Sistemi in tempo reale
Anno accademico 2006 - 2007
Concorrenza - II

Giuseppe Lipari
http://feanor.sssup.it/~lipari

Scuola Superiore Sant'Anna
Outline

1 Introduction to concurrency

2 Models of concurrency: shared memory
   - Critical Sections
   - Synchronization

3 Semaphores

4 Solutions
The need for concurrency

There are many reason for concurrency

- functional
- performance
- expressive power

Functional

- many users may be connected to the same system at the same time
  - each user can have its own processes that execute concurrently with the processes of the other users
- perform many operations concurrently
  - for example, listen to music, write with a word processor, burn a CD, etc...
  - they are all different and independent activities
  - they can be done at the same time
The need for concurrency (2)

Performance
- take advantage of blocking time
  - while some thread waits for a blocking condition, another thread performs another operation
- parallelism in multi-processor machines
  - if we have a multi-processor machine, independent activities can be carried out on different processors at the same time

Expressive power
- many control application are inherently concurrent
- concurrency support helps in expressing concurrency, making application development simpler
Concurrency model

- a system is a set of **concurrent activities**
  - they can be processes or threads
- they interact in two ways
  - they access the hardware resources (processor, disk, memory, etc.)
  - they exchange data
- these activities **compete** for the resources and/or **cooperate** for some common objective
Resources

- a resource can be
  - a HW resource like a I/O device
  - a SW resource, i.e. a data structure
  - in both cases, access to a resource must be regulated to avoid interference

example 1
- if two processes want to print on the same printer, their access must be sequentialised, otherwise the two printing could be intermangled!

example 2
- if two threads access the same data structure, the operation on the data must be sequentialized otherwise the data could be inconsistent!
Interaction model

Activities can interact according to two fundamental models:

- **shared memory**
  - All activities access the same memory space

- **message passing**
  - All activities communicate each other by sending messages through OS primitives

- We will analyse both models in the following slides
Outline

1. Introduction to concurrency

2. Models of concurrency: shared memory
   - Critical Sections
   - Synchronization

3. Semaphores

4. Solutions
Shared memory

Shared memory communication
- it was the first one to be supported in old OS
- it is the simplest one and the closest to the machine
- all threads can access the same memory locations
Mutual Exclusion Problem

- We do not know in advance the relative speed of the processes
  - hence, we do not know the order of execution of the hardware instructions
- Recall the example of incrementing variable x
  - incrementing x is not an atomic operation
  - atomic behaviour can be obtained using interrupt disabling or special atomic instructions
Example 1

```c
/* Shared memory */
int x;

void *threadA(void *)
{
    ...;
    x = x + 1;
    ...;
}

void *threadB(void *)
{
    ...;
    x = x + 1;
    ...;
}
```

- **Bad Interleaving:**

```
LD    R0, x   (TA)  x = 0
LD    R0, x   (TB)  x = 0
INC   R0     (TB)  x = 0
ST x, R0    (TB)  x = 1
INC   R0     (TA)  x = 1
ST x, R0    (TA)  x = 1
...```

Example 2

```c
// Shared object (sw resource)
class A {
    int a;
    int b;
public:
    A() : a(1), b(1) {};
    void inc() {
        a = a + 1; b = b + 1;
    }
    void mult() {
        b = b * 2; a = a * 2;
    }
} obj;

void * threadA(void *)
{
    ...
    obj.inc();
    ...
}

void * threadB(void *)
{
    ...
    obj.mult();
    ...
}
```
Example 2

// Shared object (sw resource)
class A {
    int a;
    int b;
public:
    A() : a(1), b(1) {};
    void inc() {
        a = a + 1; b = b + 1;
    }
    void mult() {
        b = b * 2; a = a * 2;
    }
} obj;

Consistency:
After each operation, a == b

void * threadA(void *)
{
    ...;
    obj.inc();
    ...
}

void * threadB(void *)
{
    ...
    obj.mult();
    ...
}
Example 2

```cpp
// Shared object (sw resource)
class A {
  int a;
  int b;
public:
  A() : a(1), b(1) {};
  void inc() {
    a = a + 1; b = b + 1;
  }
  void mult() {
    b = b * 2; a = a * 2;
  }
} obj;

