Sistemi in tempo reale
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Concorrenza - II

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Outline

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 are 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

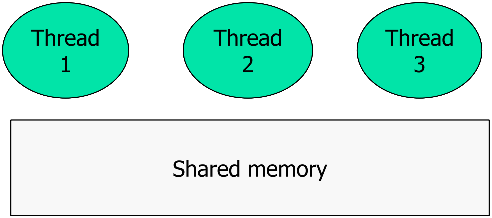
- shared memory
  - All activities access the same memory space
- message passing
  - All activities communicate each other by sending messages through OS primitives
- we will analyse both models in the following slides

Outline

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

```
/* 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

```
// 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 *)
{
    ...
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Consistency:
After each operation, a == b

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

```
a = a + 1;    TA    a = 2
b = b * 2;    TB    b = 2
b = b + 1;    TA    b = 3
a = a * 2;    TB    a = 4
```

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Consistency:
After each operation, a == b

Resource in a non-consistent state!!

```
a = a + 1;    TA    a = 2
b = b * 2;    TB    b = 2
b = b + 1;    TA    b = 3
a = a * 2;    TB    a = 4
```

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.

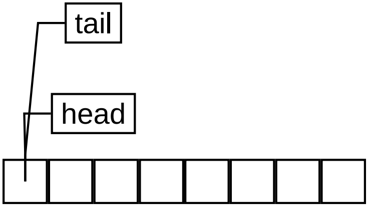
Example: Circular Array

Implementation of a FIFO queue.

```
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

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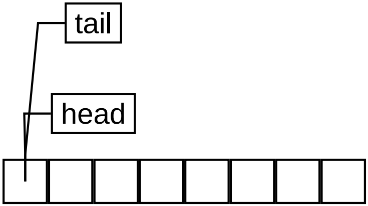

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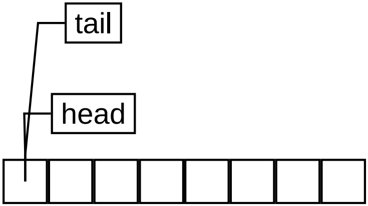
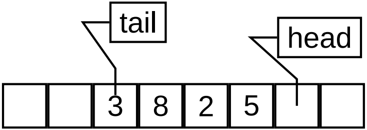


- head: index of the first free element in the queue
  - here will be inserted the next element
- tail: index of the first occupied element in the queue
  - will be the one that will be extracted next time
- the queue is empty, hence head == tail

Example: insert

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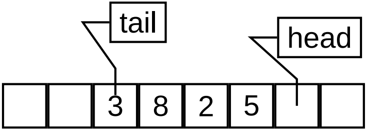


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- num = (head - tail) % 8 $\rightarrow$ num = 4;

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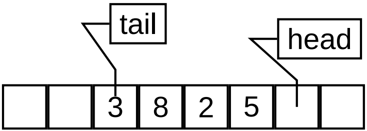


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- insert(ca, 9);

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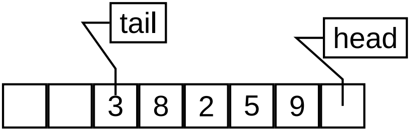


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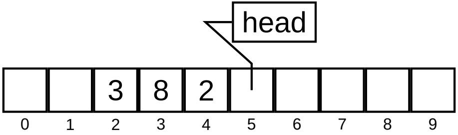
- num = (head - tail) % 8 $\rightarrow$ num = 4;
- insert(ca, 9);
- head and num have been increased

Example: concurrent insert



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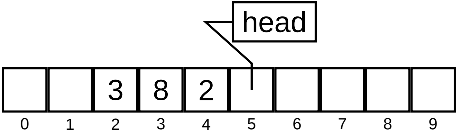

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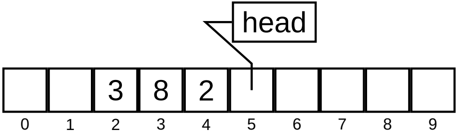


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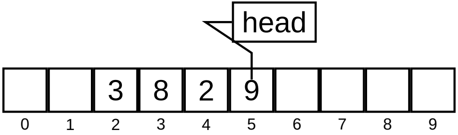


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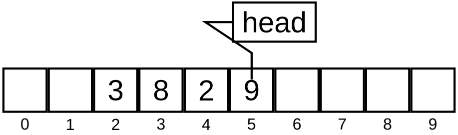


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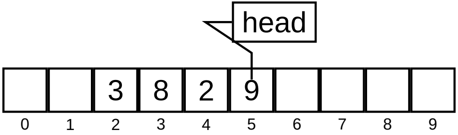

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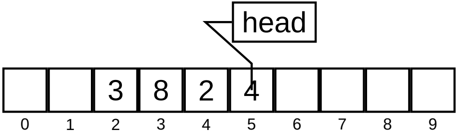


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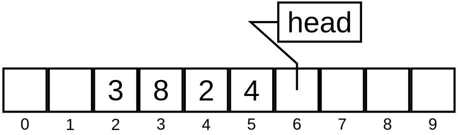


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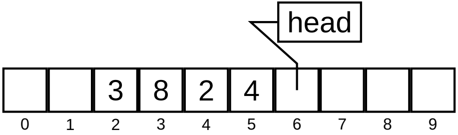


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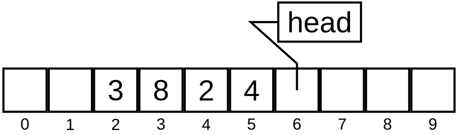

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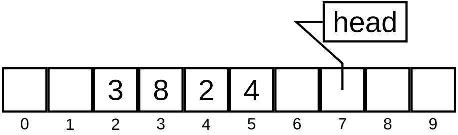

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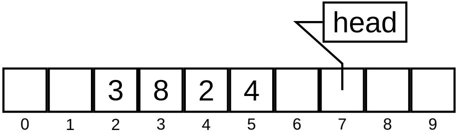


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- Two threads, the first calls insert(9), the second calls insert(4);
- thread 1 calls insert(ca, 9);
- preemption by second thread
- second thread completes
- there is a hole! At some point, the extract will read a 4 and a random value, instead of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

Consistency properties for struct CA

1. when the queue is empty, or when the queue is full, `head == tail`
2. `num` is equal to the number of times insert has been called minus the number of times that extract has been called
3. ...
4. if element x has been inserted, eventually it must be extracted with an appropriate number of extracts
5. 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.

Insert and Extract - II

- What happens if we exchange the sequence of instructions in insert?

