Operating Systems
CS2006

Chapter: 6
Process Synchronization

Process Synchronization

- Processes may be **independent** or **cooperating**
- Cooperating process can affect or be affected by other processes

- Cooperating process can share data
  - Inter-Process communication in case of heavy-weight processes
  - Same logical address space in case of threads
  - Message passing

Why synchronization?

- When we have multiple processes running at the same time (i.e. **concurrently**) we know that we must protect them from one another
  - E.g. protect one process' memory from access by another process
- But, what if we want to have those processes/ threads cooperate to solve a single problem?
  - E.g. one thread that manages, the mouse and keyboard, another that manages the display and a third that runs your programs
  - In this case, the processes/threads must be **synchronized**

The Synchronization Problem

- Concurrent access to shared data may result in data inconsistency

- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes

The Synchronization Problem

- One process/thread should not get into the way of another process/thread when doing critical activities

- Proper sequence of execution should be followed when dependencies are present
  - A produces data, B prints it
  - Before printing B should wait while A is producing data
  - B is dependent on A

If there is no synchronization

Example (Producer-Consumer)

- Let's revisit an earlier example…
- The producer-consumer problem with a bounded buffer i.e. BUFFER SIZE − 1 in the original solution.
- Suppose we want to modify the algorithm to remedy this deficiency!
- Add an integer variable `counter` initialized to 0.
- Increment/decrement `counter` every time we add/remove a new item to/from the buffer.

Producer (Modified code)

```
while (true) {
     /* produce an item in next
produced */

   while (counter == BUFFER_SIZE) ;
         /* do nothing */
     buffer[in] = next_produced;
     in = (in + 1) % BUFFER_SIZE;
     counter++;
}
```

Consumer (Modified code)

```
while (true) {
        while (counter == 0)
              ; /* do nothing */
        next_consumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;

           counter--;
        /* consume the item in next
consumed */
}
```

Synchronization Issue

- Producer and consumer routines shown above are correct separately, they may not function correctly when executed concurrently.
- Suppose that the value of the variable counter is currently 5 and that the producer and consumer processes concurrently execute the statements "counter++" and "counter--"
- What might be the possible values of counter…. and which one is correct?

Synchronization Issue (2)

We can show that the value of counter may be incorrect as follows.

- **`counter++`** could be implemented in machine language as

```
register1 = counter
register1 = register1 + 1
counter = register1
```

- **`counter--`** could be implemented as

```
register2 = counter
register2 = register2 - 1
counter = register2
```

- where *register*1,2 are the local CPU registers.

Synchronization Issue (3)

- The concurrent execution of "counter++" and "counter–" is equivalent to a sequential execution.
- Consider this execution interleaving with "counter = 5" initially:

T0: producer execute `register1 = counter` **{register1 = 5}**
T1: producer execute `register1 = register1 + 1` **{register1 = 6}**
T2: consumer execute `register2 = counter` **{register2 = 5}**
T3: consumer execute `register2 = register2 - 1` **{register2 = 4}**
T4: producer execute `counter = register1` **{counter = 6 }**
T5: consumer execute `counter = register2` **{counter = 4}**

- Notice that we have arrived at the incorrect state "counter == 4", indicating that four buffers are full, when, in fact, five buffers are full.
- If we reversed the order of the statements at *T*4 and *T*5, we would arrive at the incorrect state "counter == 6".