Consistency:
After each operation, a == b
```

```
<table>
<thead>
<tr>
<th>Operation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a = a + 1;</td>
<td>TA a = 2</td>
</tr>
<tr>
<td>b = b + 1;</td>
<td>TA b = 3</td>
</tr>
<tr>
<td>a = a * 2;</td>
<td>TB a = 4</td>
</tr>
</tbody>
</table>
```

```cpp
void * threadA(void *)
{
  ...
  obj.inc();
  ...
}
```

```cpp
void * threadB(void *)
{
  ...
  obj.mult();
  ...
}
```
Example 2

// Shared object (sw resource)
class A {
  int a;
  int b;

public:
  A() : a(1), b(1) {};
  void inc() {
    a = a + 1; b = b +1;
  }
  void mult() {
    b = b * 2; a = a * 2;
  }
  obj;
}

Consistency:
After each operation, a == b

void * threadA(void *)
{
  ...
  obj.inc();
  ...
}

void * threadB(void *)
{
  ...
  obj.mult();
  ...
}

Resource in a non-consistent state!!
Consistency

- for any resource, we can state a set of consistency properties
  - a consistency property $C_i$ is a boolean expression on the values of the internal variables
  - a consistency property must hold before and after each operation
  - it does not need to hold during an operation
  - if the operations are properly sequentialized, the consistency properties will always hold

formal verification

- let $R$ be a resource, and let $C(R)$ be a set of consistency properties on the resource
  - $C(R) = \{C_i\}$
- A concurrent program is correct if, for every possible interleaving of the operations on the resource, $\forall C_i \in C(R)$, $C_i$ holds.
Example: Circular Array
Implementation of a FIFO queue.

```c
struct CA {
    int array[10];
    int head, tail, num;
};

void init(struct CA * ca) {
    ca->head=0; ca->tail=0;
    ca->num=0;
}

boolean insert(struct CA * ca, int elem) {
    if (ca->num == 10) return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head + 1) % 10;
    ca->num ++;
    return true;
}

boolean extract(struct CA * ca, int * elem) {
    if (ca->num == 0) return false;
    *elem = ca->array[ca->tail];
    ca->tail = (ca->tail + 1) % 10;
    ca->num--;
    return true;
}
```
Example: empty queue

- head: index of the first free element in the queue
- here will be inserted the next element
Example: empty queue

- head: index of the first free element in the queue
  - here will be inserted the next element
- tail: index of the first occupied element in the queue
  - will be the one that will be extracted next time
Example: empty queue

- **head**: index of the first free element in the queue
  - Here will be inserted the next element
- **tail**: index of the first occupied element in the queue
  - Will be the one that will be extracted next time
- The queue is empty, hence head == tail
Example: insert

```c
boolean insert(struct CA *ca, int elem) {
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```
Example: insert

```c
boolean insert(struct CA *ca, int elem) {
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```

num = (head - tail) % 8 \rightarrow num = 4;
Example: insert

```
boolean insert(struct CA * ca, int elem)
{
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```

- num = (head - tail) % 8 → num = 4;
- insert(ca, 9);
Example: insert

- $\text{num} = (\text{head} - \text{tail}) \mod 8 \rightarrow \text{num} = 4$
- $\text{insert}(\text{ca}, 9)$
- head and num have been increased

```
boolean insert(struct CA * ca, int elem)
{
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1) % 10;
    ca->num++;
    return true;
}
```
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);

```c
boolean insert(struct CA *ca, int elem) {
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
}
```
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);

```c
boolean insert(struct CA *ca, int elem) {
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
}
```
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);
- preemption by second thread

```c
boolean insert(struct CA *ca, int elem) {
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
}
```
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);
- preemption by second thread

```c
boolean insert(struct CA *ca, int elem) {
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head + 1) % 10;
    ca->num++;
    return true;
}
```
Example: concurrent insert

- Two threads, the first calls `insert(9)`, the second calls `insert(4)`;
- thread 1 calls `insert(ca, 9)`;
- preemption by second thread.

```c
boolean insert(struct CA *ca, int elem) {
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);
- preemption by second thread

```c
boolean insert(struct CA *ca, int elem)
{
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```
Example: concurrent insert

- Two threads, the first calls `insert(9)`, the second calls `insert(4)`;
- thread 1 calls `insert(ca, 9)`;
- preemption by second thread
- second thread completes

```c
boolean insert(struct CA *ca, int elem)
{
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```
Example: concurrent insert

- Two threads, the first calls insert(9),
  the second calls insert(4);
- thread 1 calls insert(ca, 9);
- preemption by second thread
- second thread completes

