Concurrent Algorithms (Overview)

Prof R. Guerraoui
Distributed Programming Laboratory

In short

This course is about the principles of robust concurrent computing

Today

- *Logistics*
- *Motivation*
- *Content*

WARNING

- This course is different from the course : **Distributed Algorithms**
- shared memory vs message passing
- It does make a lot of sense to take both

This course

- *Theoretical but no specific theoretical background is required*
- *Exercices throughout the semester*
- *Mid term + Final exam + Bonus project*

New York Times, 8 May 2004: Major chip manufacturers announced what is perceived as a major paradigm shift in computing:

Multiprocessors vs faster processors

Major chip manufacturers have announced a major paradigm shift:

Intel … [has] decided to focus its development efforts on «dual core» processors … with two engines instead of one, allowing for greater efficiency because the processor workload is essentially shared.

Moore (65-75): the number of transistors on the same chip doubles every two years

But

Dennard (74): the frequency can double every year without doubling energy

The clock speed of a processor cannot be increased without overheating

But

More and more processors can fit in the same space

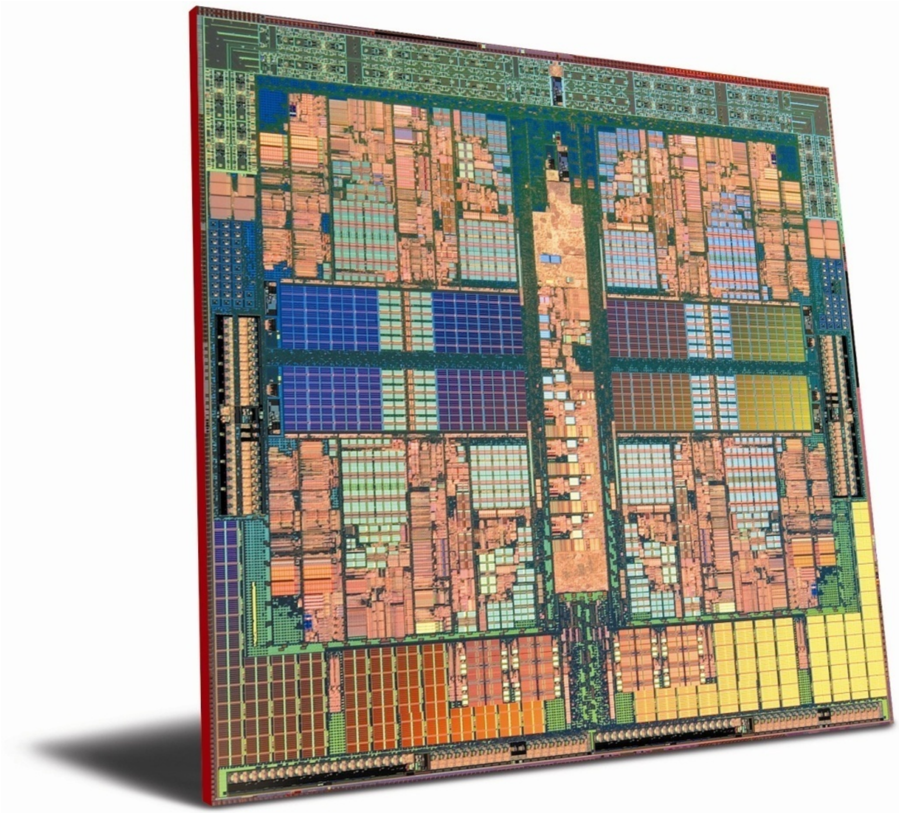
Multicores are almost everywhere

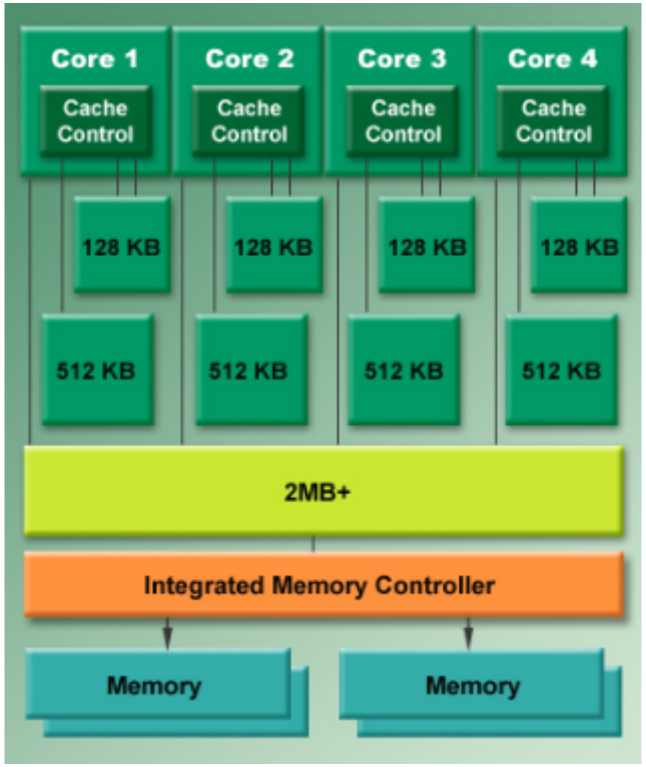
- Dual-core commonplace in laptops
- Quad-core in desktops
- Dual quad-core in servers
- All major chip manufacturers produce multicore CPUs
  - SUN Niagara (8 cores, 32 threads)
  - Intel Xeon (4 cores)
  - AMD Opteron (4 cores)

Multicores are almost everywhere

- **Quad-core in laptops**
- **Octa-core in desktops**
- **2*12 cores in servers**
- **All major chip manufacturers produce multicore CPUs**
  - **Oracle Sparc (32 cores, 256 threads)**
  - **Intel Xeon (12-16 cores)**
  - **AMD Opteron (12-16 cores)**

AMD Opteron (4 cores)



