Scuola Superiore Sant'Anna

Real-Time Systems Laboratory

Operating Systems and Concurrent Programming

Giuseppe Lipari

AA 2006 – 2007

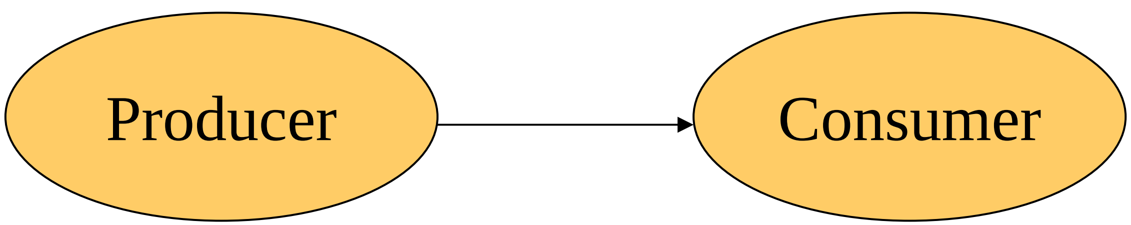
Message passing

- 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)

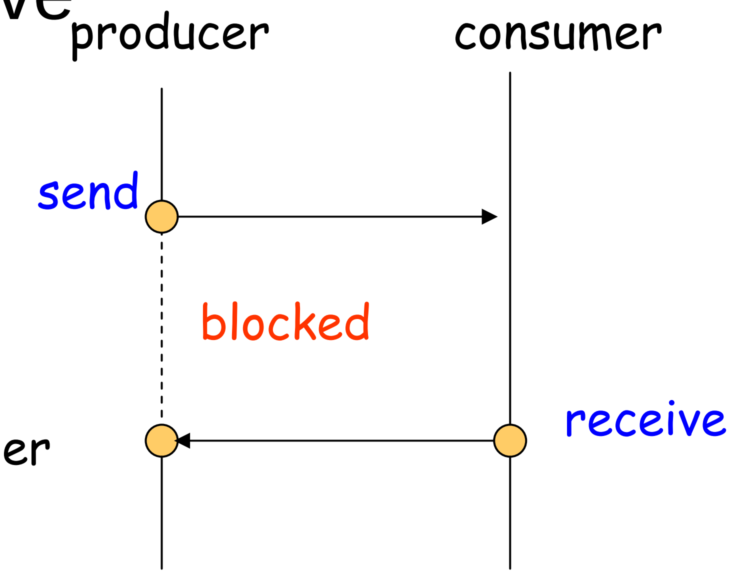


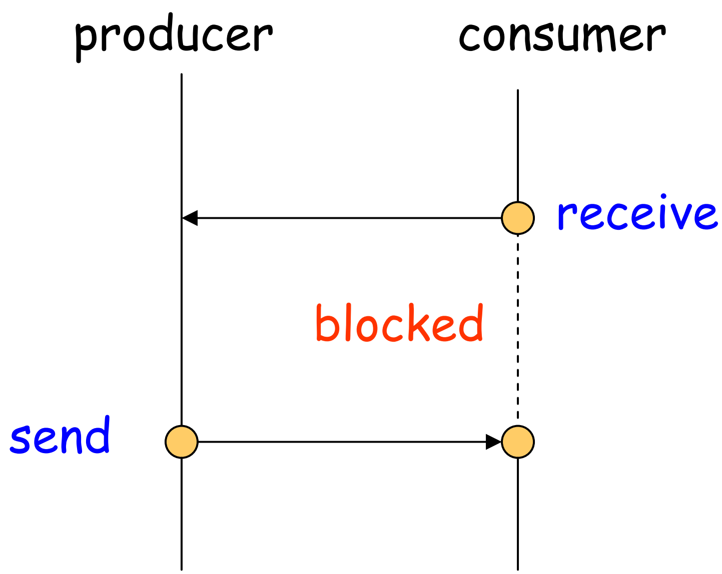
Synchronous communication

- Synchronous send/receive

producer:
  s_send(consumer, d);

consumer:
  s_receive(producer, &d);