```c
boolean insert(struct CA *ca, int elem)
{
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```
Example: concurrent insert

- Two threads, the first calls `insert(9)`, the second calls `insert(4)`;
- thread 1 calls `insert(ca, 9)`;
- preemption by second thread
- second thread completes

```c
boolean insert(struct CA *ca, int elem)
{
    if (ca->num == 10)
        return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```
Example: concurrent insert

- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);
- preemption by second thread
- second thread completes
- there is a hole! At some point, the extract will read a 4 and a random value, instead of a 9 and a 4.

```c
boolean insert(struct CA *ca, int elem)
{
    if (ca->num == 10) return false;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    ca->num++;
    return true;
}
```
Consistency properties for struct CA

- when the queue is empty, or when the queue is full, 
  \( \text{head} == \text{tail} \)
- \( \text{num} \) is equal to the number of times \text{insert} has been called minus the number of times that \text{extract} has been called
- ...
- if element \( x \) has been inserted, eventually it must be extracted with an appropriate number of extracts
- Every element that is extracted, has been inserted sometime in the past.

Last two can also be expressed as:
- Let \((x_1, x_2, \ldots, x_k)\) be the sequence of inserted elements, and let \((y_1, y_2, \ldots, y_k)\) be the sequence of extracted elements;
- then \( \forall i = 1, \ldots, k \quad y_i = x_i \)
Correctness of Circular Array implementation

- The previous program is not correct, as the last property is not verified
  - the sequence of elements extracted does not correspond to the sequence of elements inserted
  - The problem is that the first thread was preempted while updating the data structure in a critical point.
  - we must prevent thread 2 from accessing the data structure while another thread is completing an operation on it
- Proving non-correctness is easy, in the sense that we must find a counterexample
- Proving correctness is a very complex task!
  - it is necessary to prove the correctness for every possible interleaving of every operation, for every possible input data, and for every possible internal state
Insert and Extract

Let's assume that increments and decrements are atomic operations

- **Producer**: thread that inserts elements
- **Consumer**: thread that extracts elements

It can be proved that interleaving exactly one producer and one consumer does not bring any problem

- **proof**: if $0 < num < 10$, `insert()` and `extract()` are independent
- If `num==0`
  - If `extract()` begins before `insert`, it immediately returns false,
  - If `insert` begins before, `extract` will still return false, so it cannot interfere with `insert`
- Same thing when `num==10`

Correctness is guaranteed for one consumer and one producer.
What happens if we exchange the sequence of instructions in `insert`?

```c
boolean insert(struct CA *ca,
               int elem)
{
    if (ca->num == 10)
        return false;
    ca->num++;  // Change here
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    return true;
}
```
What happens if we exchange the sequence of instructions in insert?

