OPERATING SYSTEMS: COMMUNICATION AND SYNCHRONIZATION AMONG PROCESSES

Concurrent processes and synchronization

To remember…

Before classes	Class	After class

Prepare the prerequisites.

Study the material associated with the **bibliography**: slides alone are not enough.
Please ask questions (especially after study).

Exercising skills:

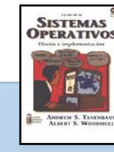
- Perform all **exercises**.
- Carrying out the **practice notebooks** and **the practical exercises** progressively.

Recommended reading

Base

1. Carretero 2020:
   1. Cap. 6
2. Carretero 2007:
   1. Cap. 6.1 and 6.2

Suggested



1. Tanenbaum 2006:
   1. (es) Chap. 5
   2. (en) Chap. 5
2. Stallings 2005:
   1. 5.1, 5.2 and 5.3
3. Silberschatz 2006:
   1. 6.1, 6.2, 6.5 and 6.6

Contents

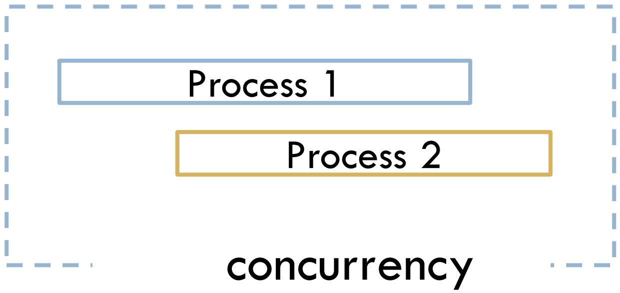
- Introduction (definitions):
  - Concurrent processes.
  - Concurrency, communication and synchronization.
  - Critical section and Race conditions.
  - Mutual exclusion and critical section.
- Synchronization mechanisms (I):
  - Initial basic primitives.
  - Semaphores.
- Classic concurrency problems (I):
  - Producer-consumer
  - Reader-writers
- Synchronization mechanisms of threads (II)
  - Semaphores
    - System calls for semaphores.
    - Classic concurrency problems.
  - Mutex and condition variables
    - System calls for mutex.
    - Classic concurrency problems.
- Case study: concurrent server development

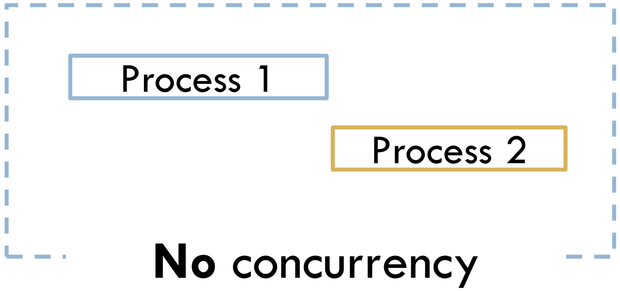
Contents

Concurrent process

- <u>Two processes</u> are <u>concurrent</u> when they run so that their execution intervals overlap.

- By default, the same result is expected in both cases.



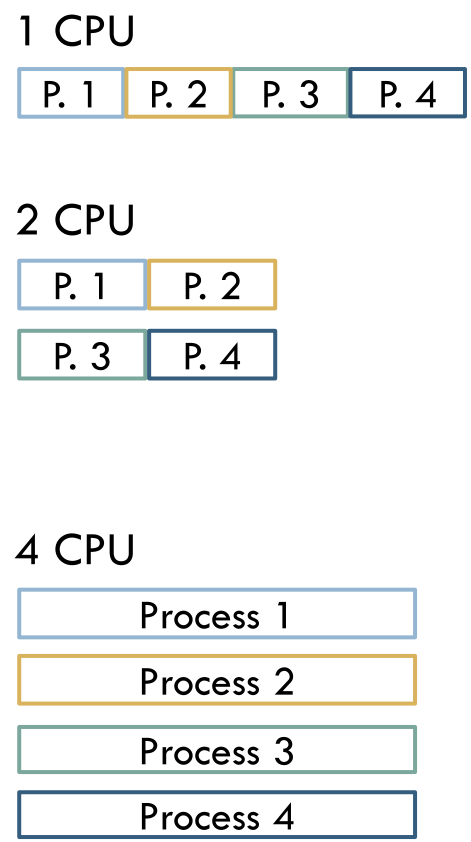


How to achieve concurrence

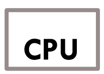
Types of concurrence

- Apparent concurrence:
  There are more processes than processors.
  - Processes are multiplexed in time.
  - Pseudoparallelism.

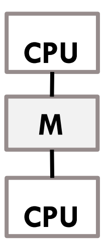
- Real concurrence:
  Each process runs on a processor.
  - The processes are simultaneous in time.
  - Parallel execution occurs.
  - Real parallelism.



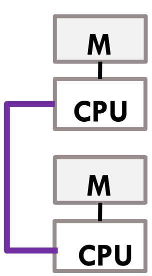
Concurrent programming models



- <u>Multiprogramming</u> with a single processor
  - The operating system is responsible for allocating time among the processes
    - preemptive/non-preemptive scheduling.



- <u>Multiprocessor</u>
  - Real parallelism and pseudo-parallelism combined.
    - Usually more processes than processors (CPU).



- <u>Distributed system</u>
  - Several computers connected by network.

Advantages of concurrent execution

- Facilitates programming.
  - Various tasks can be structured in separate processes.
  - Example: Web server where each process attends to each request.
- Accelerates the execution of calculations.
  - Division of calculations into processes executed in parallel.
  - Example: simulations, electricity market, financial portfolio evaluation.
- Improves CPU utilization.
  - The I/O phases of an application are used for processing other applications.
- Improved interactivity of applications.
  - Processing tasks can be separated from user service tasks.
  - Example: printing and editing.

Disadvantages of concurrent execution

- Resource sharing.
  - Resource sharing needs synchronization.
  - Example: shared variable with updates/reads (w-w, w-r).
- Difficulty in debugging and finding errors.
  - Executions are not always deterministic or reproducible.
  - Examples: particular execution interleaving with problems.
- O.S. Difficulties for optimal resource management.
  - Difficulties of the operating system for optimal resource management.

Interactions between processes

Types of interaction services

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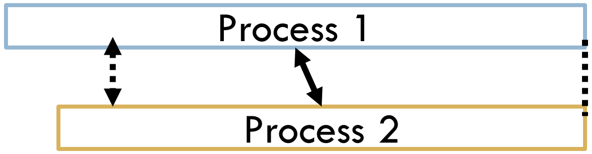
- Communication:
  - Enable the transfer of information between processes.
  - Example: a process sends measured data for processing.
  - Mechanisms: files, pipes, SHARED MEMORY, message passing.
- Synchronization:
  - They allow waiting until an event occurs in another process (stopping its execution until it occurs)
  - Example: a submission process should be waiting for all calculation processes to finish.
  - Mechanisms: signals, pipes, semaphores, mutex, conditions, message passing.



