Operating Systems

5. Synchronization

Synchronization

- Many processes/threads interact (shared memory / message passing)
  - Results of interactions not guaranteed to be deterministic
  - Concurrent writes to the same address
  - Result depends on the order of operations
- OS manage
  - Large number of resources
  - Common data structures
- Need to provide good coordination mechanisms
  - Access to the data structures
  - Ensure consistency
- Objective
  - Identify general synchronization problems
  - Provide OS support for synchronization

Example: Too Much Milk

Alice	Bob
3:00 Look in fridge - no milk	
3:05 Leave for shop	Look in fridge - no milk
3:10 Arrive at shop	Leave for shop
3:15 Leave shop	Arrive at shop
3:20 Back home - put milk in fridge	Leave shop
3:25	Back home - put milk in fridge
	Oooops!

Problem: Need to ensure that only one process is doing something at a time (e.g., getting milk)

Example: Money Flies Away …

BALANCE: 2000 €

Bank thread A	Bank thread B
Read a := BALANCE	Read b:= BALANCE
a := a + 500	b := b – 200
Write BALANCE := a	Write BALANCE := b

Oooops!! BALANCE: 1800 €!!!!

Problem: need to ensure that each process is executing its critical section (e.g updating BALANCE) exclusively (one at a time)

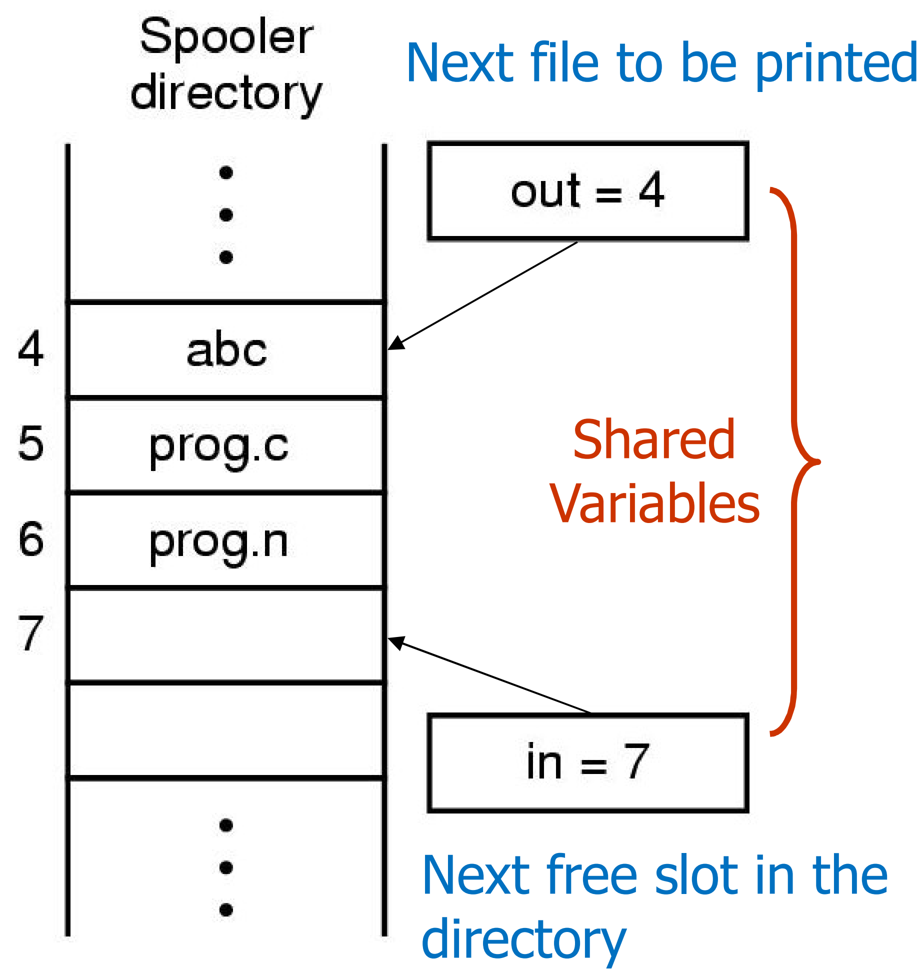
Example: Print Spooler

- If a process wishes to print a file
  - It adds its name in a Spooler Directory

- The printer process
  - Periodically checks the spooler directory
  - Prints a file
  - Removes its name from the directory

Example: Print Spooler

- If any process wants to print a file it will execute the following code
  1. Read the value of `in` in a local variable `next_free_slot`
  2. Store the name of its file in the `next_free_slot`
  3. Increment `next_free_slot`
  4. Store back in `in`



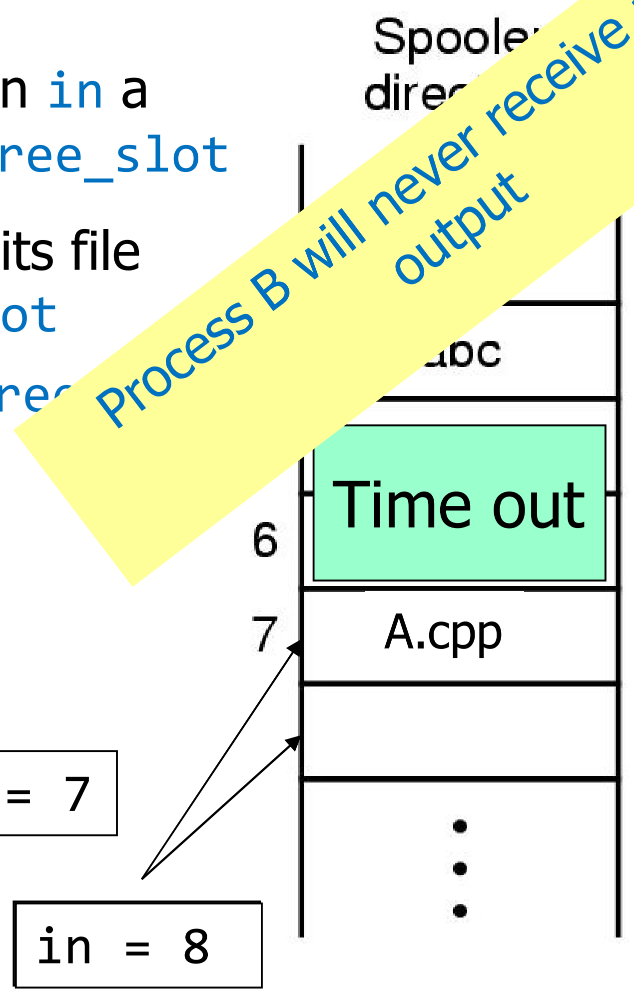
Example: Print Spooler

Let A and B be processes who want… print their files

Process B will never receive any output

Process A

1. Read the value of in `in` a local variable `next_free_slot`
2. Store the name of its file in the `next_free_slot`
3. Increment `next_free`…
4. Store back in `in`



Process B

1. …ad the value of in `in` a …cal variable `next_free_slot`
2. Store the name of its file in the `next_free_slot`
3. Increment `next_free_slot`
4. Store back in `in`