```c
boolean insert(struct CA *ca,
               int elem)
{
    if (ca->num == 10)
        return false;
    ca->num++;
    ca->array[ca->head] = elem;
    ca->head = (ca->head+1)%10;
    return true;
}
```

It is easy to prove that in this case `insert()` cannot be interleaved with `extract`. 
Outline

1. Introduction to concurrency

2. Models of concurrency: shared memory
   - Critical Sections
   - Synchronization

3. Semaphores

4. Solutions
Critical sections

- the shared object where the conflict may happen is a resource
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called **critical sections**
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called critical sections
- a critical section is a sequence of operations that cannot be interleaved with other operations on the same resource
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called critical sections
- a critical section is a sequence of operations that cannot be interleaved with other operations on the same resource
- two critical sections on the same resource must be properly sequentialized
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called critical sections
- a critical section is a sequence of operations that cannot be interleaved with other operations on the same resource
- two critical sections on the same resource must be properly sequentialized
- we say that two critical sections on the same resource must execute in MUTUAL EXCLUSION
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called critical sections
- a critical section is a sequence of operations that cannot be interleaved with other operations on the same resource
- two critical sections on the same resource must be properly sequentialized
- we say that two critical sections on the same resource must execute in mutual exclusion
- there are three ways to obtain mutual exclusion
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called critical sections
- a critical section is a sequence of operations that cannot be interleaved with other operations on the same resource
- two critical sections on the same resource must be properly sequentialized
- we say that two critical sections on the same resource must execute in MUTUAL EXCLUSION
- there are three ways to obtain mutual exclusion
  - implementing the critical section as an atomic operation
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called critical sections
- a critical section is a sequence of operations that cannot be interleaved with other operations on the same resource
- two critical sections on the same resource must be properly sequentialized
- we say that two critical sections on the same resource must execute in **MUTUAL EXCLUSION**
- there are three ways to obtain mutual exclusion
  - implementing the critical section as an atomic operation
  - disabling the preemption (system-wide)
Critical sections

- the shared object where the conflict may happen is a resource
- the parts of the code where the problem may happen are called **critical sections**
- a critical section is a sequence of operations that cannot be interleaved with other operations on the same resource
- two critical sections on the same resource must be properly sequentialized
- we say that two critical sections on the same resource must execute in **mutual exclusion**
- there are three ways to obtain mutual exclusion
  - implementing the critical section as an atomic operation
  - disabling the preemption (system-wide)
  - selectively disabling the preemption (using semaphores and mutex)
Implementing atomic operations

- In single processor systems
  - disable interrupts during a critical section
  - non-voluntary context switch is disabled

CLI;
<critical section>
STI;
Implementing atomic operations

- In single processor systems
  - disable interrupts during a critical section
  - non-voluntary context switch is disabled!

- Limitations:
  - if the critical section is long, no interrupt can arrive during the critical section
    - consider a timer interrupt that arrives every 1 msec.
    - if a critical section lasts for more than 1 msec, a timer interrupt could be lost
      - It must be done only for very short critical section;
  - Non voluntary context switch is disabled during the critical section
    - Disabling interrupts is a very low level solution: it is not possible in user space.
Atomic operations on multiprocessors

- Disabling interrupts is not sufficient
  - disabling interrupts on one processor lets a thread on another processor free to access the resource
- Solution: use `lock()` and `unlock()` operations
  - define a flag for each resource, and then surround a critical section with `lock(s)` and `unlock(s)`;

```c
int s;
...
lock(s);
<critical section>
unlock(s);
...
```
Disabling preemption

- On single processor systems
  - in some scheduler, it is possible to disable preemption for a limited interval of time
- problems:
  - if a high priority critical thread needs to execute, it cannot make preemption and it is delayed
  - even if the high priority task does not access the resource!

```c
disable_preemption();
<critical section>
enable_preemption();
```

no context switch may happen during the critical section, but interrupts are enabled
Critical sections: a general approach

- General techniques exists to protect critical sections
  - Semaphores
  - Mutex
- Properties:
  - Interrupts always enabled
  - Preemption always enabled
- Basic idea:
  - if a thread is inside a critical section on a given resource
  - all other threads are blocked upon entrance on a critical section on the same resource
- We will study such techniques in the following
Outline

1. Introduction to concurrency

2. Models of concurrency: shared memory
   - Critical Sections
   - Synchronization

3. Semaphores

4. Solutions
Producer / Consumer model

- mutual exclusion is not the only problem
  - we need a way of synchronise two or more threads
- example: producer/consumer
  - suppose we have two threads,
  - one produces some integers and sends them to another thread (PRODUCER)
  - another one takes the integer and elaborates it (CONSUMER)
Implementation with the circular array

Suppose that the two threads have different speeds
  for example, the producer is much faster than the consumer
  we need to store the temporary results of the producer in
      some memory buffer
  for our example, we will use the circular array structure
Producer/Consumer implementation

```c
#include "queue.h"

struct CA qu;

void *producer(void *)
{
    bool res;
    int data;
    while(1) {
        <obtain data>
        while (!insert(&qu, data));
    }
}

c void *consumer(void *)
{
    bool res;
    int data;
    while(1) {
        while (!extract(&qu, &data));
        <use data>
    }
}
```

Problem with this approach:
- if the queue is full, the producer waits *actively*
- if the queue is empty, the consumer waits *actively*
A more general approach

- we need to provide a general mechanism for synchronisation and mutual exclusion
- requirements
  - provide mutual exclusion between critical sections
    - avoid two interleaved insert operations
    - (semaphores, mutexes)
  - synchronise two threads on one condition
    - for example, block the producer when the queue is full
    - (semaphores, condition variables)
Outline

1. Introduction to concurrency

2. Models of concurrency: shared memory
   - Critical Sections
   - Synchronization

3. Semaphores

4. Solutions
A general mechanism for blocking tasks

- The semaphore mechanism was first proposed by Dijkstra
- A semaphore is an abstract data type that consists of
  - a counter
  - a blocking queue
  - operation wait
  - operation signal
- The operations on a semaphore must be atomic
  - the OS makes them atomic by appropriate low-level mechanisms
Semaphore definition

- semaphores are a basic mechanisms for providing synchronization
- it has been shown that every kind of synchronization and mutual exclusion can be implemented by using semaphores
- we will analyze possible implementation of the semaphore mechanism later

