Process Synchronization

Race Condition: Producer-Consumer Problem

```
while (1) {
  while (count == BUFFER_SIZE)
    ; // do nothing
  // produce an item and put in
    next
  buffer[in] = nextProduced;
  in = (in + 1) % BUFFER_SIZE;
  count++;
}
```

Producer Thread

```
while (1) {
  while (count == 0)
    ; // do nothing
  next =  buffer[out];
  out = (out + 1) % BUFFER_SIZE;
  count--;
  // consume the item in next
}
```

Consumer Thread

Race Condition

- count++ could be implemented as

```
register1 = count
register1 = register1 + 1
count = register1
```

- count-- could be implemented as

```
register2 = count
register2 = register2 - 1
count = register2
```

- Consider this execution: initially, count = 5

Producer:	Consumer:	Values:
register1 = count		{register1 = 5}
register1 = register1 + 1		{register1 = 6}
	register2 = count	{register2 = 5}
	register2 = register2 – 1	{register2 = 4}
count = register1		{count = 6}
	count = register2	{count = 4}

Why can such interleaving (race) exist?

- Operating system scheduling is non-deterministic
- Context switch can happen at any arbitrary instructions
- In the previous example, any permutation of interleaving for the producer/consumer is possible
- Correct algorithm should not rely on the order to which threads of execution are scheduled

Example: Shared Linked List

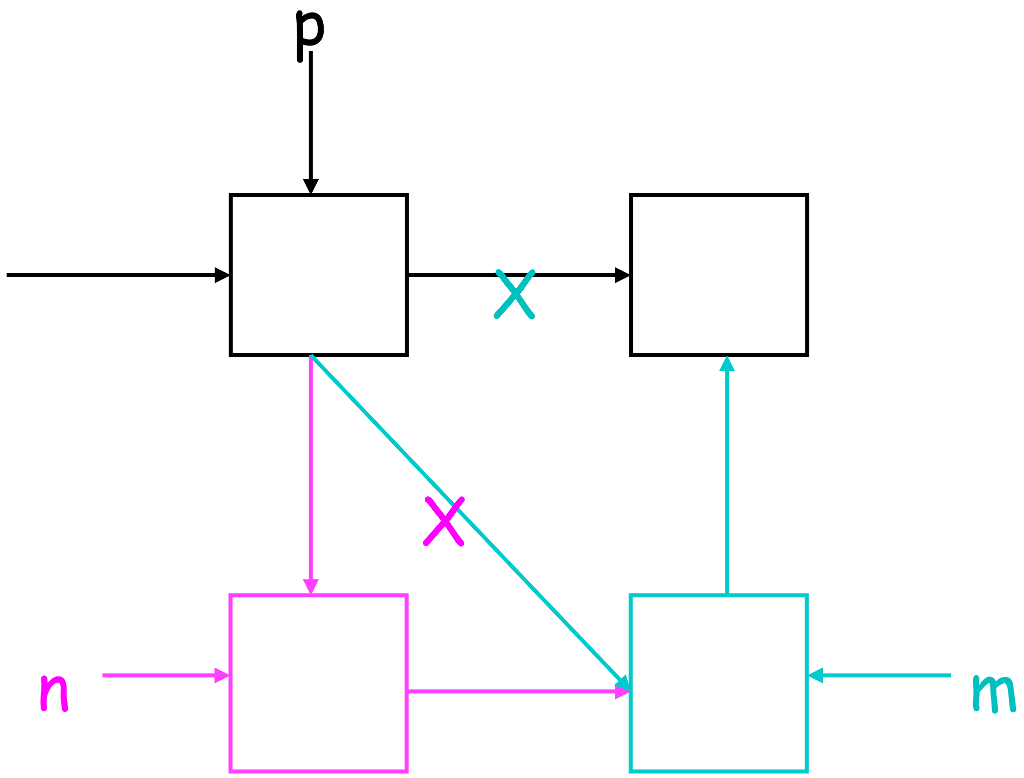
(1) n->next = p->next

(2) p->next = n

(a) m->next = p->next

(b) p->next = m

Order: a b 1 2



Example: Shared Linked List

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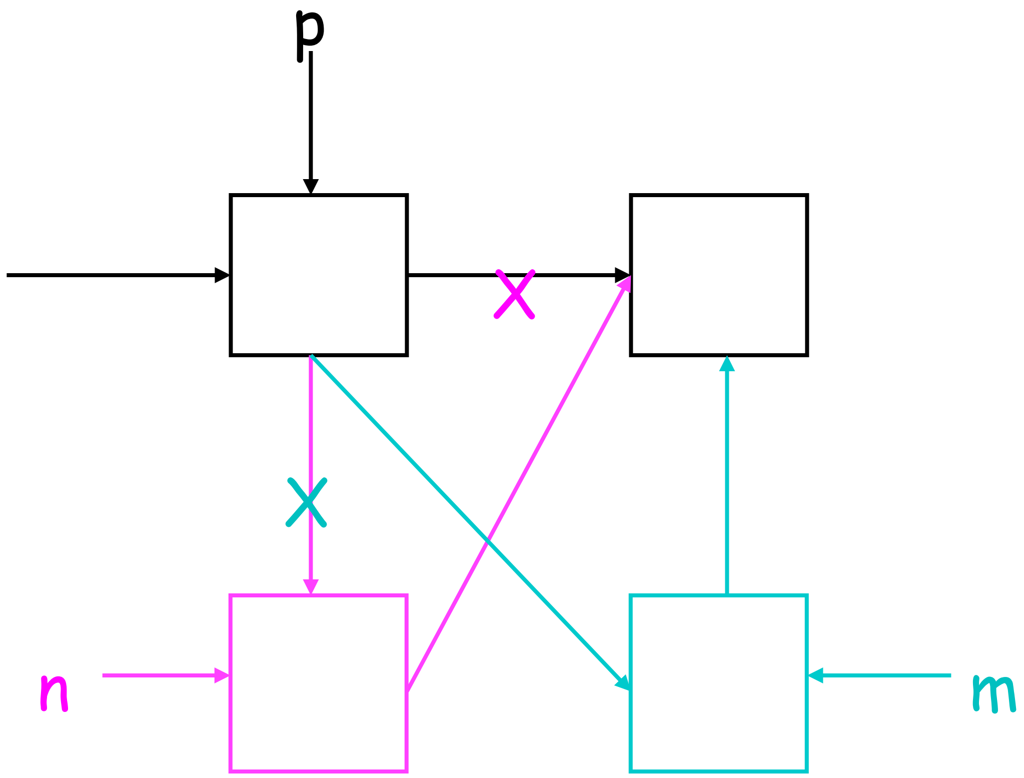


