Concurrency

Paolo Burgio
paolo.burgio@unimore.it

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA
High Performance Real Time Lab


FRATELLI
QUANDO LA MAMMA ESCE DI CASA
RIDI CHE È GRATIS
QUANDO TORNA A CASA

Why concurrency?

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

Performance

- Take advantage of blocking time
- While some thread waits for a blocking condition, another thread performs another operation
- On a multi-core machine, independent activities can be carried out on different cores are the same time

Cooperative vs. Competitive

Competitive concurrency

- Different activities compete for the resources
- One activity does not know anything about the other
- The OS must manage the resources so to
  - Avoid conflicts
  - Be fair

Cooperative concurrency

- Many activities cooperate to perform an operation
- Every activity knows about the others
- They must synchronize on particular events

Competitive

Competing actvities need to be “protected” from each other

- Separate memory spaces, as with different processes

The **allocation** of the resource and the synchronization must be **centralized**

- Competitive activities request for services to a central manager (the OS or some dedicated process) which allocates the resources in a fair way

Client/Server model

- Communication is usually done through **messages**

More suitable to the **process** model of execution

Client/server model

A server manages the resource **exclusively**

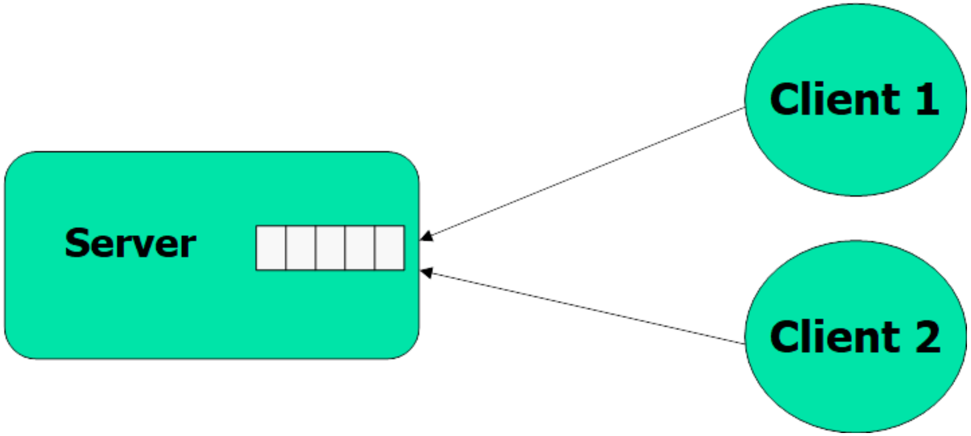
- For example, the printer

If a process needs to access the resource, it sends a **request to the server**

- For example, printing a file, or asking for the status
- The server can send back the responses
- The server can also be on a remote system

Two basic primitives:

- **send** and **receive**



Cooperative model

Cooperative activities **know** about each other

- They do not need memory protection (less overhead)

They need to access the same data structures

- Allocation of the resource is **de-centralized**
- **Shared memory** model

More suitable to the **thread** model of execution

Competition vs. cooperation

Competition is best resolved by using the **message passing** model

- However it can be implemented using a shared memory paradigm too

Cooperation is best implemented by using the **shared memory** paradigm

- However, it can be realized by using pure message passing mechanisms

General purpose OS needs to support both models

- Protection for competing activities
- Client/server models → message passing primitives
- Shared memory for reducing the overhead

Some special OS supports only one of the two

- RTOS supports only shared memory

Models of concurrency

Message passing

Message passing systems are based on the basic concept of message

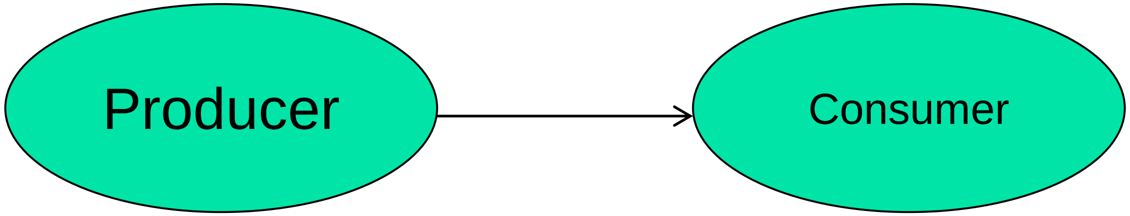
Two basic operations

– send(destination, message);
- send can be synchronous or asynchronous *(fire-and-forget)*

– receive(source, &message);
- receive can be symmetric or asymmetric

Producer/Consumer with MP

- The producer executes `send(consumer, data)`
- the consumer executes `receive(producer, data)`
- no need for a special communication structure (already contained in the send/receive semantic)



Resources and message passing

There are no shared resources in the message passing model
–all the resources are allocated statically, accessed in a dedicated way

Each resource is handled by a manager process that is the only one that has right to access to a resource

The consistency of a data structure is guaranteed by the manager process
–there is no more competition, only cooperation!!!

Synchronous communication

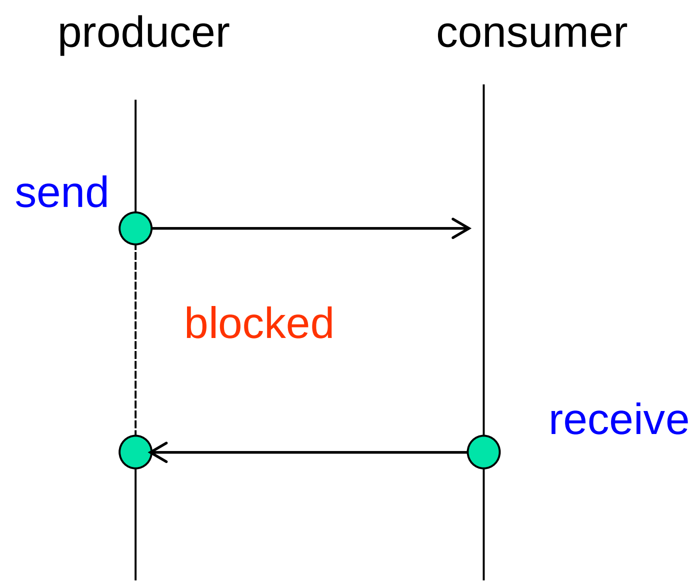
synchronous send/receive
–no buffers!

