Scuola Superiore Sant'Anna

Real-Time System Laboratory

A design Methodology for Concurrent programs

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A DESIGN METHODOLOGY FOR SHARED MEMORY PROGRAMS

Methodology

- We present here a structured methodology for programming in shared memory systems
- The methodology leads to “safe” programs
- Not necessarily optimized!
- Programmers can always use their intelligence and come up with “elegant” solutions

Shared memory programming

- A program is a set of
  - threads that interact by accessing ...
  - data structures (*shared resources*)
- A data structure can be seen as
  - a set of variables
  - a set of functions operating on the variables
- Threads
  - access the data structures only through functions

Object Oriented programming

- In C++

```
class SharedData {
        int array[10];
        int first, last;
        ...
public:
        SharedData();
        int insert(int a);
        int extract();
}
```

- In C

```
struct SharedData {
        int array[10];
        int first, last;
};      ...

SharedData_init(struct SharedData *d);
int SharedData_insert(struct SharedData *d,  int a);
int SharedData_extract(struct SharedData *d);
```

Shared Data structure

- Encapsulating the semaphores
  - The data structure
    - should already include the mechanisms for mutual exclusion and synchronization
    - for example, the CircularArray data structure
  - Functions on the data structure
    - should use the semaphores inside the function
  - Threads
    - can only access the data structure through functions

How to program the data structure?

- Some design considerations
  - First, design the interface: that is, which functions the threads need to call
  - Mutual exclusion
    - for simplicity, all functions on the same data struture should be in mutual exclusion
    - maybe, this is not optimized, but it is SAFE!

Mutual exclusion

- For each data structure,
  - define a mutual exclusion semaphore, initialized to 1
- For each function
  - just after starting the function, take the semaphore, and leave it before returning

Mutual exclusion

- Example

```
class MyData {
        ...;
        sem_t m;
        ...;
public:
        MyData() {
                ...
                sem_init(&m, 0, 1);
        }

        int myfun() {
                sem_wait(&m);
                ....
                sem_post(&m);
        }
};
```

Synchronization

- Design consideration
  - – Specify the behavior of the functions
    - under which conditions a calling thread should be blocked?
  - – Identify all different blocking conditions

Synchronization

- Other design considerations
  - identify unblocking conditions
    - when a blocked thread should be unblocked
    - mark the functions that should unblock those threads
- Putting all togheter
  - draw a state diagram for the resource
  - STATES: the various states of the resource
  - EVENTS: threads that call the functions

Example: CircularArray with Manager

- Problem explaination
- Design the data structure interface
- Identify blocking and unblocking conditions
- Draw the state diagram

Coding Rules

- For each blocking condition
  - a semaphore initialized to 0 (*blocking semaphore)*
  - an integer that counts the number of blocked threads on the condition (*blocking counter*) (init to 0)
- One (or more) integer variable(s) to code the state
- Write the initialization function (constructor in C++)

The functions

- Finally, code the functions
  - take the mutex at the beginning
  - check the blocking conditions (if any)
  - if the thread has to be blocked,
    - increment the blocking counter, signal on the mutex, wait on the blocking semaphore, wait on the mutex
  - perform the code, change state if necessary
  - check unblocking conditions
  - if a thread has to be unblocked
    - decrement the blocked counter, signal the semaphore

The code

A subtle error

- The “man in the middle” problem
- Solution:
  - check blocking conditions in a while() loop

Passing “le baton”

- A (more elegant) solution

MONITORS

PTHREADS – MUTEXES AND CONDITION VARIABLES

Monitors

- Monitors are a language structure equivalent to semaphores, but cleaner
  - A monitor is similar to an object in a OO language
  - It contains variables and provides procedures to other software modules
  - Only one thread can execute a procedure at a certain time
    - ✓ Any other thread that has invoked the procedure is blocked and waits for the first threads to exit
    - ✓ Therefore, a monitor implicitely provides mutual exclusion