Critical Section

- What is a critical section?
  - Each thread has a segment of code, in which the thread may be changing common variables, updating shared data structures …
  - Code that must be executed mutually exclusively
  - Contains a race condition
- What is a race condition?
  - Outcome depends on the order threads execute
  - Different outcomes are possible
- Necessary conditions
  - Concurrency
  - Shared data
  - Interference

Solution to Critical-Section Problem

1. Mutual Exclusion - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2. Progress - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely
3. Bounded Waiting - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted

Mutual Exclusion – Hardware Support

- Interrupt disabling

```
while (true) {
   /* disable interrupts */;
   /* critical section */;
   /* enable interrupts */;
   /* remainder */;
}
```

Mutual Exclusion – Hardware Support

- Special machine instructions
  - Exchange instruction (e.g., xchg)
  - Compare&Exchange instruction

```
void exchange
(int register, int memory)
{
    int temp;
    temp = memory;
    memory = register;
    register = temp;
}
```

Statements are executed atomically

spinlock

```
int  keyi = 1;
do
     exchange(keyi, lock);
while (keyi!=0)
    /* critical section */;
    lock = 0;
    /* remainder */;
}
```

Mutual Exclusion – Hardware Support

- Advantages
  - It is simple and therefore easy to verify
  - Applicable to any number of processes sharing main memory
  - It can be used to support multiple critical sections
- Disadvantages
  - Busy-waiting consumes processor time
  - Starvation is possible
  - Deadlock is possible
    - E.g., priority-driven preemptive scheduling

Mutual Exclusion – Software Support

- Semaphore:
  - An integer value used for signalling among processes.
  - Three operations, each of which is ***atomic:***
    - initialize
    - decrement
      - P, wait, semWait, or acquire
    - increment
      - V, signal, semSignal, or release

Semaphore Implementation

- Must guarantee that no two processes can execute acquire() and release() on the same semaphore at the same time
- Thus implementation becomes the critical section problem
  - Busy waiting (spinlock) in critical section implementation
    - Implementation code is short
    - Little busy waiting if critical section rarely occupied
    - More busy waiting → waste of CPU resources
  - Applications may spend lots of time in critical sections
    - Performance issues need to be addressed

Semaphore Implementation with no Busy waiting

- With each semaphore there is an associated waiting queue.

- Two operations:
  - block – place the process invoking the operation on the appropriate waiting queue.
  - wakeup – remove one of processes in the waiting queue and place it in the ready queue.

Semaphore Implementation

- Both operations are atomic

```
acquire(S){
  value--;
  if (value < 0) {
    add this process to list
    block;
  }
}
```

```
release(S){
  value++;
  if (value <= 0) {
    remove a process P from
    list
    wakeup(P);
  }
}
```

Semaphore

- **Counting** semaphore
  - An integer value can range over an unrestricted domain
- **Binary** semaphore
  - An integer value can range only between 0 and 1; can be simpler to implement
  - Also known as mutex locks

```
Semaphore S; // initialized to 1
acquire(S);
criticalSection();
release(S);
```

Semaphore

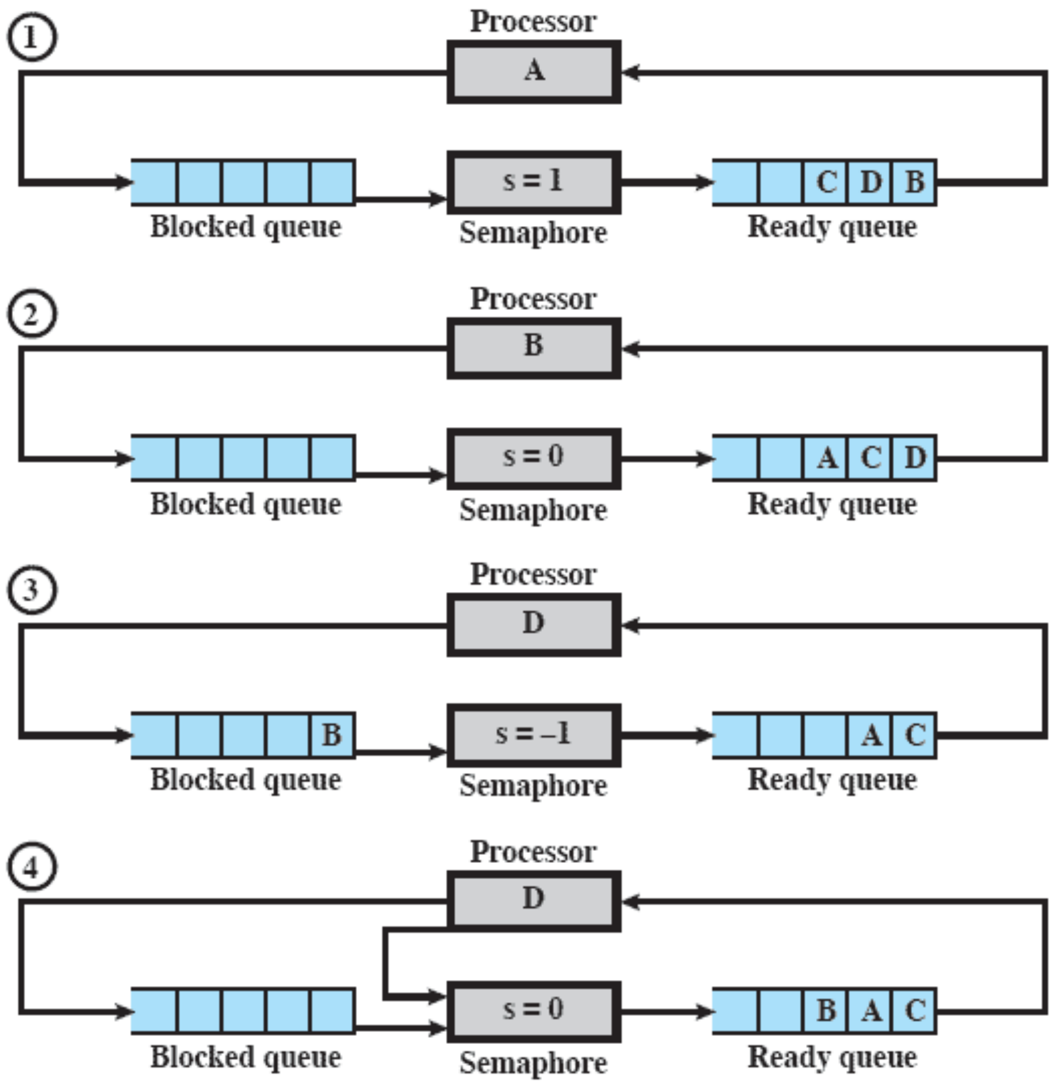
```
struct semaphore {
     int count;
     queueType queue;
};
void semWait(semaphore s)
{
     s.count--;
     if (s.count < 0) {
          /* place this process in s.queue */;
          /* block this process */;
     }
}
void semSignal(semaphore s)
{
     s.count++;
     if (s.count <= 0) {
          /* remove a process P from s.queue */;
          /* place process P on ready list */;
     }
}
```