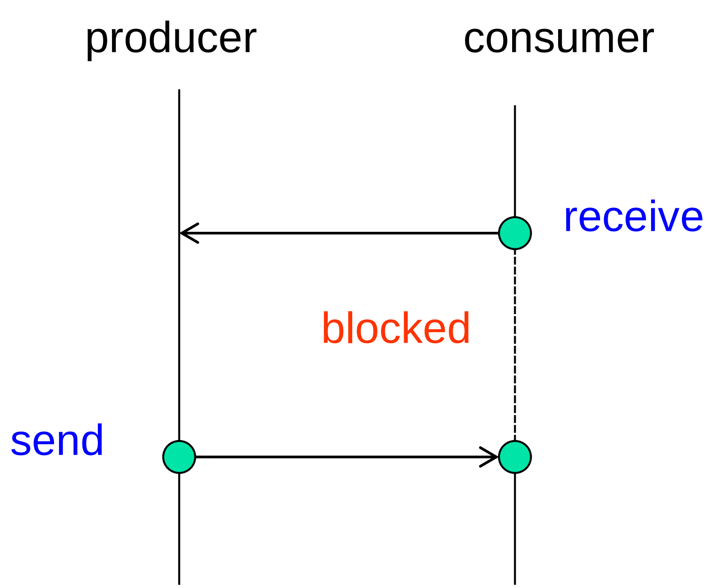
producer:

s_send(consumer, d);

consumer:

s_receive(producer, &d);



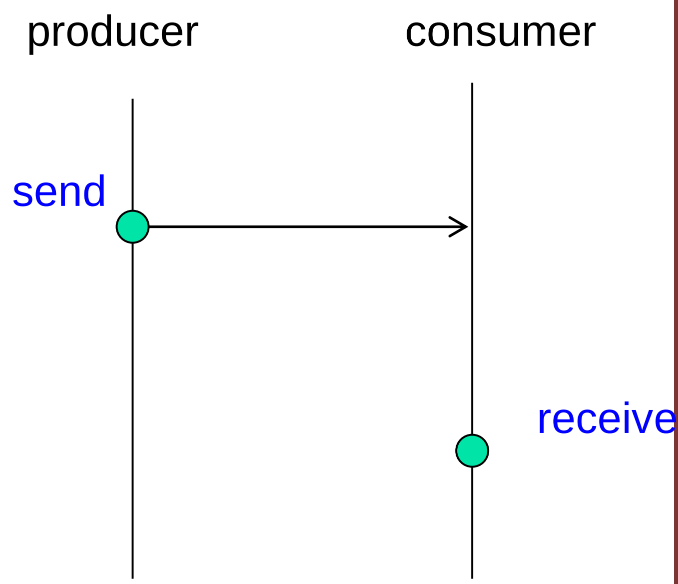


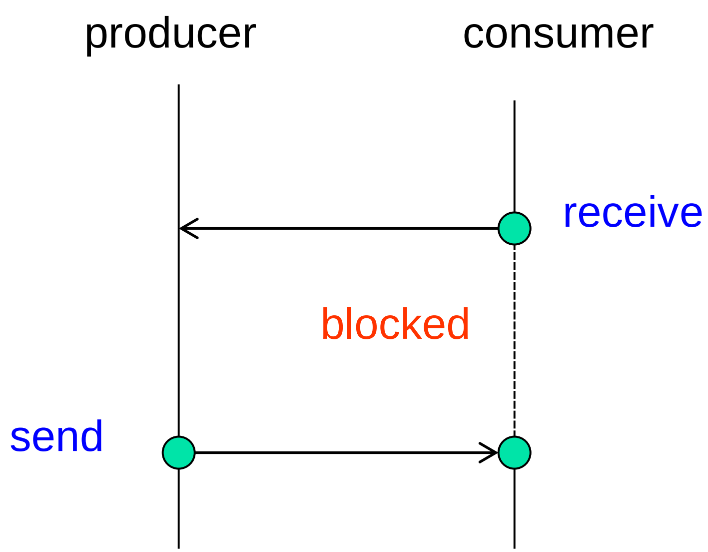
Async send/ sync receive

asynchronous send / synchronous receive
–there is probably a send buffer somewhere

producer:
  a_send(consumer, d);

consumer:
  s_receive(producer, &d);





(A)symmetric receive

Symmetric receive

– receive(source, &data);
– the programmer wants a message from a given producer

Asymmetric receive

– source = receive(&data);
– often, we do not know who is the sender

- imagine a web server;
- the programmer cannot know in advance the address of the browser that will request the service
- many browsers can ask for the same service

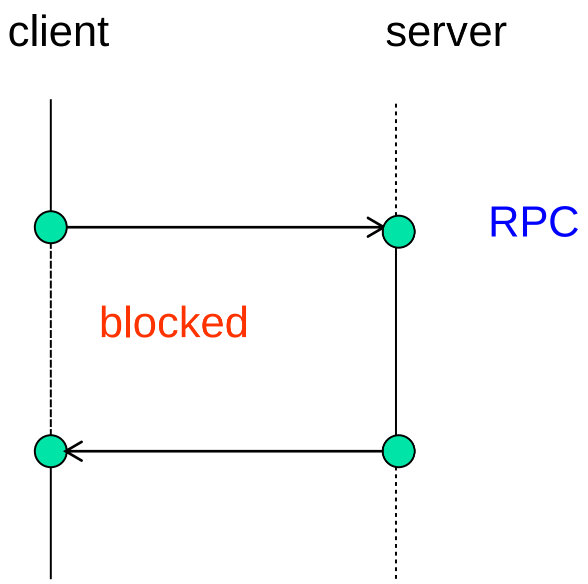
Remote procedure call

Increase expressiveness

From low-level (MP) to more «programmer friendly» (RPC) mechanism

- In a client-server system, a client wants to request an action to a server

–that is typically done using a remote procedure call (RPC)



Massage passing systems

- In message passing

–each resource needs one threads manager (often called **daemon thread**)

–the threads manager is responsible for giving access to the resource

- Example: let's try to implement mutual exclusion with message passing primitives