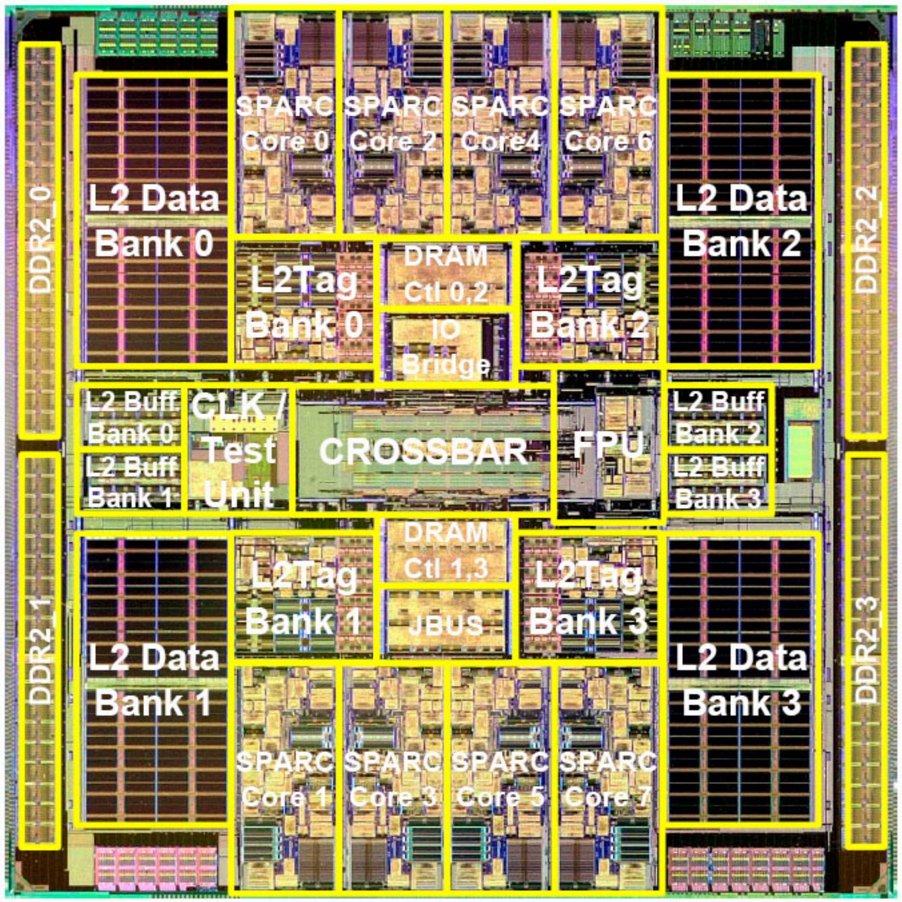


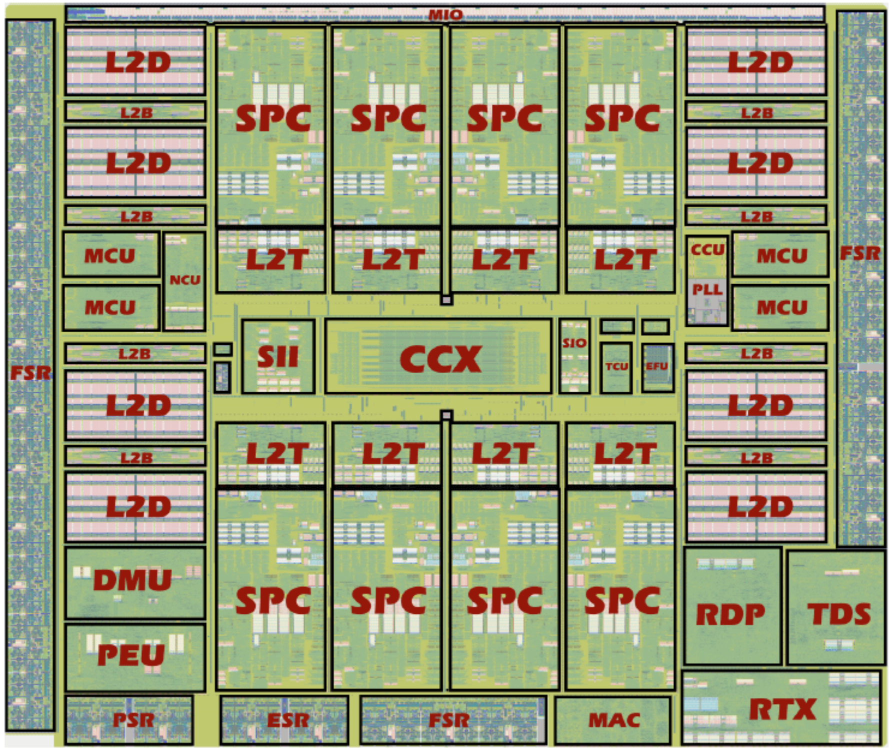
L1 cache

L2 cache

L3 cache (shared)

SUN's Niagara CPU2 (8 cores)





CCX – Crosssbar
CCU – Clock control
DMU/PEU – PCI Express
EFU – Efuse for redundancy
ESR – Ethernet SERDES
FSR – FBD SERDES
L2B – L2 write-back buffers
L2D – L2 data arrays
L2T – L2 tag arrays
MCU – Memory controller
MIO – Miscellaneous I/O
PSR – PCI Express SERDES
RDP/TDS/RTX/MAC – Ethernet
SII/SIO – I/O data path to and from memory
SPC – SPARC cores
TCU – Test and control unit

Multiprocessors

- Multiple hardware processors: each executes a series of processes (software constructs) modeling sequential programs

- Multicore architecture: multiple processors are placed on the same chip

Principles of an architecture

- Two fundamental components that ***fall apart***: ***processors*** and ***memory***