`next_free_slot`$_a$ `= 7`

`next_free_slot`$_b$ `= 7`

Example: Producer/Consumer Problem

- An integer count that keeps track of the number of full buffers
- Initially, count is set to 0
  - Count is incremented by the producer after it produces a new buffer
  - Count is decremented by the consumer after it consumes a buffer

Producer

```
while (true) {
  /*  produce an item and put in nextProduced  */
  while (counter == BUFFER_SIZE)
    ; // do nothing
  buffer [in] = nextProduced;
  in = (in + 1) % BUFFER_SIZE;
  counter++;
}
```

Example: Producer/Consumer Problem

- An integer count that keeps track of the number of full buffers
- Initially, count is set to 0
  - Count is incremented by the producer after it produces a new buffer
  - Count is decremented by the consumer after it consumes a buffer

Consumer:

```
while (true)  {
  while (counter == 0)
    ; // do nothing
  nextConsumed =  buffer[out];
  out = (out + 1) % BUFFER_SIZE;
  counter--;
  /*  consume the item in nextConsumed */
}
```

Producer/Consumer Problem – Race Condition

- `counter++` could be implemented as
  - `register1 = counter`
  - `register1 = register1 + 1`
  - `counter = register1`
- `counter--` could be implemented as
  - `register2 = counter`
  - `register2 = register2 - 1`
  - `count = register2`
- Consider this execution interleaving with “`count = 5`” initially:
  - S0: producer execute `register1 = counter {register1 = 5}`
  - S1: producer execute `register1 = register1 + 1 {register1 = 6}`
  - S2: consumer execute `register2 = counter {register2 = 5}`
  - S3: consumer execute `register2 = register2 - 1 {register2 = 4}`
  - S4: producer execute `counter = register1 {count = 6 }`
  - S5: consumer execute `counter = register2 {count = 4}`

Race Condition

- Race condition
  - Several processes access and manipulate the same data concurrently
  - Outcome of the execution depends on the particular order in which the access takes place
    - ➢ Debugging is not easy → Most test runs will run fine

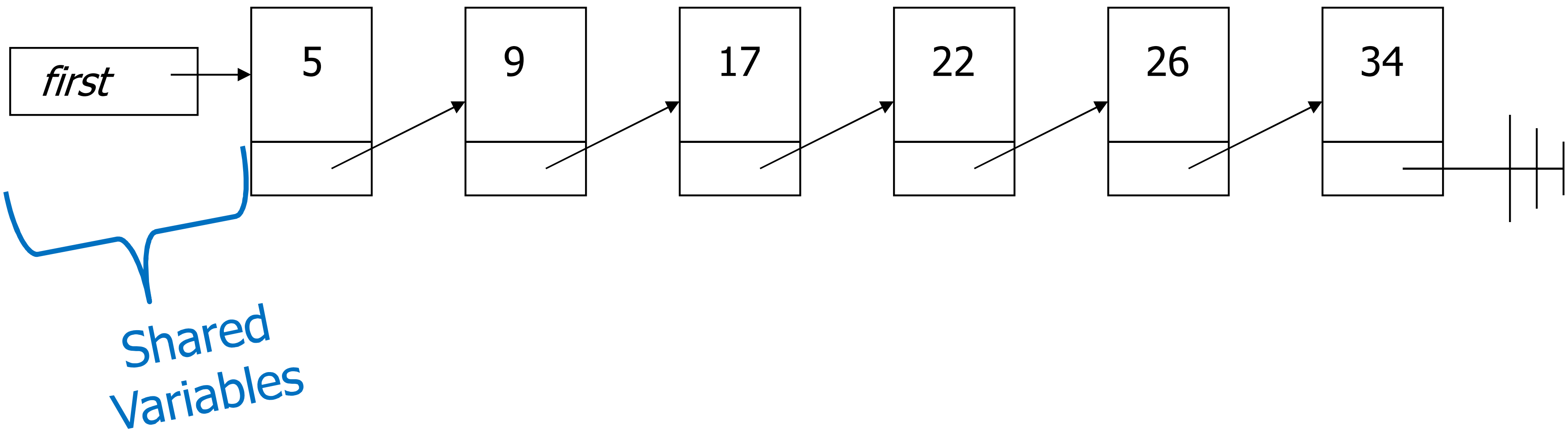
- At any given time a process is either
  - Doing internal computation → no race conditions
  - Or accessing shared data that can lead to race conditions

- Part of the program where the shared memory is accessed is called Critical Region

- Races condition can be avoided
  - If no two processes are in the critical region at the same time

Examples of Race Condition

- Adding node to a shared linked list



Critical-Section (CS) Problem

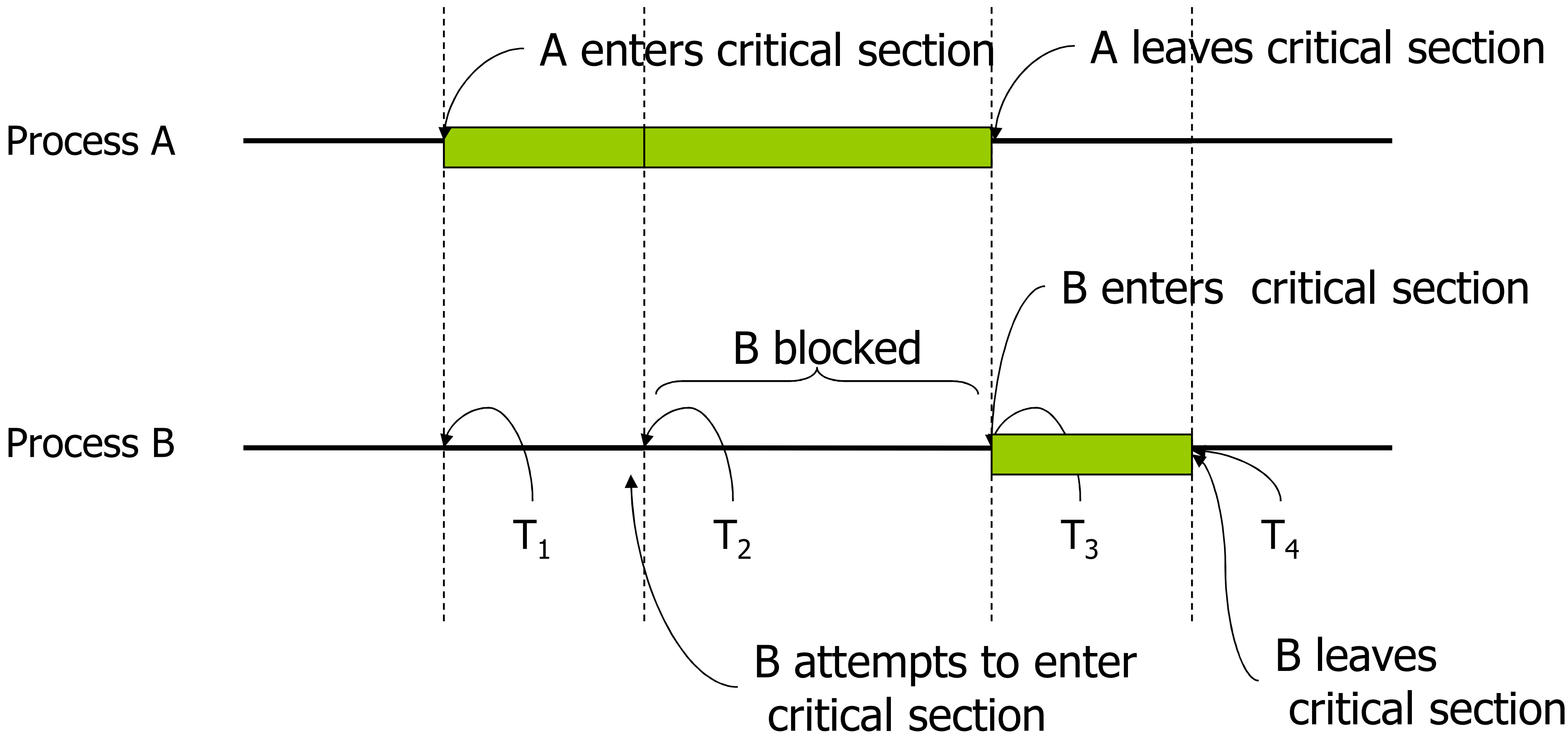
- n processes all competing to use some shared data / resource
- Each process has a code segment, called critical section, in which the shared data is accessed
- Problem: ensure that
  - Never two process are allowed to execute in their critical section at the same time
  - Access to the critical section must be an atomic action
- Structure of process P_i:

```
repeat
   entry section
      critical section
   exit section
      remainder section
until false;
```