–one thread will ensure mutual exclusion

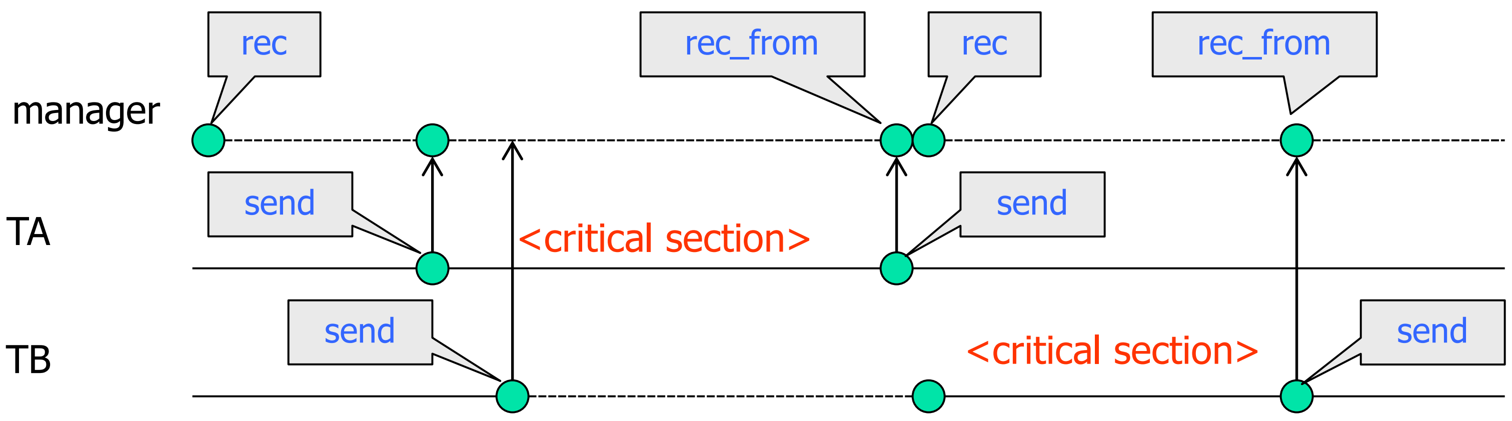
–every thread that wants to access the resource must

- send a message to the manager thread
- access the critical section
- send a message to signal the leaving of the critical section

Sync send / sync receive

```
void * manager(void *)
{
  thread_t source;
  int d;
  while (true) {
      source = s_receive(&d);
      s_receive_from(source, &d);
  }
}
```

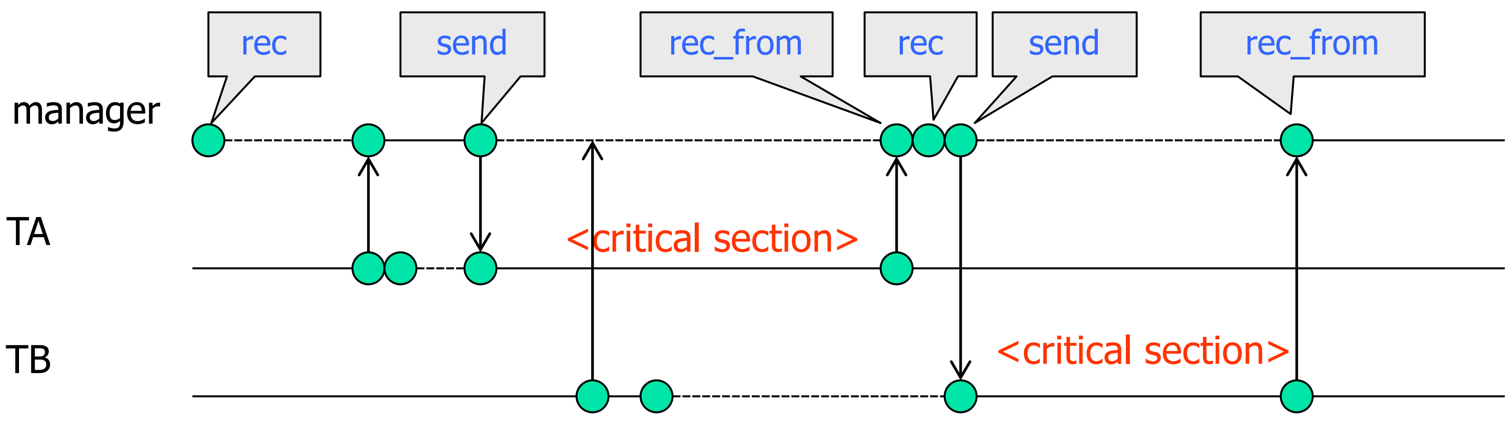
```
void * thread(void *)
{
  int d;
  while (true) {
      s_send(manager, d);
      <critical section>
      s_send(manager, d);
  }
}
```



With async send and sync receive

```
void * manager(void *)
{
  thread_t source;
  int d;
  while (true) {
      source = s_receive(&d);
      a_send(source,d);
      s_receive_from(source,&d);
  }
}
```

```
void * thread(void *)
{
  int d;
  while (true) {
      a_send(manager, d);
      s_receive_from(manager, &d);
      <critical section>
      a_send(manager, d);
  }
}
```



Problem

- Implement readers/writers with message passing
- Hints:

–define a manager thread

–the service type (read/write) can be passed as data

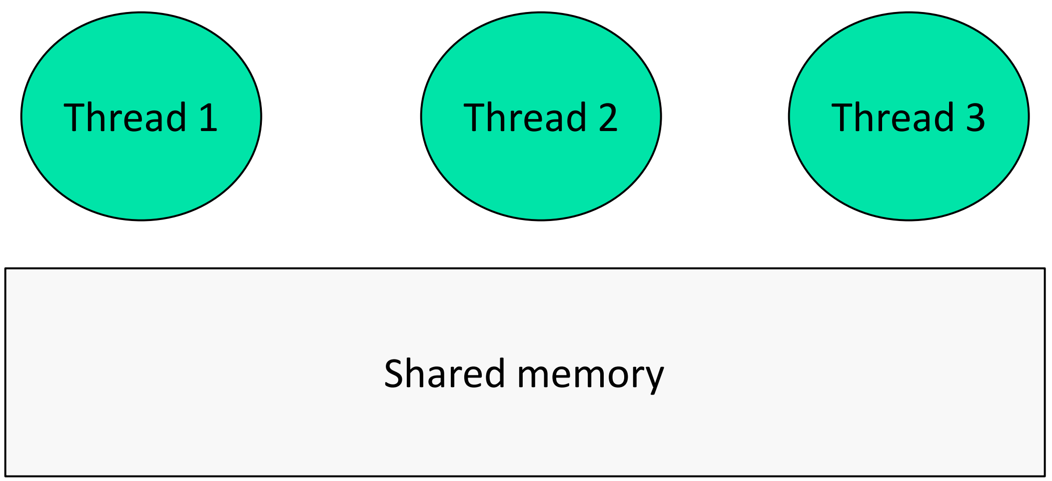
–use asynchronous send and synchronous receive