Monitors

- Monitors support synchronization with *Condition Variables*
  - A condition variable is a blocking queue
  - Two operations are defined on a condition variable
    - ✓ wait() -> suspends the calling thread on the queue
    - ✓ signal() -> resume execution of one thread blocked on the queue
- Important note:
  - wait() and signal() operation on a condition variable are different from wait and signal on a semaphore!
  - There is not any counter in a condition variable!
  - If we do a signal on a condition variable with an empty queue, the signal is lost

Monitors in Java

- Java provides something that vaguely resembles monitors
  - the “synchronized” keyword allows to define classes with protected functions
  - every “synchronized” class has one implicit condition variable
  - you can “signal” one thread with notify(); and all threads with notifyAll();

Monitors in POSIX

- It is not possible to provide monitors in C
  - C and C++ do not provide any concurrency control mechanism; they are “purely sequential languages”
- POSIX allows something similar to Monitors through library calls

Slides on POSIX monitors

Exercises on POSIX monitors

COMPLEX SYNCHRONIZATION PROBLEMS
READERS - WRITERS

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

Simple implementation

```
class Buffer {
            Semaphore wsem;
            Semaphore x;
            int nr;
public:
            Buffer() : wsem(1), x(1), nr(0) {}
            void read();
            void write();
} buffer;
```

```
void Buffer::read() {
      x.wait();
      nr++;
      if (nr==1) wsem.wait();
      x.signal();
      <read the buffer>
      x.wait();
      nr--;
      if (nr==0) wsem.signal();
      x.signal();
}
```

```
void Buffer::write() {
      wsem.wait();
      <write the buffer>
      wsem.signal();
}
```

Problem: 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
  - Now R2 starts to read
  - Now 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

Priority to writers!

```
class Buffer {
        Semaphore x, y, z, wsem, rsem;
        int nr, nw;
public:
        Buffer() : x(1), y(1), z(1), wsem(1), rsem(1), nr(0), nw(0) {}
}
```

```
void Buffer::write() {
        y.wait();
        nw++;
        if (nw==1) rsem.wait();
        y.signal();
        wsem.wait();
        <write the buffer>
        wsem.signal();
        y.wait();
        nw--;
        if (nw == 0) rsem.signal();
        y.signal();
}
```

```
void Buffer::read() {
        z.wait();
        rsem.wait();
        x.wait();
        nr++;
        if (nr==1) wsem.wait();
        x.signal();
        rsem.signal();
        z.signal();
        <read the buffer>
        x.wait();
        nr--;
        if (nr==0) wsem.signal();
        x.signal();
}
```

Problem

- Can you solve the readers/writers problem in the general case?
  - 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
    - ✓ One single semaphore!

Solution

```
class Buffer {
        int nbr, nbw;
        int nr, nw;
        Semaphore rsem, wsem;
        Semaphore m;
public:
        Buffer():
                nbw(0),nbr(0), nr(0), nw(0),
                rsem(0), wsem(0) {}
        void read();
        void write();
};
```

Solution

```
void Buffer::read()
{
    m.wait();
    if (nw || nbw) {
        nbr++;
        m.signal();rsem.wait();m.wait();
        while (nbr>0)
            {nbr--;rsem.signal();}
    }
    nr++;
    m.signal();
    <read buffer>;
    m.wait();
    nr--;
    if (nbw && nr == 0) wsem.signal();
    m.signal();
}
```

```
void Buffer::write()
{
    m.wait();
    if (nw || nbw || nr || nbr) {
        nbw++;
        m.signal();wsem.wait();m.wait();
        nbw--;
    }
    nw++;
    m.signal();
    <read buffer>;
    m.wait();
    nw--;
    if (nbr) {nbr--; rsem.signal();}
    else if (nbw) wsem.signal();
    m.signal();
}
```

MESSAGE PASSING

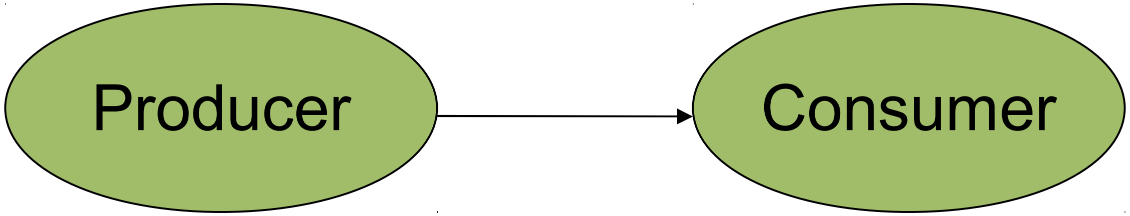
Message passing

- Message passing systems are based on the basic concept of message
- Two basic operations
  - send(destination, message);
  - receive(source, &message);