Interactions between processes

Types of concurrent processes

https://www.unf.edu/public/cop4610/ree/Notes/PPT/PPT8E/CH%2005%20-OS8e.pdf

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Relationship	Influence of one process on another	Potential problems

Independents	• **No** communication
	  • Result of one process does not affect others
	• **No** communication
	  • Temporization cannot affect	

Compete	• **No** communication • **Yes** possible synchronization	• Mutual Excl. • Interlock • Starvation

Cooperate	• **Yes** communication
	  • By sharing, with renewable resource (known indirectly)
	  • By communication, with consumable resource (known directly)
	• **Yes** possible synchronization
		• Interlock
		• Starvation
		
		Sharing adds:
		• Mutual Excl.
		• Data consistency

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Interactions between processes

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	• **Yes** possible synchronization
		• Interlock
		• Starvation
		
		Sharing adds:
		• Mutual Excl.
		• Data consistency

Two processes with shared resource
base scenario


```
int acc = 0 ;
```

```
acc += 10 ;
```

```
acc += 20 ;
```

Two processes with shared resource
base scenario

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int acc = 0 ;

acc += 10 ;

acc += 20 ;

acc == 30

By default the result of parallel execution is expected to be equal to sequential execution

Two processes with shared resource
critical section

int acc = 0 ;

acc += 10 ;

critical section:
Segment of code that manipulates a resource (and must be executed atomically: w-w, w-r).

acc += 20 ;

acc == 30

Two processes with shared resource
base scenario


```
int acc = 0 ;
```

Process 1:

```
lw $t0 acc ;
addi $t0 $t0 10;
sw $t0 acc;
```

Non-atomic critical section:
The different speed in the execution of processes allows different interlacing.

Process 2:

```
lw $t0 acc ;
addi $t0 $t0 20;
sw $t0 acc;
```

```
acc ?
```

Two processes with shared resource
race conditions

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```
int acc = 0 ;
```

```
lw $t0 acc ;
addi $t0 $t0 10;
sw $t0 acc;
```

Non-atomic critical section:
The different speed in the execution of processes allows different interlacing.

```
lw $t0 acc ;
addi $t0 $t0 20;
sw $t0 acc;
```

Race condition:
Speed of execution affects the result.

```
acc ?
```

Two processes with shared resource
race conditions


```
int acc = 0 ;
```

```
lw $t0 acc ;
addi $t0 $t0 10;
sw $t0 acc;
```

```
lw $t0 acc ;
addi $t0 $t0 20;
sw $t0 acc;
```

acc ?

Two processes with shared resource
race conditions

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```
int acc = 0 ;
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addi $t0 $t0 10;
sw $t0 acc;
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```
lw $t0 acc ;
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sw $t0 acc;
```

acc ?