Critical-Section (CS) – Example

```
void threadRoutine()
{
    int y, x, z;
    y = 3 + 5x;
    y = Global_Var;
    y = y + 1;
    Global_Var = y;
    …
    …
}
```

Critical-Section (CS)



Mutual Exclusion

At any given time, only one process is in the critical section

Requirements: Critical-Section (CS) Problem

Informally, the following are the requirements of CS problem

- No two processes may be simultaneously inside their critical sections
- No assumptions may be made about the speed or the number of processors
- No process running outside its critical section may block other processes
- No process should have to wait forever to enter its critical section

Requirements: Critical-Section Problem

- Mutual exclusion
  - Only one process at a time is allowed to execute in its critical section
- Progress
  - Processes cannot be prevented forever from entering CS

- Progress: Distinguish between
  - Fairness (no starvation): Every process makes progress
    - **Bounded waiting**
  - Deadlock freedom: At least one process can make progress
    - Process running outside the critical section should not have influence

- Assumptions
  - No process stays forever in CS
  - No assumption on the number of processors
  - No assumption on actual speed of processes

Requirements: Critical-Section Problem

1. Mutual exclusion

2. Progress

3. Bounded waiting
   – Before request by a process to enter its critical section is granted
   – A bound must exist on the number of times that other processes are allowed to enter their critical sections

Software Solution – Lock Variables

- Before entering a critical section a process should know if any other is already in the critical section or not
- Consider having a `FLAG` (also called lock)
  - `FLAG = FALSE`
    - ➢ A process is in the critical section
  - `FLAG = TRUE`
    - ➢ No process is in the critical section

```
// wait while someone else is in the
// critical region
1. while (FLAG == FALSE);
// stop others from entering critical region
2. FLAG = FALSE;
3. critical_section();
// after critical section let others enter
//the critical region
4. FLAG = TRUE;
5. noncritical_section();
```

Lock Variables

Process 1

```
1.while (FLAG == FALSE);
2.FLAG = FALSE;

3.critical_section();
4.FLAG = TRUE;
5.noncritical_section();
```

Process 2

```
1.while (FLAG == FALSE);
1.while (FLAG == FALSE);
2.FLAG = FALSE;
3.critical_section();
```

FLAG = FALSE

Timeout

No two processes may be simultaneously inside their critical sections

Process 2 's Program counter is at Line 2

Process 1 forgot that it was Process 2 turn

Lock Variables

```
// wait while someone else is in the
// critical region
1. while (FLAG == FALSE);
// stop others from entering critical region
2. FLAG = FALSE;
3. critical_section();
// after critical section let others enter
//the critical region
4. FLAG = TRUE;
5. noncritical_section();
```

- Algorithm does not satisfy critical section requirements
  - Progress is ok, but does NOT satisfy mutual exclusion

Software Solution – Strict Alternation

- We need to remember "Who's turn it is?"
- If its Process 1's turn then Process 2 should wait
- If its Process 2's turn then Process 1 should wait

Process 1

```
while(TRUE)
{
  // wait for turn
  while (turn != 1);
  critical_section();
  turn = 2;
  noncritical_section();
}
```

Process 2

```
while(TRUE)
{
  // wait for turn
  while (turn != 2);
  critical_section();
  turn = 1;
  noncritical_section();
}
```

Strict Alternation

Process 1

```
While(1)
1.while (Turn != 1);

2.critical_section();

3.Turn = 2;
4.noncritical_section();
```

Process 2

```
While(1)
1.while (Turn != 2);
1.while (Turn != 2);

2.critical_section();

3.Turn = 1;
4.noncritical_section();
```

Turn = 1

Timeout

Only one Process is in the Critical Section at a time

Process 2 's Program counter is at Line 2

Process 1 Busy Waits

Strict Alternation

Process 1

```
while(TRUE)
{
  // wait for turn
  while (turn != 1);
  critical_section();
  turn = 2;
  noncritical_section();
}
```

Process 2

```
while(TRUE)
{
  // wait for turn
  while (turn != 2);
  critical_section();
  turn = 1;
  noncritical_section();
}
```

- What is the problem with strict alteration?
  - Satisfies mutual exclusion, but not progress

Strict Alternation

Turn = 1

Process 1
```
while(TRUE)
{
  // wait for turn
  while (turn != 1);
  critical_section();
  turn = 2;
  noncritical_section();
}
```

Process 2
```
while(TRUE)
{
  // wait for turn
  while (turn != 2);
  critical_section();
  turn = 1;
  noncritical_section();
}
```

- Process 1
  - Runs, Enters its critical section, Exits critical section, Sets turn to 2
- Process 1 is now in its non-critical section
  - Assume this non-critical procedure takes a long time
- Process 2, which is a much faster process, now runs
  - Once it has left its critical section, sets turn to 1
- Process 2 executes its non-critical section very quickly and returns to the top of the procedure

Strict Alternation

Turn = 1

Process 1

```
while(TRUE)
{
  // wait for turn
  while (turn != 1);
  critical_section();
  turn = 2;
  noncritical_section();
}
```

Process 2

```
while(TRUE)
{
  // wait for turn
  while (turn != 2);
  critical_section();
  turn = 1;
  noncritical_section();
}
```

- Process 1 is in its non-critical section
- Process 2 is waiting for turn to be set to 2
  - There is no reason why process 2 cannot enter its critical region as process 1 is not in its critical region

Strict Alternation

Process 1

```
while(TRUE)
{
  // wait for turn
  while (turn != 1);
  critical_section();
  turn = 2;
  noncritical_section();
}
```

Process 2

```
while(TRUE)
{
  // wait for turn
  while (turn != 2);
  critical_section();
  turn = 1;
  noncritical_section();
}
```

Problem with strict alteration

- Violation: No process running outside its critical section may block other processes
- This algorithm requires that the processes strictly alternate in entering the critical section
- Taking turns is not a good idea if one of the processes is slower