–use symmetric and asymmetric receive

Shared memory model

Shared memory

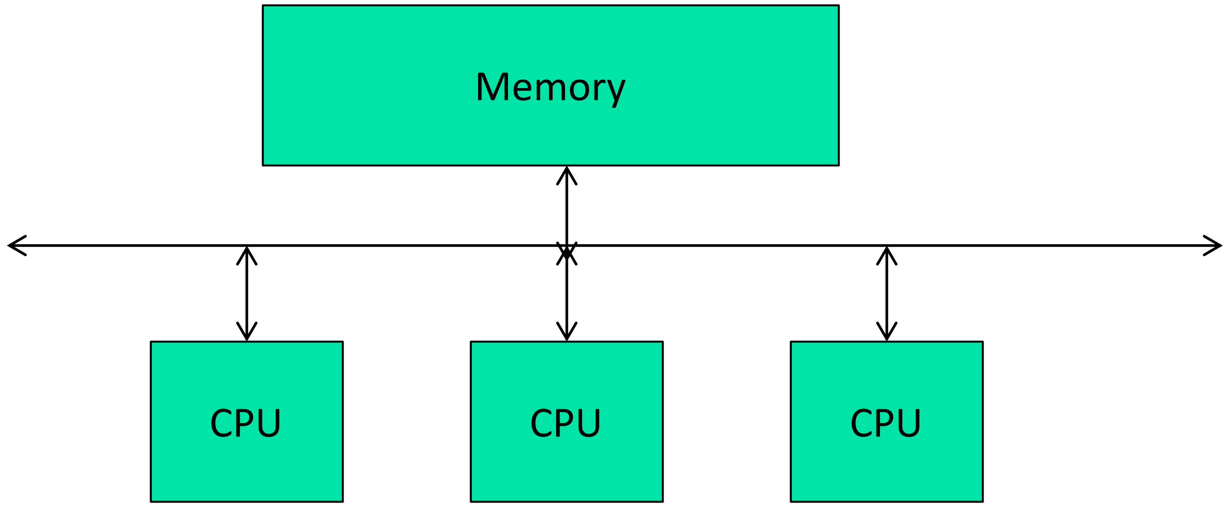
- The first one being supported in old OS
- The simplest one and the closest to the machine
- All threads can access the same memory locations



Hardware analogy

An abstract model that presents a good analogy is the following

- Many HW CPU, each one running one activity (thread)
- One shared memory



Resource allocation

- Allocation of resource can be
  - **Static**: once the resource is granted, it is never revoked
  - **Dynamic**: resource can be granted and revoked dynamically
    - Manager

- Access to a resource can be
  - **Dedicated**: only one activity at a time may request access to the resource
  - **Shared**: many activities may access the resource at the same time
    - Mutual exclusion

	Dedicated	Shared
Static	Compile Time	Manager
Dynamic	Manager	Manager

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

- Example:
  - Incrementing a variable x is NOT an atomic operation

Atomicity

- A hardware instruction is atomic if it cannot be "interleaved" with other instructions
  - Atomic operations are always sequentialized
  - Atomic operations cannot be interrupted
    - They are safe operations
    - For example, transferring one word from memory to register or viceversa
  - Non atomic operations can be interrupted
    - They are not "safe" operations
    - Non elementary operations are not atomic

Non-atomic operations

- Consider a "simple" operation like:
  -

```
x = x+1;
```

- In assembler:
  -

```
LD  R0, x
INC R0
ST  x, RO
```

- A simple operation like incrementing a memory variable, may be composed by three machine instructions
  -

Example 1

- Bad interleaving:

shared memory

```
int x ;
```

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

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

		...	
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

- Bad interleaving

Shared object (sw resource)

```
struct A_t {
int a;
int b;
} A;

void A_init(A_t *x) { x->a=1;        x->b=1; }
void A_inc(A_t *x) { x->a++;         x->b++; }
void A_mul(A_t *x){ x->b*=2;     x->a*=2;}
```

```
void *threadA(void *)
{
...
A_inc(&A);
...
}
```

```
void *threadB(void *)
{
...
A_mul(&A);
...
}
```

consistency: after each operation, a == b

x->a++;	TA	*a = 2*
x->b*=2;	TB	*b = 2*
x->b++;	TA	*b = 3*
x->a*=2;	TB	*a = 4*

resource in a non-consistent state!

Consistency

- For each resource, we can state some consistency property
  - 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 hold during an operation
  - If the operations are properly sequentialized, the consistency properties must hold
- Formal verification
  - Let *R* be a resource, and let *C(R)* be a set of consistency properties on the resource
    - $C(R) = \{ C_i \}$

› Definition: a concurrent program is *correct* if, for every possible interleaving of the operations on the resource, the consistency properties hold after each operation

Example 3: circular array

```
struct CircularArray_t {
 int array[10];
 int head, tail, num;
} queue;

void init_CA(struct CircularArray_t *a)
{ a->head=0; a->tail=0; a->num=0; }

int insert_CA(struct CircularArray_t *a,
    int elem)
{
  if (a->num == 10) return 0;
  a->array[a->head] = elem;
  a->head = (a->head + 1) % 10;
  a->num++;
  return 1;
}

int extract_CA(struct CircularArray_t *a,
    int *elem)
{
  if (a->num == 0) return 0;
  *elem = a->array[a->tail];
  a->tail = (a->tail + 1) % 10;
  a->num--;
  return 1;
}
/* suppose num++ e num- atomic */
```

Consistency properties

(suppose num++ and num-- atomic)

C_1: if (num == 0 || num == 10)
head == tail;

