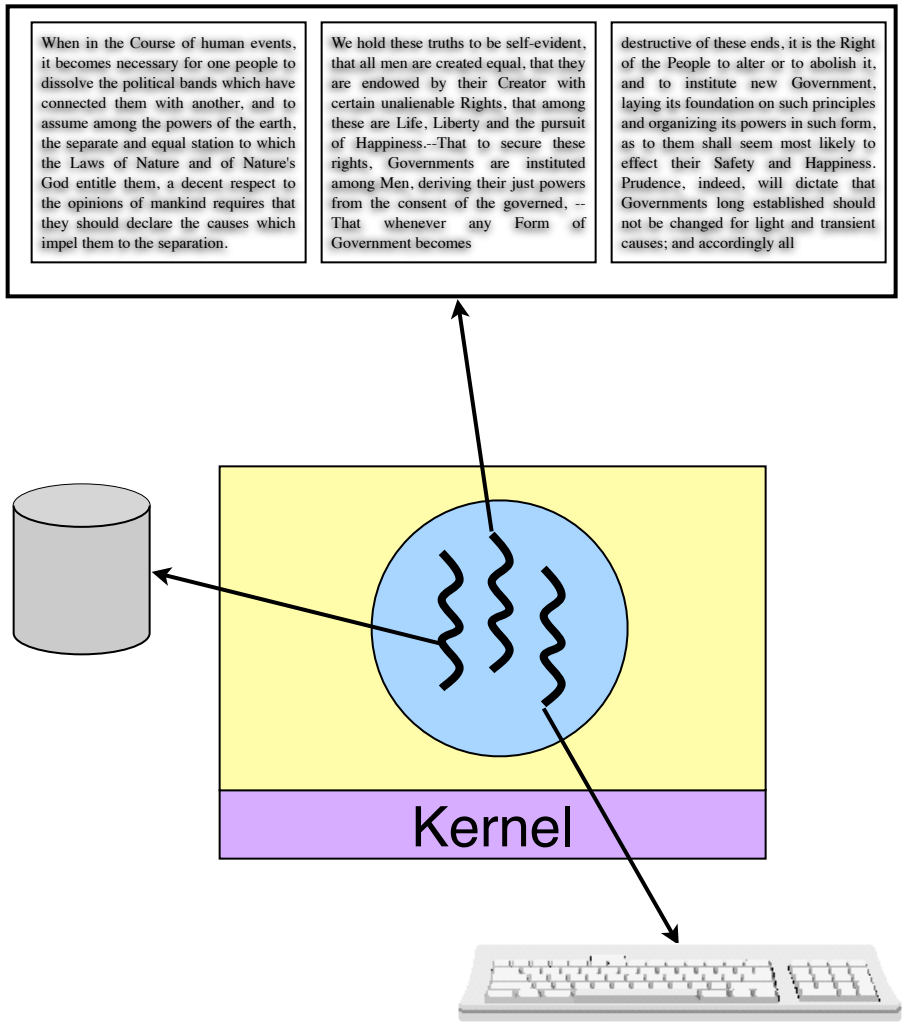
Threads & stacks



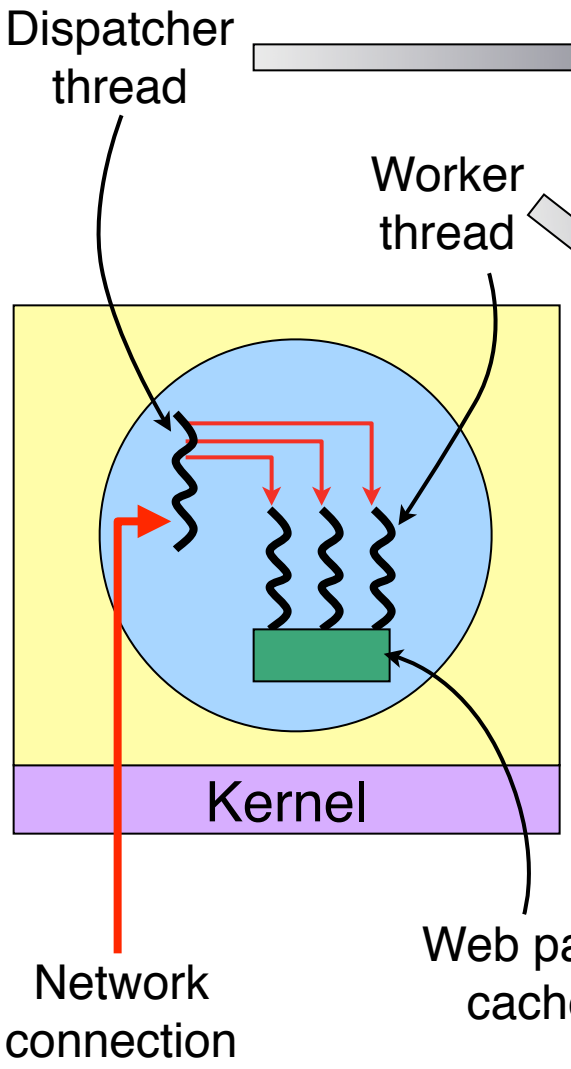
➡ Each thread has its own stack!

Why use threads?

- Allow a single application to do many things at once
  - Simpler programming model
  - Less waiting
- Threads are faster to create or destroy
  - No separate address space
- Overlap computation and I/O
  - Could be done without threads, but it's harder
- Example: word processor
  - Thread to read from keyboard
  - Thread to format document
  - Thread to write to disk



Multithreaded Web server



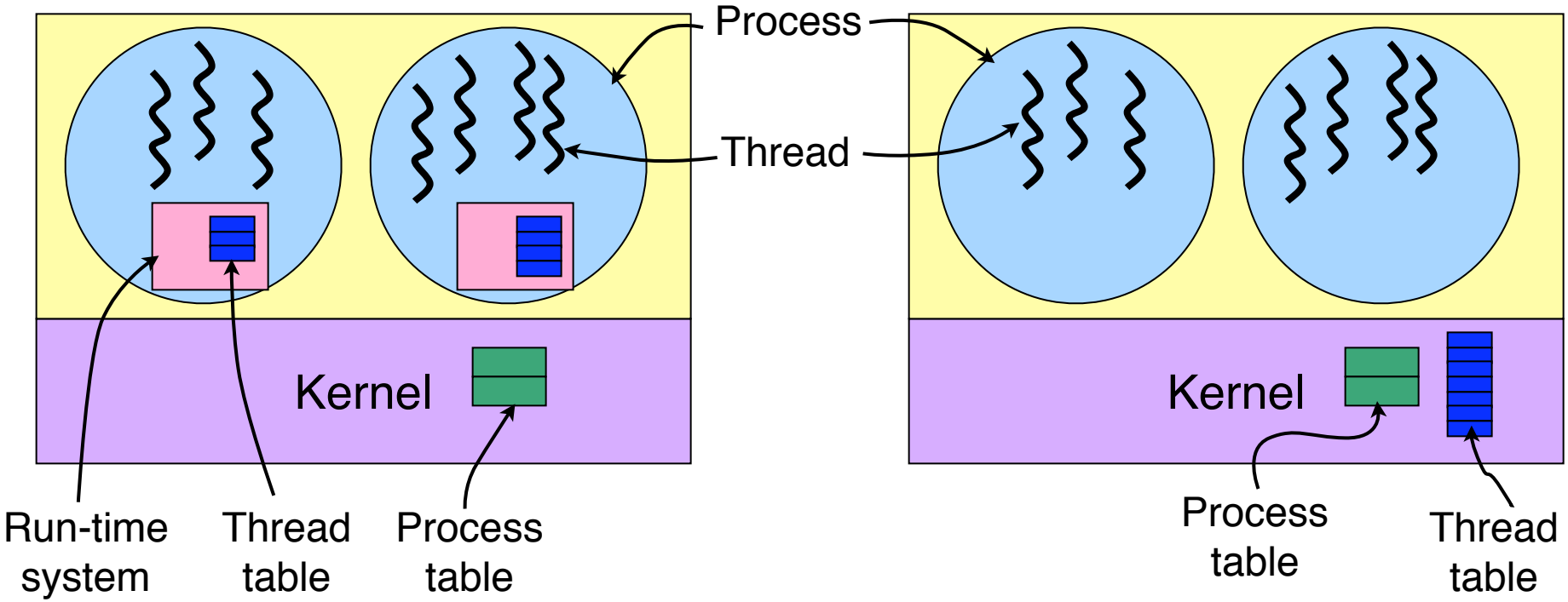

```
while(TRUE) {
  getNextRequest(&buf);
  handoffWork(&buf);
}
```

```
while(TRUE) {
  waitForWork(&buf);
  lookForPageInCache(&buf,&page);
  if(pageNotInCache(&page)) {
    readPageFromDisk(&buf,&page);
  }
  returnPage(&page);
}
```