Yet Another Solution

- Strick alternation
  - Although it was Process 1's turn
  - But Process 1 was not interested
- Solution: Remember whether a process is interested in CS or not
  - Replace `int turn` with `bool interested[2]`
  - For example `interested[0] = FALSE` → Process 0 is not interested

Process 0

```
while(TRUE)
{
  interested[0] = TRUE;
  // wait for turn
  while(interested[1]!=FALSE);
  critical_section();
  interested[0] = FALSE;
  noncritical_section();
}
```

Process 1

```
while(TRUE)
{
  interested[1] = TRUE;
  // wait for turn
  while(interested[0]!=FALSE);
  critical_section();
  interested[1] = FALSE;
  noncritical_section();
}
```

Yet Another Solution

Process 0

```
while(TRUE)
{
  interested[0] = TRUE;


   while(interested[1]!=FALSE);
```

Process 1

```
while(TRUE)
{
  interested[1] = TRUE;


e(interested[0]!=FALSE);
```

Timeout

DEADLOCK

Peterson's Algorithm

- Combine previous two algorithms
  - `int turn` with `bool interested`

Process P_i

```
while(TRUE)
{
  interested[i] = TRUE;
  turn = j;
  // wait
  while(interested[j]==TRUE && turn == j );
  critical_section();
  interested[i] = FALSE;
  noncritical_section();
}
```

Peterson’s Algorithm

Process 0

```
while(TRUE)
{
  interested[0] = TRUE;
  turn = 1;
  // wait
  while(intere F        &&        T == 1 );
 critical_section();
 interested[0] = FALSE;
  noncritical_section();
}
```

Timeout

Process 1

```
while(TRUE)
{
  interested[1] = TRUE;
  turn = 0;
  // wait
  while(interest F        &&        T  0 );

  critical_section();
  interested[1] = FALSE;
  noncritical_section();
}
```

Peterson’s Algorithm

Process 0

```
while(TRUE)
{
   interested[0] = TRUE;
   turn = 1;

   // wait
   while(interes T      &&    F == 1 );

   critical_section();
   interested[0] = FALSE;
   noncritical_section();
}
```

Process 1

```
while(TRUE)
{
   interested[1] = TRUE;
   turn = 0;
   // wait
   while(intere F      &&    T == 0 );

   critical_section();
   interested[1] = FALSE;
   noncritical_section();
}
```

Timeout

Can not be TRUE at the same time.
Thus used to break tie

Lamport's Bakery Algorithm (For n processes)

Idea

- Before entering its critical section, each process receives a number
- Holder of the smallest number enters the critical section
  - Fairness
  - No deadlock
- If processes P_i and P_j receive the same number
  - **if** $i < j$, then P_i is served first
  - **else** P_j is served first
- While processes are trying to enter CS
  - The numbering scheme generates numbers in increasing order of enumeration; i.e., 1,2,3,3,3,3,4,5

Lamport's Bakery Algorithm

- Peterson's algorithm solves the critical-section problem for two processes
  - For multiple processes, bakery algorithm is used

```
Shared var choosing: array [0..n – 1] of boolean (init false);
           number: array [0..n – 1] of integer (init 0),
Process Pi
repeat
  choosing[i] := true;
  number[i] := max(number[0],number[1], …,number [n – 1])+1;
  choosing[i] := false;
  for j := 0 to n – 1 do begin
    while choosing[j] do no-op;
    while number[j] ≠ 0 and (number[j],j) < (number[i], i) do
        no-op;
  end;
  critical section
  number[i] := 0;
  remainder section
until false;
```

CS Problem: Software-based Solutions

- Peterson and Bakery algorithms solve critical section problem
- These algorithms are not used in practice
  - Mutual exclusion depends on the order of steps in the software based algorithms
  - However, modern Compilers often reorder instructions to enhance performance

Mutual Exclusion: Hardware Support

- Interrupt Disabling
  - A process runs until it invokes an operating-system service or until it is interrupted
  - Disabling interrupts guarantees mutual exclusion

```
while(true){
   /* disable interrupts */
      critical section
   /* enable interrupts */
      remainder section
}
```

- Disadvantage
  - Processor is limited in its ability to interleave programs
  - Multiprocessors: Disable interrupts on one processor will not guarantee mutual exclusion
  - User programs cannot directly disabled interrupts

Mutual Exclusion: Other Hardware Support

- Special Machine Instructions
  - Performed in a single instruction cycle: Reading and writing in one atomic step

- Not subject to interference from other instructions
  - Uniprocessor system: Executed without interrupt
  - Multiprocessor system: Executed with locked system bus

Test and Set (TSL)

Test and Set Instruction

```
boolean testset (int & i) {
    if (i == 0) {
        i = 1;
        return false;
    }
    else return true;
}
```

Test and Set Instruction

```
boolean testset (Boolean *target) {
    boolean rv = *target;
    *target = true;
    return rv;
}
```

- Atomic processor instructions
- Idea: Only one process at a time succeeds to set lock=1

Test and Set (TSL)

Test and Set Instruction

```
boolean testset(int& i) {
    if (i == 0) {
        i = 1;
        return false;
    }
    else return true;
}
```

```
void P(int i){
    while (true) {
        while (testset(bolt));
        critical section
        bolt = 0;
        remainder section
    }
}

void main()
{
    bolt =0;
    parbegin(P(1), …, P(N));
}
```

- Atomic processor instructions
- Idea: Only one process at a time succeeds to set lock=1

Exchange (Swap)

Exchange Instruction

```
void exchange(int& mem1,int& mem2)
{
    int temp = mem1;
    mem1 = mem2;
    mem2 = temp;
}
```

```
void P(int i){
  while (true) {
    int key = 1;
    while(key) {
      exchange(bolt,key);
    }
    critical section
    exchange(bolt,key);
    remainder section
  }
}

void main(){
  bolt =0;
  parbegin(P(1), …, P(N));
}
```

- Atomic processor instructions
- Idea: Only one process at a time will be able to set key = 0

Mutual Exclusion Using Machine Instructions

Advantages

- Applicable to any number of processes on single or multiple CPUs sharing main memory
- It is simple and therefore easy to verify

Disadvantages

- Busy-waiting consumes processor time
- Starvation is possible
  - A process leaves a CS
  - More than one process is waiting
- Deadlock possible if used in priority-based scheduling systems: Ex. scenario
  - Low priority process has the critical region
  - Higher priority process needs it
  - The higher priority process will obtain the CPU to wait for the critical region

Avoiding Starvation

- Bounded waiting with Test and Set instruction

```
do {
   waiting[i] = TRUE;
   key = TRUE;
   while (waiting[i] && key)
      key = TestAndSet(&lock);
   waiting[i] = FALSE;
   // critical section
   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = FALSE;
   else
      waiting[j] = FALSE;
   // remainder section
} while (TRUE);
```

Priority Inversion

- Consider three processes
  - Process L with low priority that requires a resource R
  - Process H with high priority that also requires a resource R
  - Process M with medium priority

