Chapter 2: Processes & Threads

Processes and threads

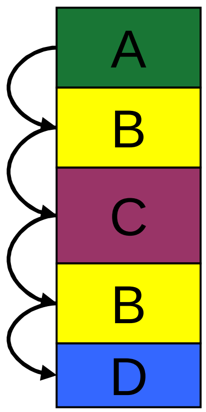
- Processes
- Threads
- Scheduling
- Interprocess communication
- Classical IPC problems

What is a process?

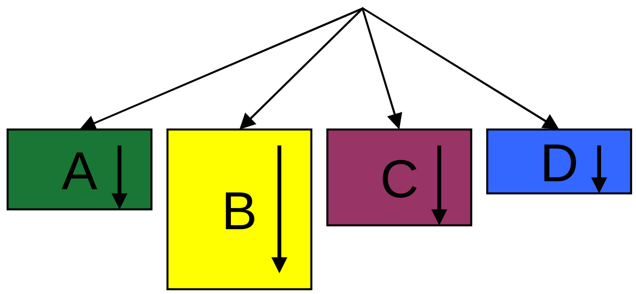
- Code, data, and stack
  - Usually (but not always) has its own address space
- Program state
  - CPU registers
  - Program counter (current location in the code)
  - Stack pointer
- Only one process can be running in the CPU at any given time!

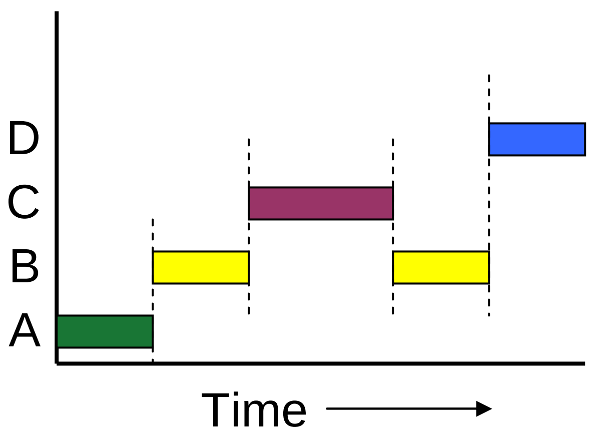
The process model

Single PC
(CPU's point of view)



Multiple PCs
(process point of view)





- 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…

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

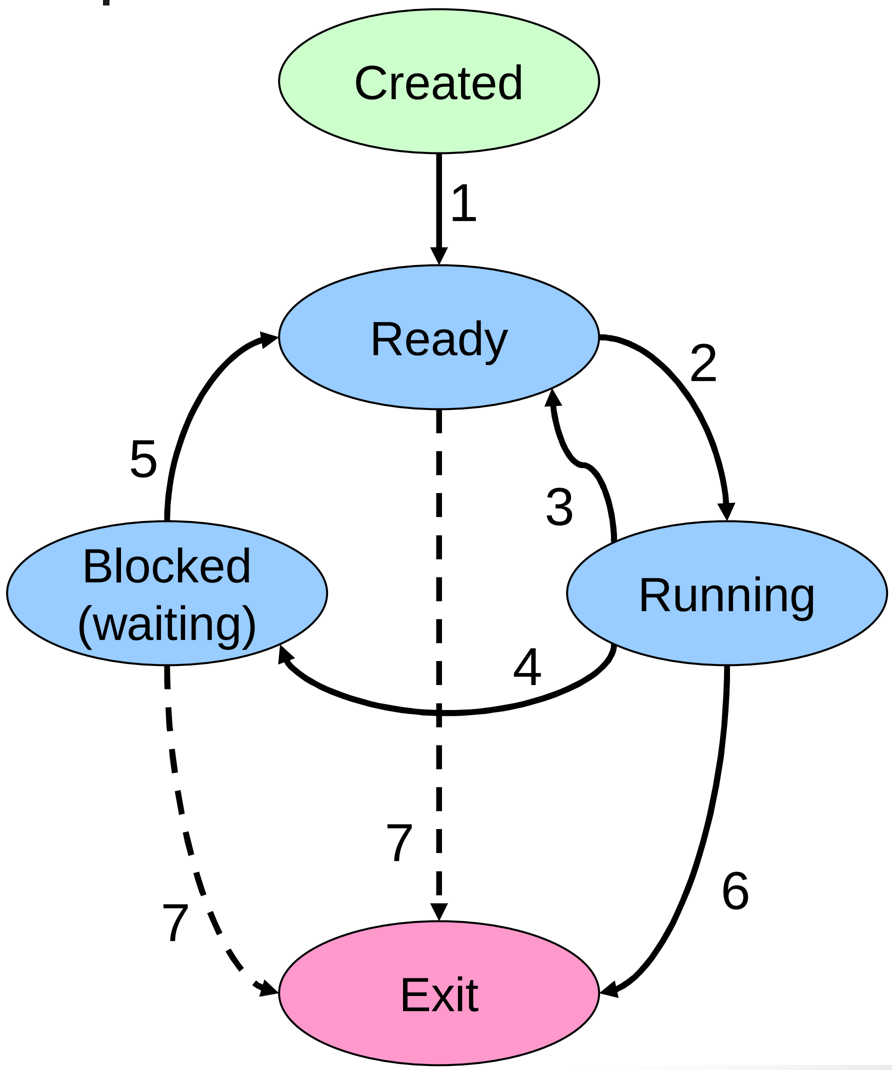
When do processes end?

- 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 exits, its children are “inherited” by the exiting process’s parent
- Windows has no concept of process hierarchy
  - All processes are created equal

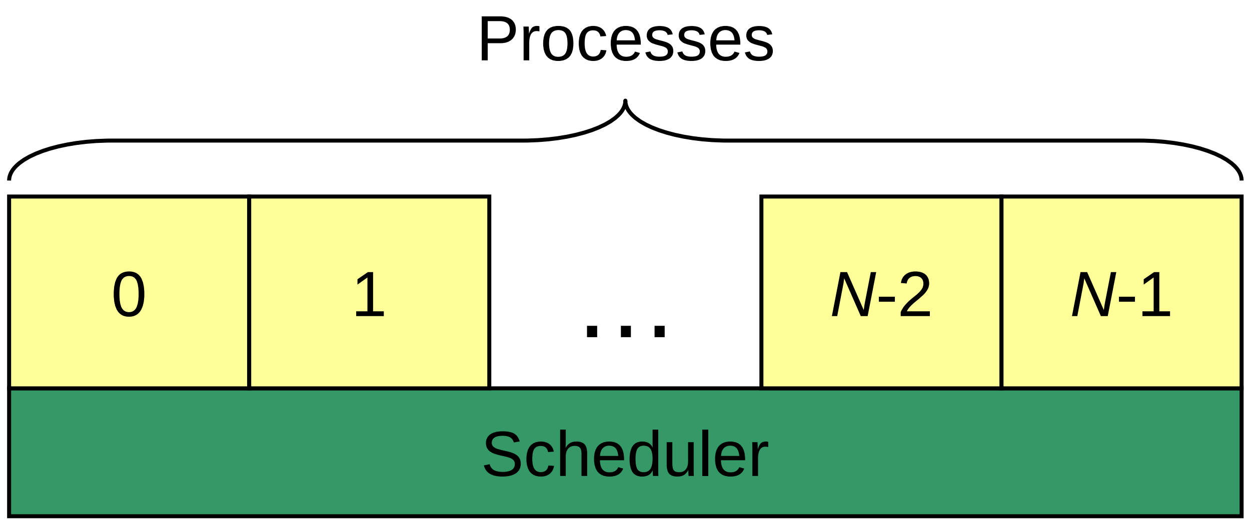
Process states



- Process in one of 5 states
  - Created
  - Ready
  - Running
  - Blocked
  - Exit
- Transitions between states
  1. Process enters ready queue
  2. Scheduler picks this process
  3. Scheduler picks a different process
  4. Process waits for event (such as I/O)
  5. Event occurs
  6. Process exits
  7. 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?