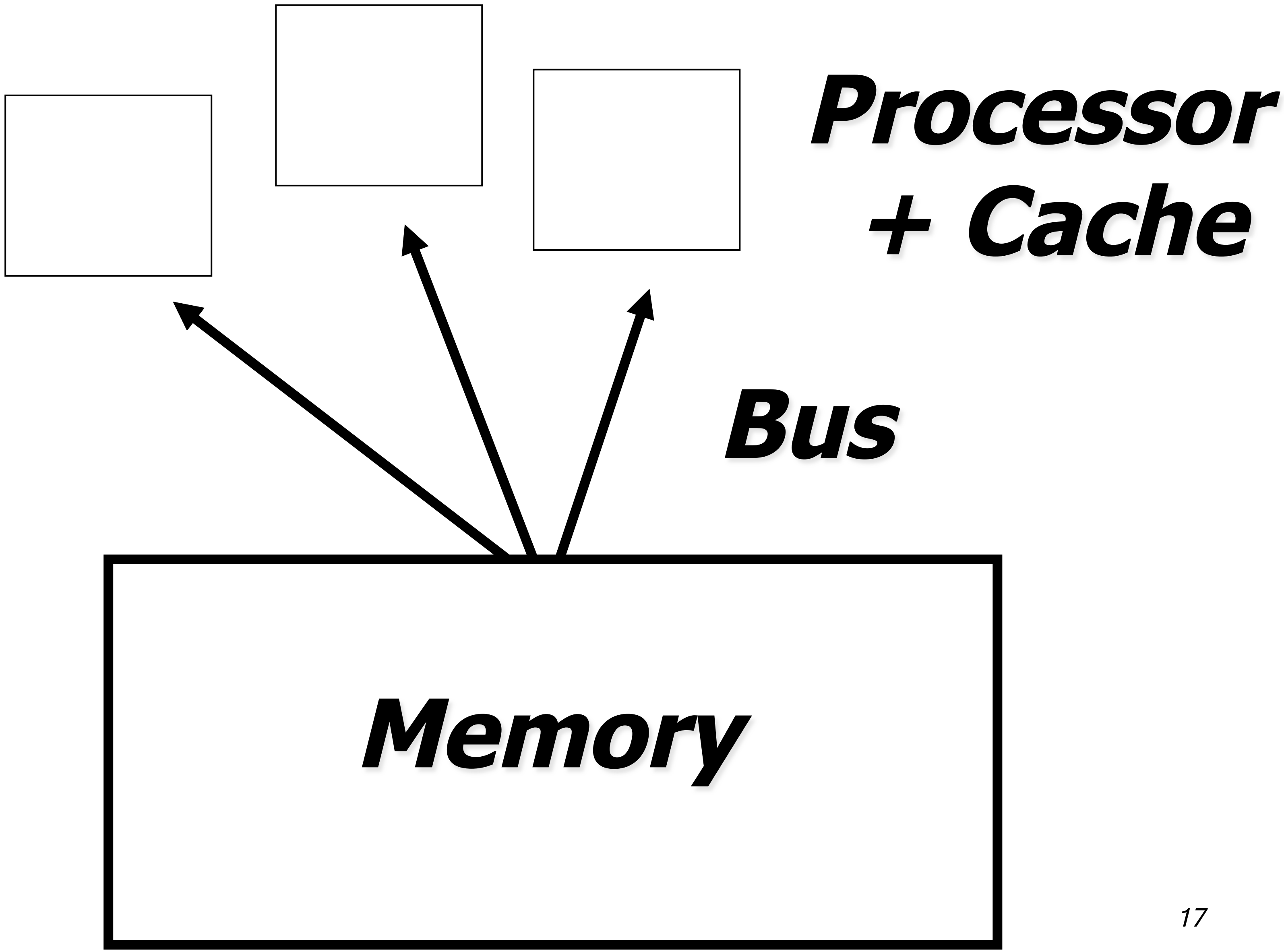
- The Interconnect links the processors with the memory:
- \- ***SMP*** (symmetric): bus (a tiny Ethernet)
- \- ***NUMA*** (network): point-to-point network

Cycles

- The basic unit of time is the *cycle*: time to execute an instruction

- This changes with technology but the relative cost of instructions (local vs memory) does not

Simple view



Hardware synchronization objects

- The basic unit of communication is the *read* and *write* to the memory (through the cache)

- More sophisticated objects are typically provided and, as we will see, necessary: C&S, T&S, LL/SC

The free ride is over

- Cannot rely on CPUs getting faster in every generation
- Utilizing more than one CPU core requires concurrency

The free ride is over

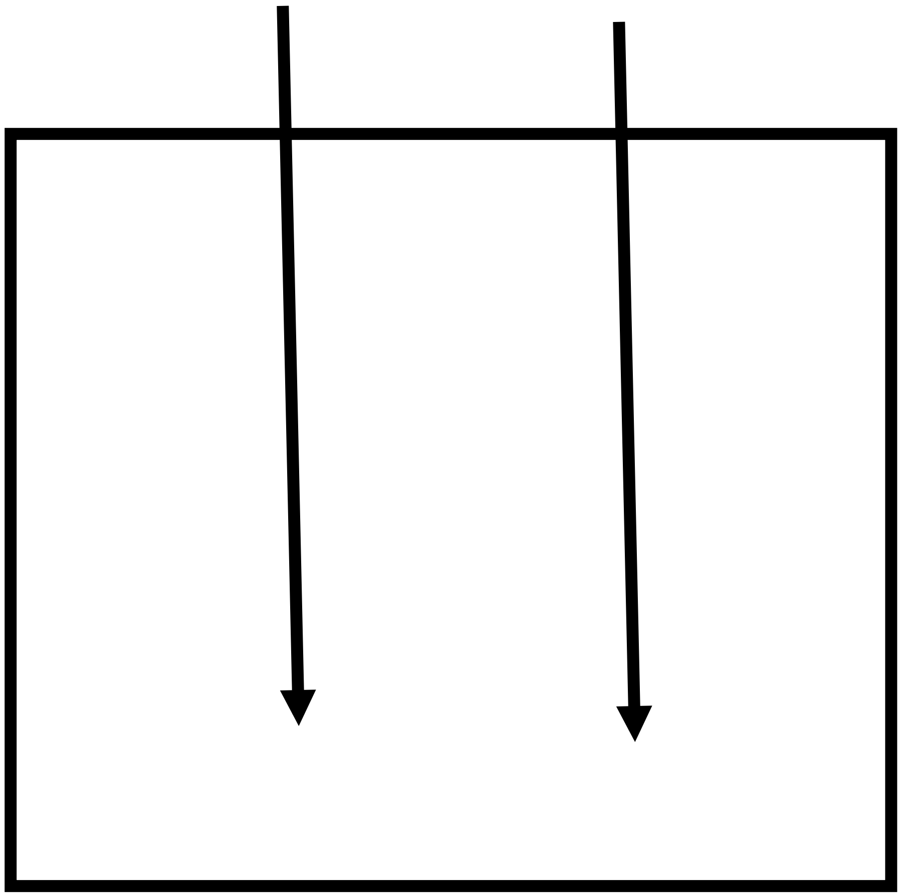
- One of the biggest software challenges: exploiting concurrency
  - Every programmer will have to deal with it
  - Concurrent programming is hard to get right

Speed will be achieved by having several processors work on independent parts of a task