- If H starts after L has acquired resource R
  - H has to wait to run until L relinquishes resource R
- Now when M starts
  - M is higher priority unblocked process, it will be scheduled before L
    - Since L has been preempted by M, L cannot relinquish R
  - M will run until it is finished
    - Then L will run - at least up to a point where it can relinquish R
    - Then H will run
- **Priority inversion:** Process with the medium priority ran before a process with high priority

Priority Inheritance

- If high priority process has to wait for some resource shared with an executing low priority process
- Low priority process is temporarily assigned the priority of the highest waiting priority process
- Medium priority processes are prevented from pre-empting (originally) low priority process avoiding priority inversion

Semaphores

- Higher-level synchronization construct
  - Designed by Edsger Dijkstra in 1960's

Semaphores

- Synchronization variable accessed by
  - System calls of the operating system
  - Associated with a queue of **blocked processes**
- Accessible via atomic `wait()` and `signal()` operations
  - Originally called `P()` and `V()`

wait():	Process blocks until a signal is received
signal():	Another process can make progress: Process in the queue, next process calling wait()

- Different semaphore semantics possible
  - Binary: Only one process at a time makes progress
  - General (counting): n processes at a time make progress

Binary Semaphore

- Wait: Process blocks if state of semaphore is 0
- Signal: Unblocks a process or sets the state of the semaphore to 1

```
wait () / P() {
   while S <= 0 ; // no-op
   S--;
}
```

Atomic

```
signal () / V()  {
   S++;
}
```

Atomic

An atomic operation that waits for semaphore to become positive then decrements it by 1

An atomic operation that increments semaphore by 1

How to avoid busy waiting?

Busy-waiting

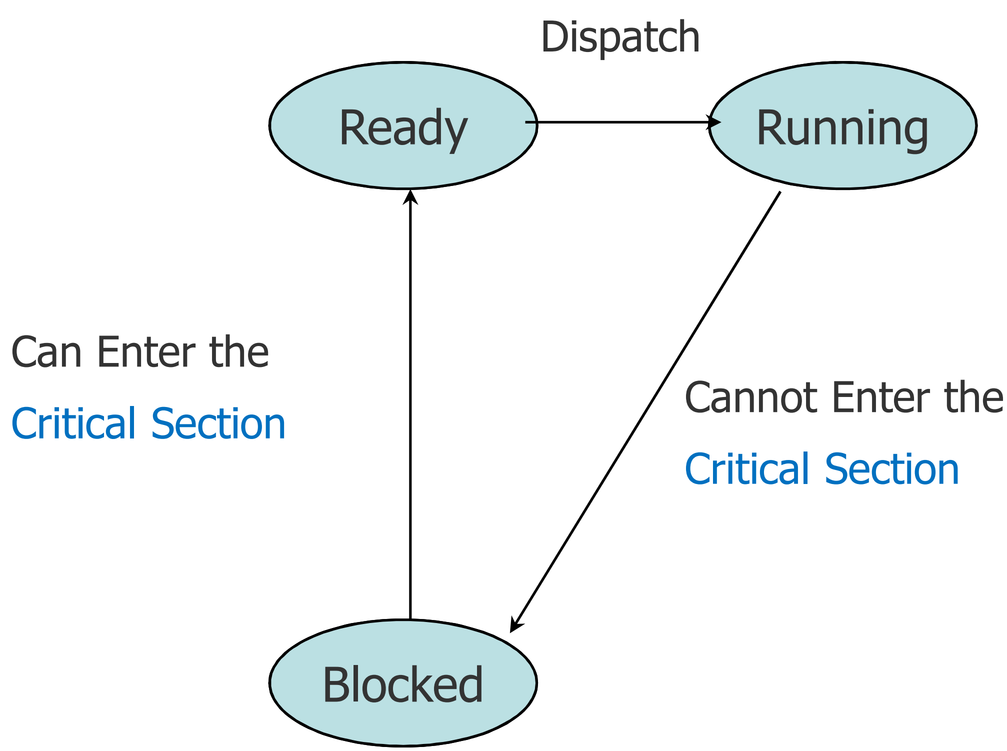
- Problem with hardware and software based implementations
  - If one thread already has the lock, and another thread T wants to acquire the lock
  - Acquiring thread T waste CPU's time by executing the Idle loop

To avoid CPU time

- If a thread (process) T cannot enter critical section
  - T's status should be changed from Running to Blocked
  - T should be removed from the ready list and entered in a block list

- When T enters critical section
  - T's status should be changed from Blocked to Ready/Running
  - T should be entered in the ready list

Busy-waiting



No CPU time wastage

Sleep/Block and Wakeup Implementation

- `sleep()/block()` and `wakeup()` **can** be two system calls

- When a process P_i determines that it can not enter the CS it calls `sleep()/block()`
  - Pi entered in the block list

- When the other process finishes with the CS, it wakes up P_i, `wakeup(`P_i`)`
  - P_i entered in the ready list

- `wakeup()` takes a single input parameter, which is the ID of the process to be unblocked

Binary Semaphore

- Wait: Process blocks if state of semaphore is 0
- Signal: Unblocks a process or sets the state of the semaphore to 1

```
struct bin_sem_t {
    enum {zero, one} value;
    queueType queue;
    /* Can be linked list of PCB */
};
int wait(bin_sem_t s) {
   if (s.value==1)
        s.value=0;
   else{
       /* block and place current
          process  in s.queue  */
       state(current) = BLOCKED
       append(s.queue, current)
   }
}
```

```
int signal(bin_sem_t s) {
   if (isempty(s.queue))
       s.value=1;
   else{
       /* unblock and remove first
          process from s */
       p=pop(s.queue);
       state(p) = READY/RUNNING
   }
}
```

Counting Semaphore

- Count: Determines no. of processes that can still pass semaphore
- Wait: Decreases count and blocks if count is < 0
- Signal: Unblocks a process or increases count

```
struct sem_t {
   int count;
   queueType queue;
};

int wait(sem_t s) {
   s.count--;
   if (s.count < 0)
      /* block and place current
           process  in s.queue  */
      state(current) = BLOCKED
      append(s.queue, current)
   }
}
```

```
int signal(sem_t s) {
   s.count++;
   if (s.count ≤ 0){
     /* unblock and remove
        first  process from s */
     p=pop(s.queue);
     state(p) = RUNNING/READY
   }
}
```

How to ensure atomicity?

Implementing Semaphores

- Problem: Concurrent calls of signal and wait
- Solution: Use hardware synchronization!
- Properties: Still limited busy waiting

```
int wait(sem_t s)
{
    /* mode switch */
   while (testset(s.flag));
   s.count--;
   if (s.count < 0) {
      /* block and place current
         process  in s.queue  */
      state(current) = BLOCKED
      append(s.queue, current)
   }
   s.flag=0;
}
```

```
int signal(sem_t s) {
   /* mode switch */
   while (testset(s.flag));
   s.count++;
   if (s.count ≤ 0) {
      /* unblock and remove
         first  process from s */
      p=pop(s.queue);
      state(p) = RUNNING
   }
   s.flag=0;
}
```

Critical Section Using Semaphores

```
Shared var mutex  of semaphore (init =1)

Process Pi:
repeat
  wait(mutex)
    critical section
  signal(mutex);
    remainder section
until false;
```

Properties:

- Again simple
- No busy waiting
- Fair if queues of semaphores are implemented fair

Bad Use of Semaphores Can Lead to Deadlocks!