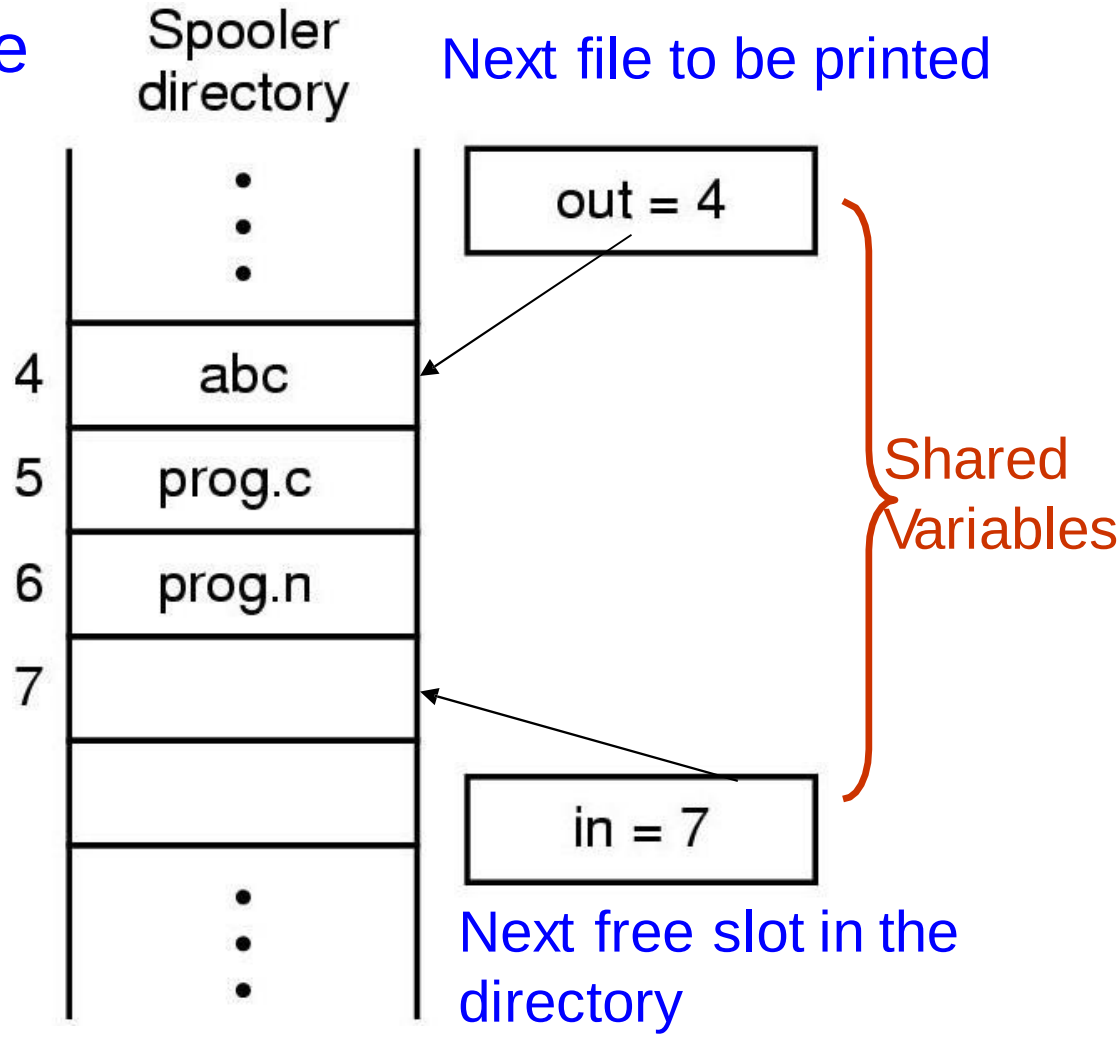
Example Print Spooler

- 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 wh their files

Process A

1.Read the value of in in a local variable next_free_slot

2.Store the name of its fil in the next_free_slot

3. Increment next_free_slot

4. Store back in in

Process B

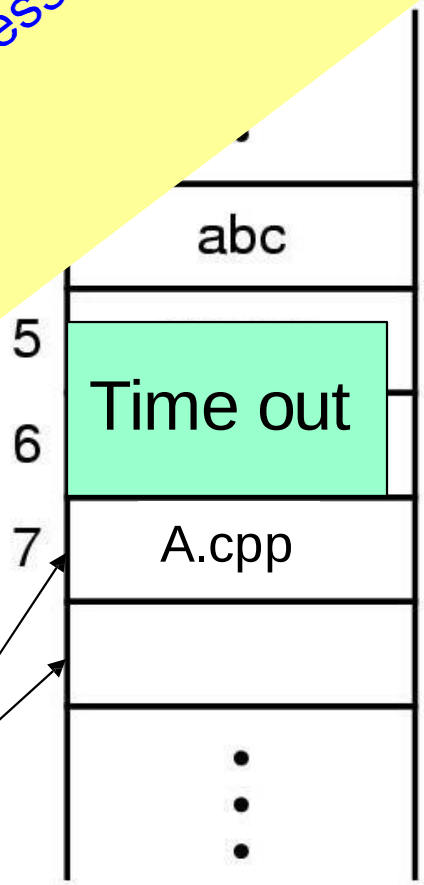
1.Read the value of in in a local variable next_free_slot