Async send/ Sync receive

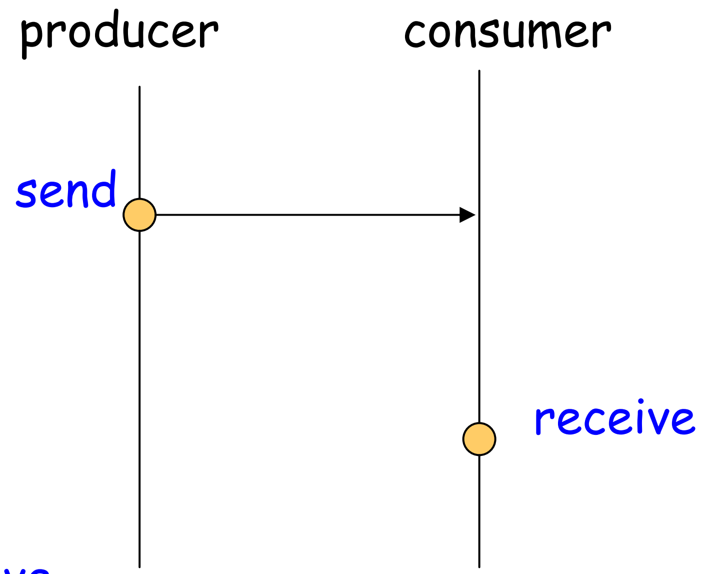
- Asynchronous send / synchronous receive

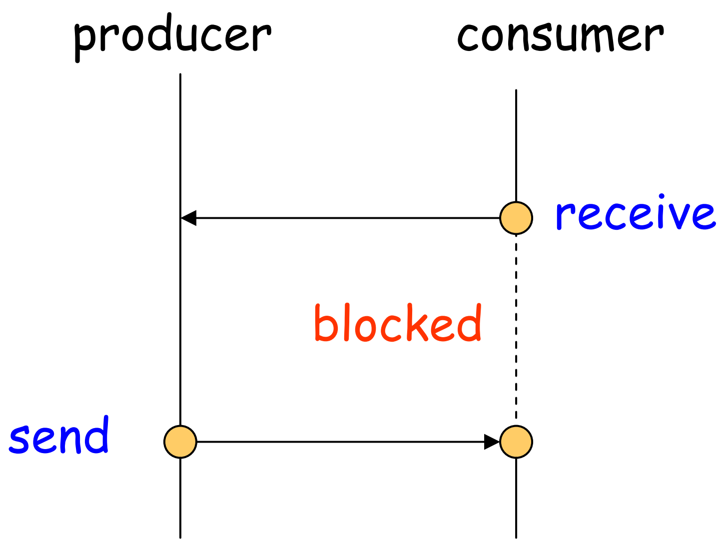
producer:

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);