Three ways to build a server

- Thread model
  - Parallelism
  - Blocking system calls
- Single-threaded process: slow, but easier to do
  - No parallelism
  - Blocking system calls
- Finite-state machine (event model)
  - Each activity has its own state
  - States change when system calls complete or interrupts occur
  - Parallelism
  - Nonblocking system calls
  - Interrupts

Implementing threads



User-level threads

+ No need for kernel support
- May be slower than kernel threads
- Harder to do non-blocking I/O

Kernel-level threads

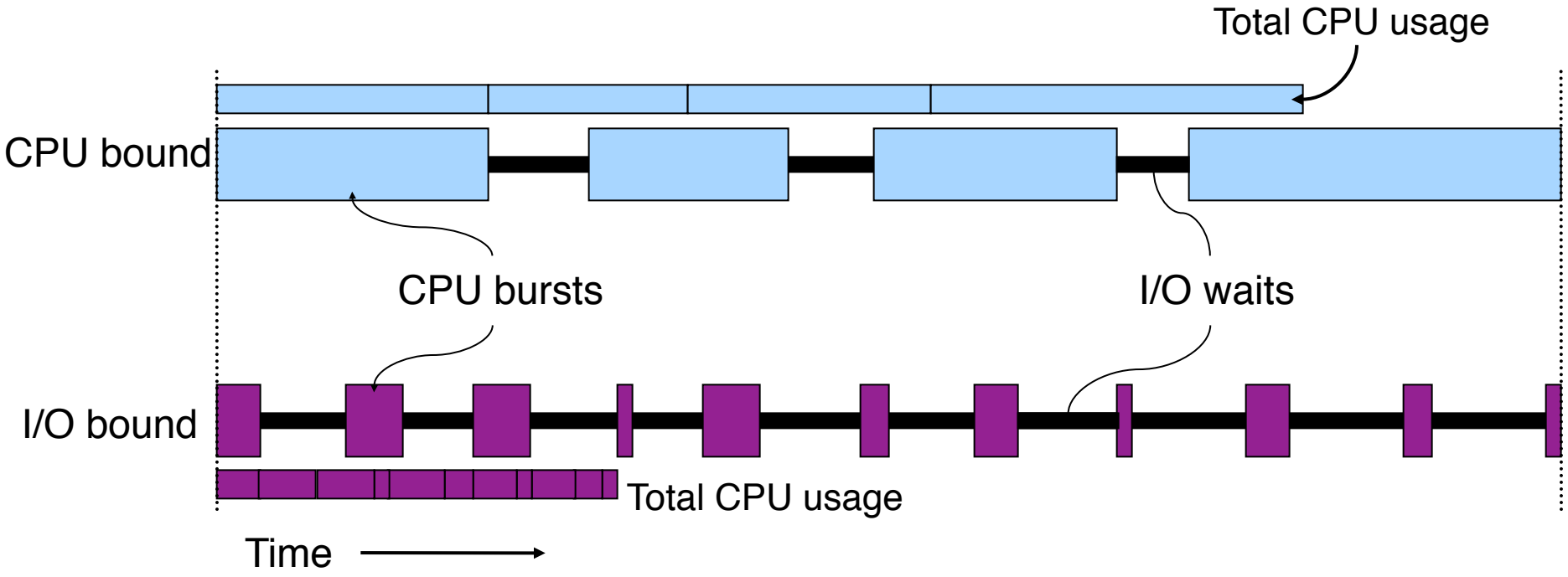
+ More flexible scheduling
+ Non-blocking I/O
- Not portable

Scheduling

- What is scheduling?
  - Goals
  - Mechanisms
- Scheduling on batch systems
- Scheduling on interactive systems
- Other kinds of scheduling
  - Real-time scheduling

Why schedule processes?

- Bursts of CPU usage alternate with periods of I/O wait
- Some processes are CPU-bound: they don't many I/O requests
- Other processes are I/O-bound and make many kernel requests



When are processes scheduled?

- At the time they enter the system
  - Common in batch systems
  - Two types of batch scheduling
    - Submission of a new job causes the scheduler to run
    - Scheduling only done when a job voluntarily gives up the CPU (i.e., while waiting for an I/O request)
- At relatively fixed intervals (clock interrupts)
  - Necessary for interactive systems
  - May also be used for batch systems
  - Scheduling algorithms at each interrupt, and picks the next process from the pool of "ready" processes

Scheduling goals

- All systems
  - Fairness: give each process a fair share of the CPU
  - Enforcement: ensure that the stated policy is carried out
  - Balance: keep all parts of the system busy
- Batch systems
  - Throughput: maximize jobs per unit time (hour)
  - Turnaround time: minimize time users wait for jobs
  - CPU utilization: keep the CPU as busy as possible
- Interactive systems
  - Response time: respond quickly to users' requests
  - Proportionality: meet users' expectations
- Real-time systems
  - Meet deadlines: missing deadlines is a system failure!
  - Predictability: same type of behavior for each time slice

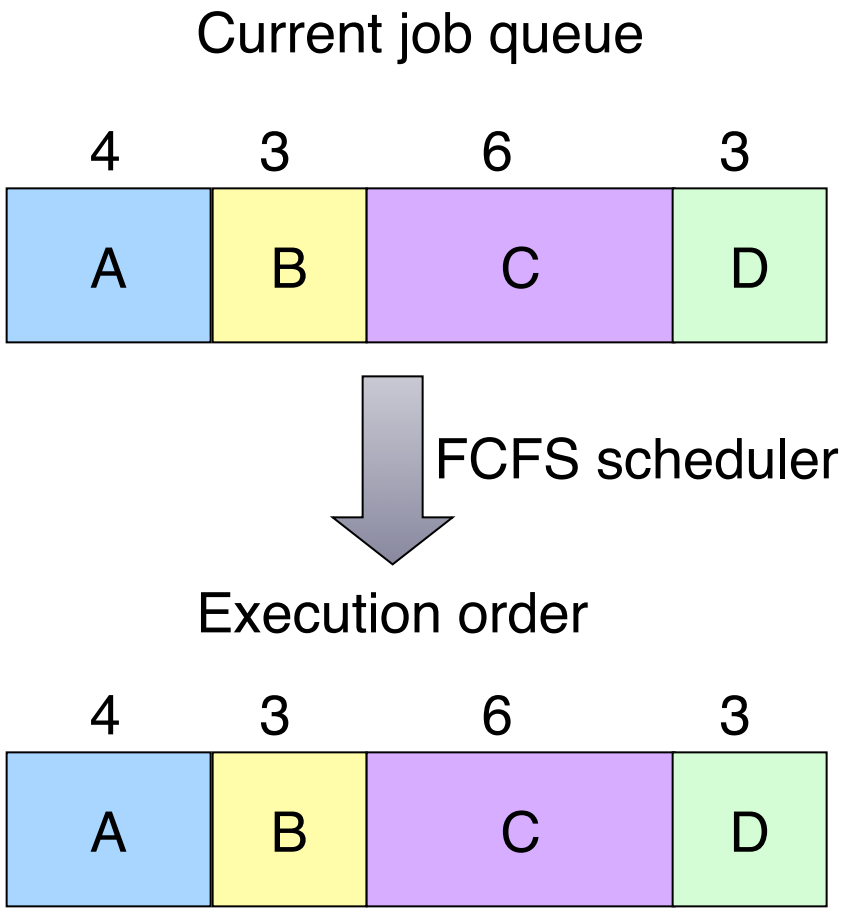
Measuring scheduling performance

- Throughput
  - Amount of work completed per second (minute, hour)
  - Higher throughput usually means better utilized system
- Response time
  - Response time is time from when a command is submitted until results are returned
  - Can measure average, variance, minimum, maximum, …
  - May be more useful to measure time spent waiting
- Turnaround time
  - Like response time, but for batch jobs (response is the completion of the process)
- Usually not possible to optimize for ***all*** metrics with a single scheduling algorithm