sys/ in Xinu: screate.c sdelete.c wait.c signal.c

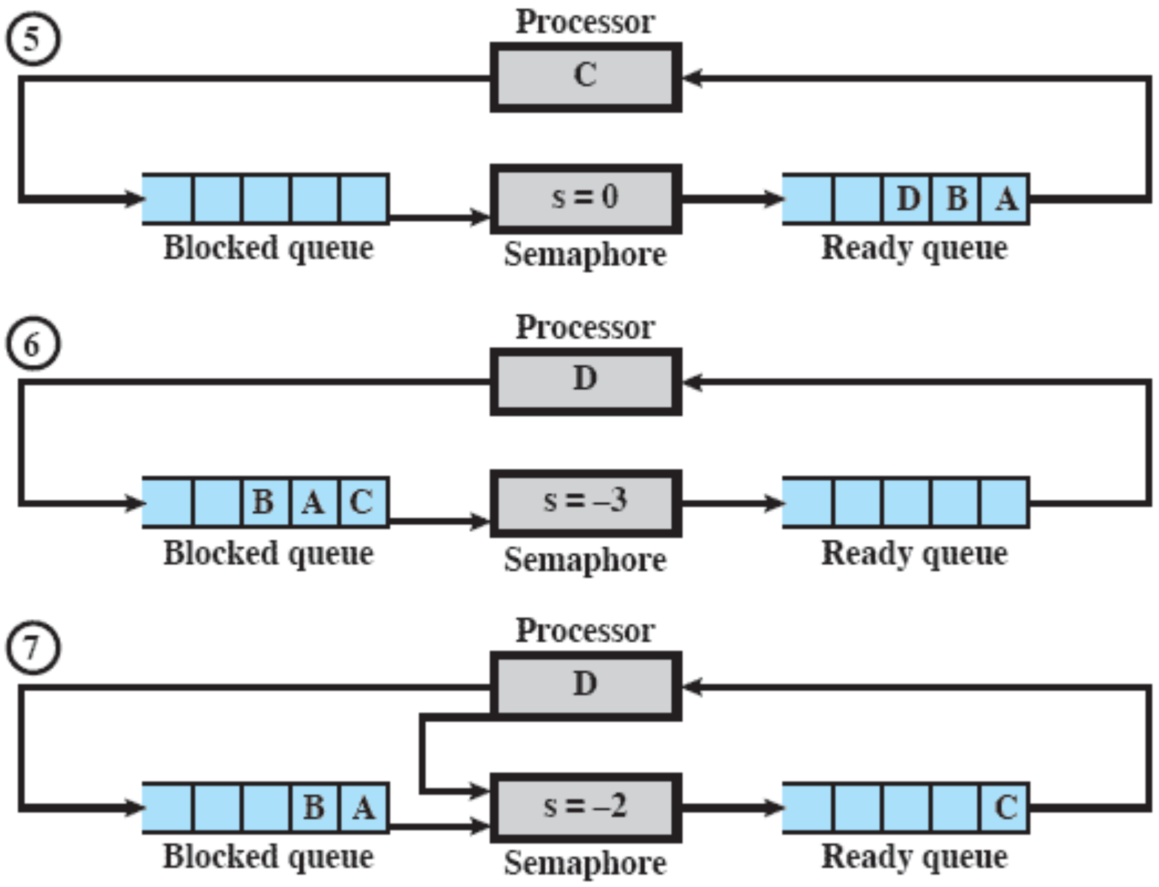
Strong/Weak Semaphore

- A queue is used to hold processes waiting on the semaphore
    - In what order are processes removed from the queue?
- **Strong Semaphores** use FIFO
- **Weak Semaphores** don’t specify the order of removal from the queue

Example of Strong Semaphore



Example of Semaphore Mechanism



Problems with Semaphores

- Used in pairs
  - acquire(mutex)… release(mutex)
- Incorrect use of semaphore operations:
  - release (mutex) …. acquire(mutex)
  - release (mutex) … release (mutex)
  - Omitting of release (mutex) or acquire (mutex) (or both)