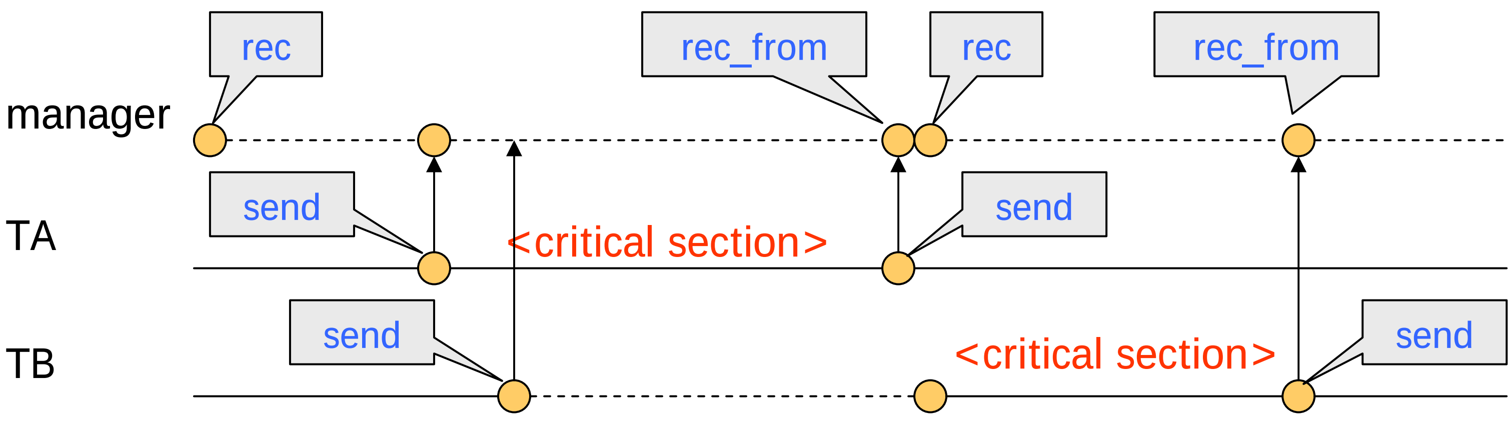
Message passing systems

- 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);
      }
}
```

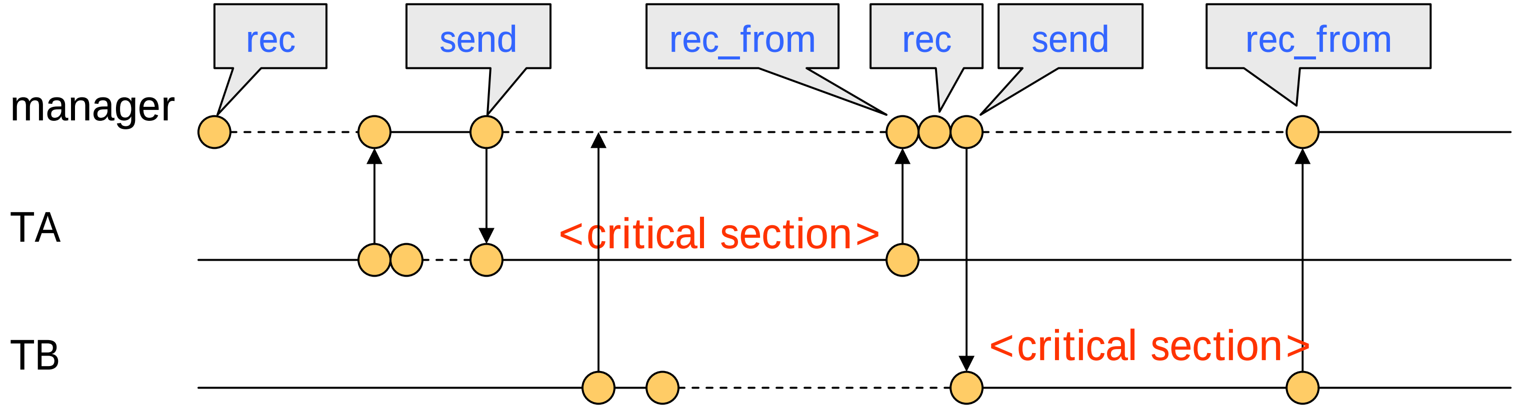
```
void * thread(void *)
{
      int d;
      while (true) {
          s_send(manager, d);
          <critical section>
          s_send(manager, d);
      }
}
```



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);
    }
}
```



DEADLOCK

Deadlock

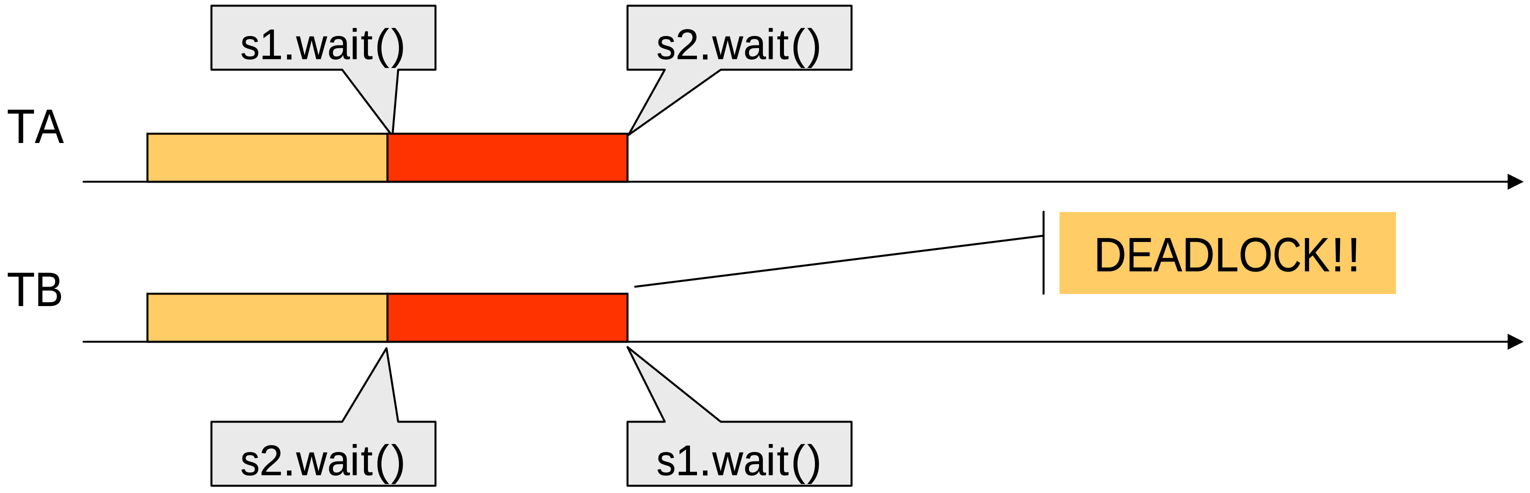
- Deadlock is the situation in which a group of threads are permanently blocked waiting for some resource
- Deadlock can happen in many subtle cases
- Here we will study ways of avoiding deadlock situations