- Let S and Q be two semaphores initialized to 1

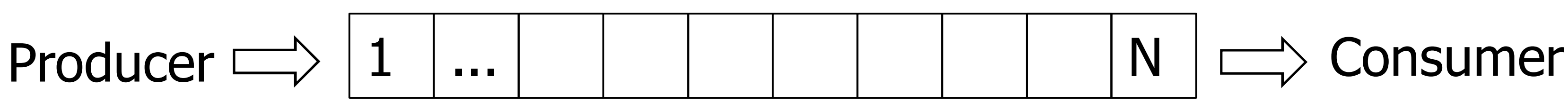
```
      P0                 P1

1  wait(S);          2  wait(Q);
3  wait(Q);          4  wait(S);
       ⋮                   ⋮
   signal(S);           signal(Q);
   signal(Q):           signal(S);
```

Synchronization Problems

- Critical section synchronization very common
- **Problems**
  - Synchronization on many variables becomes increasingly complicated
  - Deadlock because of bad programming likely to happen
- **Idea:** Understand useful synchronization patterns that match IPC patterns
  - Consumers/Producer problem
    - ➢ High degree of concurrency by decoupling of tasks
  - Dining Philosophers
    - ➢ Coordinate access to resources
  - Readers Writers Problem
    - ➢ Coordinate access to shared data structures

Producer/Consumer Problem Revisited

- Also known as bounded buffer problem



- Overall problem description
  - A buffer can hold N items
  - Producer pushes items into the buffer
  - Consumer pulls items from the buffer
  - Producer needs to wait when buffer is full
  - Consumer needs to wait when the buffer is empty

Producer/Consumer Problem Revisited

```
int BUFFER_SIZE = 100; int count = 0;
void producer(void) { int item;
    while(TRUE) {
        produce_item(&item);
        if(count == BUFFER_SIZE)
            sleep ();
        enter_item(item);
        count++;
        if(count == 1)
            wakeup(consumer);
    }
}
void consumer(void) { int item;
    while(TRUE) {
        if(count == 0)
            sleep ();
        remove_item(&item);
        count--;
        if(count == BUFFER_SIZE - 1)
            wakeup(producer);
        consume_item(&item);
    }
}
```

1 Producer must wait for consumer to empty buffers

2 Consumer must wait for producer to fill buffers

3 A thread can manipulate buffer queue at a time

Producer/Consumer Problem Revisited

- Synchronization between producer and consumer
  - Use of three separate semaphores

1. Producer must wait for consumer to empty buffers, if all full
   - Semaphore empty initialized to the value N

2. Consumer must wait for producer to fill buffers, if none full
   - Semaphore full initialized to the value 0

3. Producer/consumer can manipulate buffer queue at a time
   - Semaphore mutex initialized to the value 1

Producer/Consumer Problem Revisited

- Semaphore empty initialized to the value N
- Semaphore full initialized to the value 0
- Semaphore mutex initialized to the value 1

Producer:

```
void producer(void) {
    int item;
    while(TRUE) {
        produce_item(&item);
        wait (empty);
        wait(mutex);
        enter_item(item);
        signal(mutex);
        signal(full);
    }
}
```

Consumer:

```
void consumer(void) {
    int item;
    while(TRUE) {
        wait(full);
        wait(mutex);
        remove_item(&item);
        signal(mutex);
        signal(empty);
        consume_item(&item);
    }
}
```

Changing Order of Semaphores

Producer:

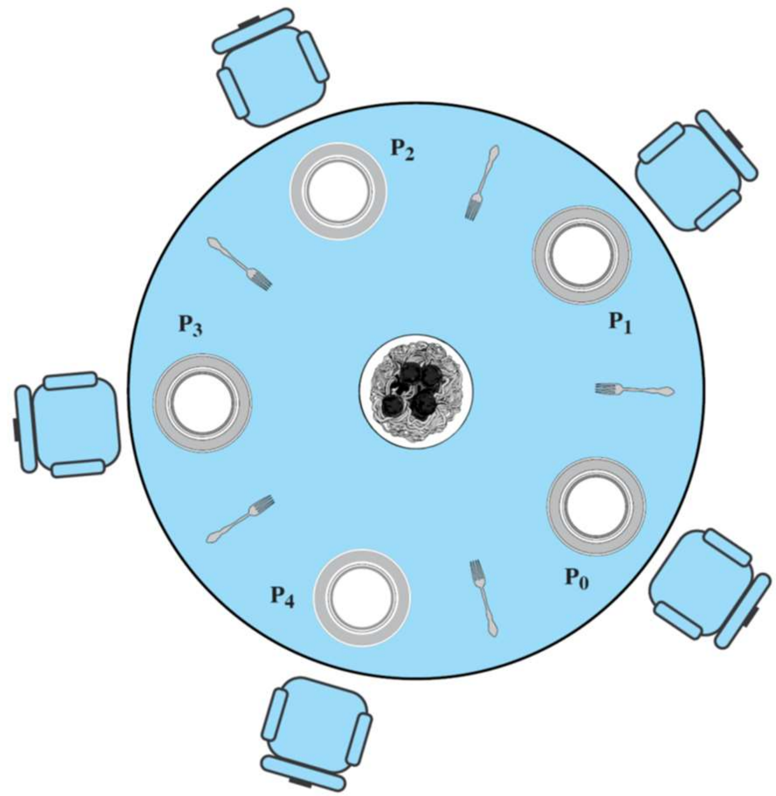
```
void producer(void) {
    int item;
    while(TRUE) {
        produce_item(&item);
        wait (mutex);
        wait(empty);
        enter_item(item);
        signal(mutex);
        signal(full);
    }
}
```

Consumer:

```
void consumer(void) {
    int item;
    while(TRUE) {
        wait(full);
        wait(mutex);
        remove_item(&item);
        signal(mutex);
        signal(empty);
        consume_item(&item);
    }
}
```

DEADLOCK

Dining Philosophers Problem [E.W. Dijkstra, 1965]



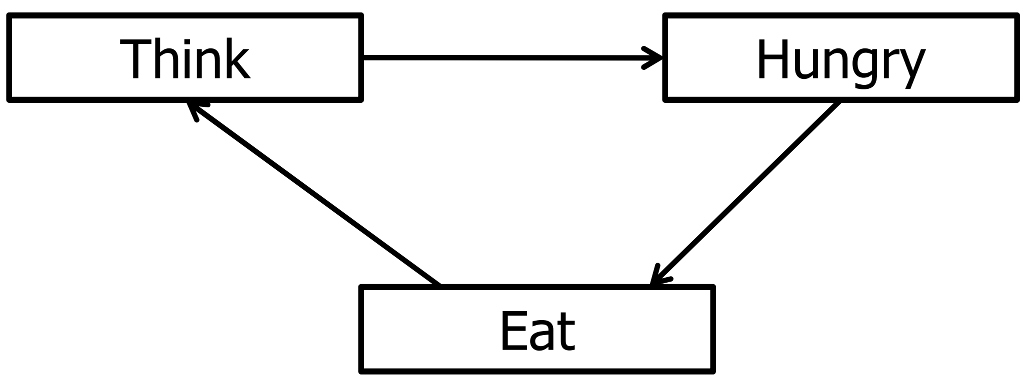
- Simplest form of the resource allocation problem