But

the processors would occasionally need to pause and synchronize

Concurrent processes



Shared object

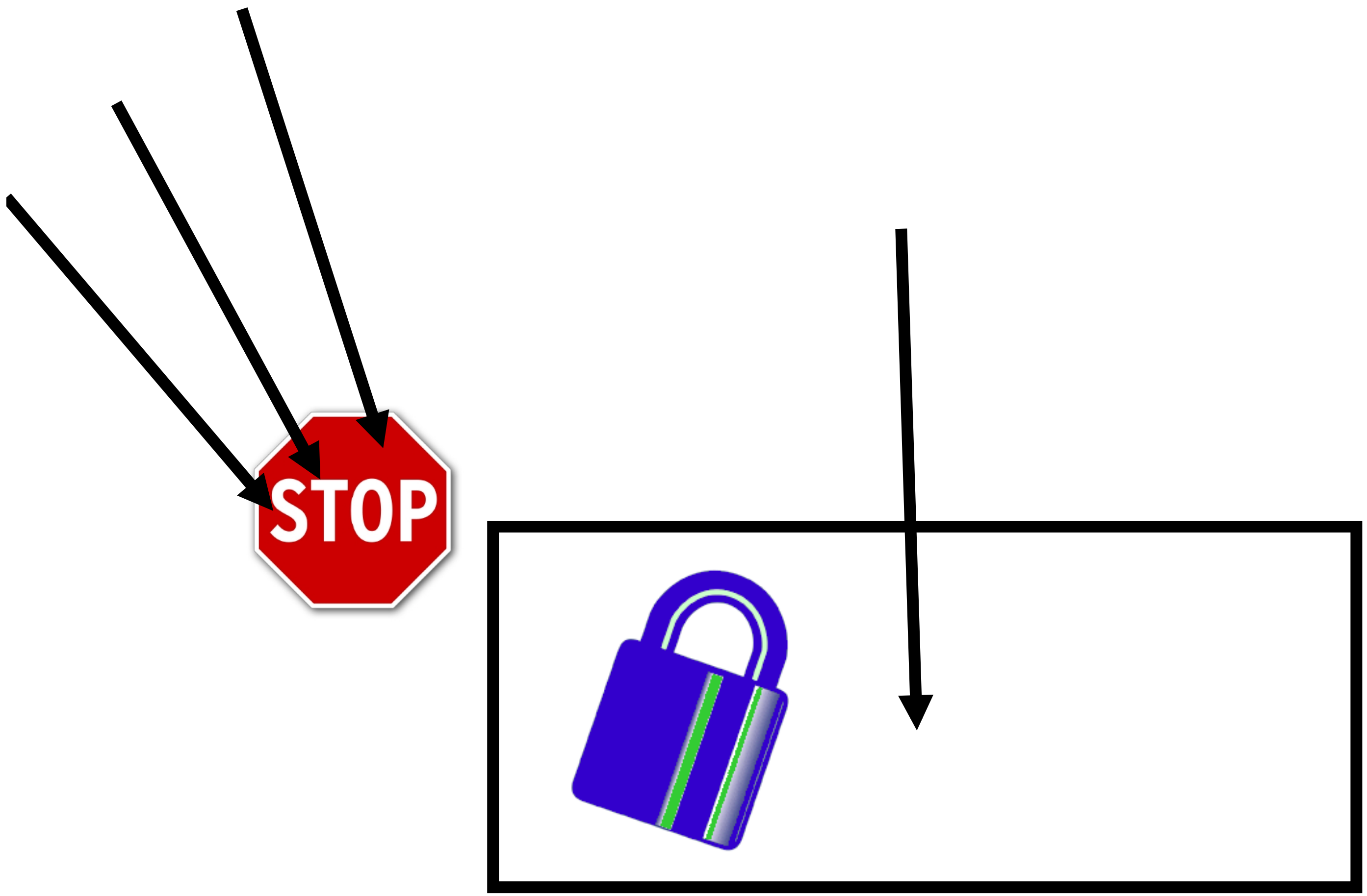
Counter

```
public class Counter

private int c = 0;

public long getAndIncrement()
{
return c++;
}
```

Locking (mutual exclusion)



Locked object

Implicit use of a lock

```
public class SynchronizedCounter {
    private int c = 0;
    public synchronized void increment() {
        c++;
    }
    public synchronized void getAndincrement()
{
        return c++;
    }
    public synchronized int value() {
        return c;
    }
}
```

Locking with compare&swap()

- A ***Compare&Swap*** object maintains a value x, init to $\perp$, and y;

- It provides one operation: ***c&s(old,new);***

✓Sequential spec:

  - c&s(old,new)

  {y := x; if x = old then x := new; return(y)}

Locking with compare&swap()

```
lock() {
repeat until
unlocked = this.c&s(unlocked,locked)
}

unlock() {
         this.c&s(locked,unlocked)
     }
```

Locking with test&set()

- A ***Test&Set*** object maintains binary values x, init to 0, and y;

- It provides one operation: ***t&s()***

  ✓Sequential spec:

  ✓ t&s() {y := x; x: = 1; return(y);}

Locking with test&set()

```
lock() {
repeat until (0 = this.t&s());
}

unlock() {
        this.setState(0);
    }
```

Locking with test&set()

```
lock() {
while (true)
 {
 repeat until (0 = this.getState());
 if 0 = (this.t&s()) return(true);
 }
}

unlock() {
        this.setState(0);
     }
```

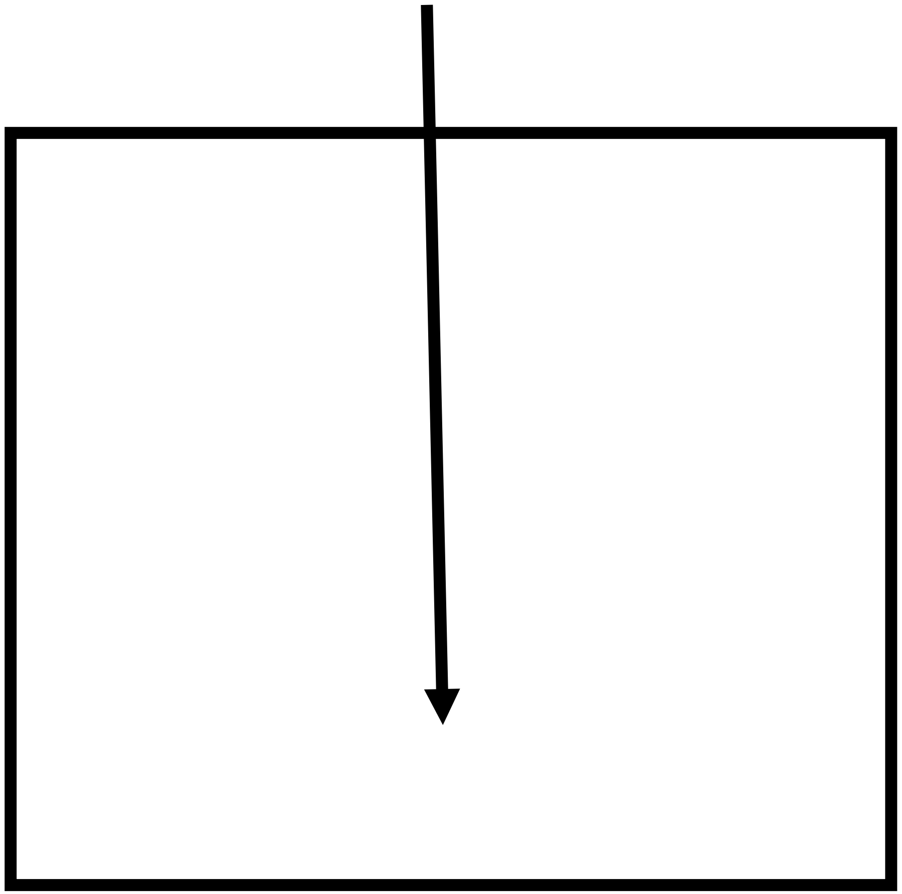
Explicit use of a lock

```
 Lock l = ...;
     l.lock();
     try {
// access the resource protected by this lock
     } finally {
          l.unlock();
     }
```