May be stored on stack: Registers, Program counter, CPU status word

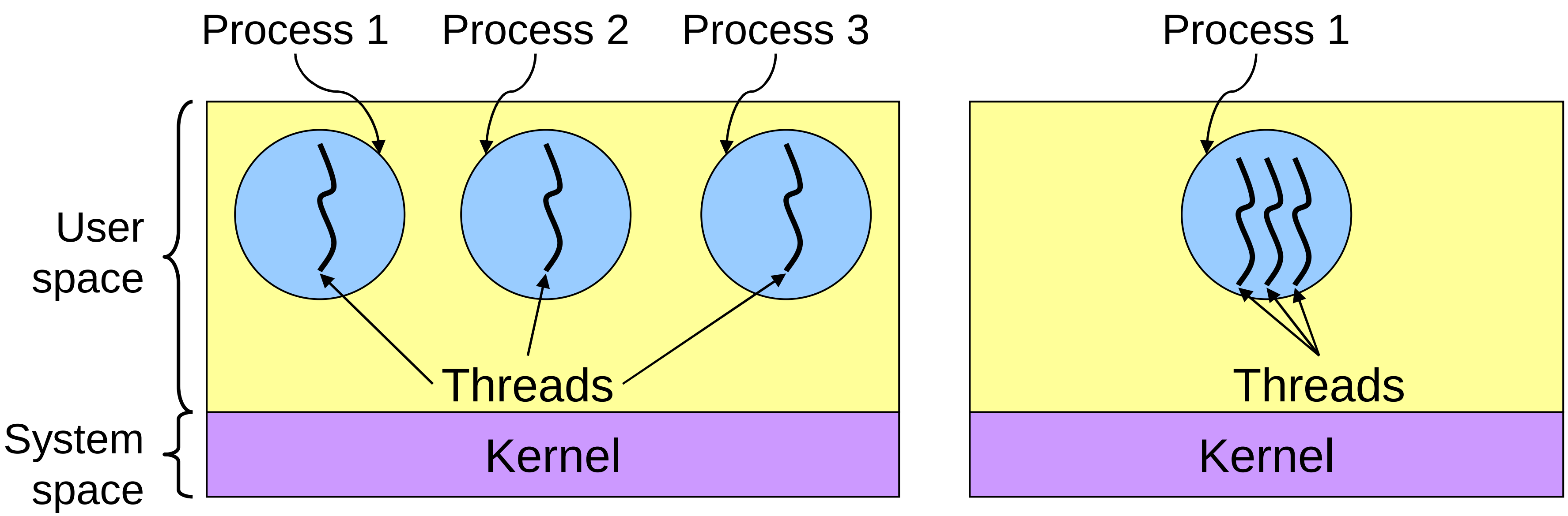
Process management	File management
Registers	Root directory
Program counter	Working (current) directory
CPU status word	File descriptors
Stack pointer	User ID
Process state	Group ID
Priority / scheduling parameters	
Process ID	**Memory management**
Parent process ID	Pointers to text, data, stack
Signals	*or*
Process start time	Pointer to page table
Total CPU usage	

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

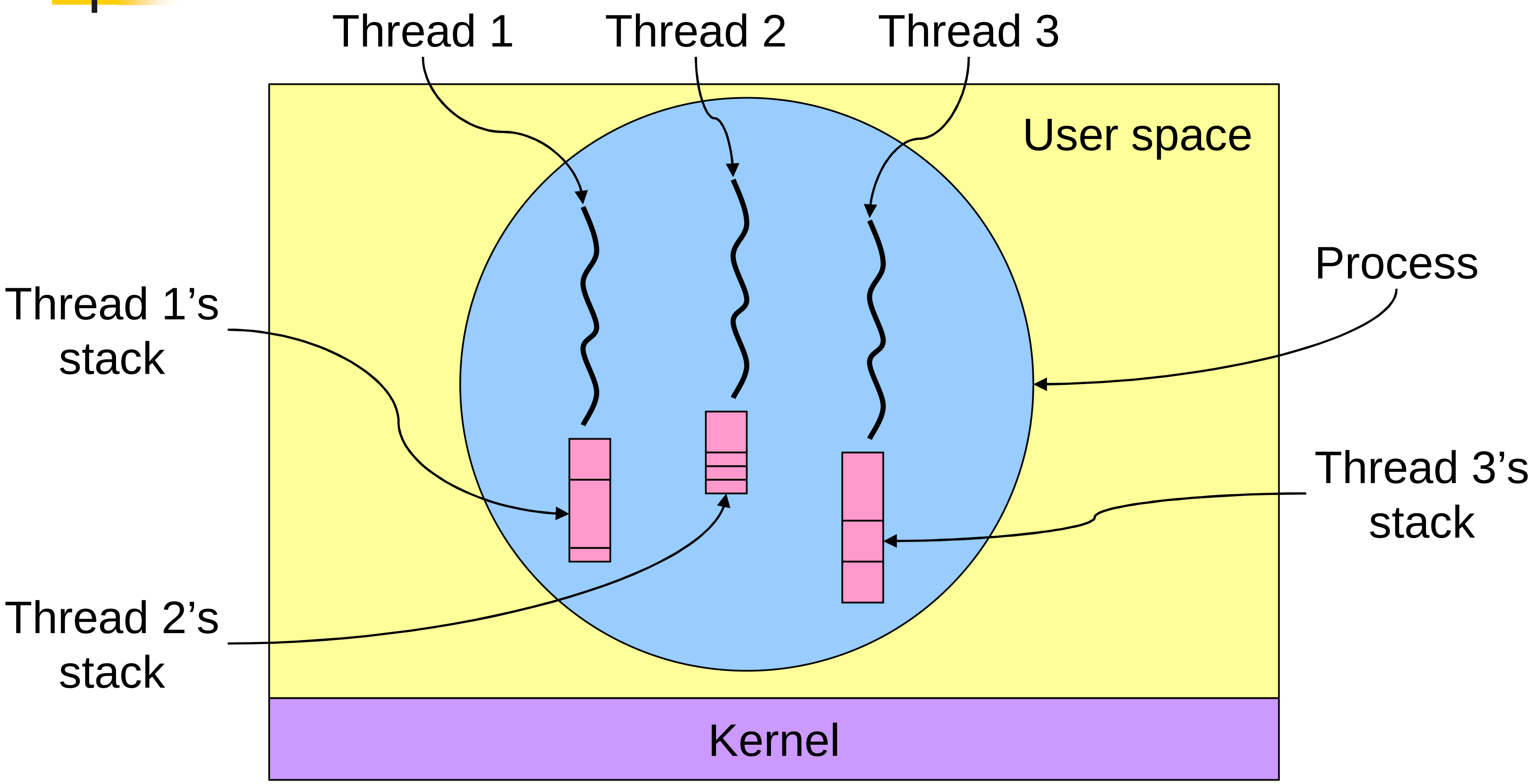


Process & thread information

Per process items
Address space
Open files
Child processes
Signals & handlers
Accounting info
Global variables