2.Store the name of its file in the next_free_slot

3 .Increment next_free_slot

4. Store back in in

Process B will never receive any output



$next\_free\_slot_a = 7$

$next\_free\_slot_b = 7$

in = 8

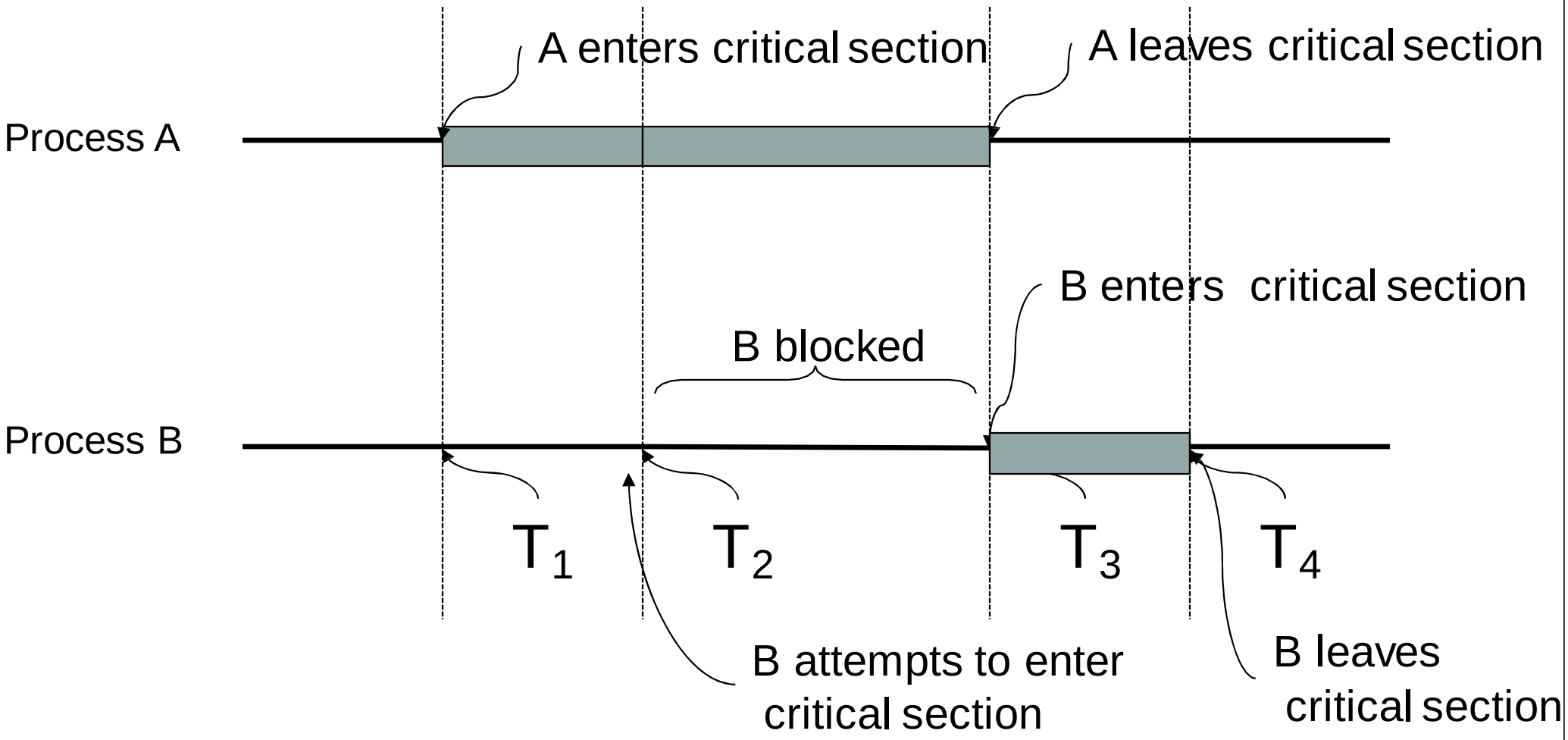
Race condition

- A situation where several processes access and manipulate the same data concurrently, and the outcome of the execution depends on the particular order in which the access takes place, is called **race condition.**
  - Debugging is not easy
  - Most test runs will run fine
  - To prevent race conditions, concurrent processes must be **synchronized**

Reason behind Race Condition

- Process Bstarted using one of the shared variables before process Awas finished with it.
- 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 can be avoided
  - **If no two processes are in the critical region at the same time.**

Critical Section



Mutual Exclusion

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

Critical Section

- Avoid race conditions by not allowing two processes to be in their critical sections at the same time
- We need a mechanism of mutual exclusion
- Some way of ensuring that one process, while using the shared variable, does not allow another process to access that variable

The Critical-Section Problem

- Each process has a code segment, called *Critical Section (CS)*, in which the shared data is accessed.

- Problem – ensure that when one process is executing in its CS, no other process is allowed to execute in its CS.

The Critical-Section Problem

- Only 2 processes, P0 and P1
- General structure of process Pi (other process Pj)

```
do {
        entry section
                critical section (CS)
        exit section
                reminder section
} while (1);
```

- Processes may share some common variables to synchronize their actions

Solution to Critical-Section Problem

- There are 3 requirements that must stand for a correct solution:
  1. **Mutual Exclusion**
  2. **Progress**
  3. **Bounded Waiting**

Solution to CS Problem - Mutual Exclusion

1. **Mutual Exclusion** – If process P_i is executing in its critical section, then no other processes can be executing in their critical sections.

- Implications:
  - Critical sections better be focused and short.
  - Better not get into an infinite loop in there.

Solution to CS Problem - Progress

2. **Progress** – If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the process that will enter the critical section next cannot be postponed indefinitely:
   - If only one process wants to enter, it should be able to.
   - If two or more want to enter, one of them should succeed.
   - No deadlock
   - No process in its remainder section can participate in this decision