Deadlock and Starvation

- Let S and Q be two semaphores initialized to 1

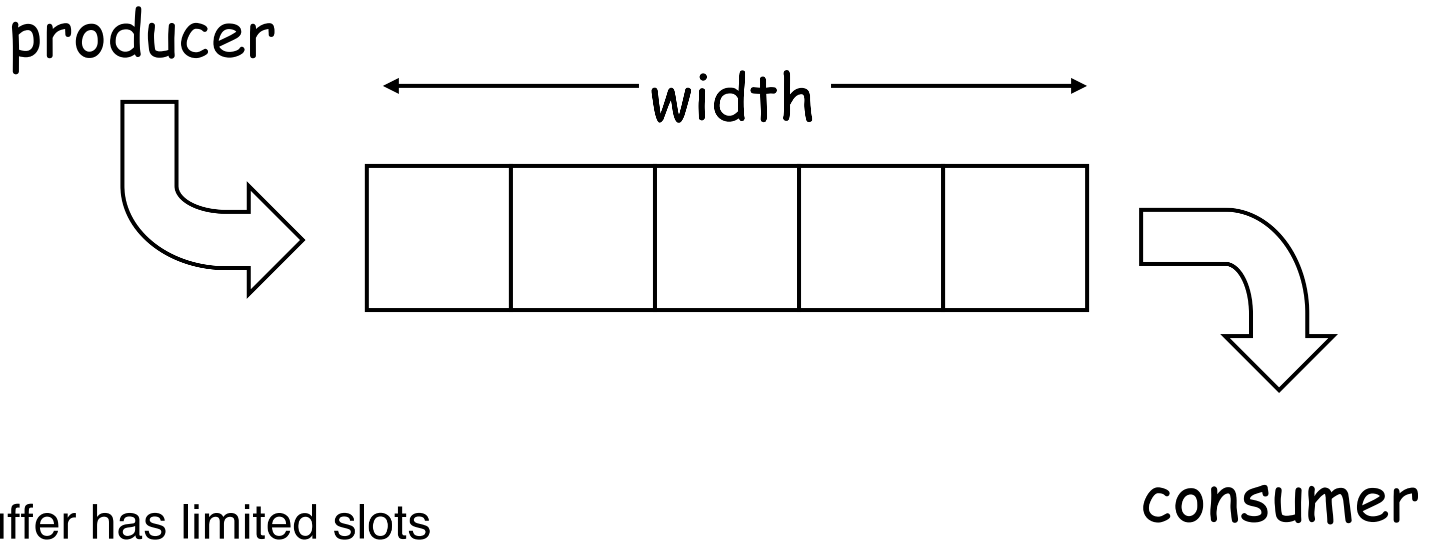
```
        P0                          P1

   acquire(S);                 acquire (Q);
   acquire(Q);                 acquire (S);
       .                           .
       .                           .
       .                           .
   release (S);                release (Q);
   release (Q);                release (S);
```

- Deadlock – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Starvation – indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended
- Priority Inversion - Scheduling problem when lower-priority process holds a lock needed by higher-priority process

Classical Problems of Synchronization

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem

Bounded Buffer



- Buffer has limited slots
- Producer waits if buffer full
- Consumer waits if buffer empty

Bounded-Buffer Problem

- Buffer size is *N*
- Semaphore mutex
  - for buffer access control
  - initialized to the value 1
- Semaphore full
  - Count full slots
  - initialized to the value 0
- Semaphore empty
  - Count empty slots
  - initialized to the value N.

Semaphore Solution for Producer

```
Item buffer[N];
int in = 0, out = 0;
Semaphore mutex = 1; // buffer access control
Semaphore empty = N; // count empty slots
Semaphore full = 0;  // count full slots


    public void insert (Item item){
      empty.aquire();
      mutex.aquire();

      // add an item to the buffer
      buffer[in] = item;
      in = (in + 1) % N;

      mutex.release();
      full.release();
    }
```

Semaphore Practice for Consumer

```
Item buffer[N];
int in = 0, out = 0;
Semaphore mutex = 1; // buffer access control
Semaphore empty = N; // count empty slots
Semaphore full = 0;  // count full slots

            public Item Remove(){

              semaphore operations?

              // remove an item
              item = buffer[out];
              out = (out + 1) % N;

              semaphore operations?

              return item;
            }
```

Readers and Writers Problem

- Protect shared data or database
  - A writer has exclusive access to data (no other concurrent writers or readers)
  - Readers can have concurrent access (allow multiple readers)
- Formally
  - nw = # of active writers
  - nr = # of active readers
  - Safety condition: (nr = 0 or nw = 0) and nw <= 1

Solution using Semaphores

```
int nr = 0;
Semaphore mutex = 1,
          db = 1;


writer() {
  while (1) {
    P(db)
      // write
    V(db)
  }
}
```

```
reader() {
  while (1) {
    P(mutex)
    nr++
    if (nr == 1) P(db)
    V(mutex)
      // read
    P(mutex)
    nr--
    if (nr == 0) V(db)
    V(mutex)
  }
}
```

Solution using Semaphores

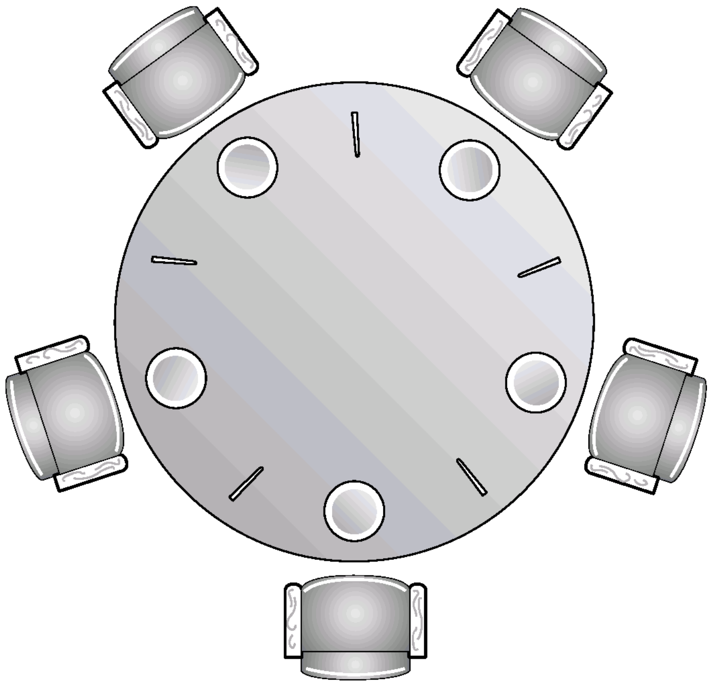
```
int nr = 0;
Semaphore mutex = 1,
          db = 1;


writer() {
  while (1) {
    P(db)
      // write
    V(db)
  }
}
```

```
reader() {
  while (1) {
    P(mutex)
    nr++
    if (nr == 1) P(db)
    V(mutex)
      // read
    P(mutex)
    nr--
    if (nr == 0) V(db)
    V(mutex)
  }
}
```

Solution using Semaphores

- What is the use of:
  - mutex?
  - db?