Per thread items	Per thread items	Per thread items
Program counter	Program counter	Program counter
Registers	Registers	Registers
Stack & stack pointer	Stack & stack pointer	Stack & stack pointer
State	State	State

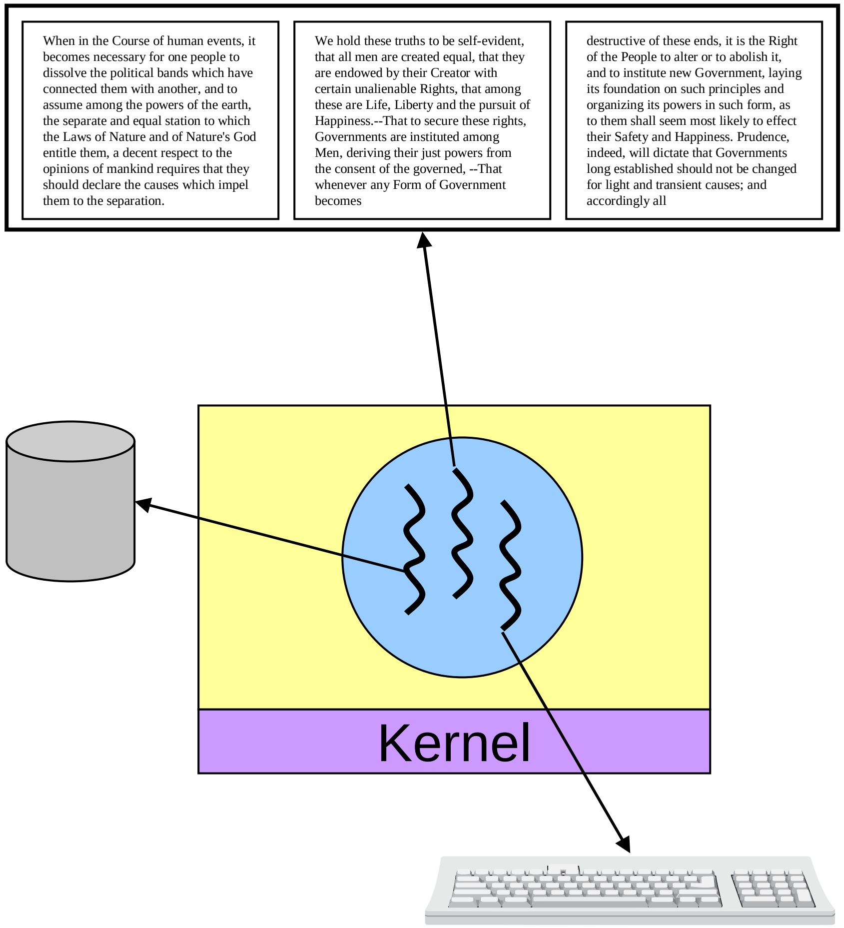
Threads & stacks



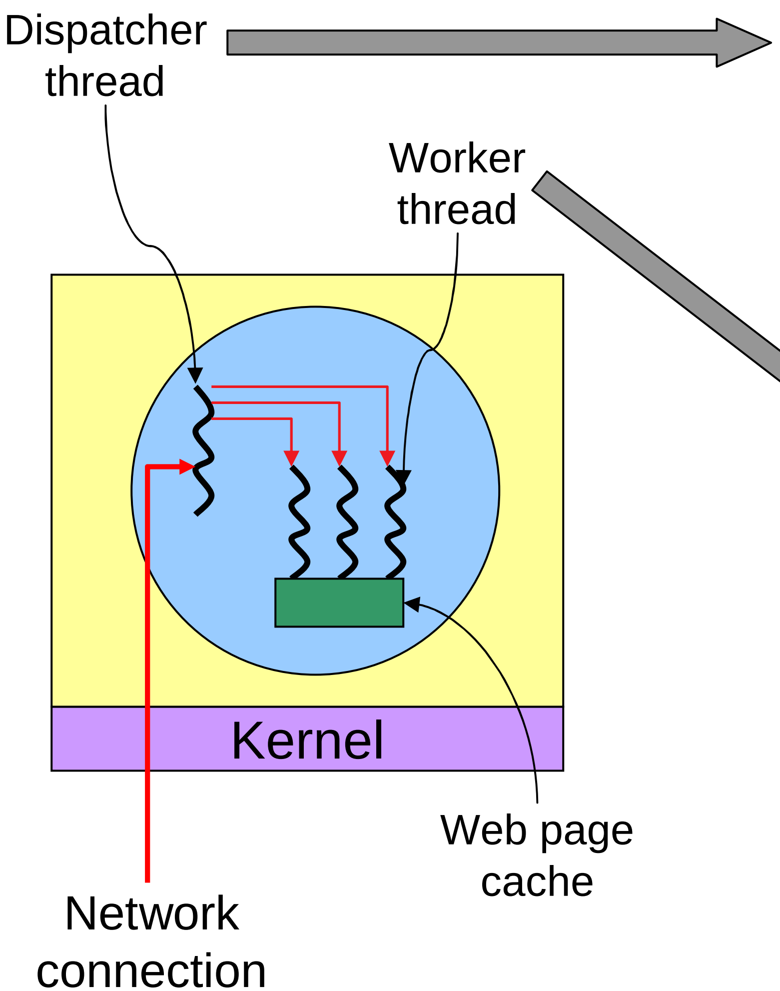
=> Each thread has its own stack!