Interactive vs. batch scheduling

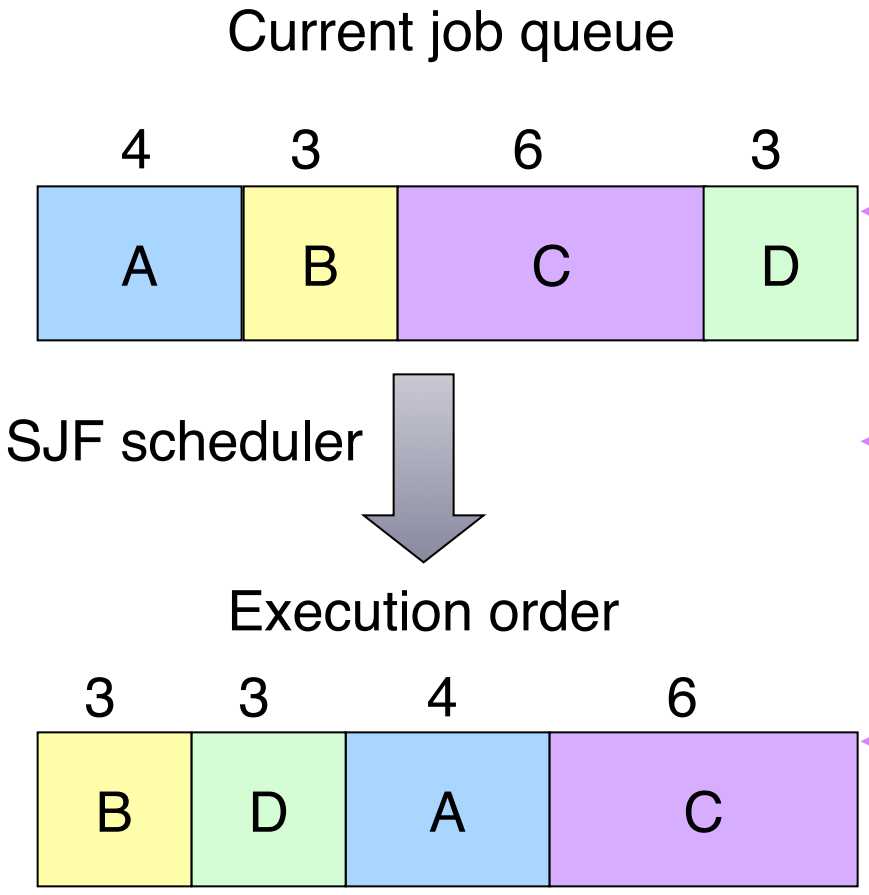
Batch	Interactive
First-Come-First-Served (FCFS)	Round-Robin (RR)
Shortest Job First (SJF)	Priority (preemptive)
Shortest Remaining Time First (SRTF)	Multi-level feedback queue
Priority (non-preemptive)	Lottery scheduling

First Come, First Served (FCFS)



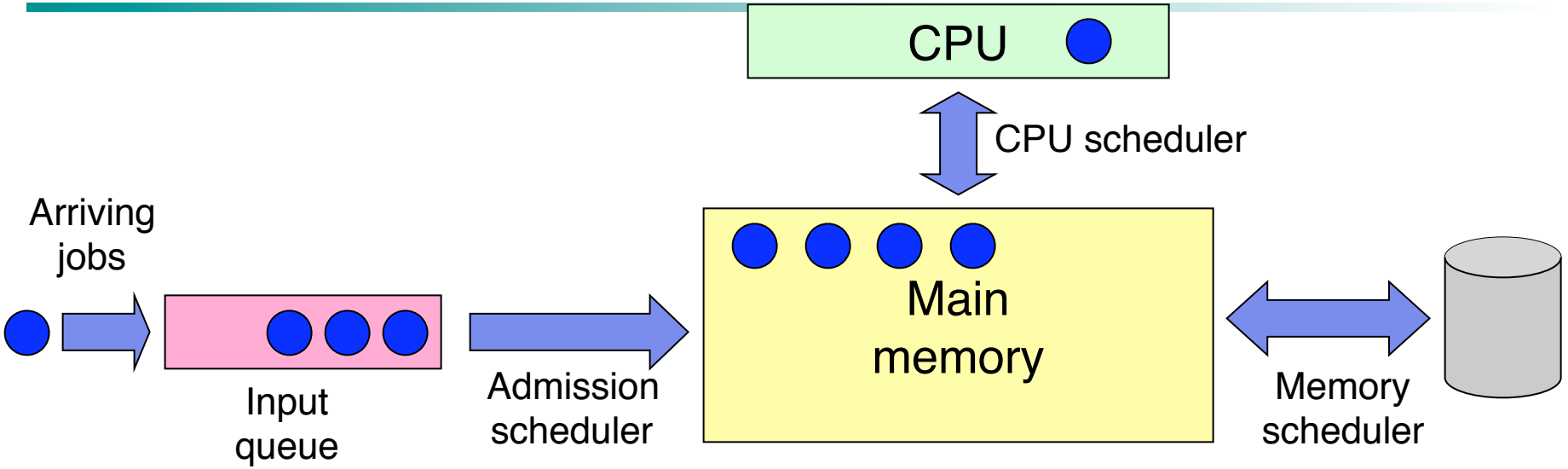
- Goal: do jobs in the order they arrive
  - Fair in the same way a bank teller line is fair
- Simple algorithm!
- Problem: long jobs delay every job after them
  - Many processes may wait for a single long job

Shortest Job First (SJF)



- Goal: do the shortest job first
  - Short jobs complete first
  - Long jobs delay every job after them
- Jobs sorted in increasing order of execution time
  - Ordering of ties doesn't matter
- Shortest Remaining Time First (SRTF): preemptive form of SJF
  - Re-evaluate when a new job is submitted
- Problem: how does the scheduler know how long a job will take?