  - Two variants
    - ✓ Both operations can be synchronous or asynchronous
    - ✓ 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)

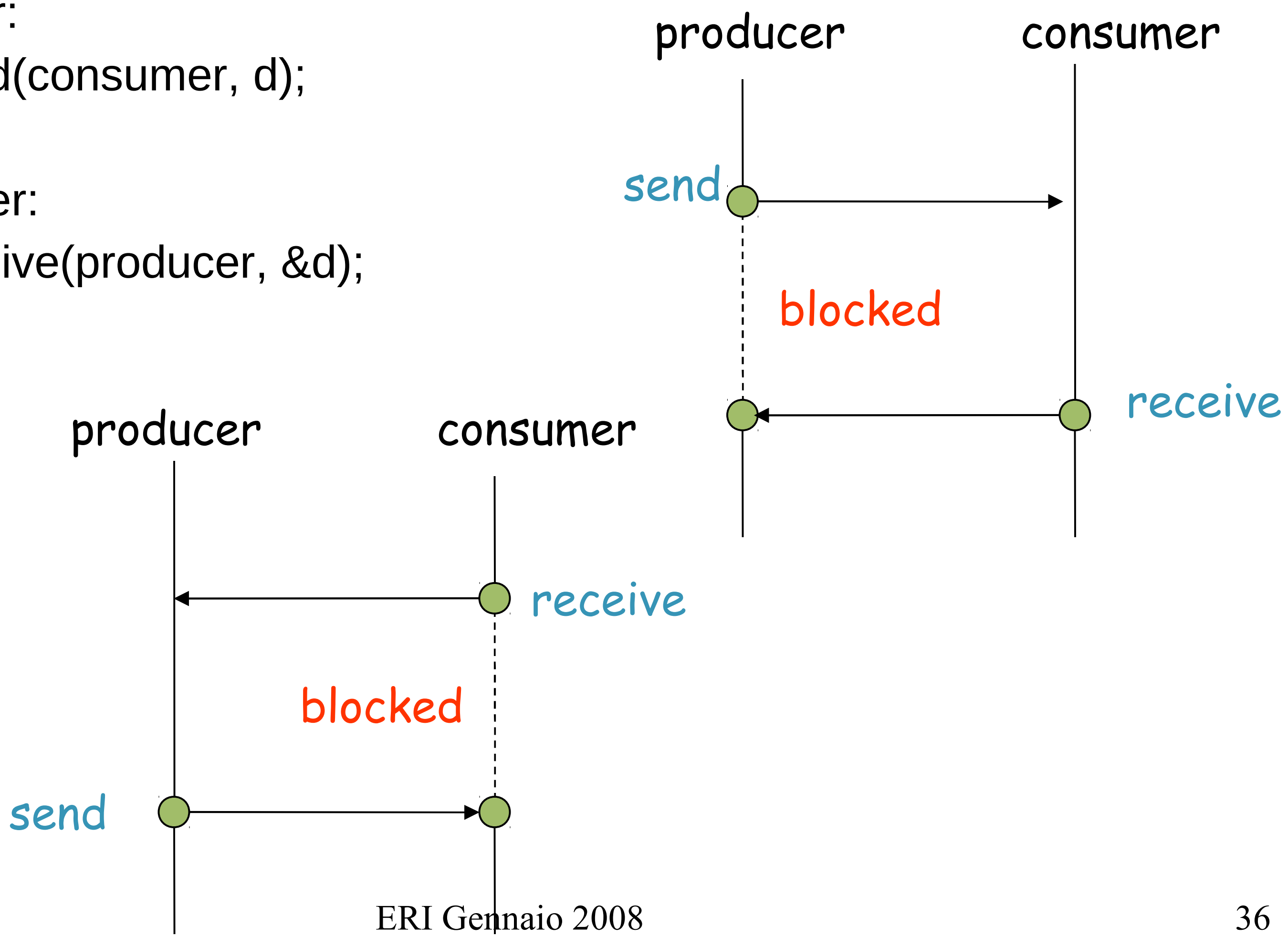


Synchronous communication

- Synchronous send/receive

```
producer:
  s_send(consumer, d);

consumer:
  s_receive(producer, &d);
```