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



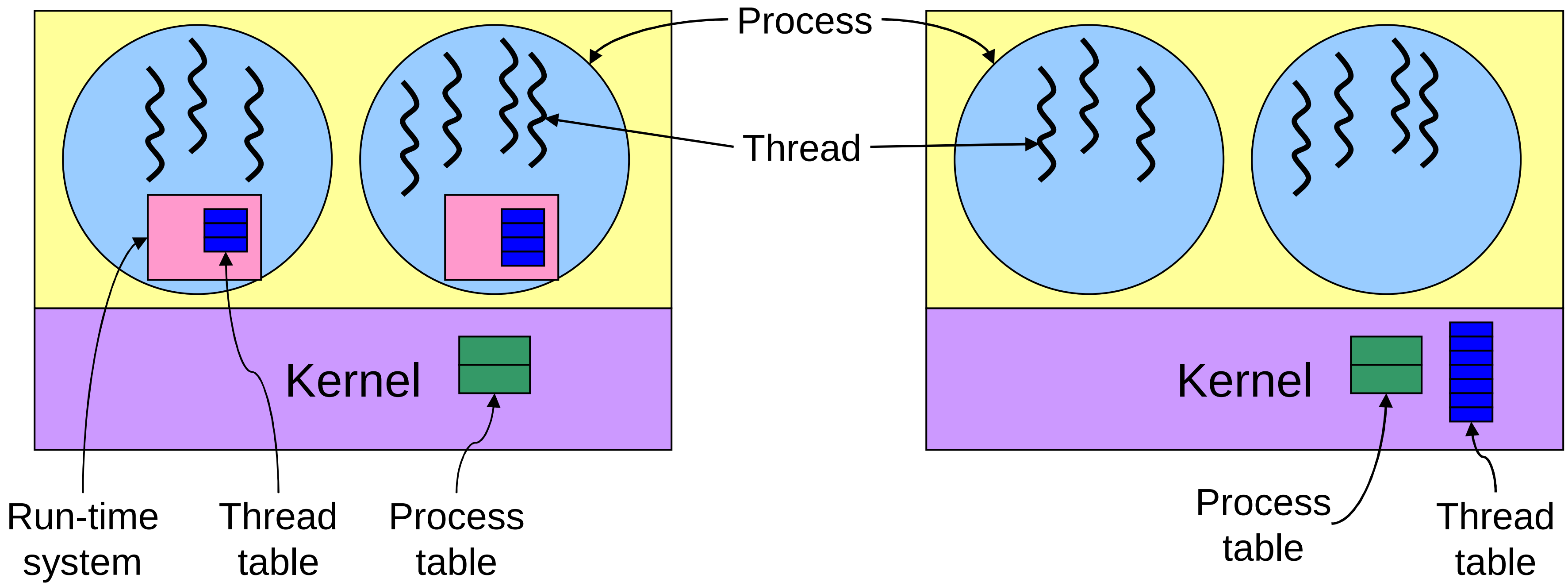

```
while(TRUE) {
  getNextRequest(&buf);
  handoffWork(&buf);
}
```

```
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
  - 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

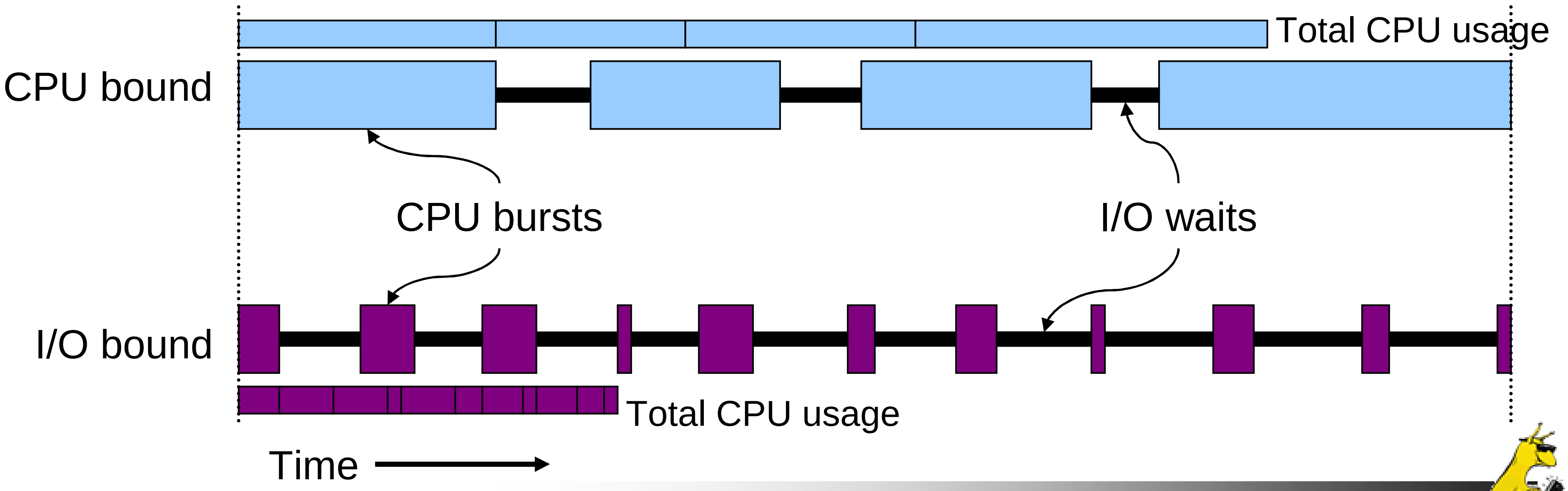
Kernel-level threads
+ More flexible scheduling
+ Non-blocking I/O
- Not portable

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

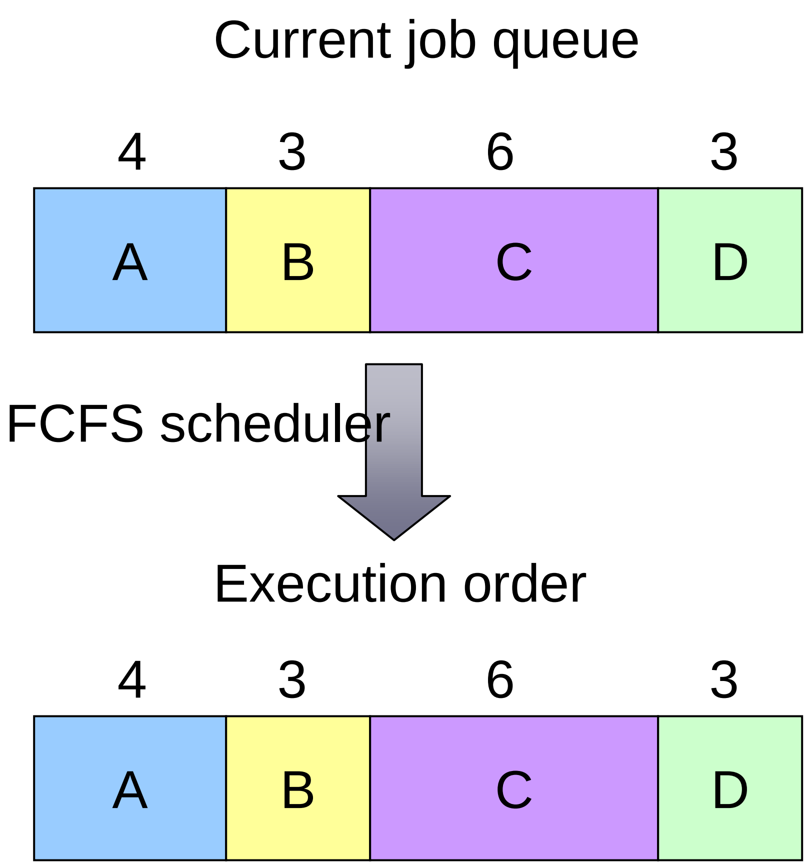
Scheduling goals

- 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

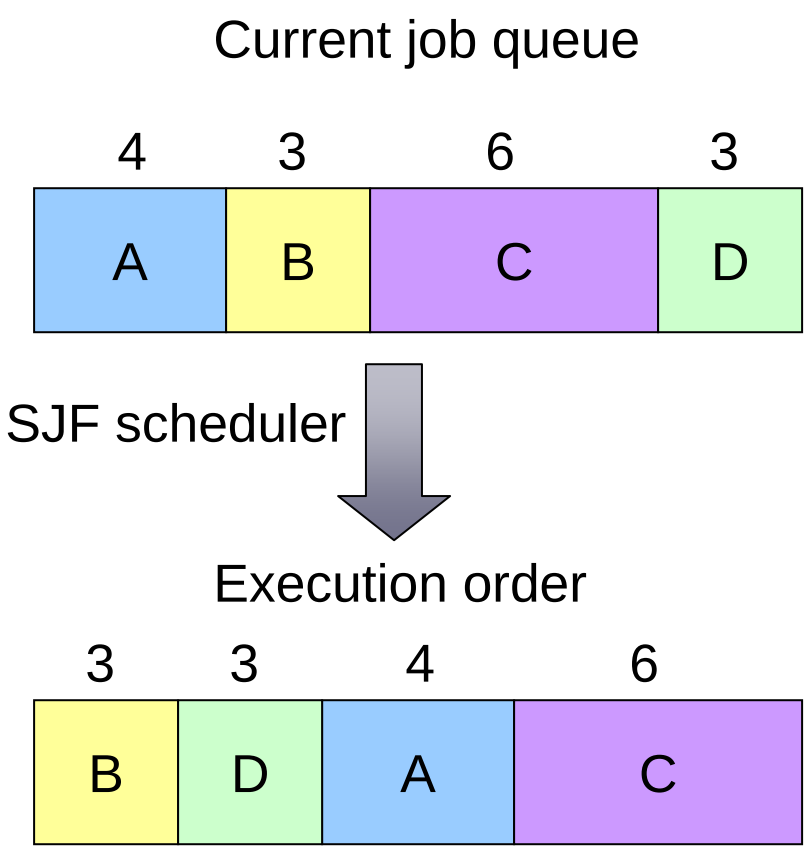
- Throughput
  - Amount of work completed per second (minute, hour)
  - Higher throughput usually means better utilized system
- Response time
  - Response time is time from when a command is submitted until results are returned
  - Can measure average, variance, minimum, maximum, …
  - May be more useful 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 the same scheduling algorithm

First Come, First Served (FCFS)



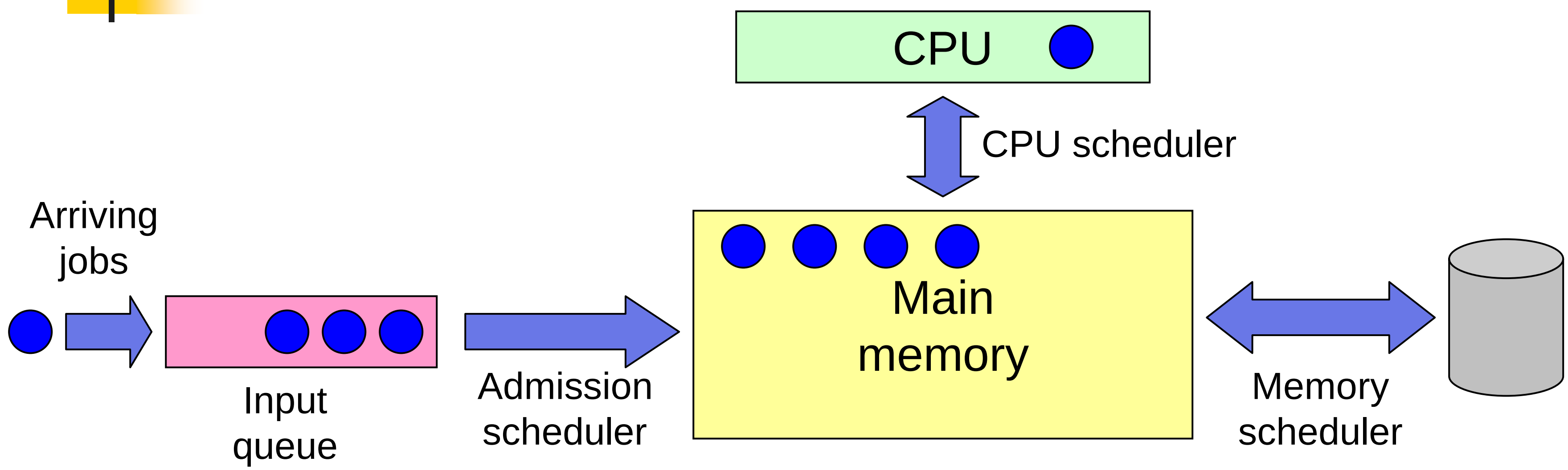
- Goal: do jobs in the order they arrive
  - Fair in the same way a bank teller line is fair
- Simple algorithm!
- Problem: long jobs delay every job after them
  - Many processes may wait for a single long job