```
boolean insert(struct CA *ca,
               int elem)
{
  if (ca->num == 10)
     return false;
  ca->num++;
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- It is easy to prove that in this case `insert()` cannot be interleaved with `extract`

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- there are three ways to obtain mutual exclusion
    - implementing the critical section as an atomic operation

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- 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!

```
CLI;
<critical section>
STI;
```

- 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 `s` for each resource, and then surround a critical section with `lock(s)` and `unlock(s)`;

```
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!

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

no context switch may happen during the critical section,
but interrupts are enabled

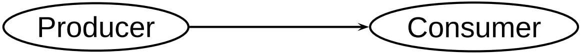
Critical sections: a general approach

- 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

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

```
struct CA qu;
```

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

```
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 synchonisation 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

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 sempahores
- we will analyze possible implementation of the semaphore mechanism later

```
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

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  - if `counter == 0`, the requiring thread is blocked;

Wait and signal

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  - if `counter > 0`, then `counter--`;

Wait and signal

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    - 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

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  - 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 `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:
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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;
    - 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++;
  }
};
```

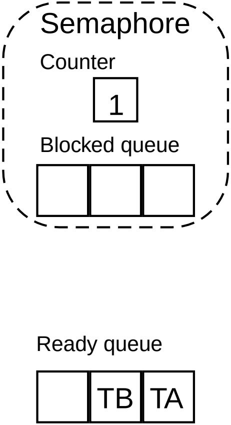
Mutual exclusion with semaphores

- 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

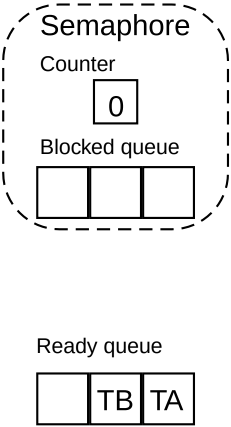
```
void *threadA(void *)
{
  ...
  s.wait();
  <critical section>
  s.signal();
  ...
}
```