Dining-Philosophers Problem



- 5 philosophers: Think, or Eat
  - Needs two forks to eat, one from each side
- Shared data

```
Semaphore fork[]  = new Semaphore[5];
```

Semaphore solution

```
Semaphore forks[5] =
  {1,1,1,1,1}

philospher(int i) {
  while (1) {
    fork[i].acquire();
    fork[(i+1)%5].acquire();
    eat;
    fork[i].release();
    fork[(i+1)%5].release();
    think;
  }
}
```

Problem?

Semaphore solution

- Problem deadlock
  - How?
- Solution
  - Allow at most 4 sitting
  - Allow one to pick up only if both forks available
  - Break symmetry, e.g., an odd person picks up left first, and even person picks up right first

Priority Inversion

- Real-time priority scheduling
  - Responsiveness: if a higher priority thread appears, serve it asap.
- Mutual exclusion
  - Integrity: if higher priority thread wants to enter critical section being hold by lower priority thread, it has to wait

An Example

- Thread τ_1 L L L R_x L
- Thread τ_2 L L ... L
- Thread τ_3 L L L R_x L ... L

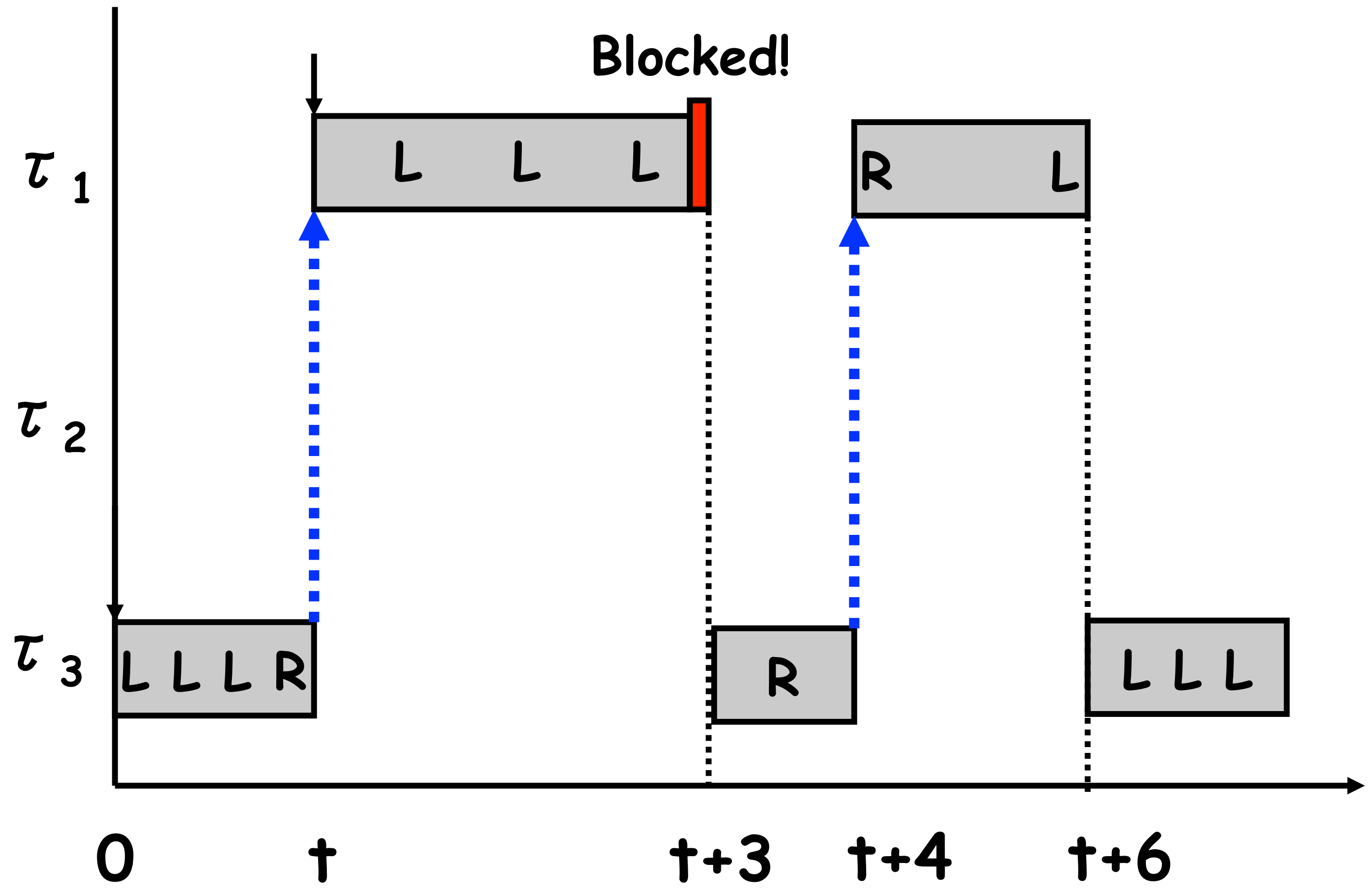
- L: local CPU burst
- R: resource required (Mutual Exclusion)