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
- Problem: how does the scheduler know how long a job will take?

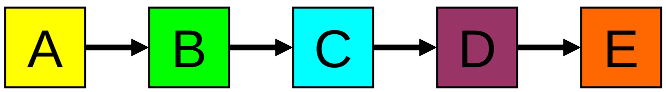
Three-level scheduling

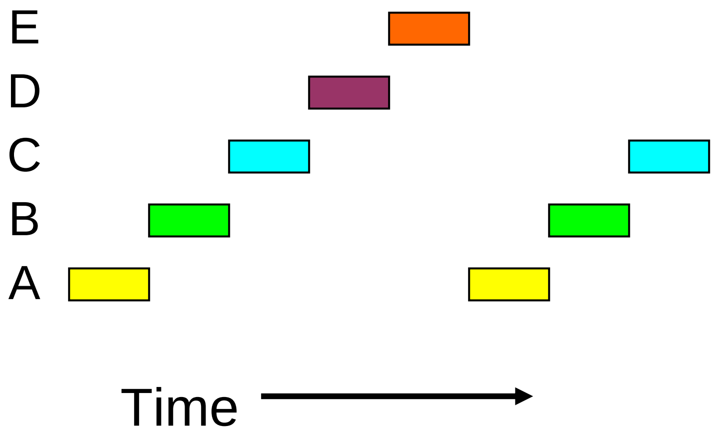


- Jobs held in input queue until moved into memory
  - Pick “complementary jobs”: small & large, CPU- & I/O-intensive
  - Jobs move into memory when admitted
- CPU scheduler picks next job to run
- Memory scheduler picks some jobs from main memory and moves them to disk if insufficient memory space

Round Robin (RR) scheduling

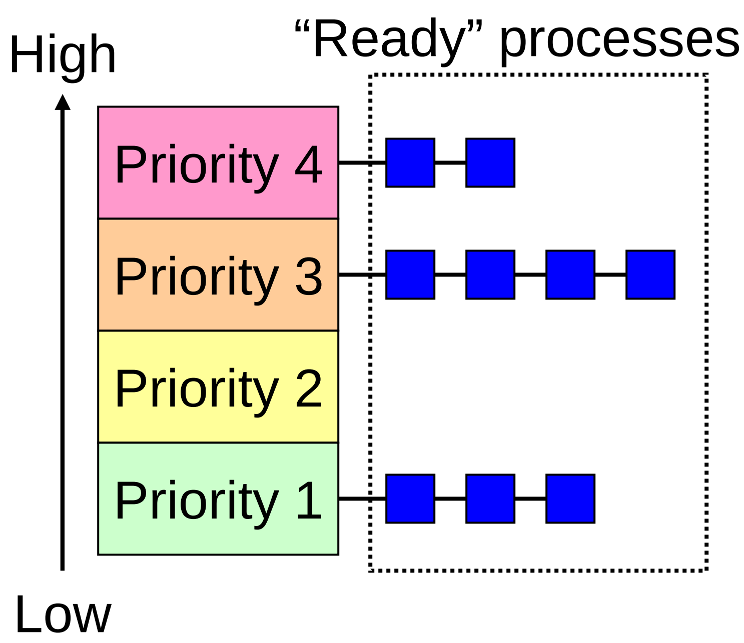
- Round Robin scheduling
  - Give each process a fixed time slot (*quantum*)
  - Rotate through “ready” processes
  - Each process makes some progress
- What’s a good quantum?
  - Too short: many process switches hurt efficiency
  - Too long: poor response to interactive requests
  - Typical length: 10–50 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!

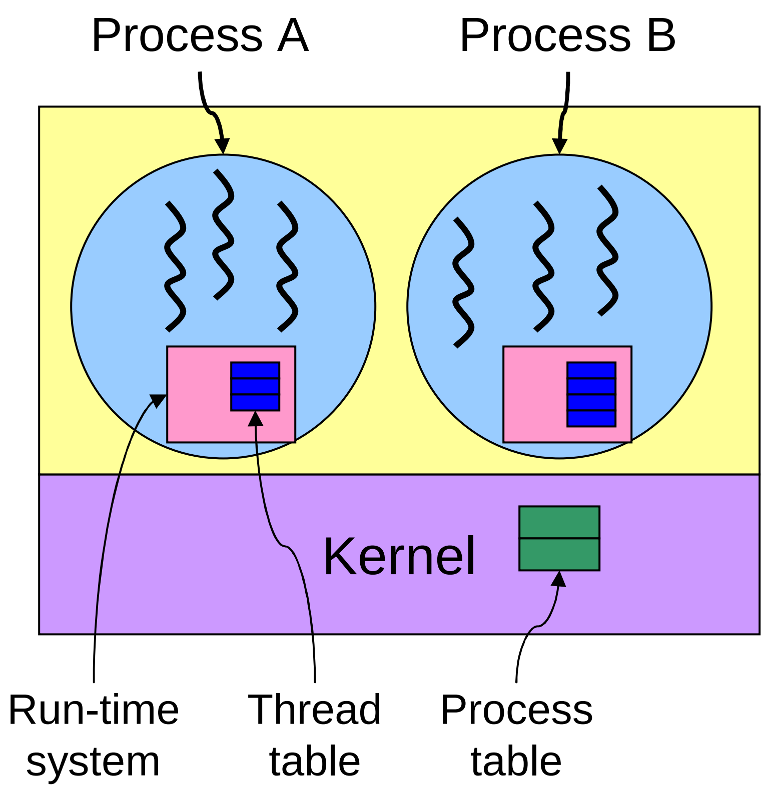
Lottery scheduling

- 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

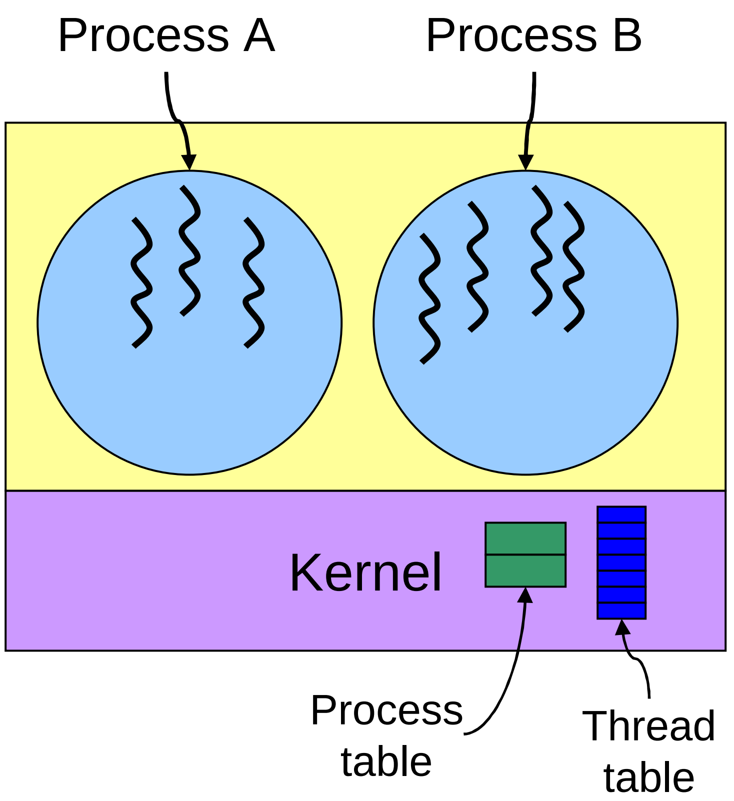
- Separate what ***may*** be done from ***how*** it is done
  - Mechanism allows
    - Priorities to be assigned to processes
    - CPU to select processes with high priorities
  - Policy set by what priorities are assigned to processes