```cpp
class Semaphore {
    <blocked queue> blocked;
    int counter;
public:
    Semaphore (int n) : count (n) {...}
    void wait();
    void signal();
};
```
Wait and signal

- a wait operation has the following behavior:
Wait and signal

- a wait operation has the following behavior:
  - if `counter == 0`, the requiring thread is blocked;
Wait and signal

- a **wait** operation has the following behavior:
  - if `counter == 0`, the requiring thread is blocked;
  - it is removed from the ready queue and inserted in the blocked queue;
Wait and signal

- A **wait** operation has the following behavior:
  - If `counter == 0`, the requiring thread is blocked;
    - It is removed from the ready queue and inserted in the blocked queue;
  - If `counter > 0`, then `counter--`;
Wait and signal

- A wait operation has the following behavior:
  - If counter == 0, the requiring thread is blocked;
  - It is removed from the ready queue and inserted in the blocked queue;
  - If counter > 0, then counter--;

- A signal operation has the following behavior:
Wait and signal

- A wait operation has the following behavior:
  - If counter == 0, the requiring thread is blocked;
  - It is removed from the ready queue and inserted in the blocked queue;
  - If counter > 0, then counter--;
- A signal operation has the following behavior:
  - If counter == 0 and there is some blocked thread, unblock it;
Wait and signal

- a wait operation has the following behavior:
  - if $\text{counter} == 0$, the requiring thread is blocked;
    - it is removed from the ready queue and inserted in the blocked queue;
  - if $\text{counter} > 0$, then $\text{counter}--$;
- a signal operation has the following behavior:
  - if $\text{counter} == 0$ and there is some blocked thread, unblock it;
    - the thread is removed from the blocked queue and inserted in the ready queue
Wait and signal

- A wait operation has the following behavior:
  - If \( \text{counter} == 0 \), the requiring thread is blocked;
  - It is removed from the ready queue and inserted in the blocked queue;
  - If \( \text{counter} > 0 \), then \( \text{counter}-- \);

- A signal operation has the following behavior:
  - If \( \text{counter} == 0 \) and there is some blocked thread, unblock it;
    - The thread is removed from the blocked queue and inserted in the ready queue;
  - Otherwise, increment counter;
Pseudo-code for wait and signal

class Semaphore {
    <blocked queue> blocked;
    int counter;
public:
    Semaphore (int n) : counter (n) {...}
    void wait() {  
            if (counter == 0)
                <block the thread>
            else counter--;
    }
    void signal() {
            if (<some blocked thread>)
                <unblock the thread>
            else counter++;
    }
};
Mutual exclusion with semaphores

- To use a semaphore for mutual exclusions:
  - define a semaphore initialized to 1
  - before entering the critical section, perform a wait
  - after leaving the critical section, perform a signal

```c
void *threadA(void *) {
    ...
    s.wait();
    <critical section>
    s.signal();
    ...
}

void *threadB(void *) {
    ...
    s.wait();
    <critical section>
    s.signal();
    ...
}
```
Mutual exclusion: example

Semaphore
Counter
1
Blocked queue

Ready queue
TB TA
Mutual exclusion: example

example1.c

s.wait();

(TA)
Mutual exclusion: example

```c
example1.c
s.wait(); (TA)
<critical section (1)> (TA)
```
Mutual exclusion: example

example1.c

```
s.wait();  (TA)
<critical section (1)>  (TA)
s.wait();  (TB)
```

Semaphore

- Counter: 0
- Blocked queue:

Ready queue

- TA
- TB
Mutual exclusion: example

element1.c
s.wait(); (TA)
<critical section (1)> (TA)
s.wait(); (TB)
<critical section (2)> (TA)
Mutual exclusion: example