Solution to CS Problem - Bounded Waiting

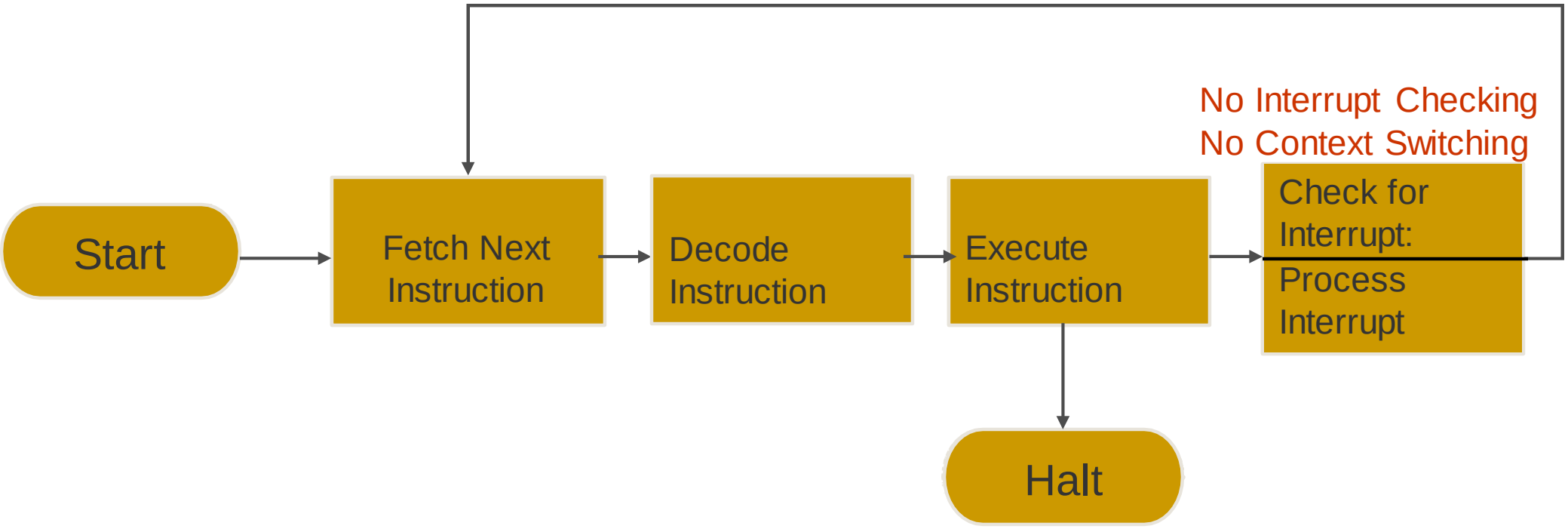
3. **Bounded Waiting** – A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted.
   - Assume that each process executes at a nonzero speed.
   - No assumption concerning relative speed of the *n* processes.
   - Deterministic algorithm, otherwise the process could suffer from starvation

Implementing Mutual Exclusion

1. Disabling Interrupts
2. Lock Variables
3. Strict Alternation

Disabling Interrupts

- The problem occurred because the CPU switched to another process due to clock interrupt
- Remember the CPU cycle



Disabling Interrupts

- Solution: A Process
  - Disable interrupts before it enters its critical section
  - Enable interrupts after it leaves its critical section
- CPU will be unable to switch a process while it is in its critical section
- Guarantees that the process can use the shared variable without another process accessing it
- Disadvantage:
  - Unwise to give user processes this much power
  - The computer will not be able to service useful interrupts
  - The process may never enable interrupts, thus (effectively) crashing the system
- However, the kernel itself can disable the interrupts