Locking (mutual exclusion)

- ***Difficult:*** 50% of the bugs reported in Java come from the mis-use of « synchronized »
- ***Fragile:*** a process holding a lock prevents all others from progressing
- ***Slow:*** the act of locking itself impacts performance

Locked object



One process at a time

Processes are asynchronous

- *Page faults*
- *Pre-emptions*
- *Failures*
- *Cache misses, …*

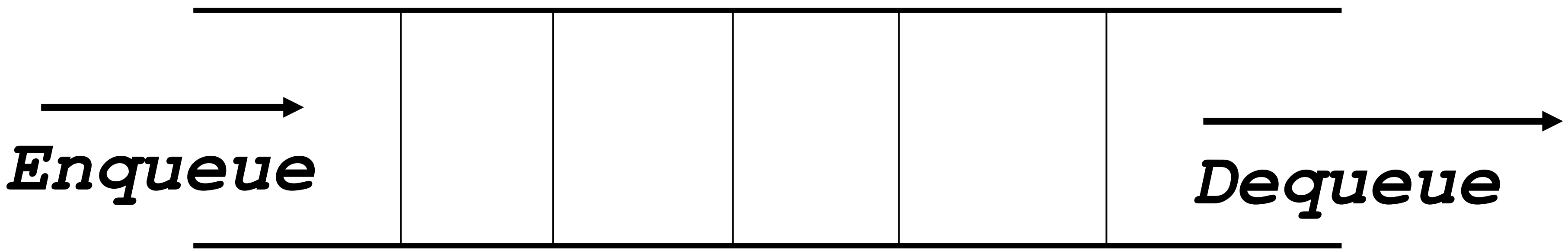
Processes are asynchronous

- A cache miss can delay a process by ten instructions
- A page fault by few millions
- An os preemption by hundreds of millions…

Coarse grained locks => slow

Fine grained locks => errors

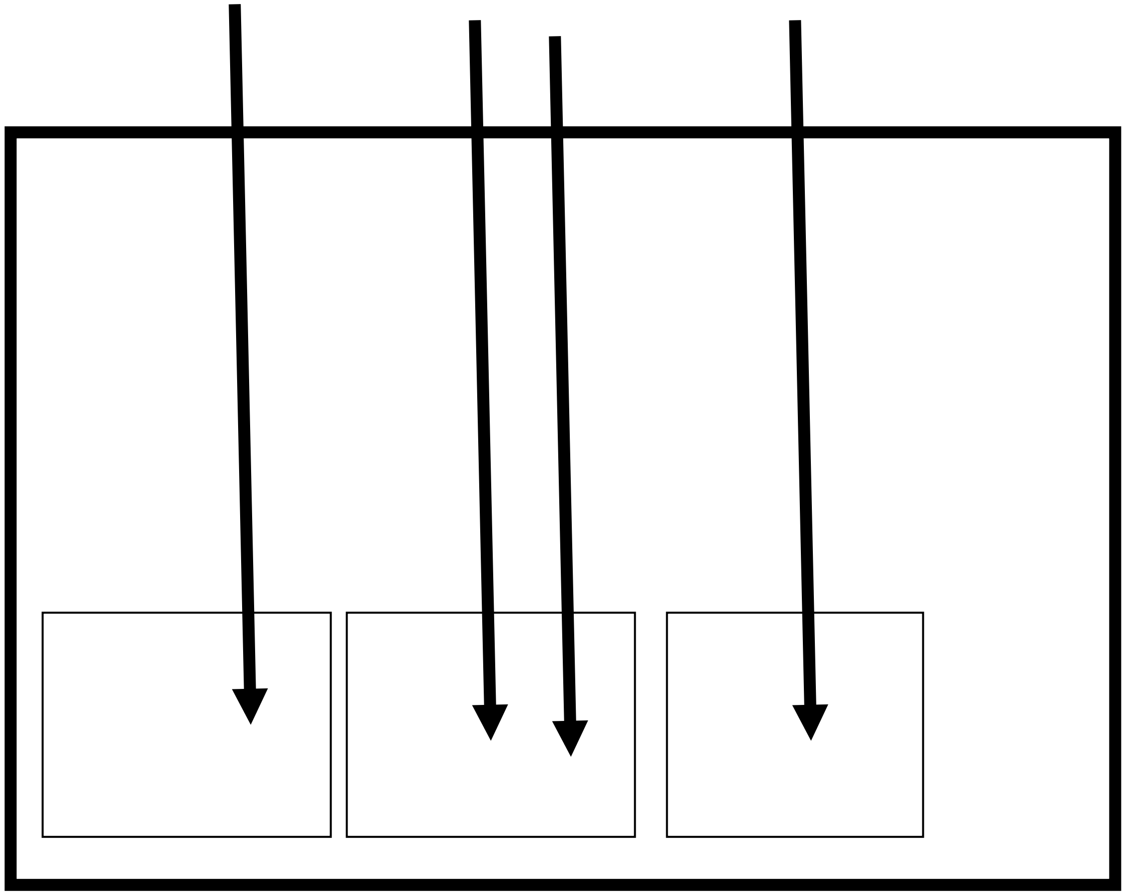
Double-ended queue



Processes are asynchronous

- ***Page faults, pre-emptions, failures, cache misses, …***
- A process can be delayed by millions of instructions …

Alternative to locking?