Example of deadlock

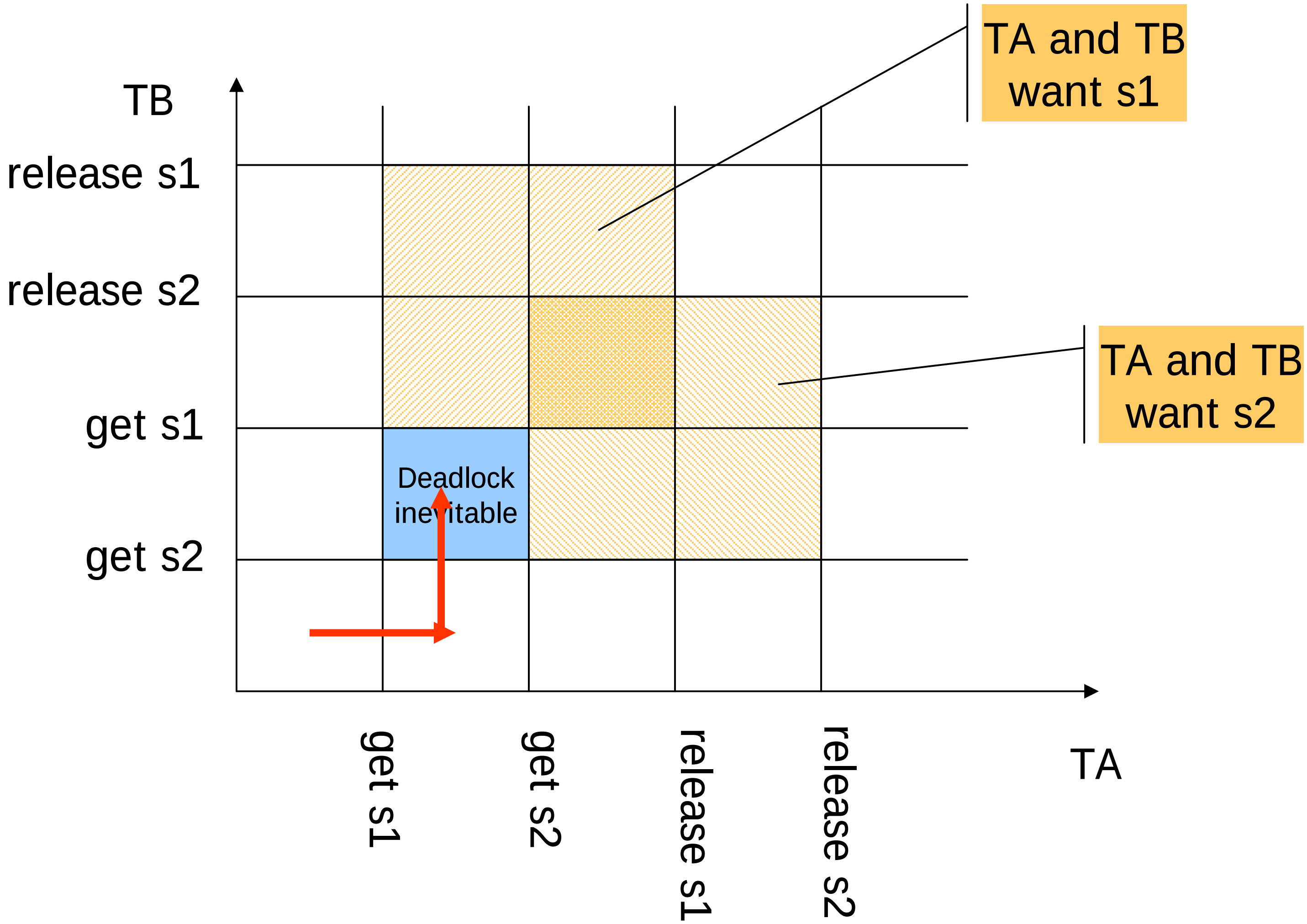
```
Semaphore s1(1);
Semaphore s2(1);
```

```
void *threadA(void *)
{
    ...
    s1.wait();
    s2.wait();
    ...
    s1.signal();
    s2.signal();
    ...
}
```