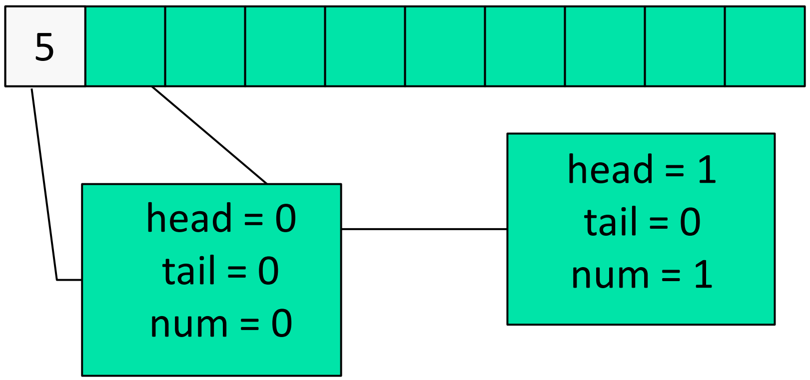
C_2: if (0 < num < 10)
num == (head – tail) % 10

C_3: num == NI - NE

C_4: (insert x)
pre: if (num < 10)
post: num == num + 1 &&
array[(head-1)%10] = x;

C_5: (extract &x)
pre: if (num > 0)
post: num == num –1 &&
x = array[(tail-1)%10];

Example 3: circular array - insert



Initial state:

head = 0; tail = 0; num = 0;

insert_CA (&queue, 5) ;

head = 1; tail = 0; num = 1;

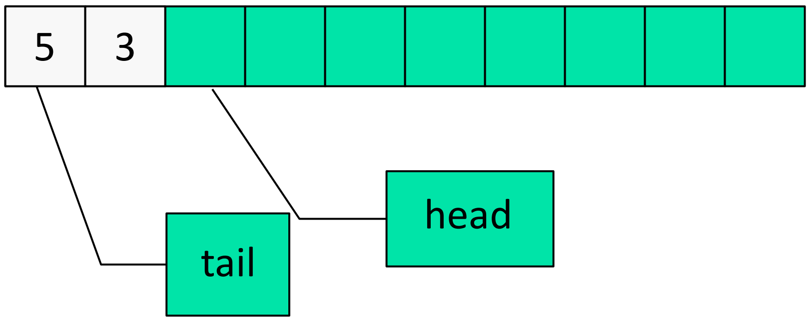
C_2, C_3, C_4 holds

C_2: if (0 < num < 10)
num == (head – tail) % 10

C_3: *num == NI – NE*

C_4: insert_CA(&queue, x)
pre: if (num < 10)
post: num == num + 1 &&
array[(head-1)%10] = x;

Example 3: circular array – insert (2)



Initial state:

head = 0; tail = 0; num = 0;

insert_CA (&queue, 5) ;

head = 1; tail = 0; num = 1;

insert_CA (&queue, 3) ;

head = 2; tail = 0; num = 2;

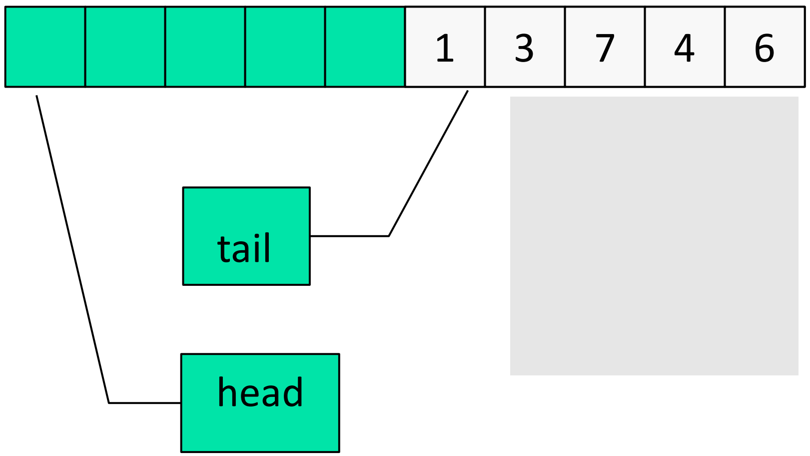
C_2, C_3, C_4 hold

C_2: if (0 < num < 10)
num == (head – tail) % 10

C_3: num == NI – NE

C_4: insert_CA(&queue, x)
pre: if (num < 10)
post: num == num + 1 &&
array[(head-1)%10] = x;

Example 3: circular array – insert (3)



Initial state:

head = 9; tail = 5; num = 4;

insert_CA (&queue, 6) ;

head = 0; tail = 5; num = 5

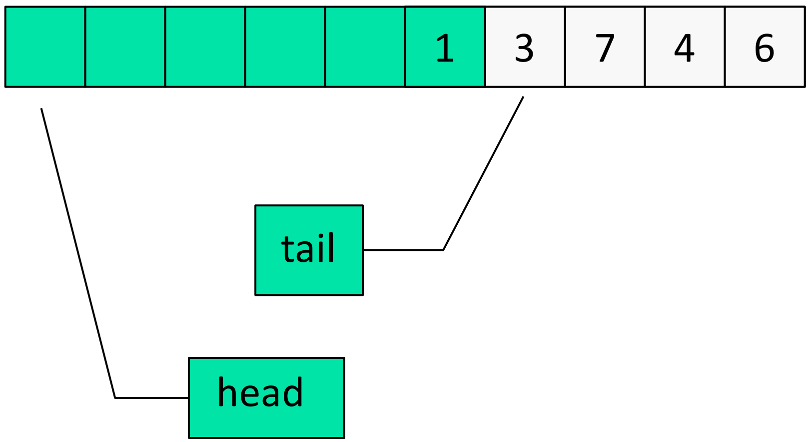
C_2, C_3, C_4 hold

C$_2$: if (0 < num < 10)
num == (head – tail) % 10

C$_3$: *num == NI – NE*

C$_4$: insert_CA (&queue, x)
pre: if (num < 10)
post: num == num + 1 &&
array[(head-1)%10] = x;

Example 3: circular array – extract



Initial state:

head = 0; tail = 5; num = 5;

extract_CA (&queue, &elem) ;

head = 0; tail = 6; num = 4

C_2, C_3, C_5 hold

C_2: if (0 < num < 10)
num == (head – tail) % 10

C_3: *num == NI – NE*

C_5: extract_CA (&queue, &x)
pre: if (num > 0)
post: num == num –1 &&
x = array[tail];

Example 3: the problem

- If the insert operation is performed by two processes, some consistency property may be violated!