- Scheduling algorithm parameterized
  - Mechanism in the kernel
  - 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 user-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

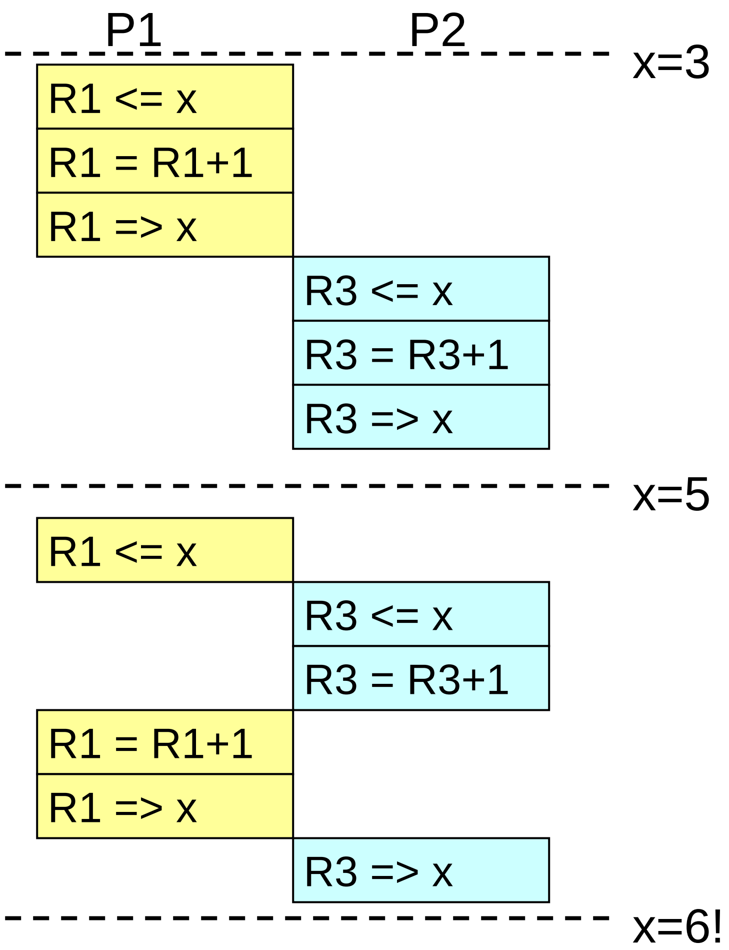
```
Item pitm;
while (1) {
  …
  produce an item into pitm
  …
  while (counter == n)
    ;
  buffer[in] = pitm;
  in = (in+1) % n;
  counter += 1;
}
```

Consumer

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

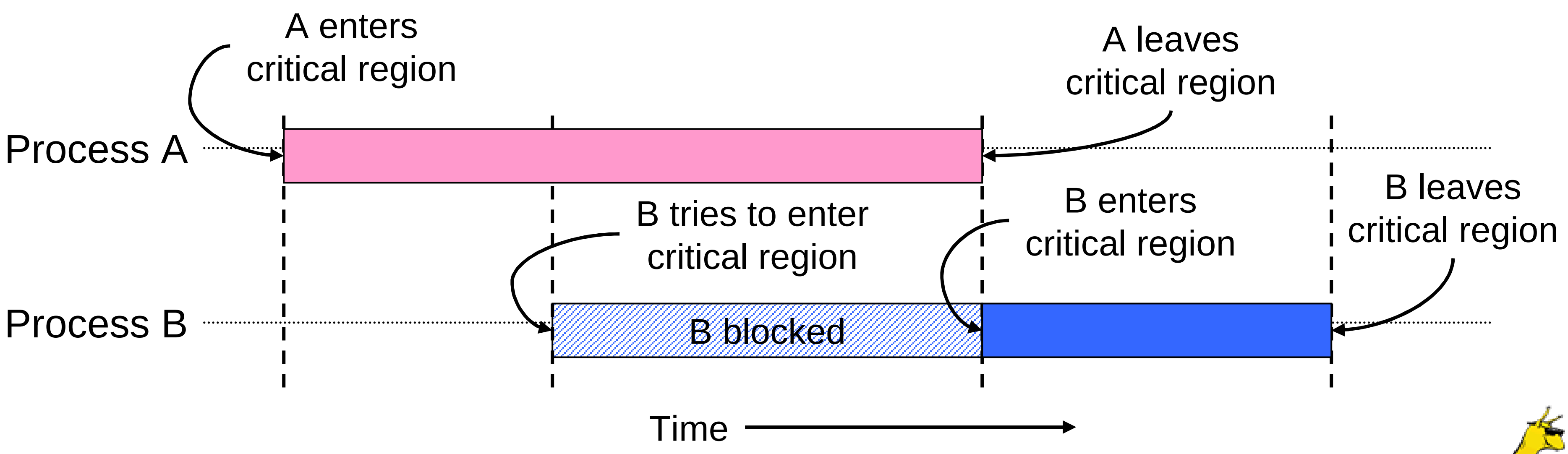
Problem: race conditions

- 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 numbers of CPUs
  - No process running outside its critical region may block another process
  - No process must 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(a0,a1,…,an-1) is a number k such that k>=ai 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 has a better number
    // than we do.  In case of a tie, allow j to go if
    // its process ID is lower than ours
    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
- 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

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

- 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

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;
};
```

```
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;
  }
}
```

