Chapter 2: Processes & Threads

Part 2

Interprocess Communication (IPC) &
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
  …
}
```

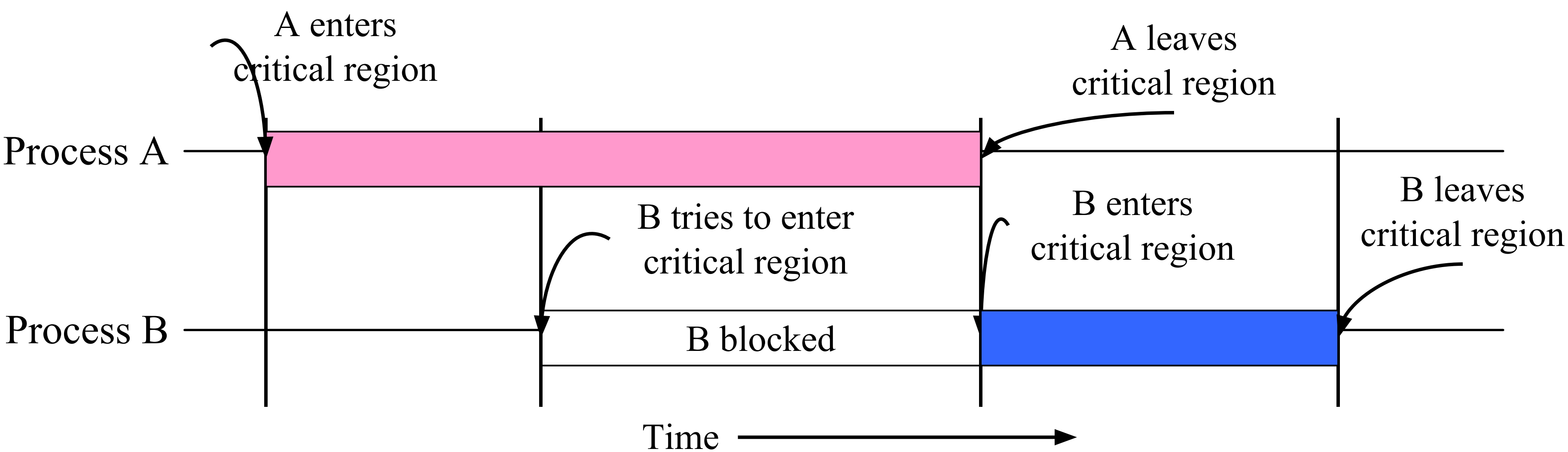
Problem: race conditions

- 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…

P1	P2	
		x=3
R1 <= x		
R1 = R1+1		
R1 => x		
	R3 <= x	
	R3 = R3+1	
	R3 => x	
		x=5
R1 <= x		
	R3 <= x	
	R3 = R3+1	
R1 = R1+1		
R1 => x		
	R3 => x	
		x=6!

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;
  }
}
```

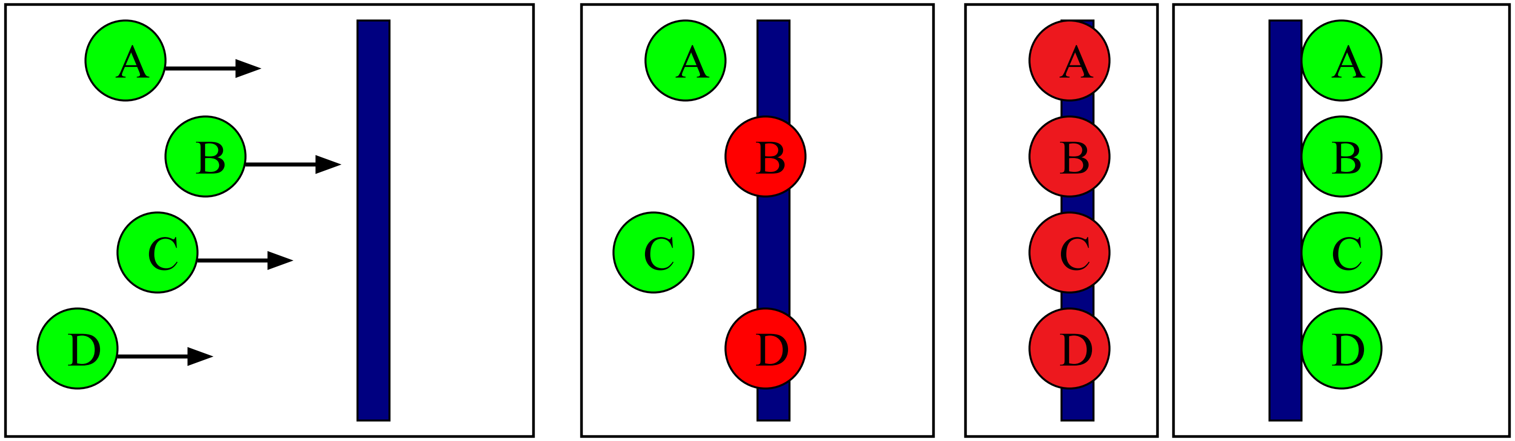
- Are these Hoare or Mesa semantics?
- Can there be multiple condition variables for a single Lock?