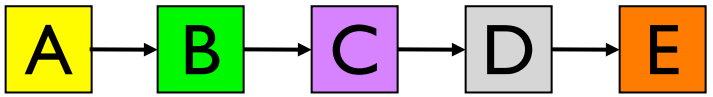
Three-level scheduling

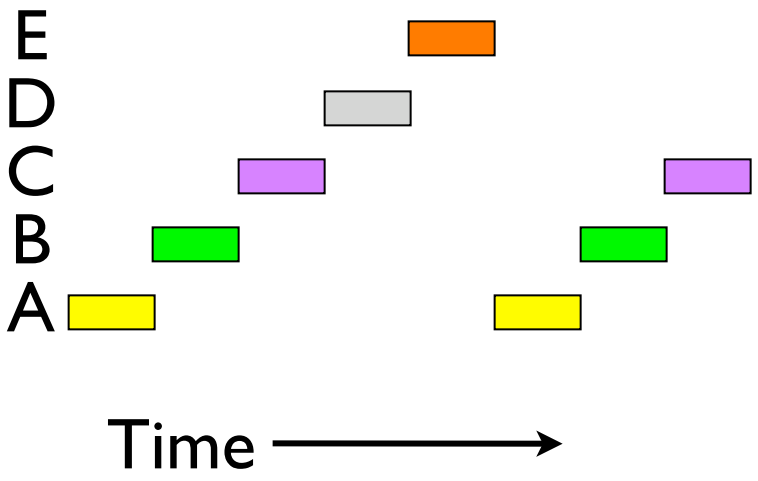


- Jobs held in input queue until moved into memory
  - Pick "complementary jobs": small & large, CPU- & I/O-intensive
  - Jobs move into memory when admitted
- CPU scheduler picks next job to run
- Memory scheduler picks some jobs from main memory and moves them to disk if insufficient memory space

Round Robin (RR) scheduling

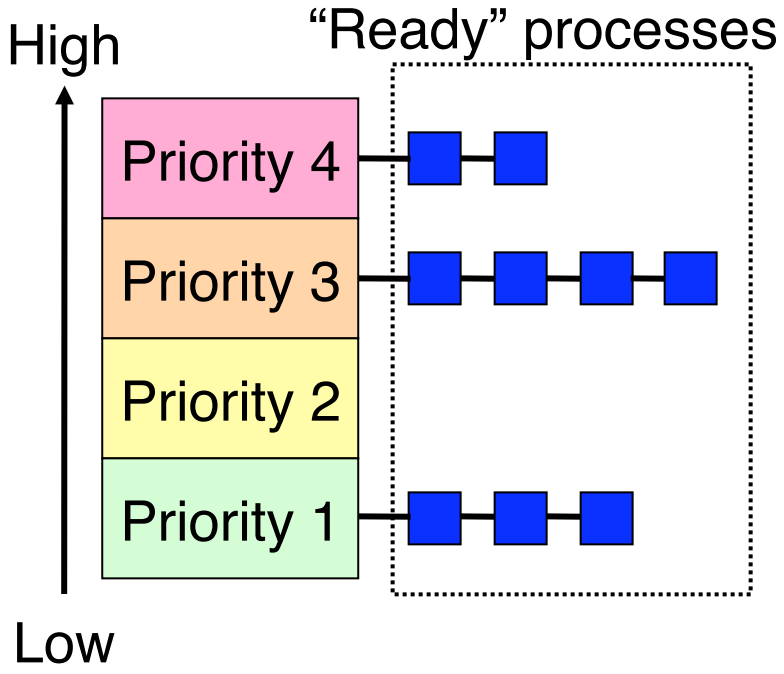
- Round Robin scheduling
  - Give each process a fixed time slot (quantum)
  - Rotate through "ready" processes
  - Each process makes some progress
- What's a good quantum?
  - Too short: many process switches hurt efficiency
  - Too long: poor response to interactive requests
  - Typical length: 10–100 ms





Priority scheduling

- Assign a priority to each process
  - "Ready" process with highest priority allowed to run
  - Running process may be interrupted after its quantum expires
- Priorities may be assigned dynamically
  - Reduced when a process uses CPU time
  - Increased when a process waits for I/O
- Often, processes grouped into multiple queues based on priority, and run round-robin per queue



Shortest process next

- Run the process that will finish the soonest
  - In interactive systems, job completion time is unknown!
- Guess at completion time based on previous runs
  - Update estimate each time the job is run
  - Estimate is a combination of previous estimate and most recent run time
- Not often used because round robin with priority works so well!

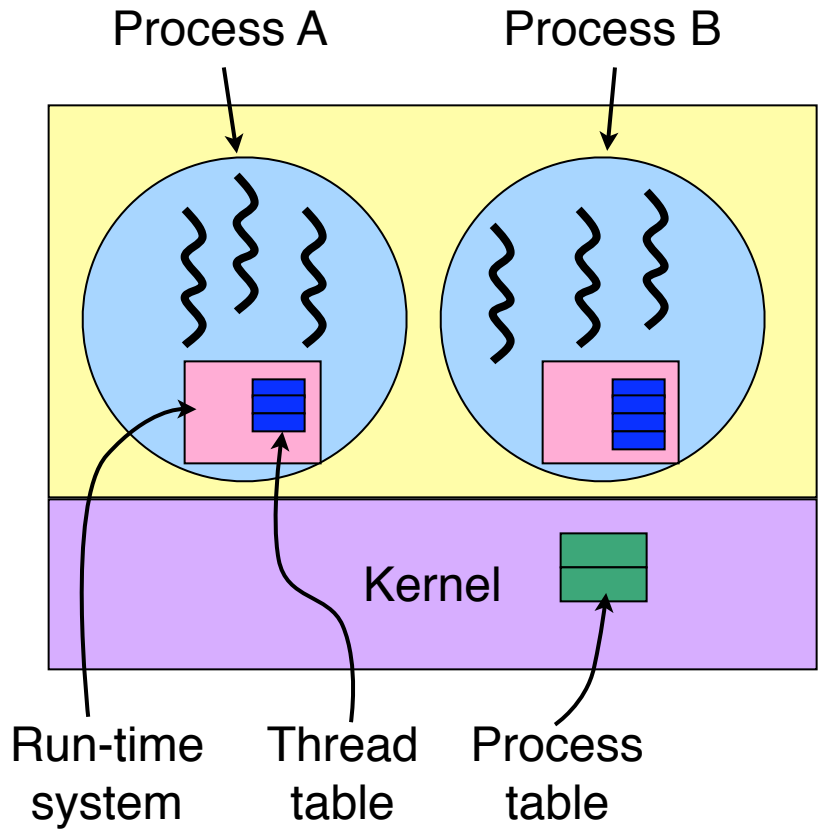
Lottery scheduling

- Give processes "tickets" for CPU time
  - More tickets => higher share of CPU
- Each quantum, pick a ticket at random
  - If there are n tickets, pick a number from 1 to n
  - Process holding the ticket gets to run for a quantum
- Over the long run, each process gets the CPU *m*/*n* of the time if the process has m of the n existing tickets
- Tickets can be transferred
  - Cooperating processes can exchange tickets
  - Clients can transfer tickets to server so it can have a higher priority

Policy versus mechanism

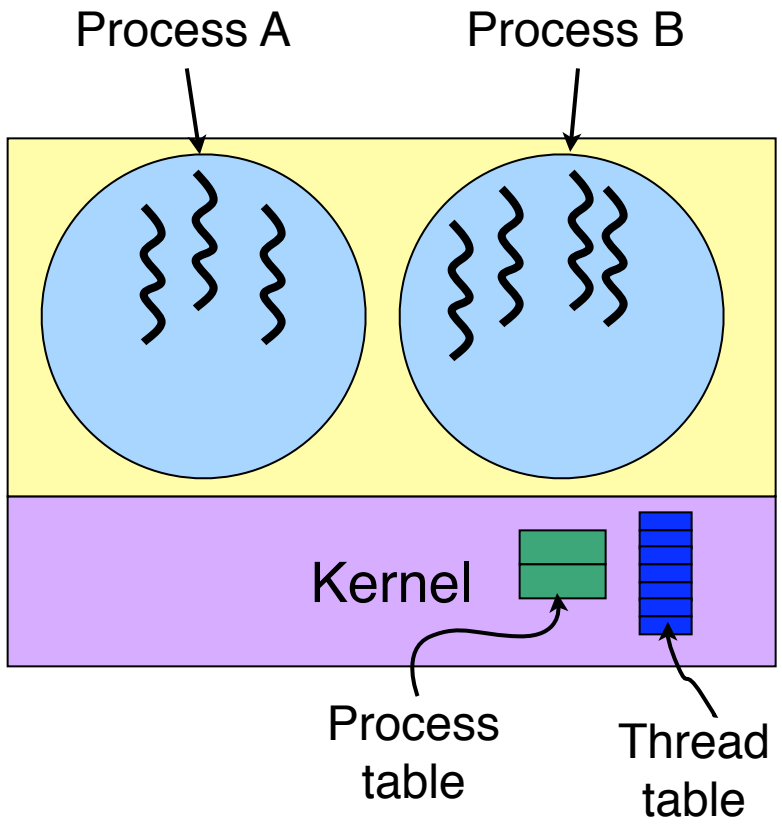
- Separate what may be done from how it is done
  - Mechanism allows
    - Priorities to be assigned to processes
    - CPU to select processes with high priorities
  - Policy set by what priorities are assigned to processes
- Scheduling algorithm parameterized
  - Mechanism in the kernel
  - Priorities assigned in the kernel or by users
- Parameters may be set by user processes
  - Don't allow a user process to take over the system!
  - Allow a user process to voluntarily lower its own priority
  - Allow a user process to assign priority to its threads