Async send/ Sync receive

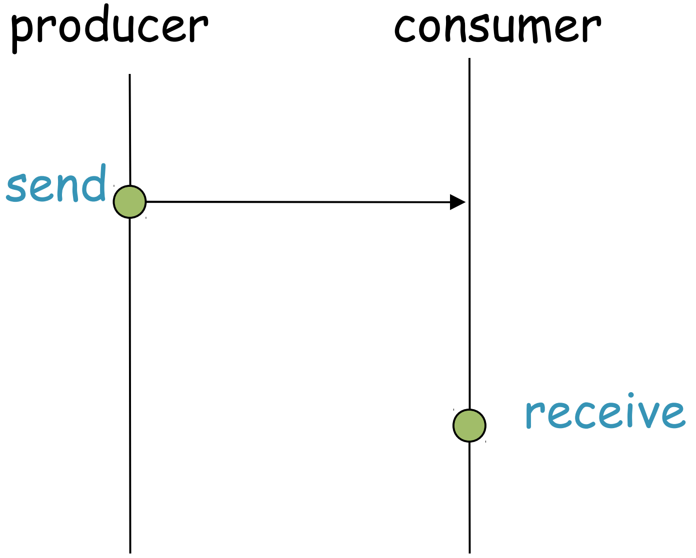
- Asynchronous send / synchronous receive

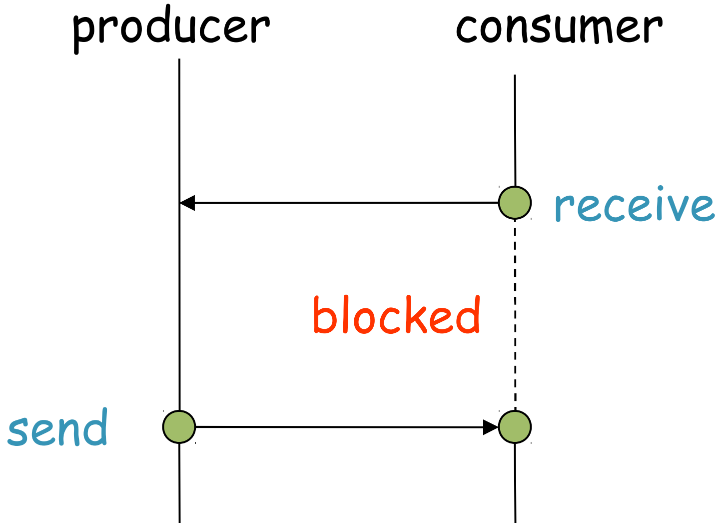
producer:

a_send(consumer, d);

consumer:

s_receive(producer, &d);





Asymmetric receive

- Symmetric receive
  - receive(source, &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 browser can ask for the same service
- Asymmetric receive
  - source = receive(&data);