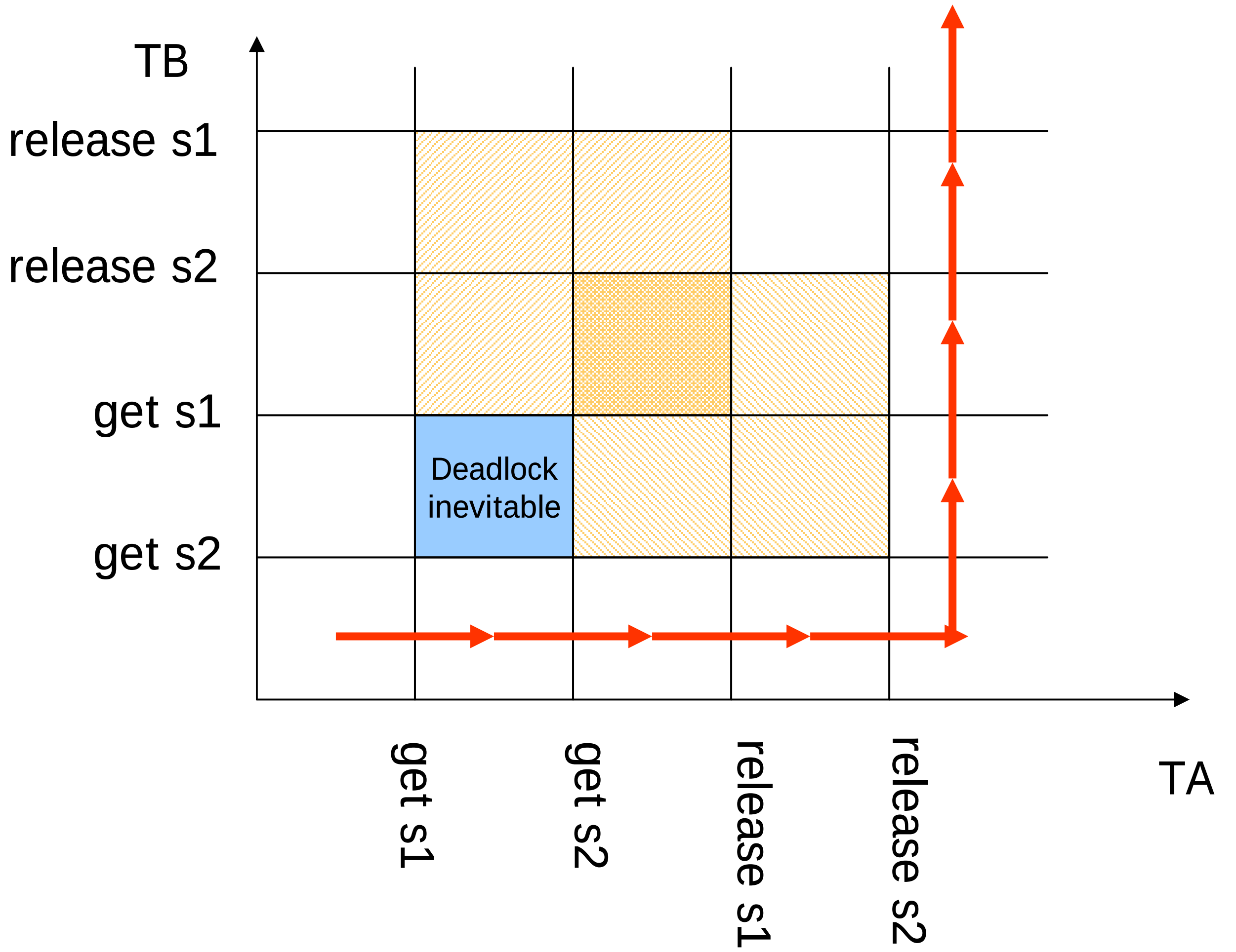
```
void *threadB(void *)
{
    ...
    s2.wait();
    s1.wait();
    ...
    s2.signal();
    s1.signal();
    ...
}
```