```
example1.c

s.wait(); (TA)
<critical section (1)> (TA)
s.wait(); (TB)
<critical section (2)> (TA)
s.signal(); (TA)
```

Semaphore

Counter

0

Blocked queue

TB

Ready queue

TA
Mutual exclusion: example

```
example1.c

s.wait(); (TA)
<critical section (1)> (TA)
s.wait(); (TB)
<critical section (2)> (TA)
s.signal(); (TA)
<critical section> (TB)
```
Mutual exclusion: example

```
example1.c
s.wait(); (TA)
<critical section (1)> (TA)
s.wait(); (TB)
<critical section (2)> (TA)
s.signal(); (TA)
<critical section> (TB)
s.signal(); (TB)
```

Semaphore

Counter

1

Blocked queue

Ready queue

```
TA  TB
```
Synchronization with semaphores

- How to use a semaphore for synchronizing two or more threads
  - define a semaphore initialized to 0
  - at the synchronization point, the task to be blocked performs a `wait`
  - at the synchronization point, the other task performs a `signal`
- Example: thread A must block if it arrives at the synchronization point before thread B

```c
Semaphore s(0);

void *threadA(void *) {
    ...
    s.wait();
    ...
}

void *threadB(void *) {
    ...
    s.signal();
    ...
}
```
Problem 1

- How to make each thread wait for the other one?
  - The first one that arrives at the synchronization point waits for the other one.
Problem 1

- How to make each thread wait for the other one?
  - The first one that arrives at the synchronization point waits for the other one.
- Solution: use two semaphores!

```c
Semaphore sa(0), sb(0);

void *threadA(void *) {
    ...
    sa.signal();
    sb.wait();
    ...
}

void *threadB(void *) {
    ...
    sb.signal();
    sa.wait();
    ...
}
```
Semaphores in POSIX

```c
sem_t sema;

int sem_init(sem_t *s, int flag, int count);
int sem_wait(sem_t *s);
int sem_trywait(sem_t *s);
int sem_post(sem_t *s);
```
Semaphores in POSIX

```c
sem_t sema;

int sem_init(sem_t *s, int flag, int count);
int sem_wait(sem_t *s);
int sem_trywait(sem_t *s);
int sem_post(sem_t *s);
```

*sem_t* is the semaphore type; it is an "opaque" C structure.
Semaphores in POSIX

```c
sem_t sema;
int sem_init(sem_t *s, int flag, int count);
int sem_wait(sem_t *s);
int sem_trywait(sem_t *s);
int sem_post(sem_t *s);
```

- `sem_t` is the semaphore type; it is an “opaque” C structure.
- `sem_init` initializes the semaphore; if `flag = 0`, the semaphore is local to the process; if `flag = 1`, the semaphore is shared with other processes; `count` is the initial value of the counter.
sem_t sema;
int sem_init(sem_t * s, int flag, int count);
int sem_wait(sem_t * s);
int sem_trywait(sem_t * s);
int sem_post(sem_t * s);

sem_t is the semaphore type; it is an “opaque” C structure
sem_init is the semaphore; if flag = 0, the semaphore is local to the process; if flag = 1, the semaphore is shared with other processes; count is the initial value of the counter
sem_wait is the normal wait operation;
Semaphores in POSIX

```c
sem_t sema;

int sem_init(sem_t *s, int flag, int count);
int sem_wait(sem_t *s);
int sem_trywait(sem_t *s);
int sem_post(sem_t *s);
```

- `sem_t` is the semaphore type; it is an "opaque" C structure.
- `sem_init` is the semaphore; if `flag = 0`, the semaphore is local to the process; if `flag = 1`, the semaphore is shared with other processes; `count` is the initial value of the counter.
- `sem_wait` is the normal wait operation.
- `sem_trywait` does not block the task, but returns with error (< 0) is the semaphore counter is 0.
Semaphores in POSIX