Wait-free atomic objects

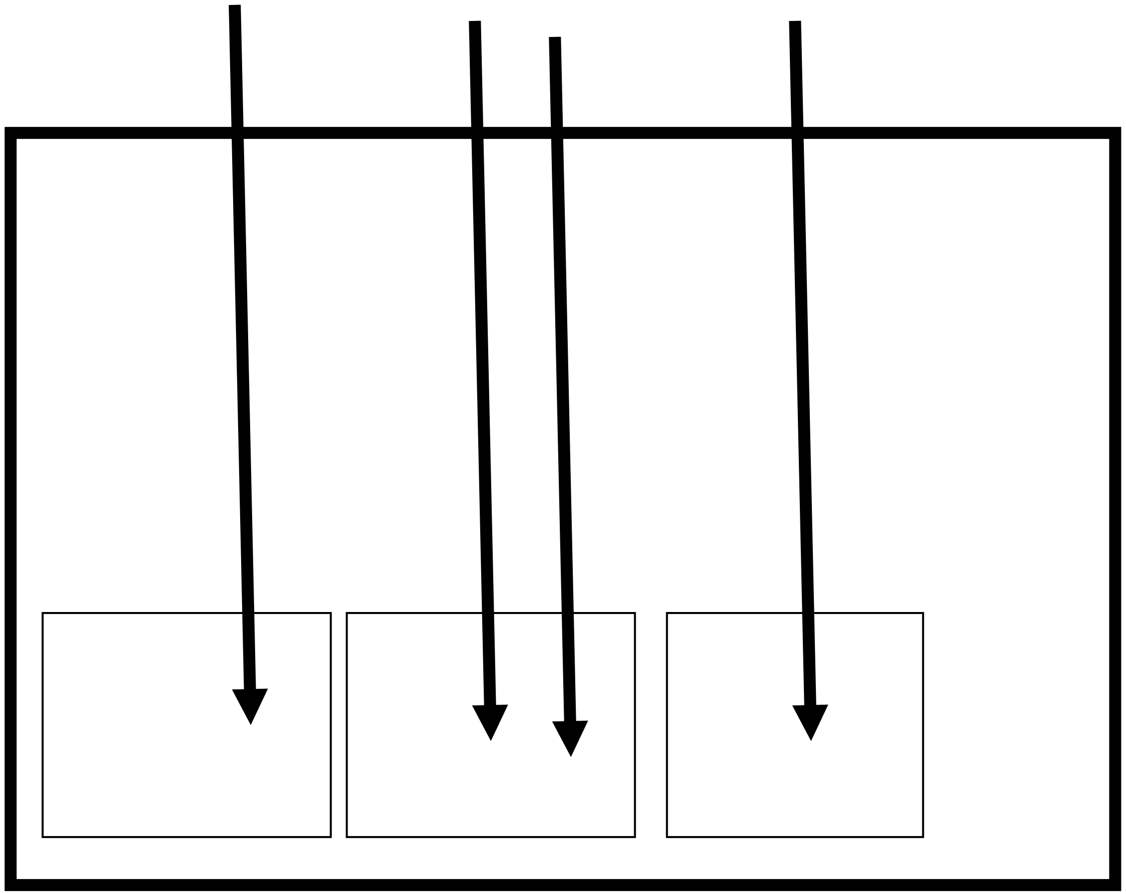
- ***Wait-freedom:*** every process that invokes an operation eventually returns from the invocation (robust … unlike locking)

- ***Atomicity:*** every operation appears to execute instantaneously (as if the object was locked…)

In short

This course shows how to
wait-free implement high-level
atomic objects out of primitive base objects

Concurrent processes



Shared object

Roadmap

- *Model*
  - *Processes and objects*
  - *Atomicity and wait-freedom*
- *Examples*
- *Content*

Processes

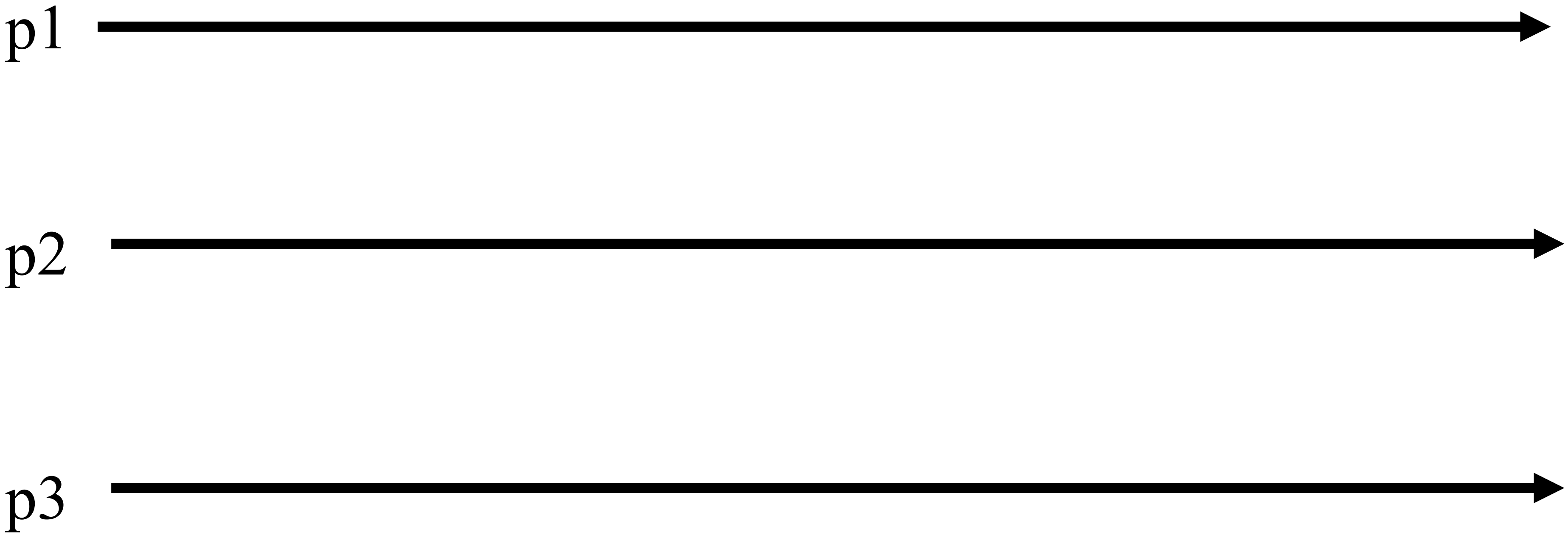
- We assume a finite set of processes
- Processes are denoted by p1,..pN or p, q, r
- Processes have unique identities and know each other (unless explicitly stated otherwise)

Processes

- Processes are ***sequential*** units of computations

- Unless explicitly stated otherwise, we make no assumption on process (relative) speed