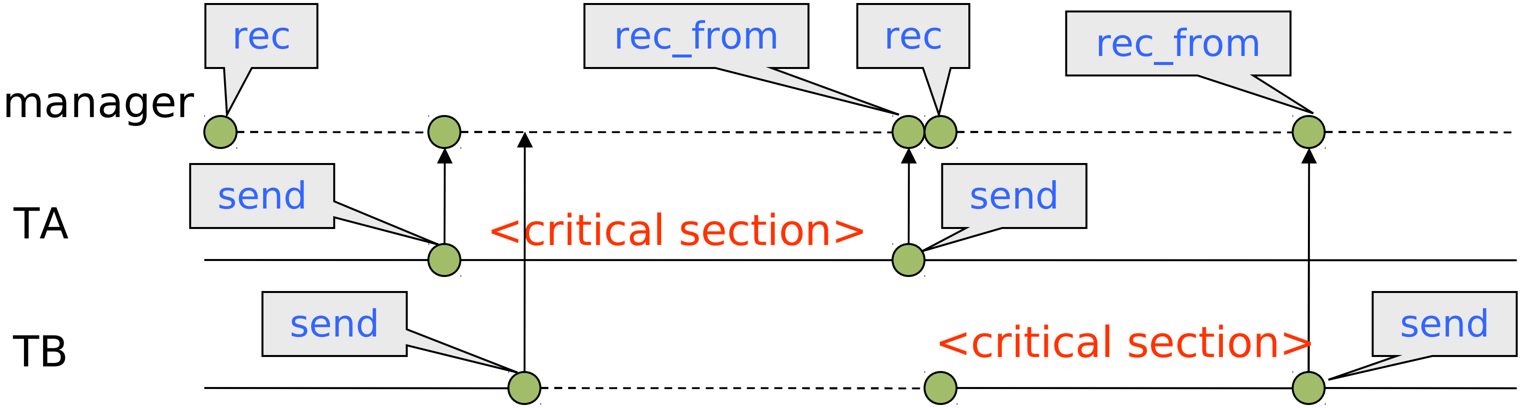
Message passing systems

- In message passing
  - Each resource needs one threads manager
  - 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 resourec 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);
	}
}
```

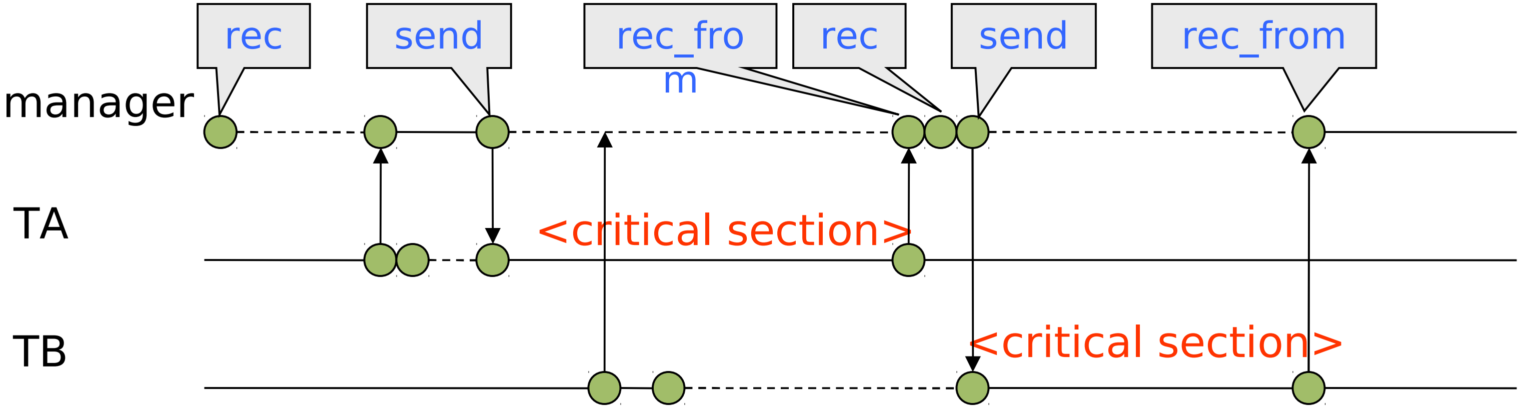
```
void * thread(void *)
{
	int d;
	while (true) {
		s_send(manager, d);
		<critical section>
		s_send(manager, d);
	}
}
```



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);
        }
}
```



A different approach

- Shared memory
  - each resource is a class
  - threads ask for services through functions calls
  - they synchronize through mutexes and condition variable

- Message Passing
  - each resource has a manager thread
  - threads ask for services through messages and receive response through messages
  - they synchronize through blocking receives

Resources and Manager

- For each resource
  - – a “manager” thread takes care of executing the services on behalf of the clients/threads
  - – general structure of a manager:
    - wait for a message
    - decode the message, execute the service
    - eventually, send back the response
  - – The manager sequentializes all services