An Example

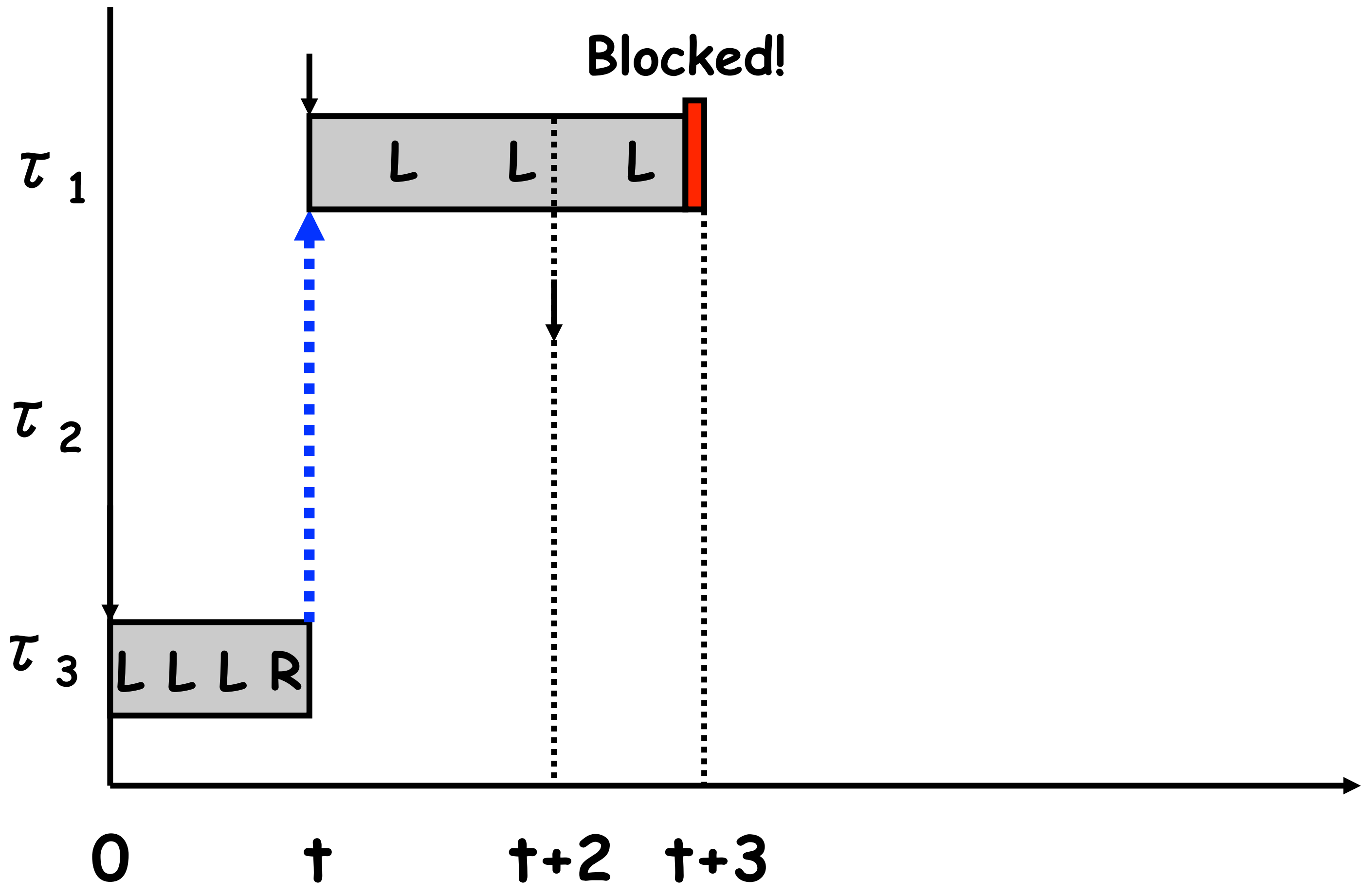
- Suppose that threads τ_1 and τ_3 share some data
- Access to the data is restricted using *semaphore* x:
  - each task executes the following code:
    - L: do local work
    - P(s): semWait(s)
      - R: access shared resource