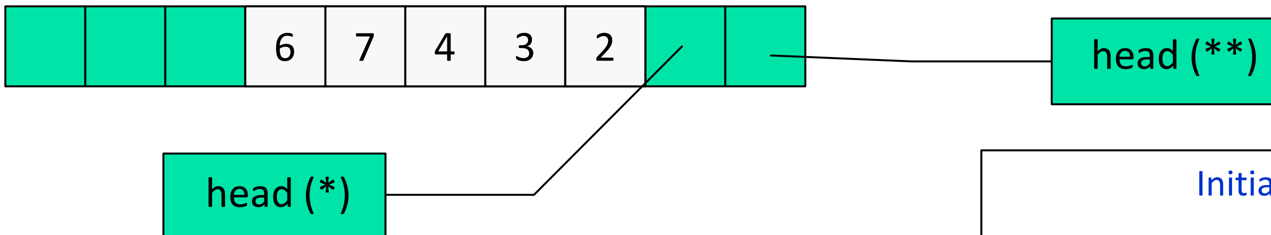
```
struct CircularArray_t queue;
```

			6	7	4	3			

```
void *threadA(void *)
{
...
insert_CA( &queue, 5);
...
}
```

```
void *threadB(void *)
{
...
insert_CA( &queue, 2);
...
}
```

Example 3: interference



Initial state:

head = 7; tail = 3; num = 4;

insert_CA (&queue, 5) ; (TA)

insert_CA (&queue, 2) ; (TB)

```
if (a->num == 10) return 0;
a->array[a->head] = 5;
a->head = (a->head + 1) % 10; (**)
a->num ++;
return 1;
```

```
if (a->num == 10) return 0;
a->array[a->head] = 2;
a->head = (a->head + 1) % 10; (*)
a->num ++;
return 1;
```

C_4 is violated!

5 != array[head – 1]

```
if (a->num == 10) return 0;          (TA)
a->array[a->head] = 5;               (TA)
if (a->num == 10) return 0;          (TB)
a->array[a->head] = 2;               (TB)
a->head = (a->head + 1) % 10;(TB) (*)
a->num ++;                           (TB)
return 1;                            (TB)
a->head = (a->head + 1) % 10;(TA) (**)
a->num ++;                           (TA)
return 1;                            (TA)
```

Final State:

head = 9; tail = 3; num = 6;

Example 3: correctness

- The previous program is not correct

–It exist a possible interleaving of two insert operations that leaves the resource in a inconsistent state

- Proving the non-correctness is easy

–it suffices to find a counter example

- Proving the correctness is not easy

–it is necessary to prove the correctness for every possible interleaving of every operation

Example 3: problem

- What if an insert and an extract are interleaved?
  - Nothing bad can happen!!
  - Proof
- if 0<num<10, insert_CA() and extract_CA() are independent
- if num==0
  - if extract_CA begins before insert_CA, it immediately returns 0, so nothing bad can happen
  - if insert_CA begins before, extract_CA will either return false, or it will find a new element to extract, depending on how it interleaves w.r.t. num++ of insert_CA (last operation of insert_CA)
- Dual thing when num==10

Example 3: CircularArray properties

- a) if more than one thread executes insert_CA()
  - inconsistency!!
- b) if we have only two threads
  - one threads calls insert_CA() and the other thread calls extract_CA()
  - no inconsistency!
- The order of the operations is important!
  - a wrong order can make the object inconsistency even under the assumption b)
    - the case is when num is incremented but the data has not yet been inserted
    - in any case, the final result depends on the timings of the dfferent requests (e.g, an insertion with the buffer full)

Example 3: questions

- Problem:

–In the previous example, we supposed that num++ and num-- are atomic operations

–What happens if they are not atomic?

- Question:

–Assuming that operation -- and ++ are not atomic, can we make the circularArray safe under the assumption b) ?

- Hint: try to substitute variable num with two boolean variables: bool empty and bool full;

Critical sections

- Definitions

–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 two ways to obtain mutual exclusion

- Disabling the preemption (valid only for single-core systems)
- Implementing the critical section as an atomic operation, using semaphores and mutexes

Critical sections: disabling preemption

- Single core 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

Critical sections: atomic operations

- There exist some general mechanisms to implement mutual exclusion only between the processes that uses a resource:
  - semaphores
  - mutexes
- Define a flag s for each resource
- Use lock(s)/unlock(s) around the critical section

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

Synchronisation

- Mutual exclusion is not the only problem

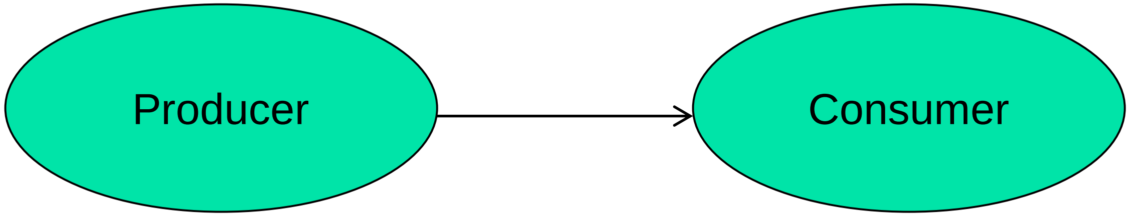
–We need a way of synchronise two or more threads

- 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)



Producer/consumer

- The two threads have different speeds

– For example the producer is much faster than the consumer

– We need to store the integers in a queue, so that no data is lost

– Let’s use the CircularArray_t structure

Producer/consumer (2)

- Problems with this approach:

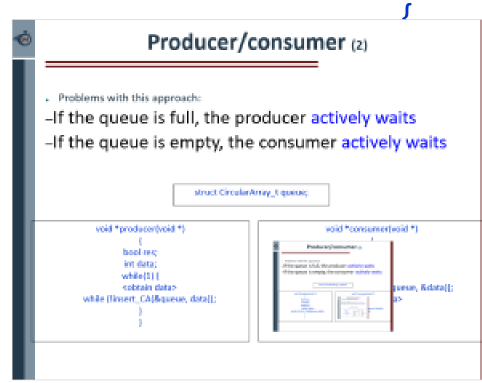
–If the queue is full, the producer actively waits

–If the queue is empty, the consumer actively waits

```
struct CircularArray_t queue;
```

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

```
void *consumer(void *)
{
queue, &data));
a>
```



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 insertions operation to interleave

– Synchronise two threads on one condition

- For example, block the producer when the queue is full

General mechanism: semaphores

- Djikstra proposed the semaphore mechanism

–A semaphore is an abstract entity that consists of

- A counter
- A blocking queue
- Operation wait
- Operation signal

–The operations on a semaphore are considered atomic

Semaphores

- Semaphores are 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

```
typedef struct {
<blocked queue> blocked;
int counter;
} sem_t;

void sem_init      (sem_t *s, int n);

void sem_wait      (sem_t *s);
void sem_post      (sem_t *s);
```

Note:
the real prototype
of sem_init is
slightly different!