```c
sem_t sema;

int sem_init(sem_t * s, int flag, int count);
int sem_wait(sem_t * s);
int sem_trywait(sem_t * s);
int sem_post(sem_t * s);
```

* `sem_t` is the semaphore type; it is an “opaque” C structure.
* `sem_init` is the semaphore; if `flag = 0`, the semaphore is local to the process; if `flag = 1`, the semaphore is shared with other processes; `count` is the initial value of the counter.
* `sem_wait` is the normal wait operation.
* `sem_trywait` does not block the task, but returns with error (<0) is the semaphore counter is 0.
Problem 2

- Generalize the previous synchronization problem to N threads
  - The first N-1 threads must block waiting for the last one
Problem 2

- Generalize the previous synchronization problem to N threads
  - The first N-1 threads must block waiting for the last one
- First solution (more elegant)
Problem 2

- Generalize the previous synchronization problem to N threads
  - The first N-1 threads must block waiting for the last one
- First solution (more elegant)
- Second solution (more practical)
Producer / Consumer

We now want to implement a mailbox with a circular array
- avoiding busy wait
  - The producer must be blocked when the mailbox is full
  - The consumer must be blocked when the mailbox is empty
  - We use appropriate semaphores to block these threads
- Initially we consider only one producer and one consumer
Implementation

circulararray1.c

```c
#define N 10

class CA {
    int array[N];
    int head(0);
    int tail(0);

    Semaphore empty(0);
    Semaphore full(N);

public:
    void insert(int elem);
    void extract(int &elem);
};

void CA::insert(int elem) {
    full.wait();
    array[head++] = elem;
    head = head % N;
    empty.signal();
}

void CA::extract(int &elem) {
    empty.wait();
    elem = array[tail++];
    tail = tail % N;
    full.signal();
}
```
Proof of correctness

- When the number of elements in the queue is between 1 and 9, there is no problem;
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
- insert and extract work on different variables (head and tail respectively) and different elements of the array;
- The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
  - The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;
- when there is no element in the queue, head = tail, counter of empty = 0, counter of full = N;
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
  - The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;
- when there is no element in the queue, head = tail, counter of empty = 0, counter of full = N;
  - If the extract begins before the end of an insert, it will be blocked
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
  - The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;
- when there is no element in the queue, head = tail, counter of empty = 0, counter of full = N;
  - If the extract begins before the end of an insert, it will be blocked
  - After an insert, there is an element in the queue, so we are in the previous case
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
  - The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;
- when there is no element in the queue, head = tail, counter of empty = 0, counter of full = N;
  - If the extract begins before the end of an insert, it will be blocked
  - After an insert, there is an element in the queue, so we are in the previous case
- For symmetry, the same holds for the case of N elements in the queue. Again, head = tail, counter of empty = N, counter of full = 0;
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
  - The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;
- when there is no element in the queue, head = tail, counter of empty = 0, counter of full = N;
  - If the extract begins before the end of an insert, it will be blocked
  - After an insert, there is an element in the queue, so we are in the previous case
- For symmetry, the same holds for the case of N elements in the queue. Again, head = tail, counter of empty = N, counter of full = 0;
  - If the insert begins before the end of an extract, it will be blocked
Proof of correctness

- when the number of elements in the queue is between 1 and 9, there is no problem;
  - insert and extract work on different variables (head and tail respectively) and different elements of the array;
  - The value of full and empty is always greater than 0, so neither the producer nor the consumer can block;

- when there is no element in the queue, head = tail, counter of empty = 0, counter of full = N;
  - If the extract begins before the end of an insert, it will be blocked
  - After an insert, there is an element in the queue, so we are in the previous case

- For symmetry, the same holds for the case of N elements in the queue. Again, head = tail, counter of empty = N, counter of full = 0;
  - If the insert begins before the end of an extract, it will be blocked
  - After an extract, we fall back in the previous case
Multiple producers/consumers

- Suppose now there are many producers and many consumers;
- all producers will act on the same variable head, and all consumers on tail;
- If one producer preempts another producer, an inconsistency can arise
  - Exercise: prove the above sentence
- Therefore, we need to combine synchronization and mutual exclusion
First solution

circulararray-wrong.c

```c
#define N 10

class CA {
    int array[N];
    int head(0);
    int tail(0);

    Semaphore empty(0);
    Semaphore full(N);
    Semaphore mutex(1);

public:
    void insert(int elem);
    void extract(int &elem);
};

circulararray-wrong.c

void CA::insert(int elem) {
    mutex.wait();
    full.wait();
    array[head++] = elem;
    head = head % N;
    empty.signal();
    mutex.signal();
}

circulararray-wrong.c

void CA::extract(int &elem) {
    mutex.wait();
    empty.wait();
    elem = array[tail++];
    tail = tail % N;
    full.signal();
    mutex.signal();
}
```
Wrong solution

- The previous solution is wrong!
- Counter example:
  - A consumer thread executes first, locks the mutex and blocks on the empty semaphore
  - All other threads (producers or consumers) will block on the mutex
- Lesson learned: never block inside a mutex!
Correct solution

circulararray-correct.c