Two processes with shared resource
race conditions

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sw $t0 acc;
```

```
acc ?
```

Two processes with shared resource
race conditions

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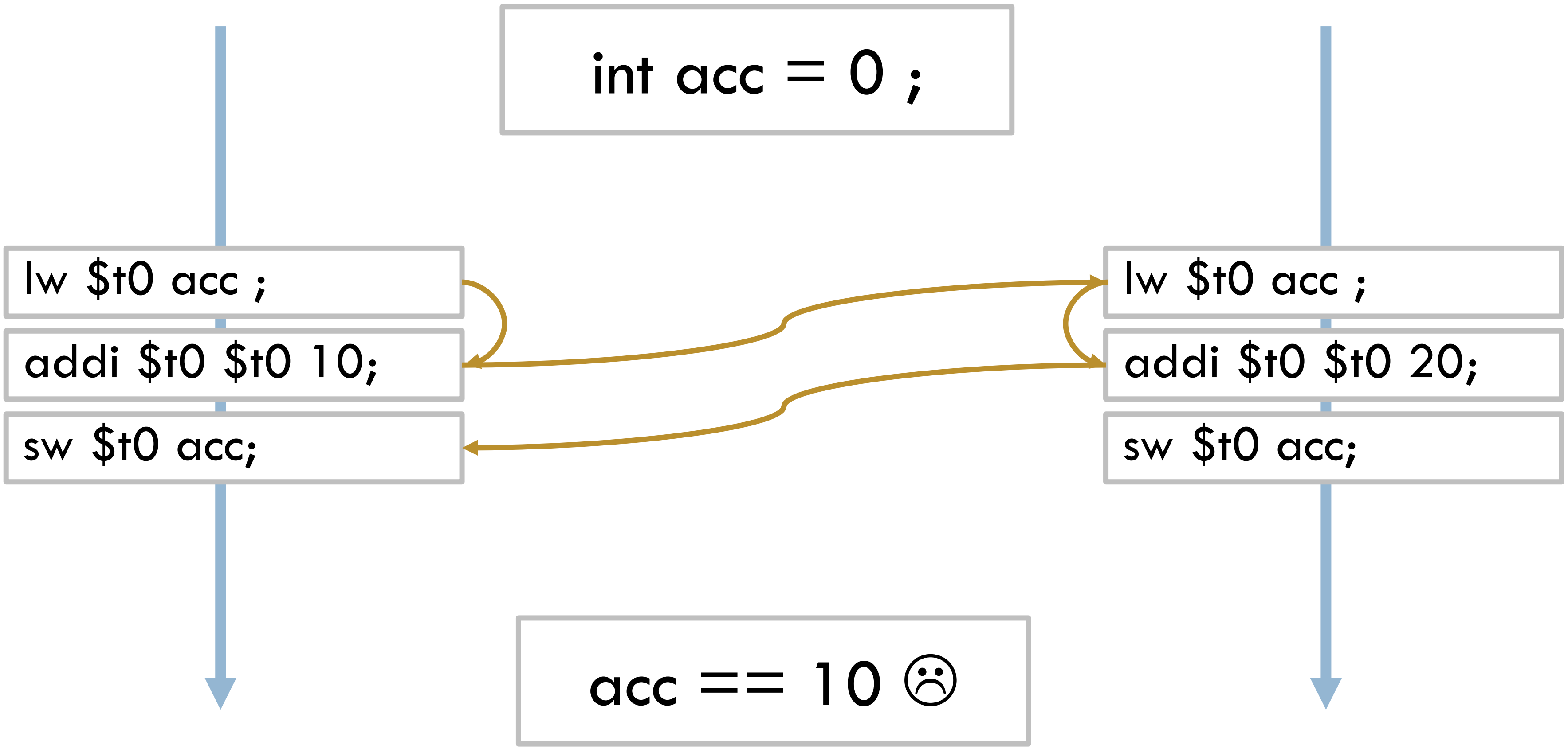

Two processes with shared resource
race conditions

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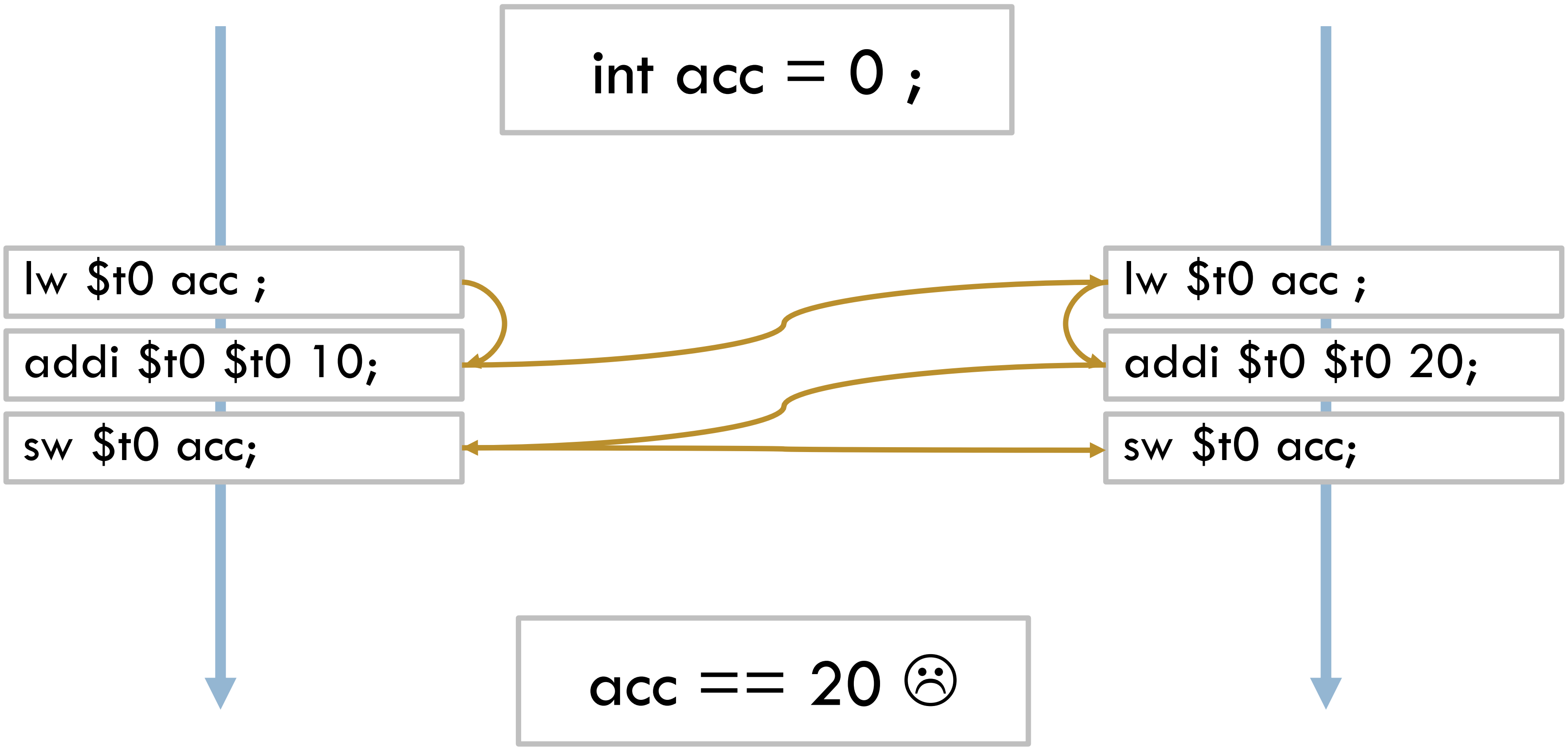

Two processes with shared resource
race conditions

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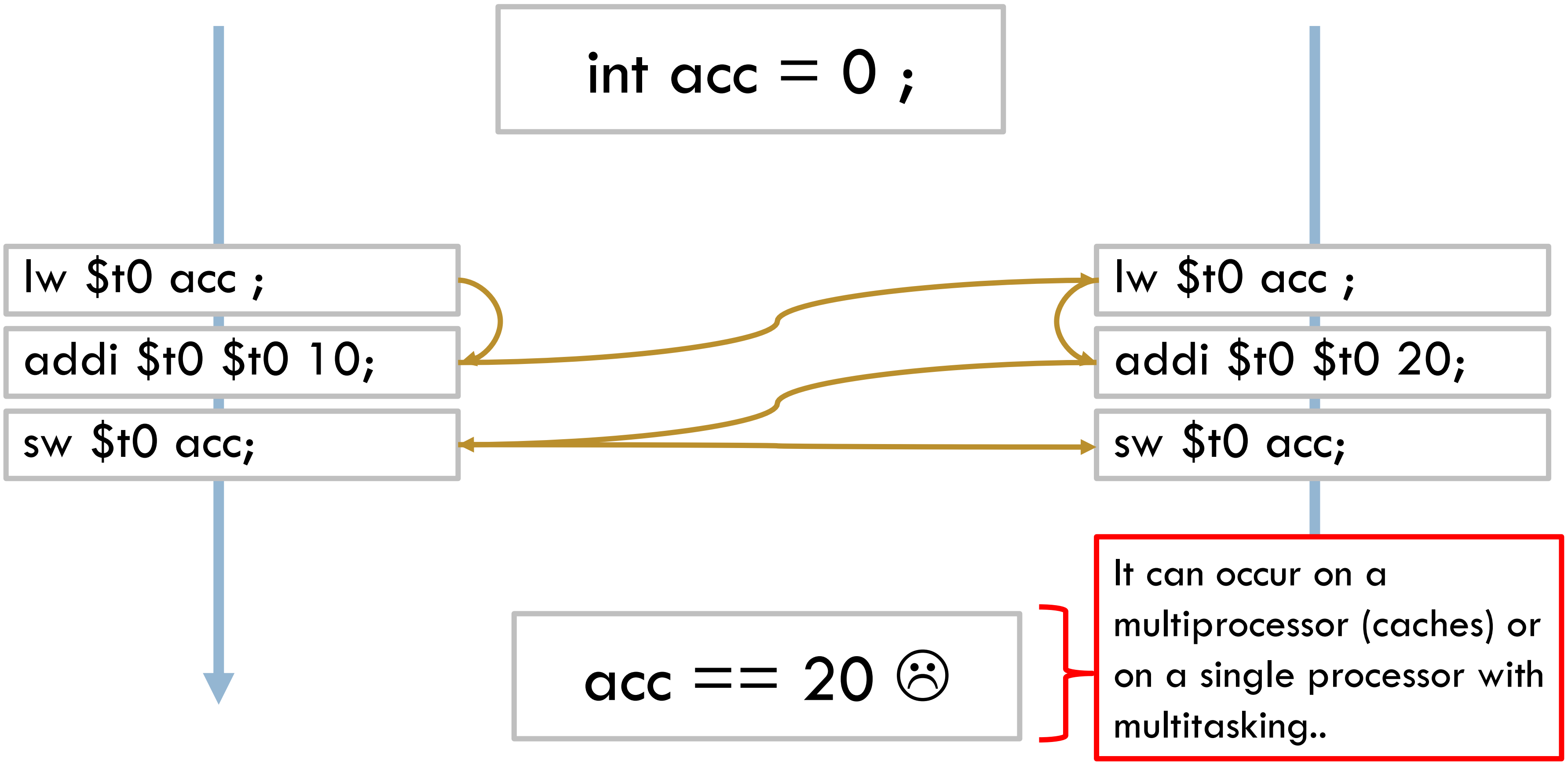

Two processes with shared resource
race conditions

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- It is necessary to ensure that the execution order does not affect the result.
  - The operation of a process and its output must be independent of its relative speed of execution with respect to other processes.