Lock Variables: Software Solution

- 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();
```

FLAG = FALSE

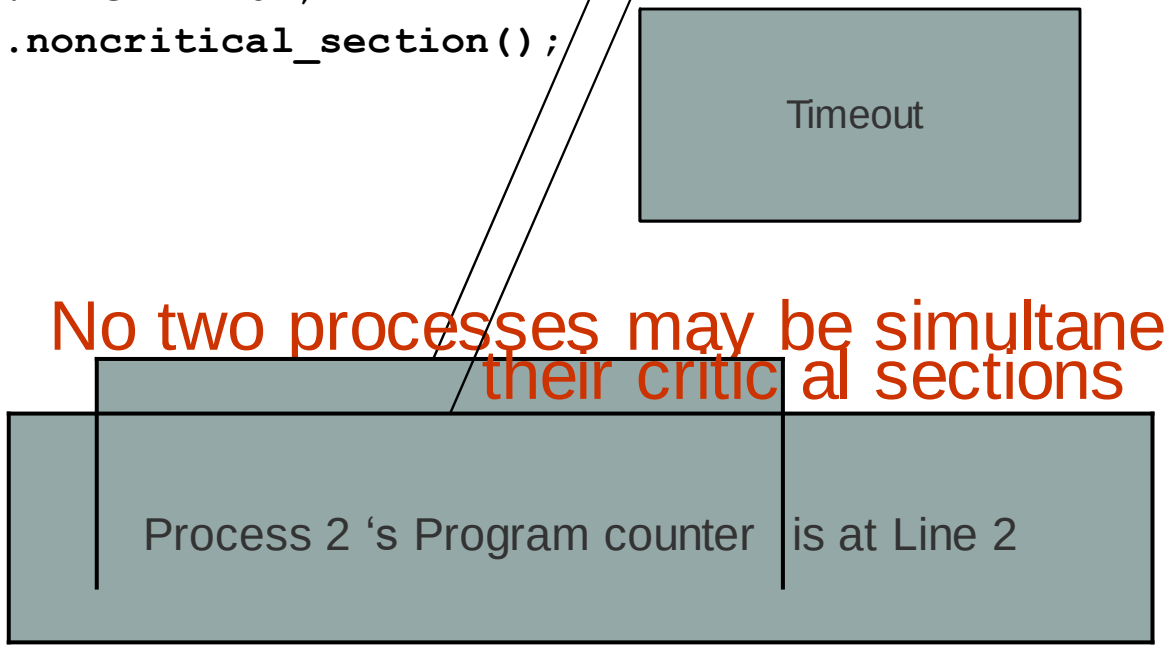
Lock Variables

Process 1

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

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

Process 2

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



No two processes may be simultaneously inside their critic al sections

Process 1 forgot that it was Process 2’s turn

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

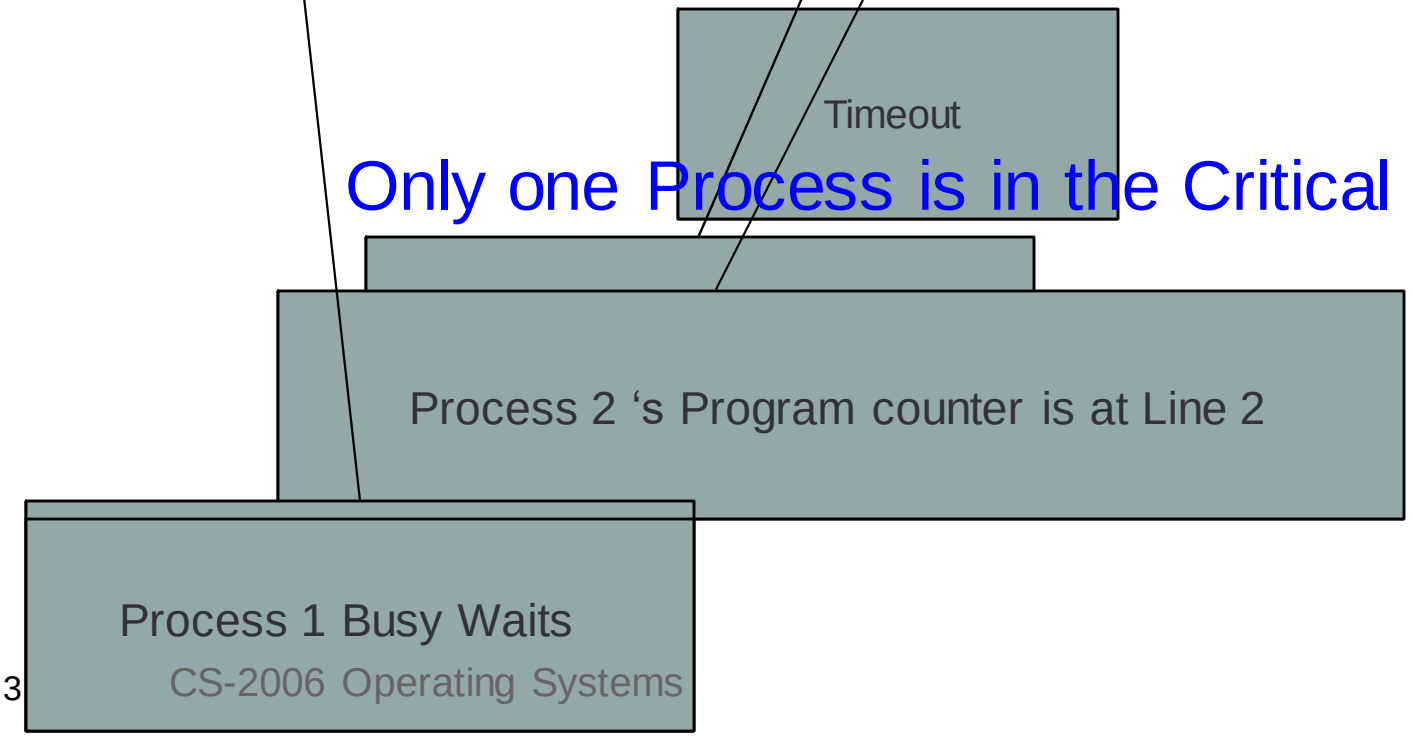
Turn = 1

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);

2.critical_section();

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



Only one Process is in the Critical Section at a time

Strict Alternation

Process 1

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

Process 2

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

- **Can you see a problem with this?**
- **Hint :What if one process is a much faster than the other**

Strict Alternation

turn = 1

Process 1

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

Process 2

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

- Process 1
  - Runs
  - Enters its critical section
  - Exits; setting 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.

turn = 1

Process 1

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

Process 2