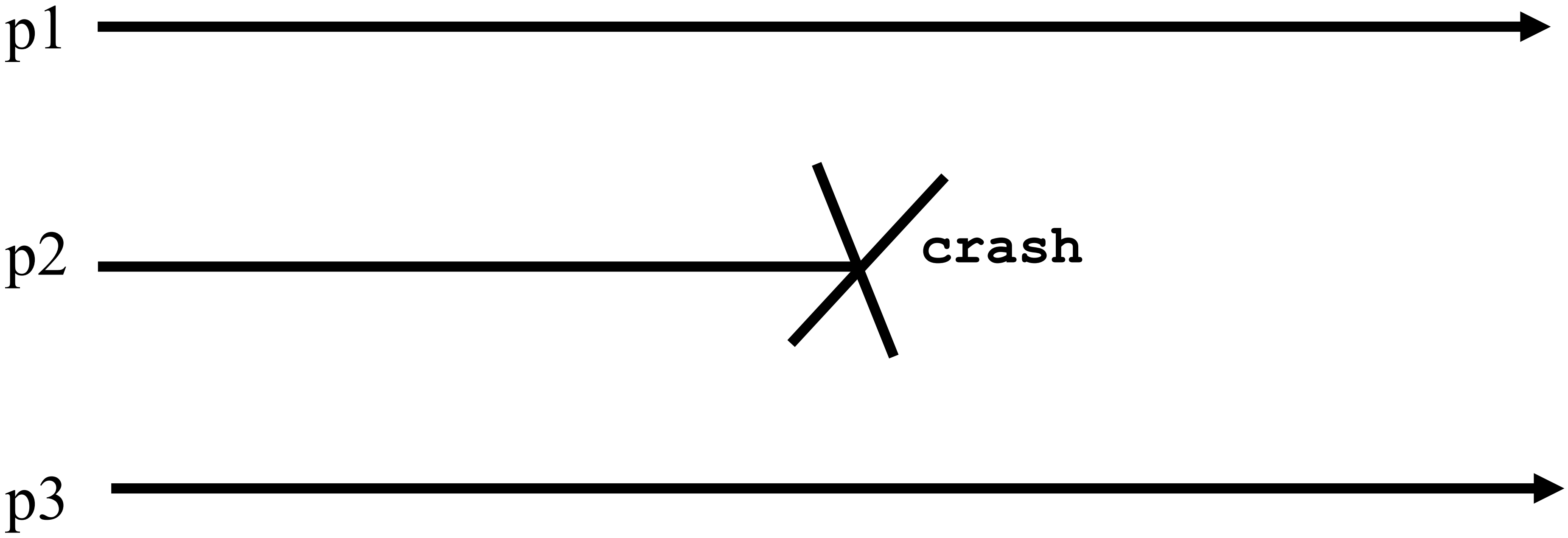
Processes



Processes

- A process either executes the algorithm assigned to it or crashes
- A process that crashes does not recover (in the context of the considered computation)
- A process that does not crash in a given execution (computation or run) is called correct (in that execution)

Processes

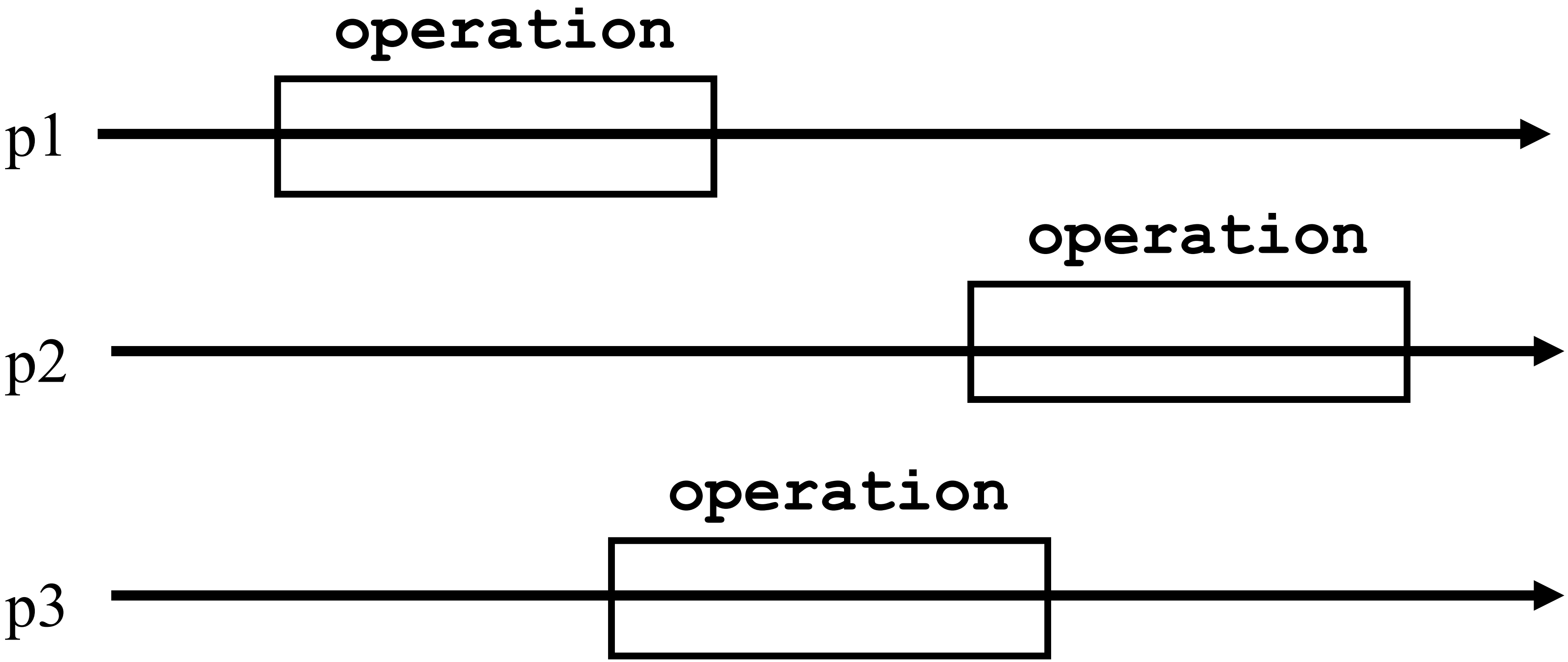


On objects and processes

- Processes execute local computation or access shared objects through their ***operations***