      critical section
    - V(s): semSignal(s)
    - L: do more local work

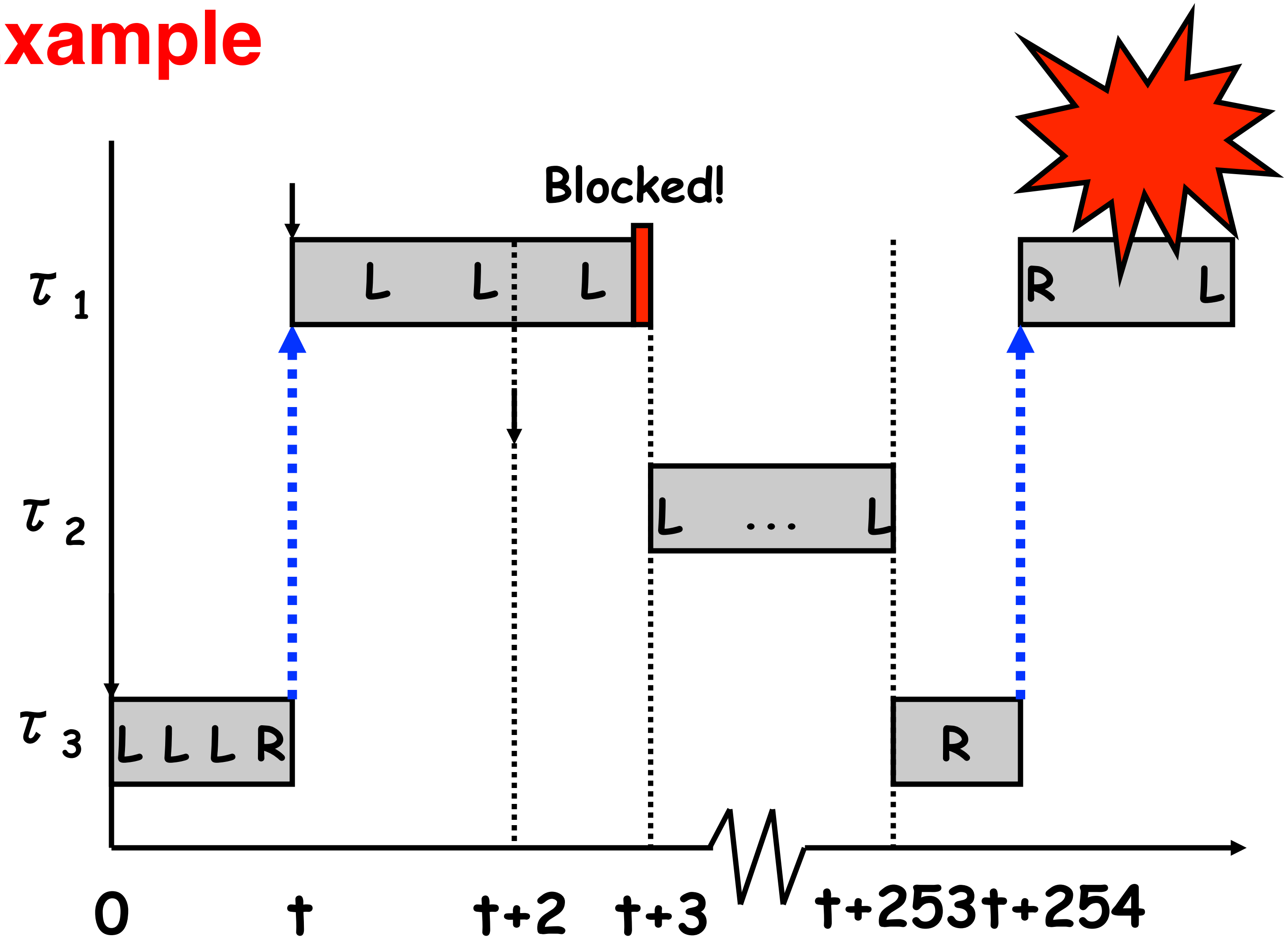
An Example



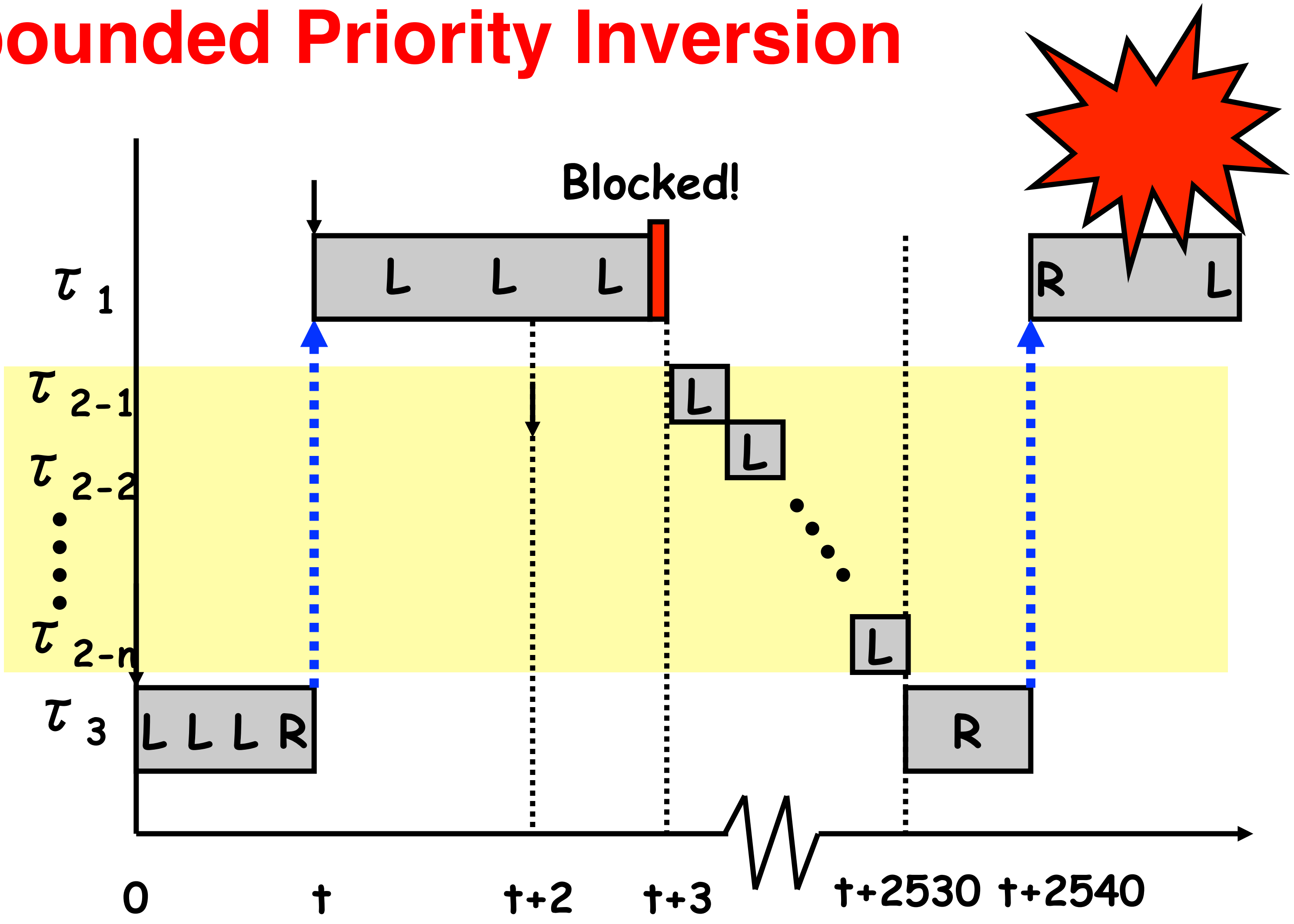
An Example



An Example



Unbounded Priority Inversion

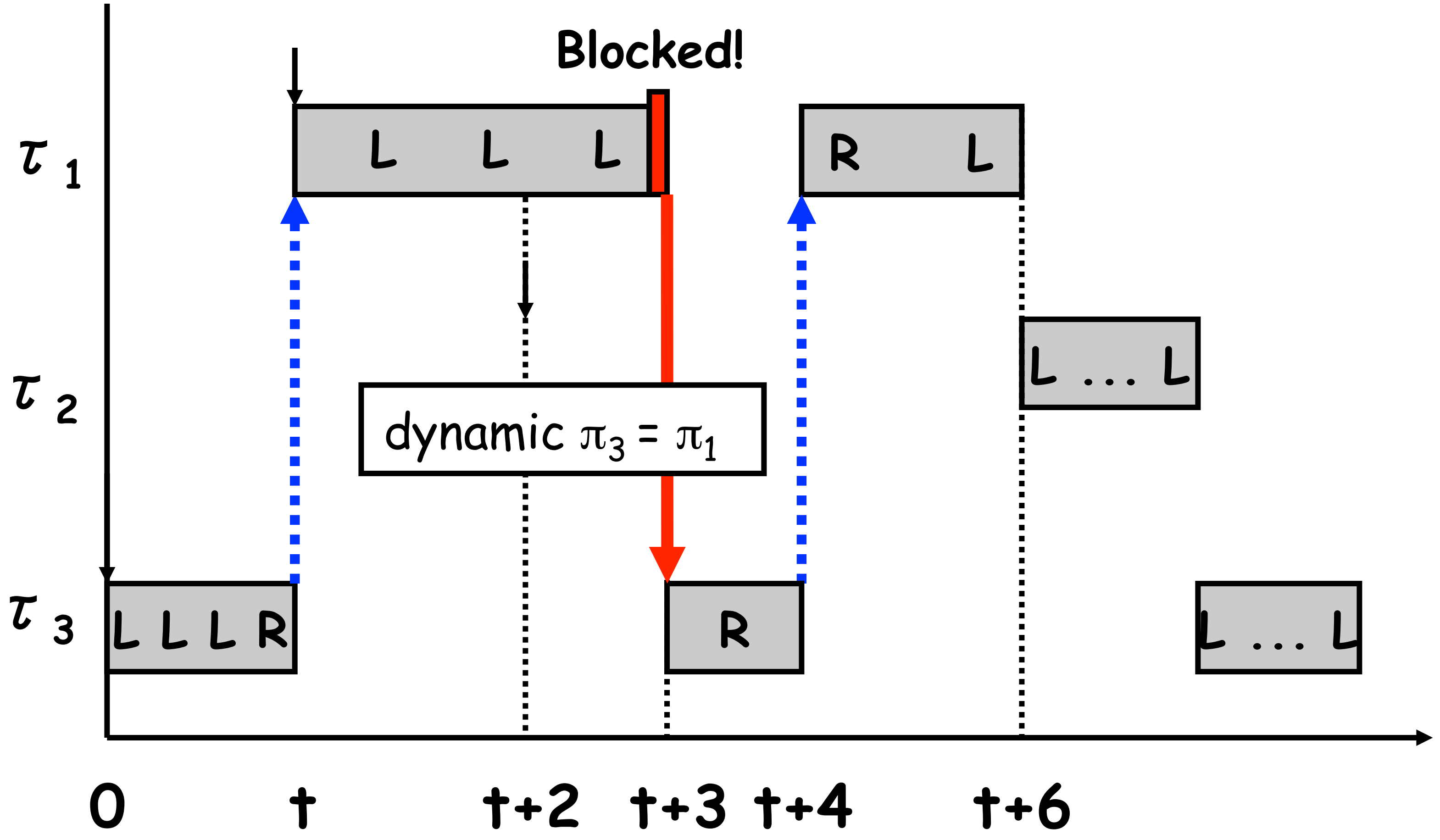


The problem…

- Priority and mutual exclusion at the same time
    - => priority inversion.

- How to resolve it? trade-off?

Priority Inheritance



Priority Inheritance Protocol

- L. Sha, R. Rajkumar, J. Lehoczky, “Priority Inheritance Protocols: An Approach to Real-Time Synchronization”, IEEE Transactions on Computers, Vol. 39, No. 9, pp. 1175-1185, 1990

Basic Priority Inheritance

- For each resource (semaphore), a list of blocked threads stored in a priority queue.
- A thread τ_i uses its assigned priority, unless it is in its critical section and blocks some higher priority threads, in which case, thread τ_i uses (**inherits**) the highest dynamic priority of all the threads it blocks.
- Priority inheritance is **transitive**; that is, if thread τ_i blocks τ_j and τ_j blocks τ_k , then τ_i can inherit the priority of τ_k.

Problems

- The Basic **Priority Inheritance Protocol** has two problems:
  - **Deadlock** - two threads need to access a pair of shared resources simultaneously. If the resources, say A and B, are accessed in opposite orders by each thread, then deadlock may occur.
  - **Blocking Chain** - the blocking duration is bounded (by at most the sum of critical section times), but that may be substantial.

Problem with Locking

- Pessimistic approach
  - Limits concurrency
- Granularity hard to control
  - Fine-granule locking increases concurrency
  - Drawbacks?
    - Deadlock, overhead
- Convoy effect