```
while(TRUE)
{
  // wait
  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
- In fact, there is no reason why process 2 cannot enter its critical region as process 1 is not in its critical region.

Strict Alternation

- What we have is a violation of one of the conditions that we listed above

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*.

Reason

- Although it was Process 1's **turn**
- But Process 1 was not **interested**.
- Solution:
  - We also need to remember
    - "**Whether it is interested or not?**"

Algorithm 2

- Replace
  - `int turn;`
- With
  - `bool Interested[2];`
- **`Interested[0] = FALSE`**
  - Process 0 is not interested
- **`Interested[0] = TRUE`**
  - Process 0 is interested
- **`Interested[1] = FALSE`**
  - Process 1 is not interested
- **`Interested[1] = TRUE`**
  - Process 1 is interested

Algorithm 2

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();
}
```

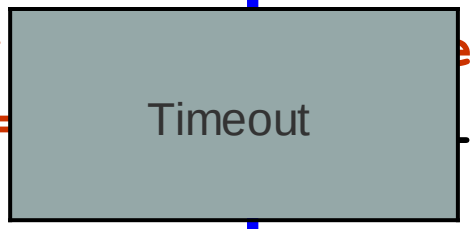
Algorithm 2

Process 0

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

Process 1

```
while(TRUE)
{
   erested[1] = TRUE;
   e(interested[0]!=FALSE);
```



DEADLOCK

Peterson's Solution

Combine the previous two algorithms:

```
int turn;
bool interested[2];
```

- **`Interested[0] = FALSE`**
  - Process 0 is not interested
- **`Interested[0] = TRUE`**
  - Process 0 is interested
- **`Interested[1] = FALSE`**
  - Process 1 is not interested
- **`Interested[1] = TRUE`**
  - Process 1 is interested

Algorithm 3: Peterson's Solution

- Two process solution (Software based solution)
- The two processes share two variables:
  - int **turn**;
  - Boolean **interested[2]**
- The variable **turn** indicates whose turn it is to enter the critical section.
- The **interested** array is used to indicate if a process is ready to enter the critical section. **interested[i] = true** implies that process $\mathbf{P_i}$ is ready

Algorithm 3: Peterson's Solution

- **Process Pi**

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

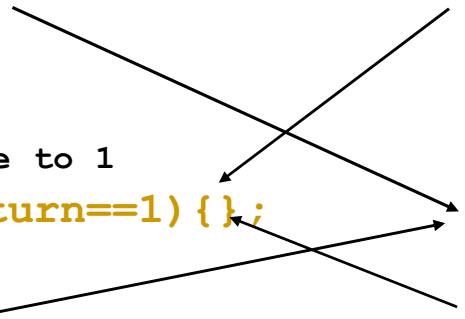
Algorithm 3: Peterson's Solution

- Meets all three requirements:
  - **Mutual Exclusion**: 'turn' can have one value at a given time (0 or 1)
  - **Bounded-waiting**: At most one entry by a process and then the second process enters into its CS
  - **Progress**: Exiting process sets its 'flag' to false … comes back quickly and set it to true again … but sets turn to the number of the other process

Two-Process Solution to the Critical-Section Problem — Peterson's Solution