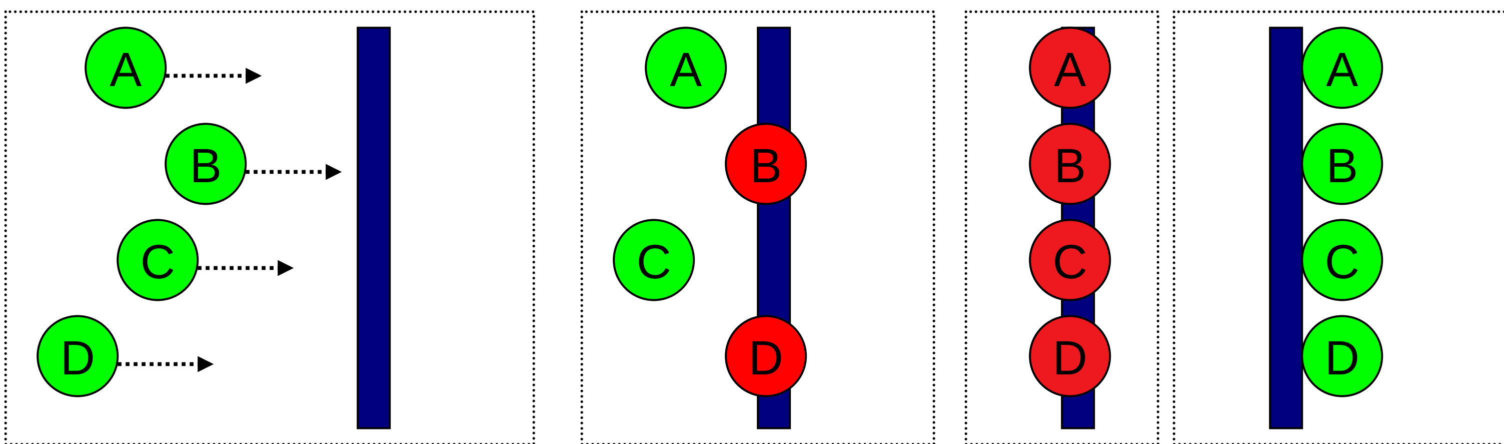
- Are these Hoare or Mesa semantics?
- Can there be multiple condition variables for a single Lock?