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

Mutual exclusion: example



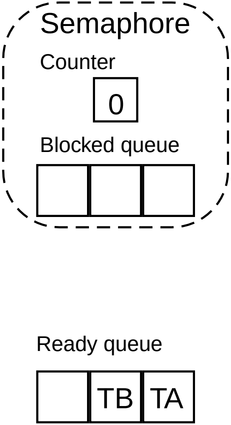
Mutual exclusion: example



example1.c

```
s.wait();                    (TA)
```

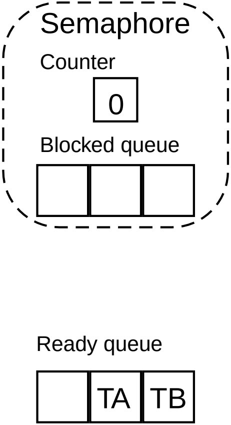
Mutual exclusion: example



example1.c

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

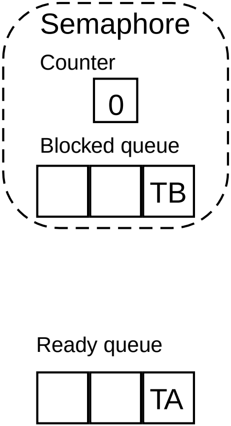
Mutual exclusion: example



example1.c

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

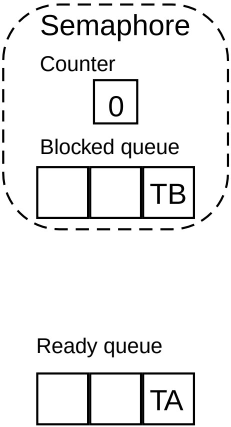
Mutual exclusion: example



example1.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)
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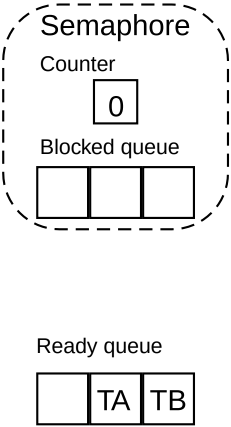
Mutual exclusion: example



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s.wait();                    (TA)
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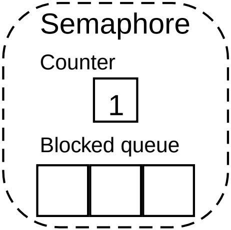

example1.c

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s.wait();                   (TA)
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s.wait();                   (TB)
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s.signal();                 (TA)
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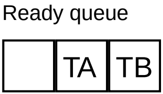
s.signal();                 (TB)
```



Synchronization with semaphores

- How to use a semaphore for synchronizing two or more threads
  - define a sempahore initialized to 0
  - at the syncronization 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 synch point before thread B

```
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!

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

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

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

Semaphores in POSIX

```
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

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`sem_init` 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

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`sem_wait` is the normal wait operation;

Semaphores in POSIX

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sem_t sema;

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`sem_trywait` does not block the task, but returns with error (< 0) is the semaphore counter is 0.

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Problem 2

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

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- First solution (more elegant)
- Second solution (more practical)

Producer / Consumer

- We now want ot 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

```
#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)
{
```

circulararray1.c

```
    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;

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- 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 mamy 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

```
#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)
{
    mutex.wait();
```

circulararray-wrong.c

```
    full.wait();
    array[head++] = elem;
    head = head % N;
    empty.signal();
    mutex.signal();
}

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

```
#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();
```

circulararray-correct.c

```
    mutex.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();
}
```

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

Semaphore implementation: pseudo-code

```
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

First solution to problem 2

Elegant solution. Uses many semaphores!

prob2-solution1.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; int j;
  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);
}
```

prob2-solution1.c

```
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");
}
```

Second solution to problem 2

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

solution2.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;
}
```

solution2.c

```
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);
  ...
}
```