Scheduling user-level threads



- Kernel picks a process to run next
- Run-time system (at user level) schedules threads
  - Run each thread for less than process quantum
  - Example: processes get 40ms each, threads get 10ms each
- Example schedule: A1,A2,A3,A1,B1,B3,B2,B3
- Not possible: A1,A2,B1,B2,A3,B3,A2,B1

Scheduling kernel-level threads



- Kernel schedules each thread
  - No restrictions on ordering
  - May be more difficult for each process to specify priorities
- Example schedule: A1,A2,A3,A1, B1,B3,B2,B3
- Also possible: A1,A2,B1,B2, A3,B3,A2,B1

Chapter 2: Processes & Threads

Part 2:
Interprocess Communication & Synchronization

Why do we need IPC?

- Each process operates sequentially
- All is fine until processes want to share data
  - Exchange data between multiple processes
  - Allow processes to navigate critical regions
  - Maintain proper sequencing of actions in multiple processes
- These issues apply to threads as well
  - Threads can share data easily (same address space)
  - Other two issues apply to threads

Example: bounded buffer problem

Shared variables

```
const int n;
typedef … Item;
Item buffer[n];
int in = 0, out = 0,
    counter = 0;
```

Atomic statements:

```
Counter += 1;
Counter -= 1;
```

Producer

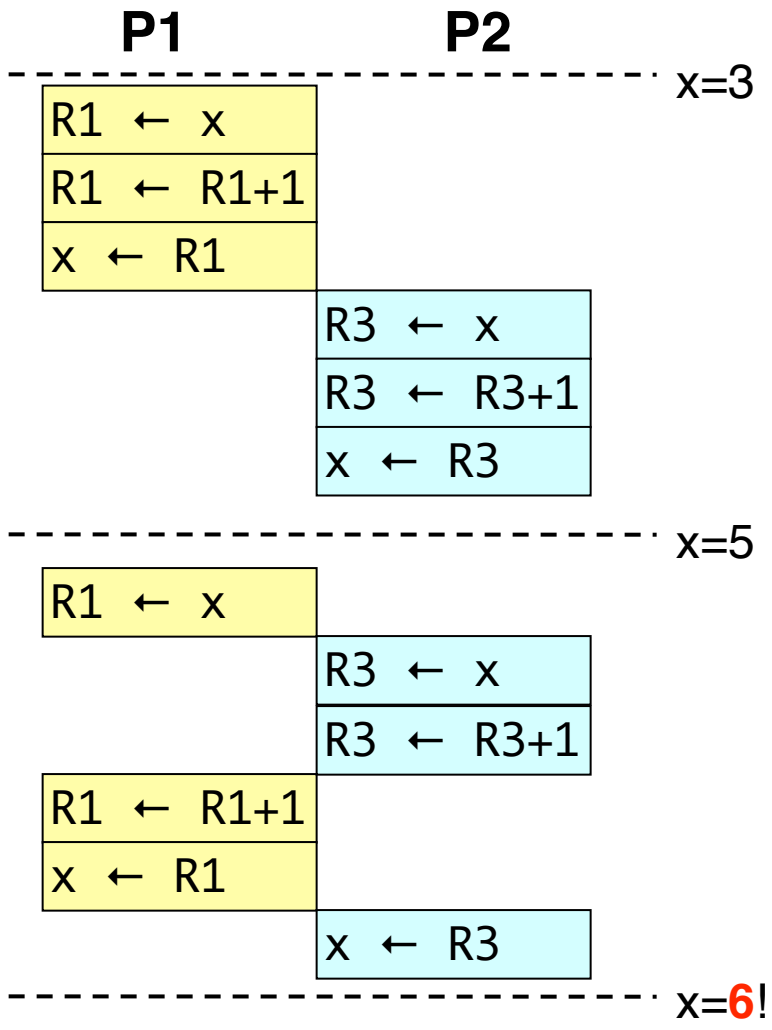
```
Item pitm;
while (1) {
  …
  produce an item into pitm
  …
  while (counter == n)
    ;
  buffer[in] = pitm;
  in = (in+1) % n;
  counter += 1;
}
```

Consumer

```
Item citm;
while (1) {
  while (counter == 0)
    ;
  citm = buffer[out];
  out = (out+1) % n;
  counter -= 1;
  …
  consume the item in citm
  …
}
```

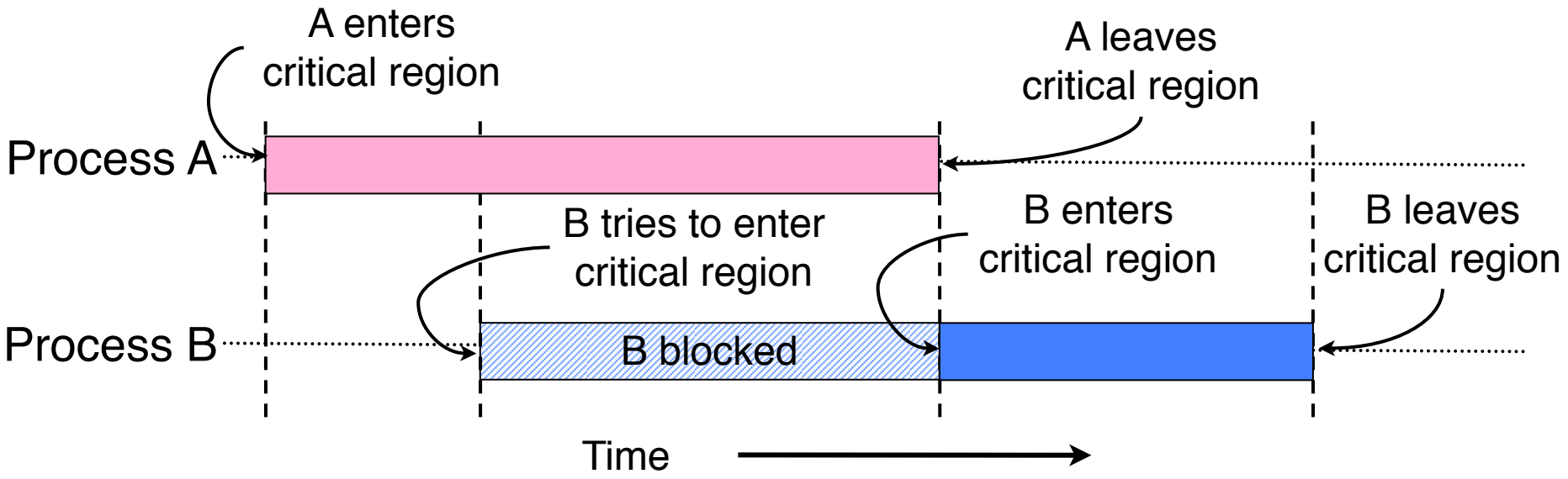
Problem: race conditions

- Cooperating processes share storage (memory)
- Both may read and write the shared memory
- Problem: can't guarantee that read followed by write is atomic
  - Ordering matters!
- This can result in erroneous results!
- We need to eliminate race conditions…