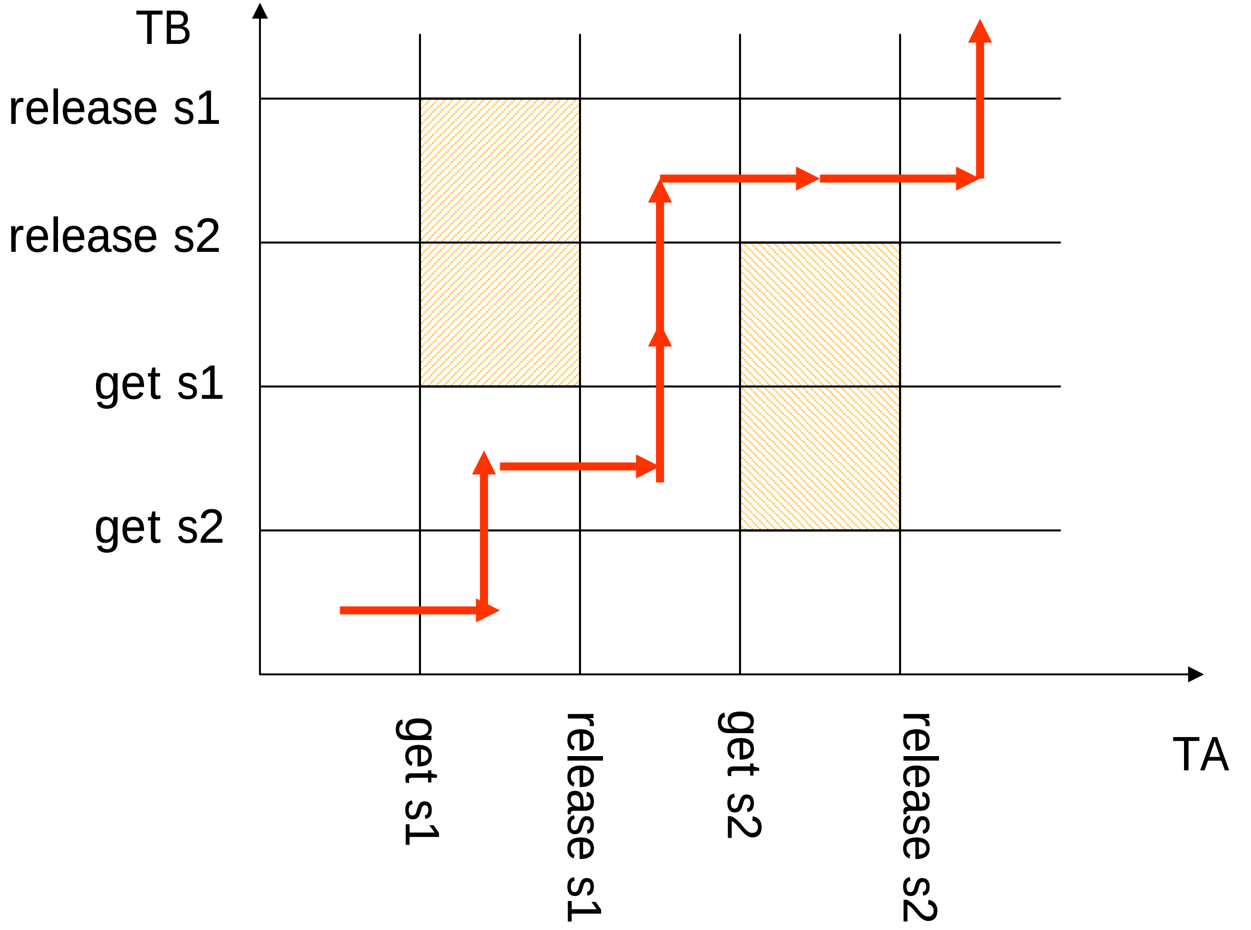
Graphical situation



Graphical situation



Example with no deadlock



Other examples of deadlock

- Bad situations can happen even when the resource is not “on-off”
- Consider a memory allocator
  - Suppose that the maximum memory allocable is 200 Kb

```
void * threadA(void *)
{
    request(80kb);
    ...
    request(60kb);
    ...
    release(140kb);
}
```

```
void * threadB(void *)
{
    request(70kb);
    ...
    request(80kb);
    ...
    release(150kb);
}
```