```c
#define N 10

class CA {
    int array[N];
    int head(0);
    int tail(0);

    Semaphore empty(0);
    Semaphore full(N);
    Semaphore mutex(1);

public:
    void insert(int elem);
    void extract(int &elem);
};

void CA::insert(int elem) {
    full.wait();
    array[head++] = elem;
    head = head % N;
    mutex.signal();
    empty.signal();
}

void CA::extract(int &elem) {
    empty.wait();
    mutex.wait();
    elem = array[tail++];
    tail = tail % N;
    mutex.signal();
    full.signal();
}
```

circulararray-correct.c
Exercises

- Solve the previous exercise with two mutex (one for the consumers and one for the producers)
  - Prove the solution is correct
- Suppose there are one producer and N consumer. Every message has to be received by each consumer.
  - Write the data structure, the insert and extract functions
  - Suppose that extract() takes an additional arguments that specifies the consumer ID (between 0 and N-1).
Internal implementation of semaphores

- `wait()` and `signal()` involve a possible thread-switch
- therefore they must be implemented as system calls!
- one blocked thread must be removed from state `RUNNING`
  and be moved in the semaphore blocking queue
- a semaphore is itself a shared resource
- `wait()` and `signal()` are critical sections!
- they must run with interrupt disabled and by using `lock()`
  and `unlock()` primitives

bullet points are:
- wait() and signal() involve a possible thread-switch
- therefore they must be implemented as system calls!
- one blocked thread must be removed from state RUNNING
  and be moved in the semaphore blocking queue
- a semaphore is itself a shared resource
- wait() and signal() are critical sections!
- they must run with interrupt disabled and by using lock() and
  unlock() primitives
## Semaphore implementation: pseudo-code

```c
void sem_wait() {
    spin_lock_irqsave();
    if (counter==0) {
        <block the thread>
        schedule();
    } else counter--;
    spin_lock_irqrestore();
}

void sem_post() {
    spin_lock_irqsave();
    if (counter== 0) {
        <unblock a thread>
        schedule();
    } else counter++;
    spin_lock_irqrestore();
}
```
Outline

1 Introduction to concurrency

2 Models of concurrency: shared memory
   - Critical Sections
   - Synchronization

3 Semaphores

4 Solutions
First solution to problem 2

Elegant solution. Uses many semaphores!

```c
#include <pthread.h>
#include <semaphore.h>
#define N 8

sem_t s[N][N];

void init()
{
    int i, j;
    for (i=0; i<N; i++)
        for (j=0; j<N; j++)
            sem_init(&s[i][j], 0, 0);
}

void * thread(void * arg)
{
    int k = (int) arg;
    printf("TH%d: before synch\n", k);
    for (j=0; j<N; j++)
        if (j!=k) sem_post(&s[k][j]);
    for (j=0; j<N; j++)
        if (j!=k) sem_wait(&s[j][k]);
    printf("TH%d: after synch\n", k);
}

int main()
{
    pthread_t tid[N];
    int i;
    init();
    for (i=0; i<N; i++)
        pthread_create(&tid[i], 0, thread, (void *)i);
    for (i=0; i<N; i++)
        pthread_join(tid[i], 0);
    printf("Main: exiting\n");
    return 0;
}
```

Second solution to problem 2

Practical solution. We need a mutex semaphore, a counter, and a semaphore to block threads.

```c
struct synch {
    int count;
    sem_t m; // mutex
    sem_t b; // blocked
    int N; // number of threads
};

void initsynch(struct synch * s, int n) {
    int i;
    s->count = 0;
    sem_init(&s->m, 0, 1);
    sem_init(&s->b, 0, 0);
    s->N = n;
}

void my_synch(struct synch *s) {
    int i;
    sem_wait(&s->m);
    if (++s->count < s->N) {
        sem_post(&s->m);
        sem_wait(&s->b);
    } else {
        for (i=0; i < s->N - 1; i++)
            sem_post(&s->b);
        sem_post(&s->m);
    }
}

struct synch sp;
void * thread(void *arg) {
    ... mysynch(&sp);
    ...
}
```