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



Processes approaching barrier | B and D at barrier | All at barrier | Barrier releases all processes

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

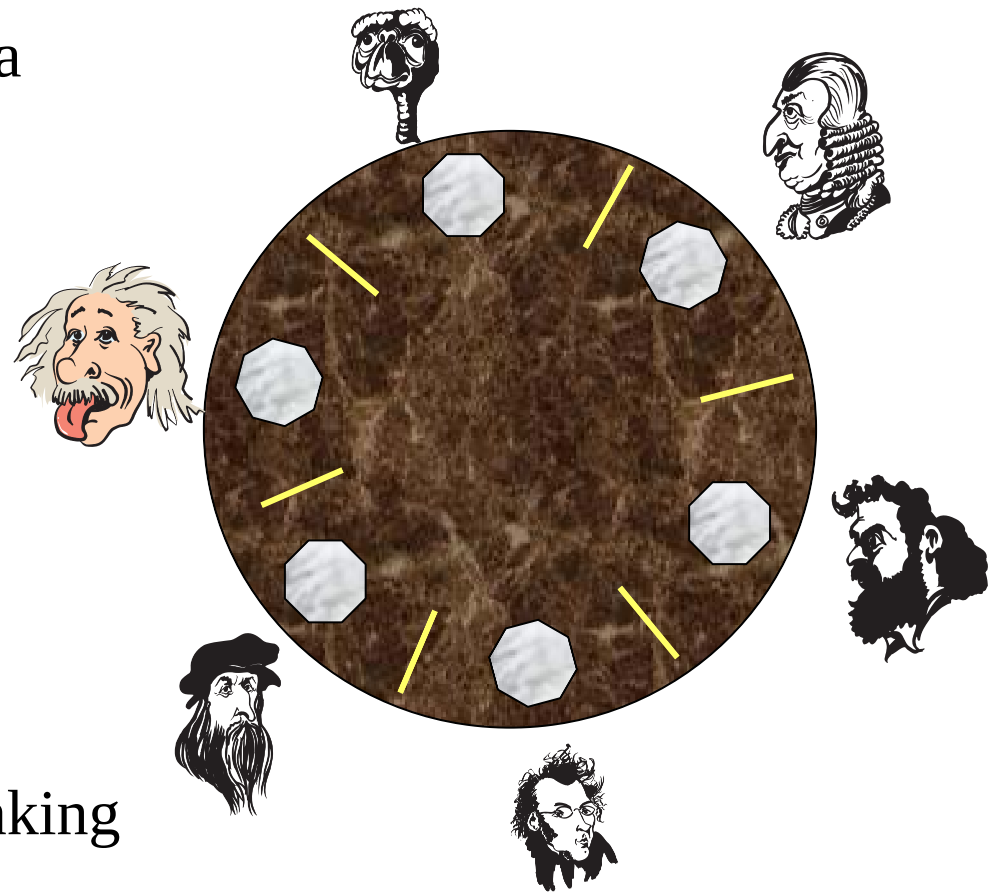
```
…
mutex.down();
nreaders += 1;
if (nreaders == 1) // wait if
  writing.down();  // 1st reader
mutex.up();
// Read some stuff
mutex.down();
nreaders -= 1;
if (nreaders == 0)   // signal if
  writing.up();      // last reader
mutex.up();
…
```

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

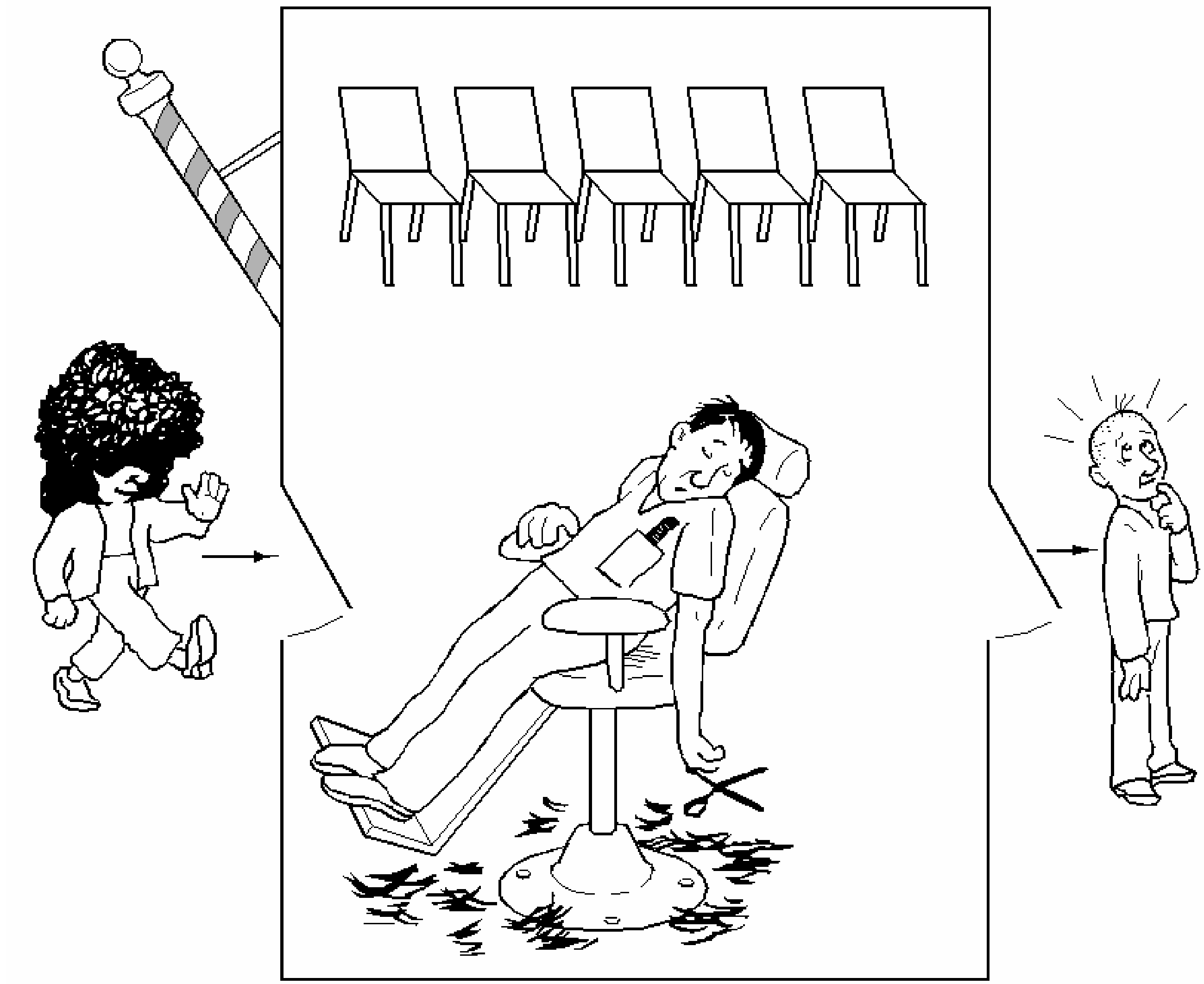
```
const int n;
// initialize to THINK
int state[n];
Lock mutex;
// use mutex for self
Condition self[n];
```

```
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



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 ();
 }
}
```