```
lw $t0 acc ;
addi $t0 $t0 10;
sw $t0 acc;
```

```
lw $t0 acc ;
addi $t0 $t0 20;
sw $t0 acc;
```

acc == 30 ☺

Two processes with shared resource
race conditions

- Instructions within the critical section (accessing a variable) must be executed **atomically**:
  - The **critical section of a process** is **mutually exclusive with respect to** the critical sections of **other processes.**

```
lw $t0 acc ;
addi $t0 $t0 10;
sw $t0 acc;
```

Goal:
to ensure that the instructions in the critical section are executed atomically

```
lw $t0 acc ;
addi $t0 $t0 20;
sw $t0 acc;
```

acc == 30 ☺

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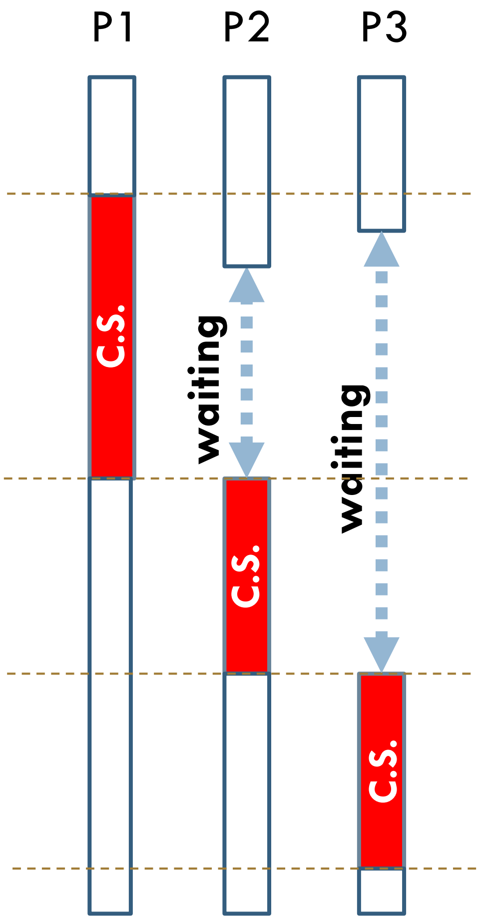
Mutual exclusion (goal)

- **Mutual exclusion:** only one process can be in the critical section of a resource at a time.
  - **critical section:** segment of code that manipulates (w-w, w-r) a resource and must be executed atomically.
  - **Exclusion mechanism:** Mechanism associated with a resource for the management of its mutual exclusion.



Mutual exclusion mechanism

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int acc = 0 ;

Enter in critical section

lw $t0 acc ;

addi $t0 $t0 10;

sw $t0 acc;

Exit from critical section

Exclusion mechanism:

- You have to synchronize the processes.
- Each process when entering C.S. asks for permission.
- Each process informs to leave C.S.

Enter in critical section

lw $t0 acc ;

addi $t0 $t0 20;

sw $t0 acc;

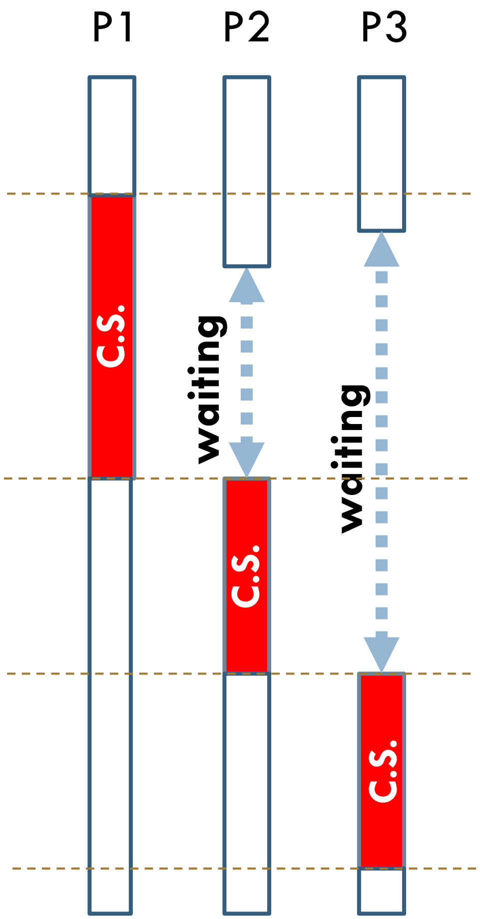
Exit from critical section

acc == 30 ☺

Mutual exclusion mechanism
conditions that must be met

https://www.unf.edu/public/cop4610/ree/Notes/PPT/PPT8E/CH%2005%20-OS8e.pdf

1. **Mutual exclusion**
   It is mandatory that only one process can be simultaneously in the critical section of a resource.
2. **Progress (no deadlock)**
   When no process is in a critical section, any process requesting entry will do so without delay.
3. **Limited waiting time (no starvation)**
   There must be an upper bound on the number of times other processes enter the c.s. after a process asks to enter and before it is granted.
   - A process remains in its critical section for a fixed period of time.
   - No assumptions can be made about the speed of the processes or the number of processors.
   - A process that terminates in its non-critical section must not interfere with other processes.

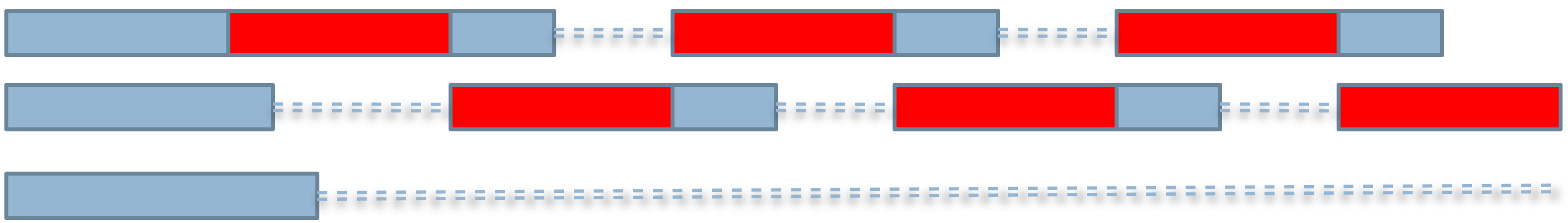


Problems in critical sections
Starvation

- A process is indefinitely blocked while waiting to enter a critical section.
  - The process P1 enters the critical section of the resource A.
  - The process P2 request to enter the critical section of the resource A.
  - The process P3 request to enter the critical section of the resource A.
  - The process P1 leaves the critical section of the resource A.
  - The process P2 enters the critical section of the resource A.
  - The process P1 request to enter the critical section of the resource A.
  - The process P2 leaves the critical section of the resource A.
  - The process P1 enters the critical section of the resource A.
  - …