Critical regions

- Use critical regions to provide mutual exclusion and help fix race conditions
- Four conditions to provide mutual exclusion
  - No two processes simultaneously in critical region
  - No assumptions made about speeds or number of CPUs
  - No process running outside its critical region may block another process
  - A process may not wait forever to enter its critical region



Busy waiting: strict alternation

Process 0

```
while (TRUE) {
  while (turn != 0)
    ; /* loop */
  critical_region ();
  turn = 1;
  noncritical_region ();
}
```

Process 1

```
while (TRUE) {
  while (turn != 1)
    ; /* loop */
  critical_region ();
  turn = 0;
  noncritical_region ();
}
```

- Use a shared variable (turn) to keep track of whose turn it is
- Waiting process continually reads the variable to see if it can proceed
  - This is called a spin lock because the waiting process "spins" in a tight loop reading the variable
- Avoids race conditions, but doesn't satisfy criterion 3 for critical regions

Busy waiting: working solution

```
#define    FALSE  0
#define    TRUE   1
#define    N   2   // # of processes
int turn;     // Whose turn is it?
int interested[N];   // Set to 1 if process j is interested

void enter_region(int process)
{
  int other = 1-process; // # of the other process
  interested[process] = TRUE;  // show interest
  turn = process;// Set it to my turn
  while (turn==process && interested[other]==TRUE)
    ;  // Wait while the other process runs
}

void leave_region (int process)
{
  interested[process] = FALSE; // I'm no longer interested
}
```

Bakery algorithm for many processes

- Notation used
  - <<< is lexicographical order on (ticket#, process ID)
  - (a,b) <<< (c,d) if (a <<< c) or ((a==c) and (b<d))
  - Max(a_0,a_1,…,a_{n-1}) is a number k such that k≥a_i for all i
- Shared data
  - choosing initialized to 0
  - number initialized to 0

```
int n; // # of processes
int choosing[n];
int number[n];
```

Bakery algorithm: code

```
while (1) {  // i is the number of the current process
  choosing[i] = 1;
  number[i] = max(number[0],number[1],…,number[n-1]) + 1;
  choosing[i] = 0;
  for (j = 0; j < n; j++) {
    while (choosing[j])  // wait while j is choosing a
      ;                  // number
    // Wait while j wants to enter and j <<< i
    while ((number[j] != 0) &&
           ((number[j] < number[i]) ||
            ((number[j] == number[i]) && (j < i))))
        ;
  }
  // critical section
  number[i] = 0;
  // rest of code
}
```

Hardware for synchronization

- Prior methods work, but…
  - May be somewhat complex
  - Require busy waiting: process spins in a loop waiting for something to happen, wasting CPU time
- Solution: use hardware
- Several hardware methods
  - Test & set: test a variable and set it in one instruction
  - Atomic swap: switch register & memory in one instruction
  - Turn off interrupts: process won't be switched out unless it asks to be suspended

Mutual exclusion using hardware

- Single shared variable lock
- Still requires busy waiting, but code is much simpler
- Two versions
  - Test and set
  - Swap
- Works for any number of processes
- Possible problem with requirements
  - Non-concurrent code can lead to unbounded waiting

```
int lock = 0;
```

Code for process P_i

```
while (1) {
  while (TestAndSet(lock))
    ;
  // critical section
  lock = 0;
  // remainder of code
}
```

Code for process P_i

```
while (1) {
  while (Swap(lock,1) == 1)
    ;
  // critical section
  lock = 0;
  // remainder of code
}
```

Eliminating busy waiting

- Problem: previous solutions waste CPU time
  - Both hardware and software solutions require spin locks
  - Allow processes to sleep while they wait to execute their critical sections
- Problem: priority inversion (higher priority process waits for lower priority process)
- Solution: use semaphores
  - Synchronization mechanism that doesn't require busy waiting during entire critical section
- Implementation
  - Semaphore S accessed by two atomic operations
    - Down(S): while (S<=0) {}; S-= 1;
    - Up(S): S+=1;
  - Down() is another name for P()
  - Up() is another name for V()
  - Modify implementation to eliminate busy wait from Down()

Critical sections using semaphores

- Define a class called Semaphore
  - Class allows more complex implementations for semaphores
  - Details hidden from processes
- Code for individual process is simple

Shared variables

```
Semaphore mutex;
```

Code for process P_i

```
while (1) {
  down(mutex);
  // critical section
  up(mutex);
  // remainder of code
}
```

Implementing semaphores with blocking

- Assume two operations:
  - Sleep(): suspends current process
  - Wakeup(P): allows process P to resume execution
- Semaphore is a class
  - Track value of semaphore
  - Keep a list of processes waiting for the semaphore
- Operations still atomic

```
class Semaphore {
  int value;
  ProcessList pl;
  void down ();
  void up ();
};
```

Semaphore code

```
Semaphore::down ()
{
  value -= 1;
  if (value < 0) {
    // add this process to pl
    Sleep ();
  }
}
Semaphore::up () {
Process P;
  value += 1;
  if (value <= 0) {
    // remove a process P
    // from pl
    Wakeup (P);
  }
}
```

Semaphores for general synchronization

- We want to execute B in P1 only after A executes in P0
- Use a semaphore initialized to 0
- Use up() to notify P1 at the appropriate time

Shared variables

```
// flag initialized to 0
Semaphore flag;
```

Process P_0

```
    .
    .
    .
// Execute code for A
flag.up ();
```

Process P_1

```
    .
    .
    .
flag.down ();
// Execute code for B
```

Types of semaphores

- Two different types of semaphores
  - Counting semaphores
  - Binary semaphores
- Counting semaphore
  - Value can range over an unrestricted range
- Binary semaphore
  - Only two values possible
    - 1 means the semaphore is available
    - 0 means a process has acquired the semaphore
  - May be simpler to implement
- Possible to implement one type using the other

Monitors

- A monitor is another kind of high-level synchronization primitive
  - One monitor has multiple entry points
  - Only one process may be in the monitor at any time
  - Enforces mutual exclusion - less chance for programming errors
- Monitors provided by high-level language
  - Variables belonging to monitor are protected from simultaneous access
  - Procedures in monitor are guaranteed to have mutual exclusion
- Monitor implementation
  - Language / compiler handles implementation
  - Can be implemented using semaphores

Monitor usage

- This looks like C++ code, but it's not supported by C++
- Provides the following features:
  - Variables foo, bar, and arr are accessible only by proc1 & proc2
  - Only one process can be executing in either proc1 or proc2 at any time

```
monitor mon {
  int foo;
  int bar;
  double arr[100];
  void proc1(…) {
  }
  void proc2(…) {
  }
  void mon() {  // initialization code
  }
}
```

Condition variables in monitors

- Problem: how can a process wait inside a monitor?
  - Can't simply sleep: there's no way for anyone else to enter
  - Solution: use a condition variable
- Condition variables support two operations
  - Wait(): suspend this process until signaled
  - Signal(): wake up exactly one process waiting on this condition variable
    - If no process is waiting, signal has no effect
    - Signals on condition variables aren't "saved up"
- Condition variables are only usable within monitors
  - Process must be in monitor to signal on a condition variable
  - Question: which process gets the monitor after Signal()?