- **Intuition:**
  - Philosophers ~ Processes which aim to execute code
  - Food ~ code which requires exclusive access to resources
  - Forks ~ conflicts on shared resources
- **Hungry** philosophers
  - Try to exclusively acquire forks shared with neighbors
- **Eat** after they have aquired both forks
  - Release forks after eating
- **Think** if not interested to eat

Dining Philosophers Problem: States and Properties

Goal

- No deadlocks
- Hungry philosophers will eventually be able to eat



States of a philosopher

Dining Philosophers Problem Using Semaphores

- Represent each fork with a semaphore
  - Semaphore `fork[5]` initialized to 1

Structure of Philosopher i

```
do  {
    wait ( fork[i] );
    wait ( fork[ (i + 1) % 5] );
    //  eat
    signal ( fork[i] );
    signal (fork[ (i + 1) % 5] );
    //  think
} while (TRUE);
```

- Solution guarantees that no two neighbors eat simultaneously
  - Deadlock can be occur

Semaphores Summary

- Semaphores can be used to solve any of traditional synchronization problems
- Semaphore have some **drawbacks**
  - They are essentially shared global variables
    - Can potentially be accessed anywhere in program
  - No connection between the semaphore and the data being controlled by the semaphore
  - Used both for critical sections (mutual exclusion) and coordination (scheduling)
  - No control or guarantee of proper usage
- Sometimes hard to use and prone to bugs
  - Another approach: Use programming language support

Monitors

Goal: Avoid problems of managing multiple semaphores

Monitor is a programming language construct (not OS)

- Controls access to shared data
- Synchronization code added by compiler, enforced at runtime

```
monitor name
{
   // shared variable

   procedure P1 ( … ) {
   …
   }
   …
   procedure PN (…){
   …
   }
    initialization (…) {
    …
   }
}
```

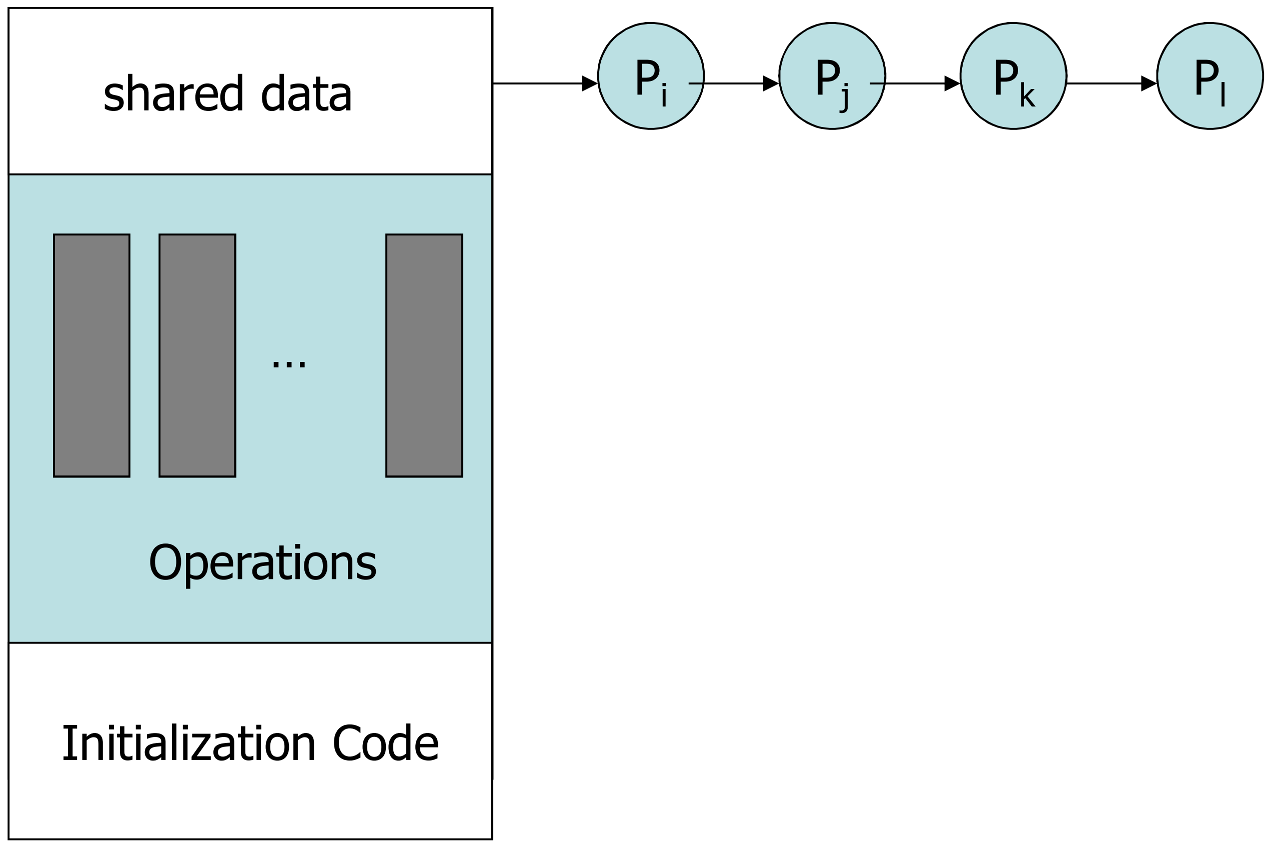
Monitors

A monitor guarantees mutual exclusion

- Only one thread can execute any monitor procedure at any time
  - The thread is "in the monitor"
- If a second thread invokes a monitor procedure when a first thread is already executing one, it blocks
  - So the monitor has to have a wait queue…
- If a thread within a monitor blocks, another one can enter

```
monitor name
{
   // shared variable

   procedure P1 ( … ) {
   …
   }
   …
   procedure PN (…){
   …
   }
    initialization (…) {
    …
   }
}
```

Monitors



Monitors

- A monitor has four components
  - Initialization
  - Share (private) data
  - Monitor procedures
  - Monitor entry queue

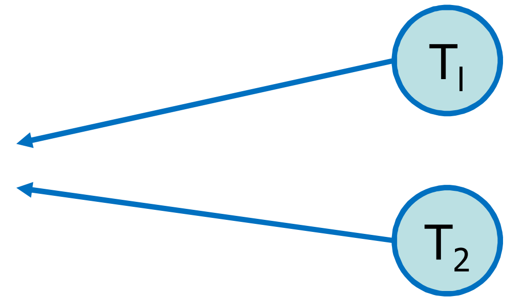
- A monitor looks like a class with
  - Constructors, private data and methods
  - Only major difference is that classes do not have entry queues

Mutual Exclusion With a Monitor

```
monitor mutual_exclusion{
   procedure CS();
        Critical Section
   end;
}

Process Pi:
1: REPEAT
2:      CS();
3:     Remainder Section
4: UNTIL false;
```

Monitors Example

```
Monitor account {
    double balance;
    double withdraw(amount) {
        balance = balance – amount;
        return balance;
    }
}
```



- Threads are blocked while waiting to get into monitor
- When first thread exists, another can enter