The process P3 never manages to enter the critical section of resource A

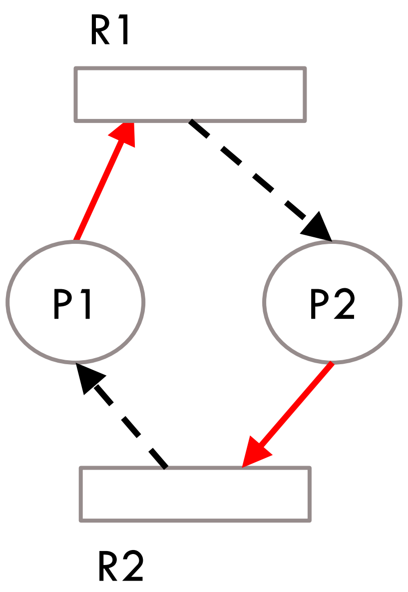
Problems in critical sections
Starvation



The P3 process never manages to enter the critical section

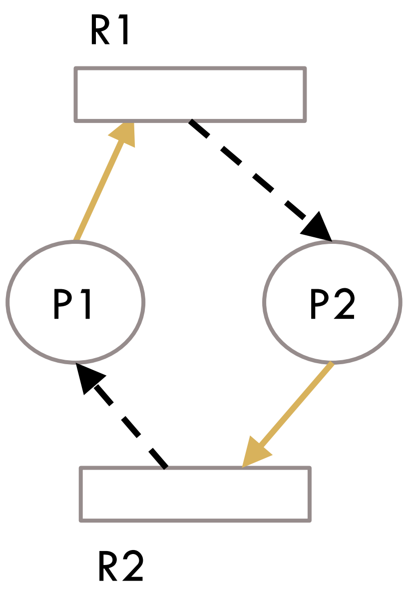
Problems in critical sections
Interlocks

- It occurs with mutual exclusion for more than one resource, the following conditions are necessary:
  1. **Mutual exclusion:** only one process can use a resource at a time. If another process requests that resource, it must wait until it is free.



Problems in critical sections
Interlocks

- It occurs with mutual exclusion for more than one resource, the following conditions are necessary:
  1. **Mutual exclusion:** only one process can use a resource at a time. If another process requests that resource, it must wait until it is free.
  2. **Retention and waiting:** a process retains some resources while waiting for other resources to be allocated to it.



Problems in critical sections
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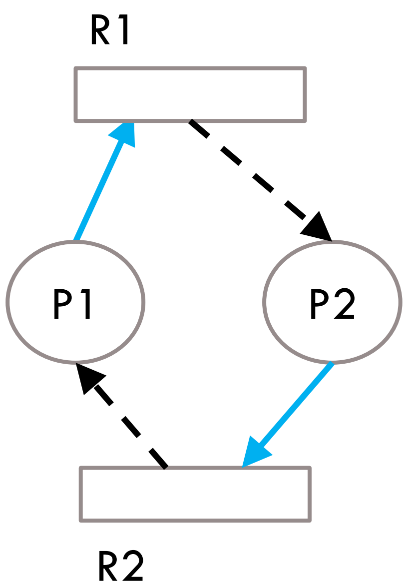
  2. **Retention and waiting:** a process retains some resources while waiting for other resources to be allocated to it.
  3. **No expropriation:** a process cannot be forced to abandon a resource that retains.



Problems in critical sections
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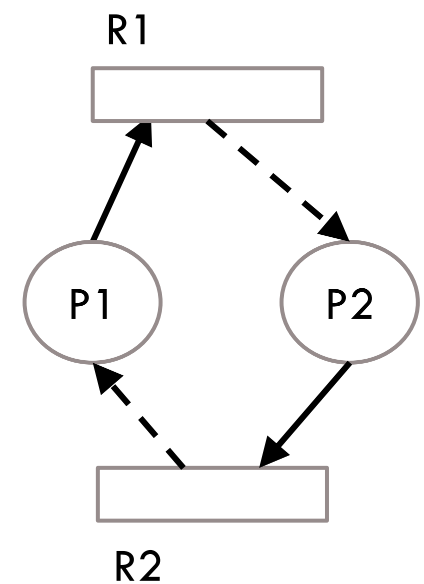
1. **Mutual exclusion**: only one process can use a resource at a time. If another process requests that resource, it must wait until it is free.
2. **Retention and waiting**: a process retains some resources while waiting for other resources to be allocated to it.
3. **No expropriation**: a process cannot be forced to abandon a resource that retains.
4. **Circular waiting**: there exists a closed chain of processes $\{P_0, \ldots, P_n\}$ in which each process has a resource and waiting for a resource from the next process in the chain.



None can move forward

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Implementation alternatives

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- Approach by software:
  - **Dekker** (Dijkstra, with 4 attempts)
  - **Peterson**
  - …
- Approach by hardware:
  - **Disable interruptions.**
    - Only valid on single-processor systems (and non-interruptible process).
  - **Special machine instructions:** test_and_set or swap.
    - Implies active waiting (misused starvation and interlocking are possible).
- Support from O.S. (and programming language):
  - **Semaphores**
  - **Monitors**
  - **Message Passing**
  - …

(1) Knowing Mechanisms and how to use them for mutual exclusion.

(2) To know how to implement some Mechanisms in function of others.

Type approx.	Mechanism	semaphores	locks	conditions	…
software	Dekker	…	…	…	…
	Petterson	…	…	…	…
	…	…	…	…	…
hardware	Disable interrupts.	…	…	…	…
	test_and_set	…	…	…	…
	swap	…	…	…	…
	…	…	…	…	…
O.S. + lenguage	semaphores	…	…	…	…
	locks	…	…	…	…
	conditions	…	…	…	…
	monitors	…	…	…	…
	message passing	…	…	…	…
	…	…	…	…	…

Contents

Test-and-set

- Test-and-set instruction
  - Active wait
  - No cache in 'lock'