Monitor semantics

- Problem: P signals on condition variable X, waking Q
  - Both can't be active in the monitor at the same time
  - Which one continues first?
- Mesa semantics
  - Signaling process (P) continues first
  - Q resumes when P leaves the monitor
  - Seems more logical: why suspend P when it signals?
- Hoare semantics
  - Awakened process (Q) continues first
  - P resumes when Q leaves the monitor
  - May be better: condition that Q wanted may no longer hold when P leaves the monitor

Locks & condition variables

- Monitors require native language support
- Provide monitor support using special data types and procedures
  - Locks (Acquire(), Release())
  - Condition variables (Wait(), Signal())
- Lock usage
  - Acquiring a lock == entering a monitor
  - Releasing a lock == leaving a monitor
- Condition variable usage
  - Each condition variable is associated with exactly one lock
  - Lock must be held to use condition variable
  - Waiting on a condition variable releases the lock implicitly
  - Returning from Wait() on a condition variable reacquires the lock

Implementing locks with semaphores

```
class Lock {
  Semaphore mutex(1);
  Semaphore next(0);
  int nextCount = 0;
};
```

```
Lock::Acquire()
{
  mutex.down();
}
```

```
Lock::Release()
{
  if (nextCount > 0)
    next.up();
  else
    mutex.up();
}
```

- Use *mutex* to ensure exclusion within the lock bounds
- Use *next* to give lock to processes with a higher priority (why?)
- *nextCount* indicates whether there are any higher priority waiters

Implementing condition variables

```
class Condition {
  Lock *lock;
  Semaphore condSem(0);
  int semCount = 0;
};
```

- Are these Hoare or Mesa semantics?
- Can there be multiple condition variables for a single Lock?

```
Condition::Wait ()
{
  semCount += 1;
  if (lock->nextCount > 0)
    lock->next.up();
  else
    lock->mutex.up();
  condSem.down ();
  semCount -= 1;
}
```

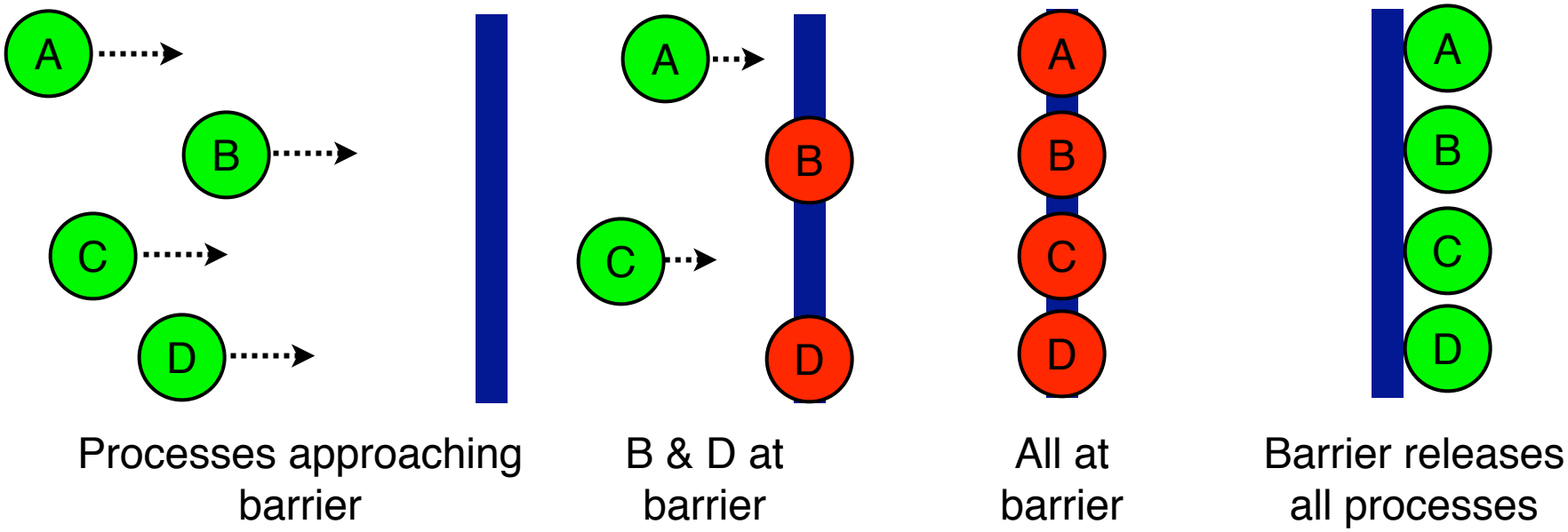
```
Condition::Signal ()
{
  if (semCount > 0) {
    lock->nextCount += 1;
    condSem.up ();
    lock->next.down ();
    lock->nextCount -= 1;
  }
}
```

Message passing

- Synchronize by exchanging messages
- Two primitives:
  - Send: send a message
  - Receive: receive a message
  - Both may specify a "channel" to use
- Issue: how does the sender know the receiver got the message?
- Issue: authentication

Barriers

- Used for synchronizing multiple processes
- Processes wait at a "barrier" until all in the group arrive
- After all have arrived, all processes can proceed
- May be implemented using locks and condition variables



Implementing barriers using semaphores

```
Barrier b;          /* contains two semaphores */
b.bsem.value = 0;   /* for the barrier */
b.mutex.value = 1; /* for mutual exclusion */
b.waiting = 0;
b.maxproc = n;      /* n processes needed at barrier */

HitBarrier (Barrier *b)
{
  SemDown (&b->mutex);
  if (++b->waiting >= b->maxproc) {
    while (--b->waiting > 0) {
      SemUp (&b->bsem);
    }
    SemUp (&b->mutex);
  } else {
    SemUp (&b->mutex);
    SemDown (&b->bsem);
  }
}
```

Use locks and condition variables

Deadlock and starvation

- Deadlock: two or more processes are waiting indefinitely for an event that can only by caused by a waiting process
  - P0 gets A, needs B
  - P1 gets B, needs A
  - Each process waiting for the other to signal
- Starvation: indefinite blocking
  - Process is never removed from the semaphore queue in which its suspended
  - May be caused by ordering in queues (priority)

Shared variables

```
Semaphore A(1),B(1);
```

Process P_0

```
A.down();
B.down();
   .
   .
   .
B.up();
A.up();
```

Process P_1

```
B.down();
A.down();
   .
   .
   .
A.up();
B.up();
```

Classical synchronization problems

- Bounded Buffer
  - Multiple producers and consumers
  - Synchronize access to shared buffer
- Readers & Writers
  - Many processes that may read and/or write
  - Only one writer allowed at any time
  - Many readers allowed, but not while a process is writing
- Dining Philosophers
  - Resource allocation problem
  - *N* processes and limited resources to perform sequence of tasks
- Goal: use semaphores to implement solutions to these problems

Bounded buffer problem

Goal: implement producer-consumer without busy waiting

```
const int n;
Semaphore empty(n),full(0),mutex(1);
Item buffer[n];
```

Producer

```
int in = 0;
Item pitem;
while (1) {
  // produce an item
  // into pitem
  empty.down();
  mutex.down();
  buffer[in] = pitem;
  in = (in+1) % n;
  mutex.up();
  full.up();
}
```

Consumer

```
int out = 0;
Item citem;
while (1) {
  full.down();
  mutex.down();
  citem = buffer[out];
  out = (out+1) % n;
  mutex.up();
  empty.up();
  // consume item from
  // citem
}
```