  - A thread/process holding a lock is preempted and suspended
  - Other threads waiting on the lock unable to progress
- Fault Tolerance
  - A thread/process holding a lock fails

Synchronization without Locks?

- Transactional memory
    - Optimistic approach
    - Processes go ahead and execute critical sections
    - Conflicts detected and resolved afterwards
        - Rollback – undo and redo
        - Sample code for producer generating one item

```
atomic {
    buffer[in] = item;
    in = (in + 1) % N;
  }
```

STM vs. Locking

- Software Transactional Memory
  - Less deadlock prone
  - High overhead
  - Better concurrency?
  - Constrained operations within critical sections
    - I/O

- Possible to combine both approaches
  - Runtime evaluation of tradeoff
  - Dynamic selection between TM-mode and Lock-mode

One More Synchronization Exercise

- H2O problem
  - H and O atoms created
    - hready() and oready() calls
    - Each atom one process
  - Processes must wait till there are at least two H atoms and one O atom present
    - Then one of them MUST call makeWater()
    - After which, two instances of hready() and one instance of oready() must return

Solution One

```
semaphore hPresent = 0;

semaphore waitForWater = 0;


void hready(){
    signal(hPresent);
  wait(waitForWater);
}
void oready() {
    wait(hPresent);
    wait(hPresent);
    makeWater();
    signal(waitForWater);
    signal(waitForWater);
}
```

Solution Two

```
semaphore numHydrogen = 0;
semaphore pairOfHydrogen = 0, oxygen = 0;

void hready(){
    numHydrogen ++;
    if ((numHydrogen % 2) == 0)  signal(pairOfHydrogen);
    wait(oxygen);
}
void oready() {
    wait(pairOfHydrogen);
    makeWater();
    signal(Oxygen);
    signal(Oxygen);
}
```