Condition Variables in Monitors

- Similar concept to semaphores
- Condition variable associated with a queue

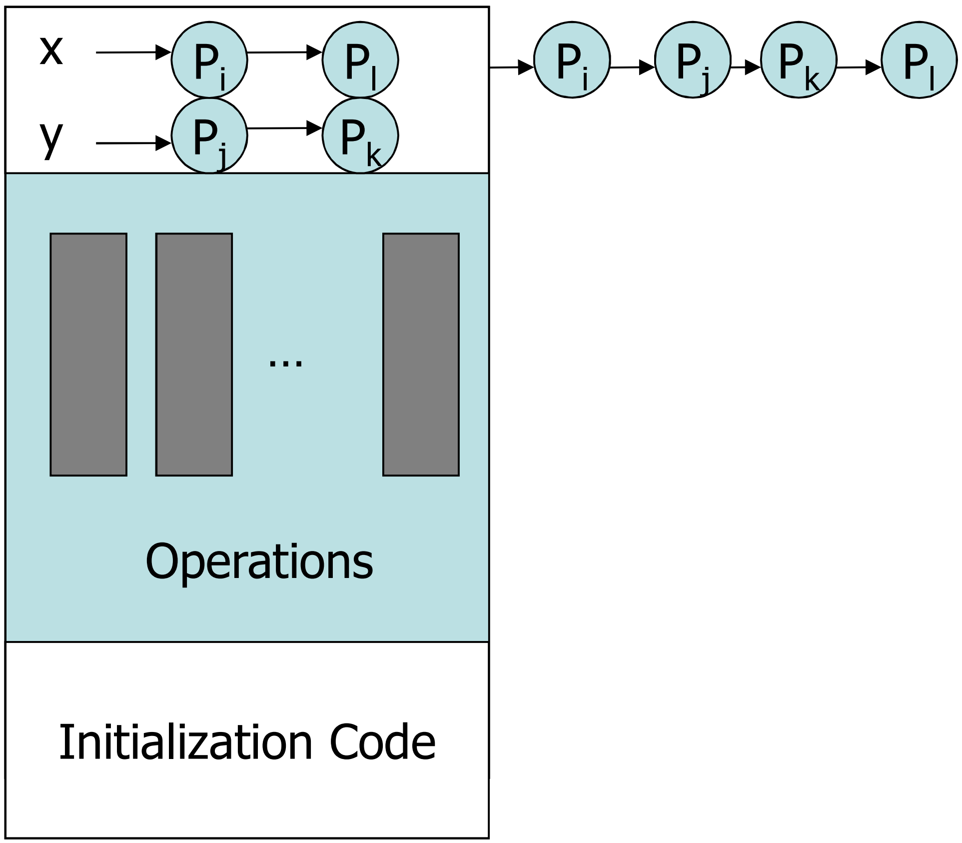
```
condition x;  // declaration
```

```
x.wait()
```

- Process which invokes this operation is blocked

```
x.signal()
```

- A blocked process can resume execution
  - If no process issue x.wait () on variable x, then it has no effect on the variable



Producer/Consumer Problem Revisited

```
monitor ProducerConsumer {
    int itemCount;
    condition full, empty;

    procedure initialization( ){
        itemCount = 0;
    }
    procedure add(item) {
        if (itemCount == BUFFER_SIZE)
            full.wait( );

        putItemIntoBuffer(item);
        itemCount = itemCount + 1;

        if (itemCount == 1)
            empty.signal();
    }
    procedure remove() {
        if (itemCount == 0)
            empty.wait( );
```

```
            item = removeItemFromBuffer();
            itemCount = itemCount - 1;

            if (itemCount == BUFFER_SIZE - 1)
                full.signal( );
            return item;
        }
}
procedure producer() {
    while (true) {
        item = produceItem();
        ProducerConsumer.add(item);
    }
}
procedure consumer() {
    while (true) {
        item = ProducerConsumer.remove();
        consumeItem(item);
    }
}
```

Signal Semantics

What happens if P executes `x.signal()` & has still code to execute?

Two possibilities

- Hoare monitors (Concurrent Pascal, original)
  - Signal and wait: P either waits for Q to leave the monitor or waits for some other condition
  - The condition that Q was anticipating is guaranteed to hold
    - `if (empty) wait(condition);`
- Mesa monitors (Mesa, Java)
  - Signal and continue: Q either waits until P leaves the monitor or for some other condition
  - Condition is not necessarily true when Q runs again
    - `while (empty) wait(condition);`

Condition Variables vs. Semaphores

Semaphore

- Can be used anywhere in a program, but should not be used in a monitor
- `wait()` does not always block the caller (i.e., when the semaphore counter is greater than zero)
- `signal()` either releases a blocked thread, if there is one, or increases the semaphore counter
- If `signal()` releases a blocked thread, the caller and the released thread both continue

Condition variables

- Can only be used in monitors
- `wait()` always blocks the caller
- `signal()` either releases a blocked thread, if there is one, or the signal is lost as if it never happens
- If `signal()` releases a blocked thread. Only one of the caller or the released thread can continue, but not both

Dining Philosophers Problem Revisited

```
monitor DiningPhilosophers {
    enum {THINK,HUNGRY,EAT) state[5];
    condition self [5];

    void pickup (int i) {
        state[i] = HUNGRY;
        test(i);
        if (state[i] != EATING)
            self [i].wait();
    }
    void putdown (int i) {
        state[i] = THINKING;
        // test left & right neighbors
        test((i + 4) % 5);
        test((i + 1) % 5);
    }
    initialization_code() {
        for (int i = 0; i < 5; i++)
            state[i] = THINKING;
    }
```

```
    void test (int i) {
        if ((state[(i+4)%5] != EATING) &&
            (state[i] == HUNGRY) &&
            (state[(i+1)%5] != EATING)) {
            state[i] = EATING ;
            self[i].signal() ;
        }
    }
}
```

Function of Philosopher i

```
Void philosopher(int i) {
    while (true) {
        DiningPhilosophers.pickup (i);
        // EAT
        DiningPhilosophers.putdown (i);
        // THINK
    }
}
```

No deadlock but starvation is possible

Condition Variables and Locks

- Condition variables are also used without monitors in conjunction with blocking locks

```
procedure( ) {
    Acquire(lock);
    /* Do something including signal and wait*/
    Release(lock);
}
```

- A monitor is "just like" a module whose state includes a condition variable and a lock
  - Difference is syntactic; with monitors, compiler adds the code
- It is "just as if" each procedure in the module calls `acquire()` on entry and `release()` on exit
  - But can be done anywhere in procedure, at finer granularity

Condition Variables and Locks – Example

```
Lock lock;
Condition cond;
int AddToQueue() {
    lock.Acquire();      // Lock before using shared data
    put item on queue;   // Ok to access shared data
    cond.signal();
    lock.Release();      // Unlock after done with shared data
}
int RemoveFromQueue() {
    lock.Acquire();
    while nothing on queue
        cond.wait(&lock); //Atomically release lock and block until signal
                          //Automatically re-acquire lock before it returns
                          // Difference in syntax, e.g., wait(cond, lock)
    remove item from queue;
    lock.Release();
    return item;
}
```

Any Question So Far?