```
flag[0],flag[1]:=false
turn := 0;
Process P0:
repeat
  flag[0]:=true;
    // 0 wants in
  turn:= 1;
   // 0 gives a chance to 1
  while(flag[1]&&turn==1){};
     CS
  flag[0]:=false;
   // 0 is done
     RS
forever
```

```
Process P1:
repeat
  flag[1]:=true;
    // 1 wants in
  turn:=0;
   // 1 gives a chance to 0
while(flag[0]&&turn==0){};
     CS
flag[1]:=false;
   // 1 is done
     RS
forever
```



- The algorithm proved to be correct. Turn can only be 0 or 1 even if both flags are set to true

Issue with Peterson solution

- Peterson solution isn't practical because it can not solve critical section problem for more than two processes at the same time
- It is only a reference solution that helps understand the background for developing a new solution

Hardware-based solutions

Elementary building blocks capable of performing certain steps atomically. Should be universal to allow for solving versatile synchronization problems. Numerous such primitives were identified:

- Test-and-set
- Fetch-and-add
- Compare-and-swap

Problems with studied synchronization methods:

Critical section framework is inconvenient for programming.

Performance penalty.

Busy waiting.

Too coarse synchronization.

Using hardware primitives directly results in non-portable code

Hardware for Synchronization

- One uniprocessor solution: Disable interrupts
- **TestAndSet hardware instruction,**

```
boolean TestAndSet (boolean *target)
{
    boolean returnValue = *target;
    *target = TRUE;
    return returnValue;
}                              //Swap() is similar
```

Mutual exclusion using TestAndSet:

```
SHARED:
   boolean lock;

Process 0:

   while (TRUE) {
      while (TestAndSet(&lock)) ;
      /* CRITICAL SECTION */
      lock = FALSE;
      /* REMAINDER SECTION */
   }

Process 1:

   while (TRUE) {
      while (TestAndSet(&lock)) ;
      /* CRITICAL SECTION */
      lock = FALSE;
      /* REMAINDER SECTION */
   }
```

Problem: Does not satisfy bounded-waiting requirement
Problem: Complicated for application programmers to use

Producer-Consumer using TestAndSet:

```
SHARED:
   boolean lock;
   double buffer[BUFFER_SIZE];
   int    counter = 0;
```

```
Producer:
     int in = 0;
     while (true) {
        // Produce item into nextProduced
        while (counter == BUFFER_SIZE) {};
        buffer[in] = nextProduced ;
        in = (in + 1) % BUFFER_SIZE;

        while (TestAndSet(&lock)) {};
        counter ++;  // CRITICAL SECTION
        lock = FALSE;

     }
```

```
Consumer:
     int out = 0;
     while (true) {
        while (counter == 0) ;
        nextConsumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;

        while (TestAndSet(&lock)) {};
        counter --;    // CRITICAL SECTION
        lock = FALSE;

        // Consume item in nextConsumed
   }
```

Test-and-Set (TS)

```
boolean test-and-set(boolean &lock)
{
   temp=lock;
   lock=TRUE;
   return temp;
}

reset(boolean &lock)
{
   lock=FALSE;
}
```

Critical section using TS

Shared *boolean lock*, initially FALSE

```
do {
   while(test-and-set(&lock));
         critical section;
   reset(&lock);
         reminder section;
} while(1);
```

Check yourself!

- Is mutual exclusion satisfied?
- Is progress satisfied?
- Is fairness satisfied?

Does not satisfies Fairness

Fetch-and-Add (FAA)

```
 s: shared, a: local
int FAA(int &s, int a)
{
    temp=s;
    s=s+a;
    return temp;
}
```

Critical section using FAA

```
Shared: int s, turn;
Initially: s = 0; turn=0;
Process Pi code:
Entry:
     me = FAA(s,1);
while(turn < me); // busy wait for my turn
     Critical section
Exit:
     FAA(turn,1);
```

Check yourself!
Is mutual exclusion satisfied?
Is progress satisfied?
Is fairness satisfied?

Using hardware primitives directly results in non-portable code

References

- Operating System Concepts (Silberschatz, 8th edition) Chapter 6