```
while (test_and_set(&lock) == 1) ;

critical section

lock = 0;

remainder section
```

```
volatile int lock = 0 ;

while (test_and_set(&lock) == 1) ;

critical section

lock = 0;

remainder section
```

Peterson's solution

- Limitations:
  - ONLY for 2 processes.
  - Assumes LOAD and STORE instructions are atomic, not interruptible.

- The 2 processes share 2 variables:
  - **int turn;**
    - indicates who will enter the critical section.
    - turn = 1 implies that P_1 will enter.
  - **bool flag[2];**
    - indicates if a process intends to enter the critical section.
    - flag[i] = true implies that Pi is ready to enter.

Peterson: algorithm for process P_i

2 processes: P_i y P_j (with j=1- i)

- i=0 => j=1 (1- i)
- i=1 => j=0 (1- i)

```
do
{
  flag[j] = TRUE;
  turn = i;
  while (flag[i] &&
         turn == i);

  critical section

  flag[j] = FALSE;
  remainder section
} while (TRUE);
```

```
do
{
  flag[i] = TRUE;
  turn = j;
  while (flag[j] && turn == j);

  critical section

  flag[i] = FALSE;
  remainder section
} while (TRUE);
```

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Semaphores (Dijkstra)

- A semaphore can be viewed as an integer variable with three associated atomic operations.
- Associated atomic operations:
  - **Initiation** to a non-negative value.
  - **semWait**:
    - Decrements the semaphore counter and if (s<0) ➔ The calling process is blocked.
  - **semSignal**:
    - Increases the value of the semaphore and if (s<=0) ➔ Unblocks one process.

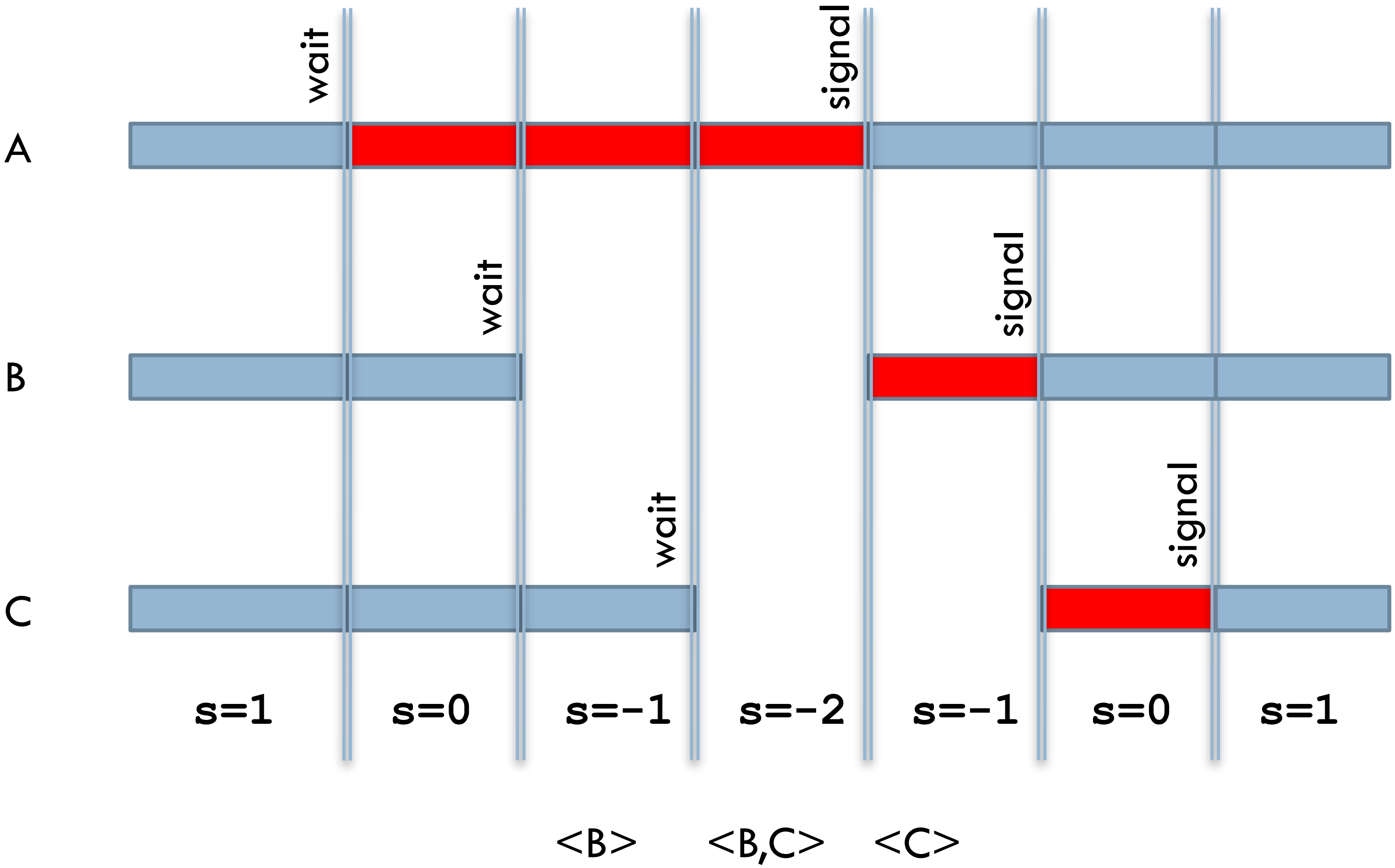
Critical sections and semaphores

- A semaphore is associated with the critical section of a resource:
  - semaphore **initiated to 1**.
- **semWait**: enter to the critical section.
- **semSignal**: exit from critical section.

```
s = 1 ;


// non-critical section
…
semWait(s);
// critical section
semSignal(s);
…
// non-critical section
```

Critical sections and semaphores



Examples of the use of semaphores

S.M.:

```
semaphore s=0;
```

A:

```
...
P(s);
...
```

B:

```
...
V(s);
...
```

"The signal"

S.M.:

```
semaphore s=1;
```

A:

```
P(s);
<SC>
V(s);
```

B:

```
P(s);
<SC>
V(s);
```

"The mutex"

S.M.:

```
semaphore s=10;
```

A:

```
P(s);
<max. 10>
V(s);
```

B:

```
P(s);
<max. 10>
V(s);
```

"The team"

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Classic concurrency problems

Type approx.	Mechanism	P-C	RR-WW	…
software	**Dekker**	P-C with Dekker	…	…
	Petterson	P-C with Petterson	<no aplica +2>	…
	…	…	…	…
hardware	**Disable interrupts.**	…	…	…
	test_and_set	…	…	…
	swap	…	…	…
	…	…	…	…
O.S. + lenguage	**semaphores**	**P-C with sem.**	**RR-WW with sem.**	…
	locks	…	…	…
	conditions	…	…	…
	monitors	…	…	…
	message passing	…	…	…
	…	…	…	…

Classic concurrency problems

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Type approx.	Mechanism	P-C	RR-WW	…
		P-C with Dekker	…	…
		P-C with Petterson	<no aplica +2>	…
		…	…	…
		…	…	…
		…	…	…
		…	…	…
		…	…	…
	semaphores	**P-C with sem.**	**RR-WW with sem.**	…
		…	…	…
		…	…	…
		…	…	…
		…	…	…
		…	…	…

(1) Know the classic concurrency problems to detect when they appear [*].

- P-C: producer-consumer
- RR-WW: reader and writer
- …

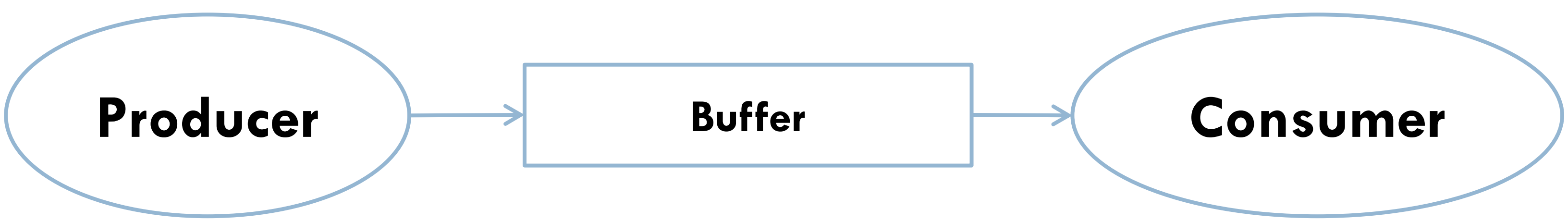
[*] 1 or a combination of several may appear.

(2) Know the solution to classic concurrency problems to be used as templates when they appear.

Contents

The producer-consumer problem

- A process produces information elements.
- A process consumes information elements.
- There is an intermediate storage space.
  - Infinite
  - Bounded (end_iite in size N)



Infinite buffer

Synchronization must be introduced

SHARED MEMORY:

```
int  begin_i, end_i;
char v[N];
```

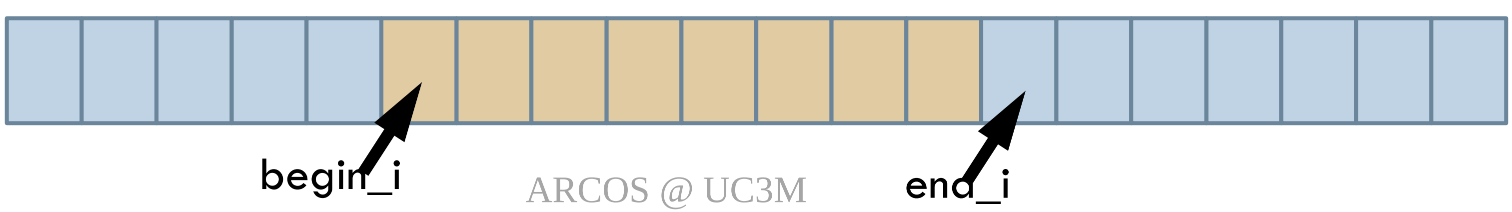
PRODUCER:

```
for (;;) {
  x= produce();
  v[end_i] = x;
  end_i++;
}
```

CONSUMIDOR:

```
for (;;) {
  while (begin_i==end_i) {}
  y=v[begin_i];
  begin_i++;
  processing(y);
}
```

Active wait



Infinite buffer

SHARED MEMORY:

```
int  begin_i, end_i;
char v[N];
semaphore s=1;
```

PRODUCER:

```
for (;;) {
  x= produce();
  semWait(s);
  v[end_i] = x;
  end_i++;
  semSignal(s);
}
```

CONSUMIDOR:

```
for (;;) {
  while (begin_i==end_i) {}
  semWait(s);
  y=v[begin_i];
  begin_i++;
  semSignal(s);
  processing(y);
}
```

Active wait

Infinite buffer

https://computationstructures.org/lectures/synchronization/synchronization.html

Alejandro Calderón Mateos

SHARED MEMORY:

```
int  begin_i, end_i;
char v[N];
semaphore s=1; semaphore n=0;
```

PRODUCER:

```
for (;;) {
  x= produce();
  semWait(s);
  v[end_i] = x;
  end_i++;
  semSignal(s);
  semSignal(n);
}
```

CONSUMIDOR:

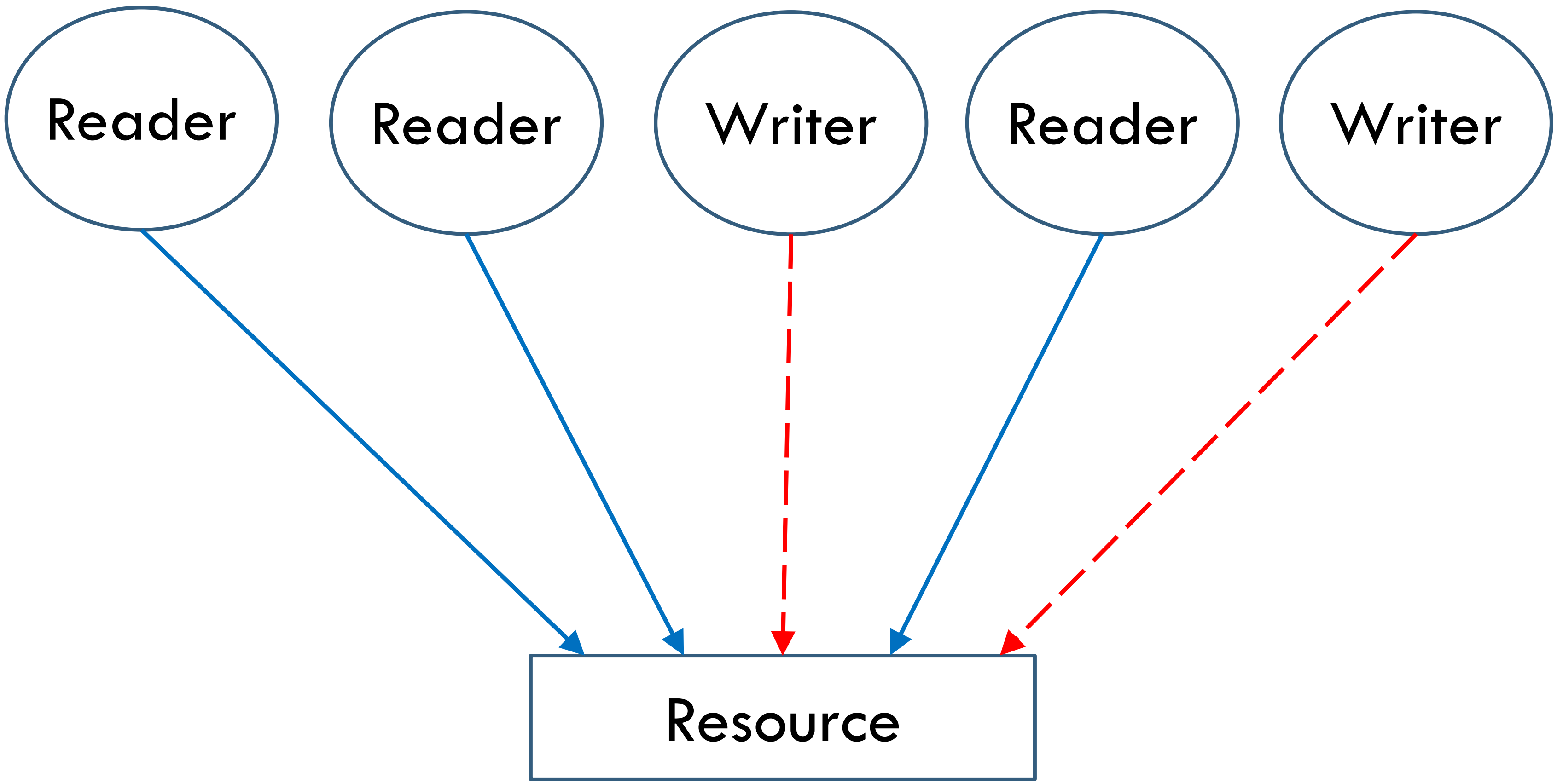
```
for (;;) {
  semWait(n);
  semWait(s);
  y=v[begin_i];
  begin_i++;
  semSignal(s);
  processing(y);
}
```

Contents

Reader-writer problem

- Problem that arises when you have:
  - A shared storage area.
  - Multiple processes read information.
  - Multiple processes write information.
- Conditions:
  - Any number of readers can read from the data zone concurrently: multiple readers possible at the same time.
  - Only one writer can modify the information at a time.
  - During a writing no reader can read.

Reader-writer problem



Differences with other problems

- Mutual exclusion:
  - In the case of mutual exclusion, only one process would be allowed to access the information.
  - No concurrence among readers would be allowed.
- Producer consumer:
  - In the producer/consumer two readers do not need to be mutually exclusive in the critical section.
  - Goal: provide a more efficient solution.

Management alternatives

A. Readers have priority.
- If there are any readers in the critical section, then other readers can enter.
- A writer can only enter the critical section if there is no process.
- **Problem**: starvation for writers.

B. Writers have priority.
- When a writer wishes to access the critical section, new readers are not allowed to enter.

Readers have priority (1/4)
writer interaction (critical section)

http://faculty.juniata.edu/rhodes/os/ch5d.htm
Alejandro Calderón Mateos

SHARED MEMORY:

```
int nlect; semaphore lec=1; semaphore escr=1;
```

WRITER:

```
for(;;) {
  semWait(escr);
  perform_write();
  semSignal(escr);
}
```

Readers have priority (2/4)

reader interaction with each other

http://faculty.juniata.edu/rhodes/os/ch5d.htm

SHARED MEMORY:

```
int nlect; semaphore lec=1; semaphore escr=1;
```

READER:

```
for(;;) {
  semWait(lec);
  nlect++;
  if (nlect==1)
      semWait(escr);
  semSignal(lec);

  perform_read();

  semWait(lec);
  nlect--;
  if (nlect==0)
      semSignal(escr);
  semSignal(lec);
}
```

WRITER:

```
for(;;) {
  semWait(escr);
  perform_write();
  semSignal(escr);
}
```

Readers have priority (3/4)

several readers with one writer

http://faculty.juniata.edu/rhodes/os/ch5d.htm

Alejandro Calderón Mateos

SHARED MEMORY:

```
int nlect; semaphore lec=1; semaphore escr=1;
```

READER:

```
for(;;) {
  semWait(lec);
  nlect++;
  if (nlect==1)
      semWait(escr);
  semSignal(lec);

  perform_read();

  semWait(lec);
  nlect--;
  if (nlect==0)
      semSignal(escr);
  semSignal(lec);
}
```

WRITER:

```
for(;;) {
  semWait(escr);
  perform_write();
  semSignal(escr);
}
```

TIP: nlect is incremented and queried NON-atomically between readers…

Readers have priority (4/4)

several readers with one writer

http://faculty.juniata.edu/rhodes/os/ch5d.htm

Alejandro Calderón Mateos

SHARED MEMORY:

```
int nlect; semaphore lec=1; semaphore escr=1;
```

READER:

```
for(;;) {
  semWait(lec);
  nlect++;
  if (nlect==1)
      semWait(escr);
  semSignal(lec);

  perform_read();

  semWait(lec);
  nlect--;
  if (nlect==0)
      semSignal(escr);
  semSignal(lec);
}
```

WRITER:

```
for(;;) {
  semWait(escr);
  perform_write();
  semSignal(escr);
}
```

Readers have priority

http://faculty.juniata.edu/rhodes/os/ch5d.htm
Alejandro Calderón Mateos

SHARED MEMORY:

```
int nlect; semaphore lec=1; semaphore escr=1;
```

READER:

```
for(;;) {
  semWait(lec);
  nlect++;
  if (nlect==1)
      semWait(escr);
  semSignal(lec);

  perform_read();

  semWait(lec);
  nlect--;
  if (nlect==0)
      semSignal(escr);
  semSignal(lec);
}
```

WRITER:

```
for(;;) {
  semWait(escr);
  perform_write();
  semSignal(escr);
}
```

Task: Design a solution for priority writers

Writers have priority

Alejandro Calderón Mateos

SHARED MEMORY:

```
int nlect, nescr = 0;  semaphore lect, escr = 1;
semaphore x, y, z = 1;
```

READER:

```
for(;;) {
      semWait(z);
      semWait(lect);
      semWait(x);
         nlect++;
         if (nlect==1)
             semWait(escr);
      semSignal(x);
      semSignal(lect);
      semSignal(z);
         // doReading();
      semWait(x);
         nlect--;
         if (nlect==0)
             semSignal(escr);
      semSignal(x);
}
```

WRITER:

```
for(;;) {
   semWait(y);
      nescr++;
      if (nescr==1)
          semWait(lect);
   semSignal(y);
   semWait(escr);
      // doWriting();
   semSignal(escr);
   semWait(y);
      nescr--;
      if (nescr==0)
          semSignal(lect);
   semSignal(y);
}
```

OPERATING SYSTEMS: COMMUNICATION AND SYNCHRONIZATION AMONG PROCESSES

Concurrent processes and synchronization