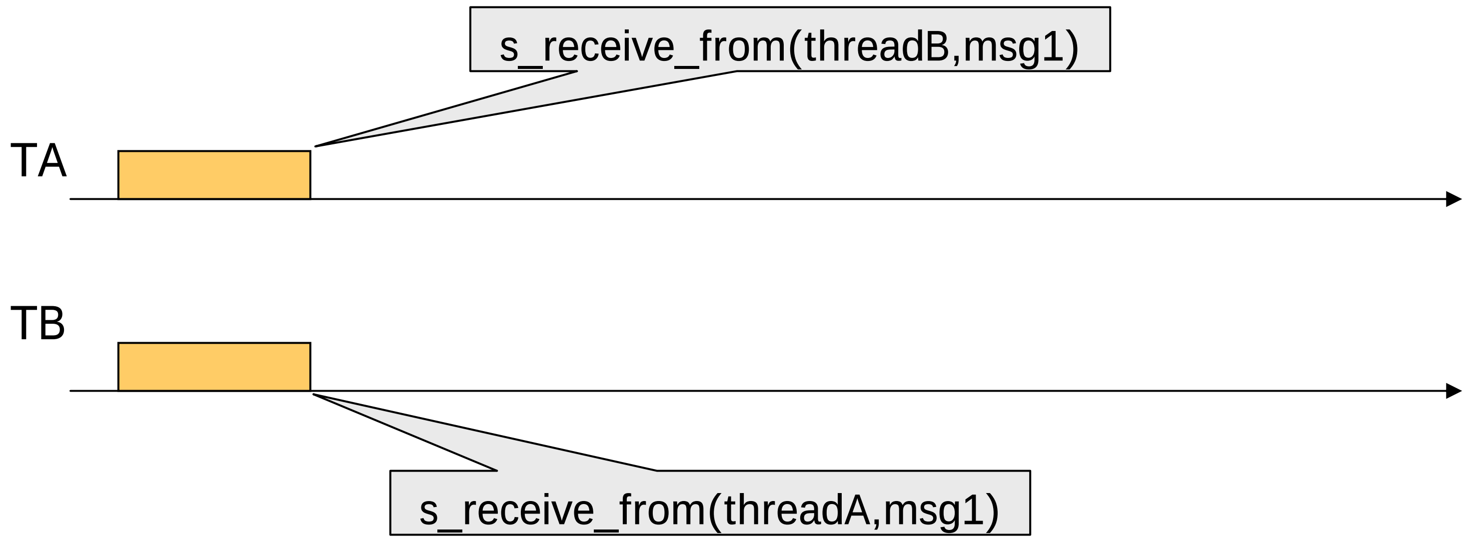
Consumable and reusable resources

- Reusable resources
  - It can be safely used by only one thread at time and is nod depleted by the use
  - Threads must request the resource and later release it, so it can be *reused* by other threads
  - Examples are processor, memory, semaphores, etc.
- Consumable resources
  - It is created and destroyed dynamically
  - Once the resource is acquired by a thread, it is immediately “destroyed” and cannot be reused
  - Examples are messages in a FIFO queue, interrupts, I/O data, etc.

Deadlock with consumable resources

```
void *threadA(void *)
{
    s_receive_from(threadB, msg1);
    ...
    s_send(threadB, msg2);
    ...
}
```

```
void *threadB(void *)
{
    s_receive_from(threadA, msg1);
    ...
    s_send(threadA, msg2);
    ...
}
```



Conditions for deadlock

- Three conditions
  - Mutual exclusion
    - Only one process may use the resource at the same time
  - Hold and wait
    - A process may hold allocated resources when it blocks
  - No preemption
    - The resource cannot be revoked
- If the three above conditions hold and
  - Circular wait
    - A closed chain of threads exists such that each thread holds at least one resources needed by the next thread in the chain
- then a deadlock can occur!
- These are necessary and sufficient conditions for a deadlock

How to solve the problem of deadlock

- To prevent deadlock from happening we can distinguish two class of techniques
  - Static: we impose strict rules in the way resources may be requested so that a deadlock cannot occur
  - Dynamic: dynamically, we avoid the system to enter in dangerous situations
- The basic idea is to avoid that one of the previous conditions hold
- Three strategies
  - Deadlock prevention (static)
  - Deadlock avoidance (dynamic)
  - Deadlock detection (dynamic)

Conditions

- Mutual exclusion
  - This cannot be disallowed. If a resource must be accessed in mutual exclusion, there is nothing else we can do!
- Hold and wait
  - We can impose the tasks to take all resources at the same time with a single operation
  - This is very restrictive! Even if we use the resource for a small interval of time, we must take it at the beginning!
  - Reduces concurrency

Conditions

- No preemption
  - This technique can be done only if we can actually suspend what we are doing on a resource and give it to another thread
  - For the “processor” resource, this is what we do with a thread switch!
  - For other kinds of resources, we should “undo” what we were doing on the resource
  - This may not be possible in many cases!

Conditions

- Circular wait
  - This condition can be prevented by defining a linear ordering of the resources
  - For example: we impose that each thread must access resources in a certain well-defined order

```
void *threadA(void *)
{
    ...
    s1.wait();
    s2.wait();
    ...
    s1.signal();
    s2.signal();
    ...
}
```

```
void *threadB(void *)
{
    ...
    s2.wait();
    s1.wait();
    ...
    s2.signal();
    s1.signal();
    ...
}
```

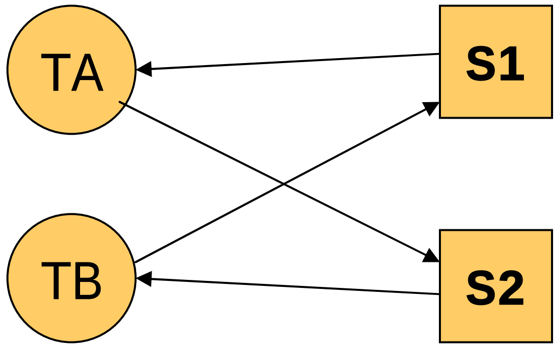
Why this strategy works?