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

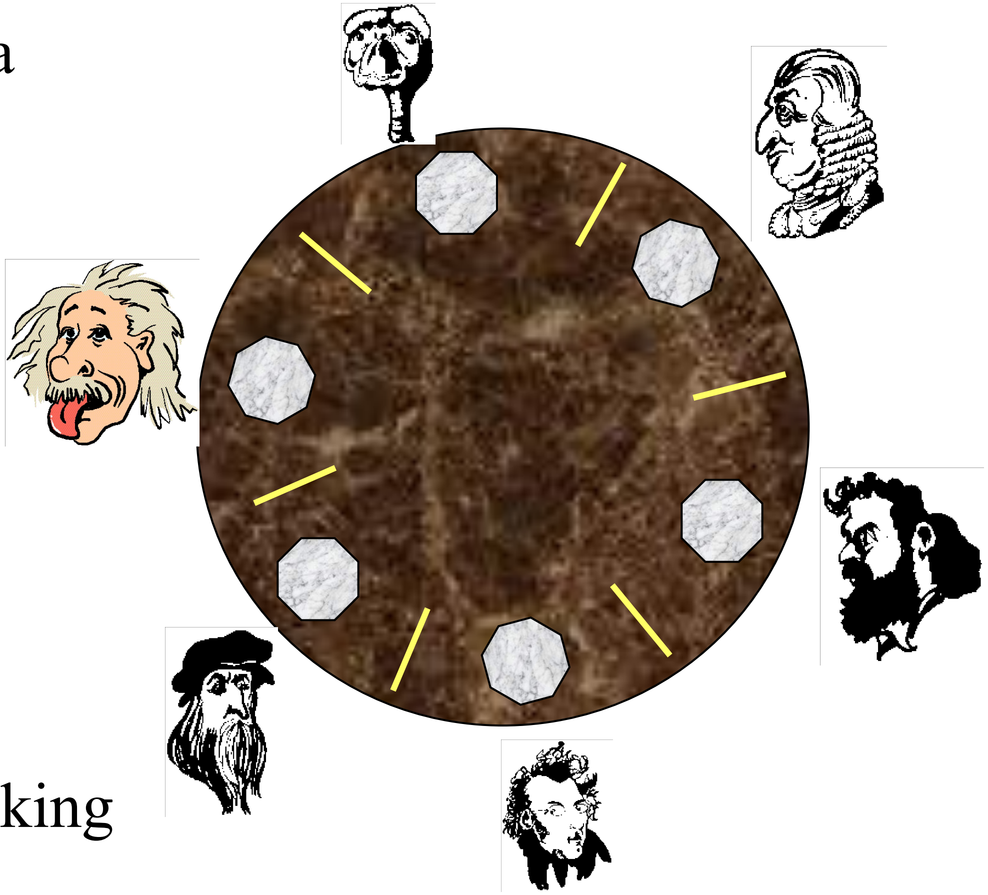
```
…
mutex.down();
nreaders += 1;
if (nreaders == 1) // wait if
  writing.down();  // 1st reader
mutex.up();
// Read some stuff
mutex.down();
nreaders -= 1;
if (nreaders == 0)     // signal if
  writing.up();    // last reader
mutex.up();
…
```

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 ();
 }
}
```