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
    - It is inserted in the blocked queue
  - If counter > 0, then counter--;
- A post operation has the following behavior
  - If counter == 0 and there is some blocked thread, unblock it
    - The thread is removed from the blocked queue
    - It is inserted in the ready queue
  - Otherwise, increment counter

Semaphores

```
void sem_init (sem_t *s, int n)
{
s->count=n;
...
}

void sem_wait(sem_t *s)
{
if (counter == 0)
<block the thread>
else
counter--;
}

void sem_post(sem_t *s)
{
if (<there are blocked threads>)
<unblock a thread>
else
counter++;
}
```

Signal semantics

- What happens when a thread blocks on a semaphore?

–In general, it is inserted in a BLOCKED queue

- Extraction from the blocking queue can follow different semantics:

–Strong semaphore

•The threads are removed in well-specified order

•For example, FIFO order, priority based ordering, ...

–Signal and suspend

•After the new thread has been unblocked, a thread switch happens

–Signal and continue

•After the new thread has been unblocked, the thread that executed the signal continues to execute

- Concurrent programs should not rely too much on the semaphore semantic

Mutual exclusion with semaphores

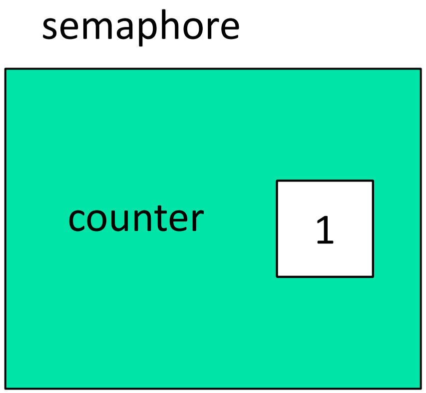
- How to use a semaphore for critical sections
  - Define a semaphore initialized to 1
  - Before entering the critical section, perform a wait
  - After leaving the critical section, perform a post

```
sem_t s;
...
sem_init(&s, 1);
```

```
void *threadA(void *arg)
{
...
sem_wait(&s);
<critical section>
sem_post(&s);
...
}
```

```
void *threadB(void *arg)
{
...
sem_wait(&s);
<critical section>
sem_post(&s);
...
}
```

Mutual exclusion with semaphores (2)



sem_wait();	(TA)
<critical section (1)>	(TA)
sem_wait()	(TB)
<critical section (2)>	(TA)
sem_post()	(TA)
<critical section>	(TB)
sem_post()	(TB)

Synchronization

- How to use a semaphore for synchronization

–Define a semaphore initialized to 0

–At the synchronization point, follower performs a wait

–At the synchronization point, producer performs a post

–In the example, threadA blocks until threadB wakes it up

```
sem_t s;
...
sem_init(&s, 0);
```

```
void *threadA(void *)
{
...
sem_wait(&s);
...
}
```

```
void *threadB(void *)
{
...
sem_post(&s);
...
}
```

–How can both A and B synchronize at the same point?

Producer/consumer

- Consider a producer/consumer system
  - One producer executes insert_CA()
    - We want the producer to be blocked when the queue is full
    - The producer will be unblocked when there is some space again
  - One consumer executes extract_CA()
    - We want the consumer to be blocked when the queue is empty
    - The consumer will be unblocked when there is some space again
  - First attempt: one producer and one consumer only

Producer/consumer (2)

```
struct CircularArray_t {
int array[10];
int head, tail;
sem_t empty, full;
}
void init_CA(struct CircularArray_t *c)
{ c->head=0; c->tail=0;
sem_init(&c->empty, 0); sem_init(&c->full, 10); }

void insert_CA(struct CircularArray_t *c, int elem) {
sem_wait(&c->full);
c->array[c->head] = elem;
c->head = (c->head + 1) % 10;
sem_post(&c->empty);
}
void extract_CA(struct CircularArray_t *c, int &elem) {
sem_wait(&c->empty);
elem = c->array[c->tail];
c->tail = (c->tail + 1) % 10;
sem_post(&c->full);
}
```

Note: there is no member called *num* as we had in Exa

Producer/consumer: properties

- Notice that
  - The value of the counter of empty is the number of elements in the queue
    - It is the number of times we can call extract without blocking
  - The value of the counter of full is the complement of the elements in the queue
    - It is the number of times we can call insert without blocking

- Exercise
  - Prove that the implementation is correct
    - insert_CA() never overwrites elements
    - extract_CA() always gets an element of the queue

Producers/consumers

- Now let's combine mutual exclusion and synchronization

– Consider a system in which there are
  - Many producers
  - Many consumers

– We want to implement synchronization

– We want to protect the data structure

Producers/consumers: does it work?

```
struct CircularArray_t {
int array[10];
int head, tail;
sem_t full, empty;
sem_t mutex;
}
void init_CA(struct CircularArray_t *c)
{
c->head=0; c->tail=0;
sem_init(&c->empty, 0); sem_init(&c->full, 10); sem_init(&c->mutex, 1);
}
```

```
void insert_CA(struct CircularArray_t *c,
               int elem)
{
sem_wait(&c->mutex);
sem_wait(&c->full);
c->array[c->head]=elem;
c->head = (c->head+1)%10;
sem_post(&c->empty);
sem_post(&c->mutex);
}
```

```
void extract_CA(struct CircularArray_t *c,
                int *elem)
{
sem_wait(&c->mutex);
sem_wait(&c->empty);
elem = c->array[c->tail];
c->tail = (c->tail+1)%10;
sem_post(&c->full);
sem_post(&c->mutex);
}
```