Readers-writers problem

Shared variables

```
int nreaders;
Semaphore mutex(1), writing(1);
```

Reader process

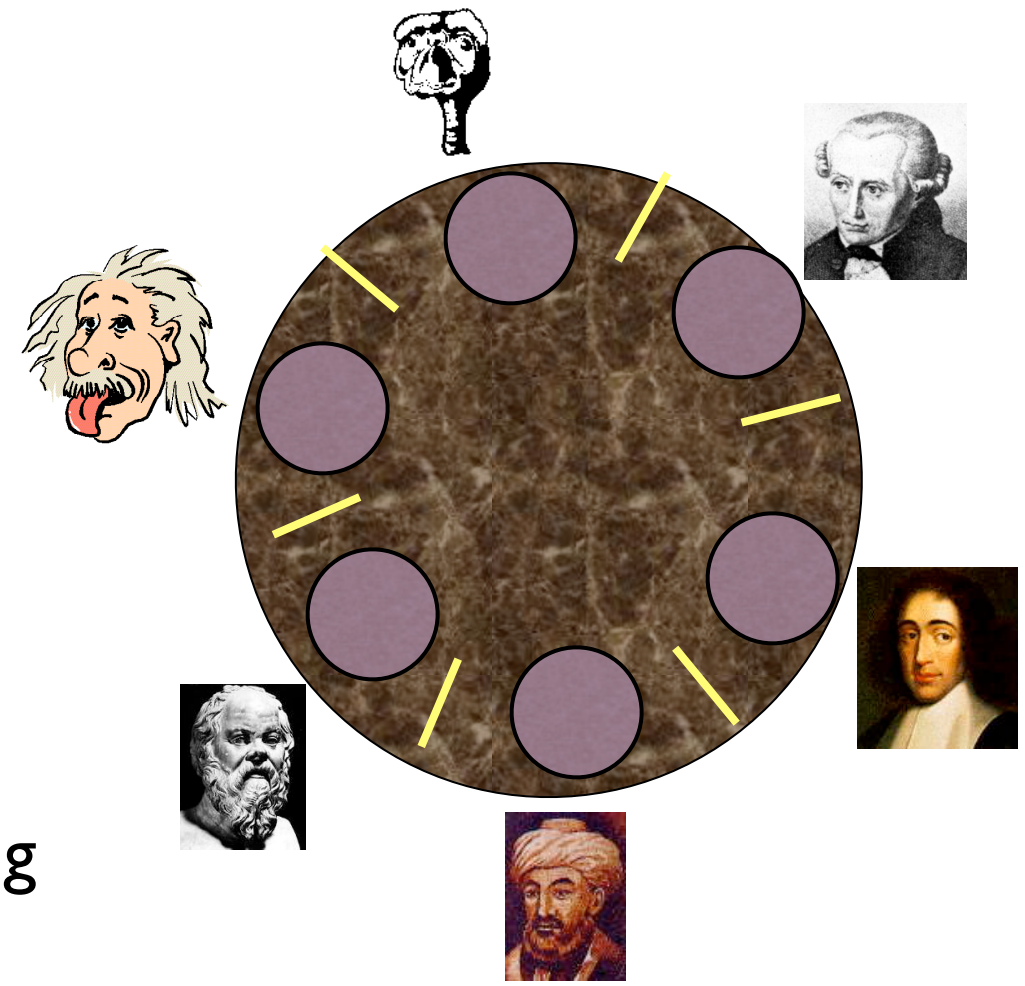
```
…
mutex.down();
nreaders += 1;
if (nreaders == 1) // wait if
  writing.down();  // 1st reader
mutex.up();
// Read some stuff
mutex.down();
nreaders -= 1;
if (nreaders == 0)  // signal if
  writing.up();     // last reader
mutex.up();
…
```

Writer process

```
…
writing.down();
// Write some stuff
writing.up();
…
```

Dining Philosophers

- *N* philosophers around a table
  - All are hungry
  - All like to think
- *N* chopsticks available
  - 1 between each pair of philosophers
- Philosophers need two chopsticks to eat
- Philosophers alternate between eating and thinking
- Goal: coordinate use of chopsticks



Dining Philosophers: solution 1

- Use a semaphore for each chopstick
- A hungry philosopher
  - Gets the chopstick to his right
  - Gets the chopstick to his left
  - Eats
  - Puts down the chopsticks
- Potential problems?
  - Deadlock
  - Fairness

Shared variables

```
const int n;
// initialize to 1
Semaphore chopstick[n];
```

Code for philosopher *i*

```
while(1) {
  chopstick[i].down();
  chopstick[(i+1)%n].down();
  // eat
  chopstick[i].up();
  chopstick[(i+1)%n].up();
  // think
}
```

Dining Philosophers: solution 2

- Use a semaphore for each chopstick
- A hungry philosopher
  - Gets lower, then higher numbered chopstick
  - Eats
  - Puts down the chopsticks
- Potential problems?
  - Deadlock
  - Fairness

Shared variables

```
const int n;
// initialize to 1
Semaphore chopstick[n];
```

Code for philosopher *i*

```
int i1,i2;
while(1) {
  if (i != (n-1)) {
    i1 = i;
    i2 = i+1;
  } else {
    i1 = 0;
    i2 = n-1;
  }
  chopstick[i1].down();
  chopstick[i2].down();
  // eat
  chopstick[i1].up();
  chopstick[i2].up();
  // think
}
```

Dining philosophers with locks

Shared variables

```
const int n;
// initialize to THINK
int state[n];
Lock mutex;
// use mutex for self
Condition self[n];
```

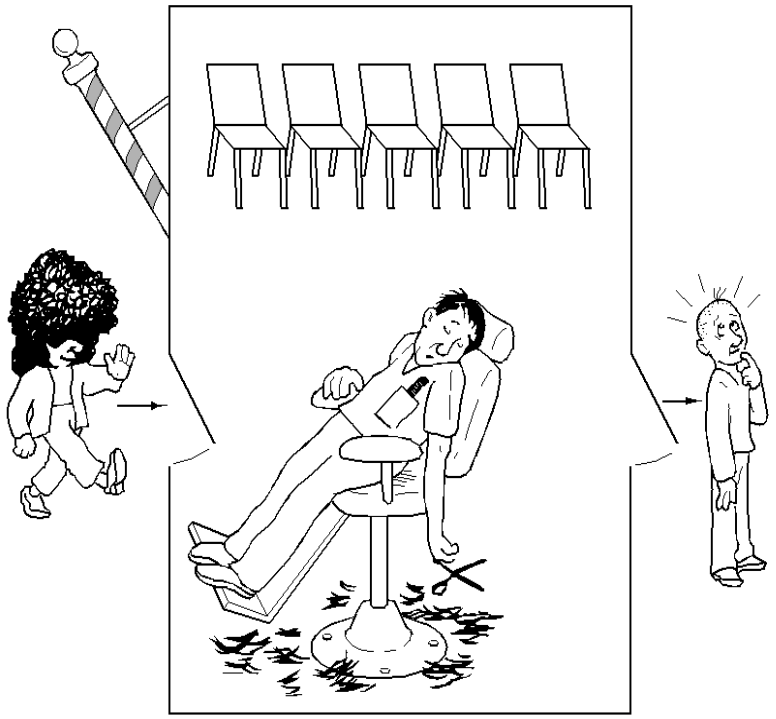
```
void test(int k)
{
  if ((state[(k+n-1)%n)]!=EAT)
&&
      (state[k]==HUNGRY) &&
      (state[(k+1)%n]!=EAT)) {
    state[k] = EAT;
    self[k].Signal();
  }
}
```

Code for philosopher *j*

```
while (1) {
  // pickup chopstick
  mutex.Acquire();
  state[j] = HUNGRY;
  test(j);
  if (state[j] != EAT)
    self[j].Wait();
  mutex.Release();
  // eat
  mutex.Acquire();
  state[j] = THINK;
  test((j+1)%n);   // next
  test((j+n-1)%n); // prev
  mutex.Release();
  // think
}
```

The Sleepy Barber Problem

- Barber wants to sleep all day
  - Wakes up to cut hair
- Customers wait in chairs until barber chair is free
  - Limited space in the waiting room
  - Leave if no space free
- Write the synchronization code for this problem...



Code for the Sleepy Barber Problem

```
#define CHAIRS 5
Semaphore customers=0;
Semaphore barbers=0;
Semaphore mutex=0;
int waiting=0;
```

```
void barber(void)
{
 while(TRUE) {
  // Sleep if no customers
  customers.down();
  // Decrement # of waiting people
  mutex.down();
  waiting -= 1;
  // Wake up a customer to cut hair
  barbers.up();
  mutex.up();
  // Do the haircut
  cut_hair();
 }
}
```

```
void customer(void)
{
 mutex.down();
 // If there is space in the chairs
 if (waiting<CHAIRS) {
  // Another customer is waiting
  waiting++;
  // Wake up the barber.  This is
  // saved up, so the barber doesn't
  // sleep if a customer is waiting
  customers.up();
  mutex.up();
  // Sleep until the barber is ready
  barbers.down();
  get_haircut();
 } else {
  // Chairs full, leave the critical
  // region
  mutex.up ();
 }
}
```