- Let us define a oriented graph
  - A vertex can be
    - a thread (round vertex)
    - a resource (square vertex)
  - An arrow from a thread to a resource denotes that the thread requires the resource
  - An arrow from a resource to a thread denotes that the resource is granted to the thread
- Deadlock definition
  - A deadlock happens if at some point in time there is a cycle in the graph

Graph

```
void *threadA(void *)
{
    ...
    s1.wait();
    s2.wait();
    ...
    s1.signal();
    s2.signal();
    ...
}
```

```
void *threadB(void *)
{
    ...
    s2.wait();
    s1.wait();
    ...
    s2.signal();
    s1.signal();
    ...
}
```



Theorem

- If all threads access resources in a given order, a deadlock cannot occur
  - Proof: by contradiction.
  - Suppose that a deadlock occurs. Then, there is a cycle.
  - By hypothesis all threads access resources by order
  - Therefore, each thread is blocked on a resource that has an order number grater than the resources it holds.
  - Starting from a thread and following the cycle, the order number of the resource should always increase. However, since there is a cycle, we go back to the first thread. Then there must be a thread T that holds a resource Ra and requests a Resource Rb with $Ra < Rb$
  - This is a contradiction!

Deadlock avoidance

- This technique consists in monitoring the system to avoid deadlock
  - We check the behaviour of the system
  - If we see that we are going into a dangerous situation, we block the thread that is doing the request, even if the resource is free

Naive approach

- Definitions
  - (R1, R2, ... Rm): total amount of each resource
  - (V1, V2, ..., Vm): amount of free resources at time t
  - Claim:

$$\begin{pmatrix} C_{11} & C_{12} & \dots \\ C_{21} & C_{22} & \dots \\ \dots & \dots & \dots \end{pmatrix}$$

  - Allocation:

$$\begin{pmatrix} A_{11} & A_{12} & \dots \\ A_{21} & A_{22} & \dots \\ \dots & \dots & \dots \end{pmatrix}$$

Naive approach

$$R_i = V_i + \sum_{k=1}^{n} A_{ki} \qquad \forall k,i : C_{ki} \le R_i \qquad \forall k,i : A_{ki} \le C_{ki}$$

- Deadlock avoidance rule:
  - A new thread T(n+1) is started only if:

$$R_i \ge C_{(n+1)i} + \sum_{k=1}^{n} C_{ki}$$

- Too restrictive!

Example

- In case of the semaphores
  - $R_1 = 1$, $R_2 = 1$
  - $C_{a1} = 1$, $C_{a2} = 1$
  - $C_{b1} = 1$, $C_{b2} = 1$
- The previous rule was:

$$R_1 \geq C_{a1} + C_{b1}$$

The banker’s algorithm

- Tries to identify “safe states”
  - Analyse a thread request
  - If the situation after the tequest is unsafe (i.e. it leads to a deadlock) block the thread
  - Otherwise, grant the resource!

The banker's algorithm

```
// M is the number of different resources
// N is the number of distinct processes
class Bank {
    int avail[M];     // How many are left for each resource
    int request[N,M];          // How much each process requires
    int assigned[N, M]; // how much each process is assigned
public:
    // p identifies the process. p is in [0,N-1]
    // r identifies the resource. r is in [0, M-1]
    bool try(int p, int r);
};
```

The banker's algorithm

```
bool Bank::try(int p, int r)
{
    bool flag[N];int i,j;
    bool ok = true;
    for (i=0; i<N; i++) flag[i]=true;
    int my_avail[M];
    for (j=0; j<M; j++)
        my_avail[j] = avail[j];
    my_avail[r]--;
    request[p,r]--;
    assigned[p,r]++;
    i=0;
    ...
```

```
    while (i<N) {
      if (flag[i]) {
          ok = true;
          for (j=0; j<M; j++)
            if (request[i,j]>my_avail[j])
                ok = false;
      }
      if (ok) {
          for (j=0; j<M; j++)
            my_avail[j] += assigned[i,j];
          flag[i] = false;
          i = 0;
      }
      else i++;
    }
    bool safe = true;
    for (i=0; i<N; i++)
      if (flag[i]) safe = false;
    if (safe)  avail[p,r]--;
    return safe;
}
```

Deadlock detection

- In this strategy, we monitor the system to check for deadlocks *after* they happen
  - We look for cycles between threads and resources
  - How often should we look?
    - It is a complex thing to do, so it takes precious processing time
    - It can be done not so often
  - Once we discover deadlock, we must *recover*
  - The idea is to kill some blocked thread

Recovery

1. Abort all threads
   – Used in almost all OS. The simplest thing to do.
2. Check point
   – All threads define safe *check points*. When the OS discover a deadlock, all involved threads are restarted to a previous check point
     - Problem. The can go in the same deadlock again!
3. Abort one thread at time
   – Threads are aborted one after the other until deadlock disappears
4. Successively preempt resources
   – Preempt resources one at time until the deadlock disappears