Producers/consumers: correct solution

```
struct CircularArray_t {
int array[10];
int head, tail;
sem_t full, empty;
sem_t mutex;
}
void init_CA(struct CircularArray_t *c)
{
c->head=0; c->tail=0;
sem_init(&c->empty, 0); sem_init(&c->full, 10); sem_init(&c->mutex, 1);
}
```

```
void insert_CA(struct CircularArray_t *c,
                int elem)
{
sem_wait(&c->full);
sem_wait(&c->mutex);
c->array[c->head]=elem;
c->head = (c->head+1)%10;
sem_post(&c->mutex);
sem_post(&c->empty);
}
```

```
void extract_CA(struct CircularArray_t *c,
                int *elem)
{
sem_wait(&c->empty);
sem_wait(&c->mutex);
elem = c->array[c->tail];
c->tail = (c->tail+1)%10;
sem_post(&c->mutex);
sem_post(&c->full);
}
```

Producers/consumers: deadlock situation

- Deadlock situation

–A thread executes sem_wait(&c->mutex) and then blocks on a synchronisation semaphore

–To be unblocked another thread must enter a critical section guarded by the same mutex semaphore!

–So, the first thread cannot be unblocked and free the mutex!

–The situation cannot be solved, and the two threads will never proceed

- As a rule, never insert a blocking synchronization inside a critical section!!!

Readers/writers

- One shared buffer
- Readers:

–They read the content of the buffer

–Many readers can read at the same time

- Writers

–They write in the buffer

–While one writer is writing no other reader or writer can access the buffer

- Use semaphores to implement the resource

Readers/writers: simple implementation

```
struct Buffer_t {
sem_t synch;
sem_t s_R;
int nr;
}
void init_B(struct Buffer_t *b)
{ sem_init(&b->synch, 1);
sem_init(&b->s_R, 1);
b->nr=0; }
```

```
void read_B(struct Buffer_t *b) {
sem_wait(&b->s_R);
b->nr++;
if (b->nr==1) sem_wait(&b->synch);
sem_post(&b->s_R);

<read the buffer>

sem_wait(&b->s_R);
b->nr--;
if (b->nr==0) sem_post(&b->synch);
sem_post(&b->s_R);
}
```

```
void write_B(struct Buffer_t *b) {
sem_wait(&b->synch);

<write the buffer>

sem_post(&b->synch);
}
```

Readers/writers: more than one pending writer

```
struct Buffer_t {
sem_t synch, mutex;
sem_t s_R, s_W;
int nr, nw;
};
```

```
void init_B(struct Buffer_t *b)
{
sem_init(&b->synch, 1); sem_init(&b->mutex(1);
sem_init(&b->s_R, 1); sem_init(&b->s_W, 1);
b->nr=0; b->nw=0;
}
```

```
void read_B(struct Buffer_t *b) {
sem_wait(&b->s_R);
b->nr++;
if (b->nr==1)
sem_wait(&b->synch);
sem_post(&b->s_R);
<read the buffer>
sem_wait(&b->s_R);
b->nr--;
if (b->nr==0)
sem_post(&b->synch);
sem_post(&b->s_R);
}
```

```
void write_B(struct Buffer_t *b) {
sem_wait(&b->s_W);
b->nw++;
if (b->nw==1) sem_wait(&b->synch);
sem_post(&b->s_W);

sem_wait(&b->mutex);
<write the buffer>
sem_post(&b->mutex);

sem_wait(&b->s_W);
b->nw--;
if (b->nw==0) sem_post(&b->synch);
sem_post(&b->s_W);
}
```

Readers/writers: starvation

- A reader will be blocked for a finite time
- The writer suffers starvation
- Suppose we have 2 readers (R1 and R2) and 1 writer W1
  - Suppose that R1 starts to read
  - While R1 is reading, W1 blocks because it wants to write
  - R2 starts to read
  - R1 finishes, but, since R2 is reading, W1 cannot be unblocked
  - Before R2 finishes to read, R1 starts to read again
  - When R2 finishes, W1 cannot be unblocked because R1 is reading
- A solution
  - Readers should not be counted whenever there is a writer waiting for them

Readers/writers: priority to writers!

```
struct Buffer_t {
sem_t synch, synch1;
sem_t s_R, s_W;
int nr, nw;
};
```

```
void init_B(struct Buffer_t *b) {
sem_init(&b->synch, 1); sem_init(&b->synch1, 1);
sem_init(&b->s_R, 1); sem_init(&b->s_W, 1);
b->nr=0; b->nw=0;
}
```

```
void read_B(struct Buffer_t *b) {

sem_wait(&b->synch1);
sem_wait(&b->s_R);
b->nr++;
if (b->nr==1) sem_wait(&b->synch);
sem_post(&b->s_R);
sem_post(&b->synch1);


<read the buffer>

sem_wait(&b->s_R);
b->nr--;
if (b->nr==0) sem_post(&b->synch);
sem_post(&b->s_R);
}
```

```
void write_B(struct Buffer_t *b) {
sem_wait(&b->s_W);
b->nw++;
if (b->nw==1) sem_wait(&b->synch1);
sem_post(&b->s_W);

sem_wait(&b->synch);
<write the buffer>
sem_post(&b->synch);

sem_wait(&b->s_W);
b->nw--;
if (b->nw == 0) sem_post(&b->synch1);
sem_post(&b->s_W);
}
```

Readers/writers: problem

- Now, there is starvation for readers
- The readers/writers problem can be solved in general?
  - No starvation for readers
  - No starvation for writers
- Solution
  - Maintain a FIFO ordering with requests
    - If at least one writer is blocked, every next reader blocks
    - If at least one reader is blocked, every next writer blocks
- We can do that using the private semaphores technique

References

Course website

- http://hipert.unimore.it/people/paolob/pub/Industrial_Informatics/index.html

My contacts

- paolo.burgio@unimore.it
- http://hipert.mat.unimore.it/people/paolob/

Resources

- Giorgio Buttazzo, “Hard Real-Time Computing Systems : Predictable Scheduling Algorithms and Applications“. 3rd Edition. 2011. Springer
- “Real-Time Embedded Systems” course by Prof. Bertogna @UNIMORE
- A "small blog"
  - http://www.google.com