- Every operation is expected to return a reply

Processes

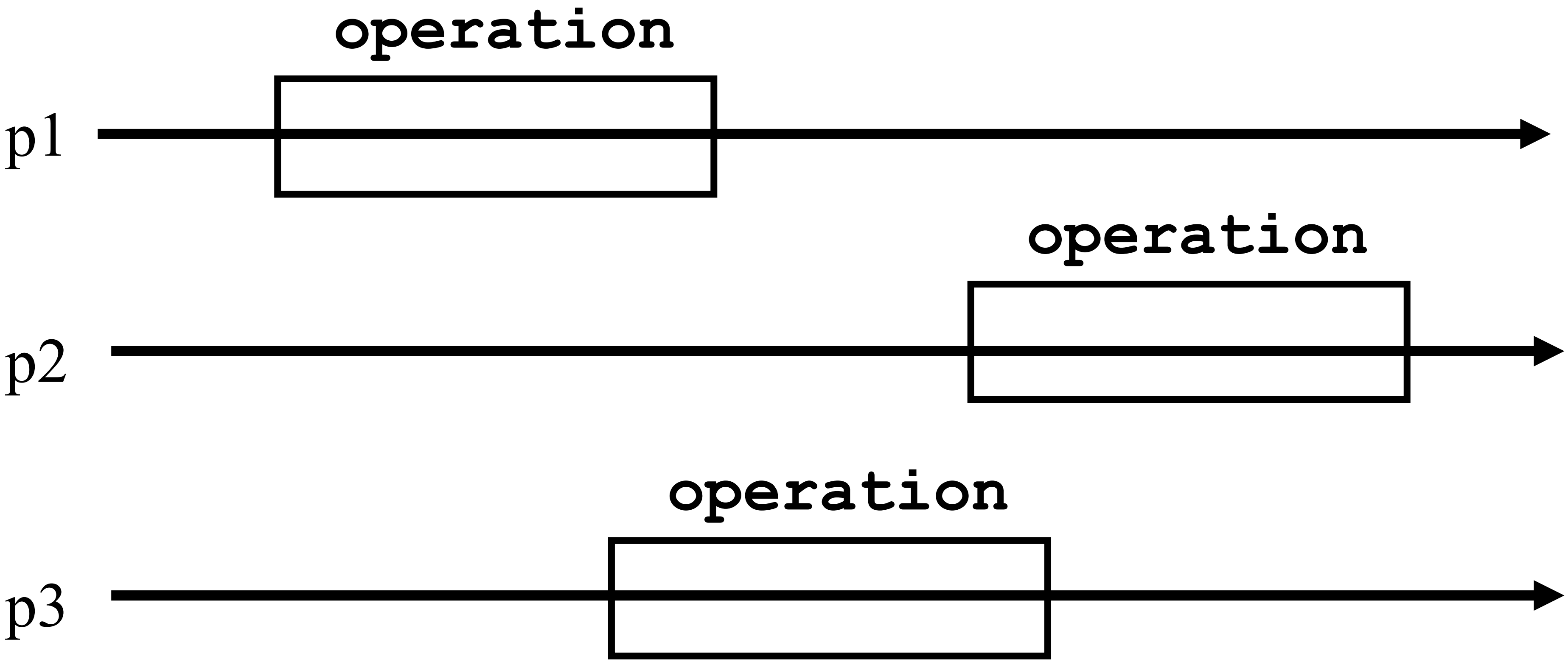


On objects and processes

- ***Sequentiality*** means here that, after invoking an operation op1 on some object O1, a process does not invoke a new operation (on the same or on some other object) until it receives the reply for op1

- ***Remark***. Sometimes we talk about operations when we should be talking about operation invocations

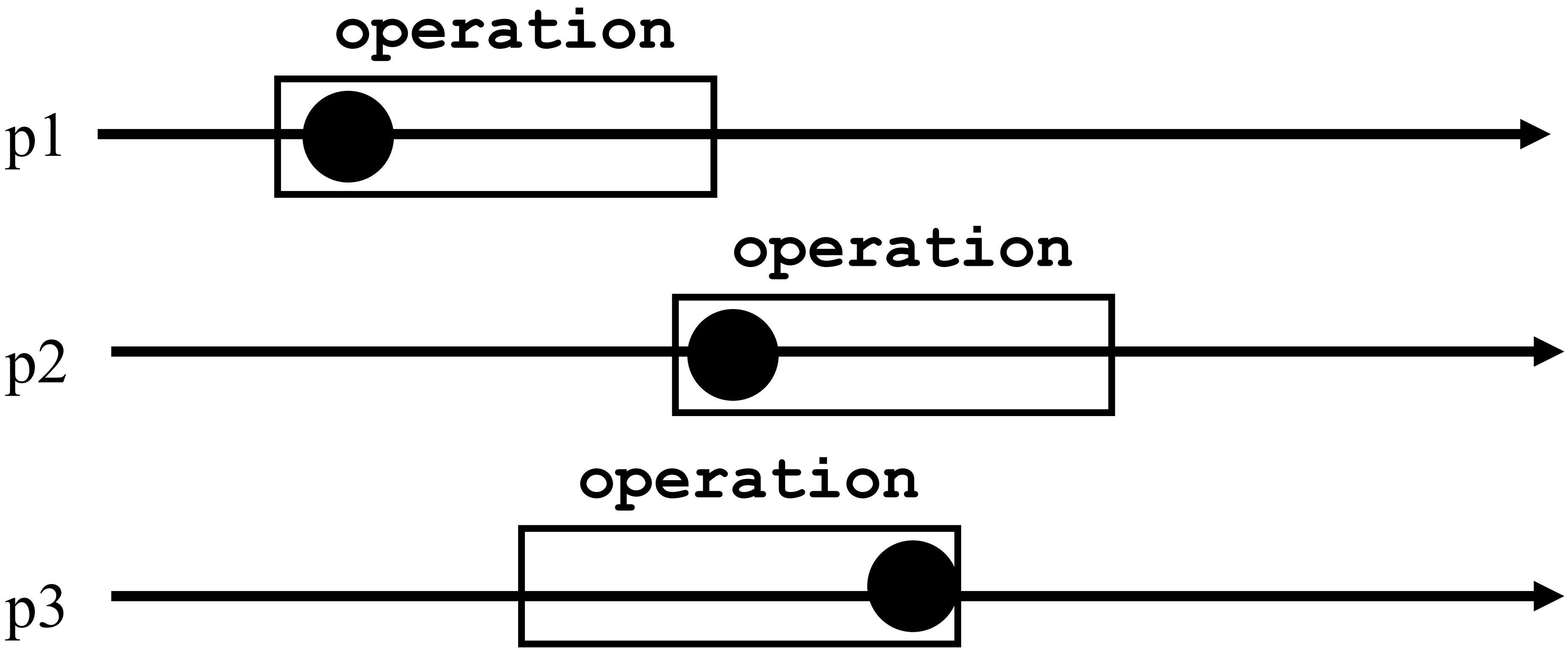
Processes



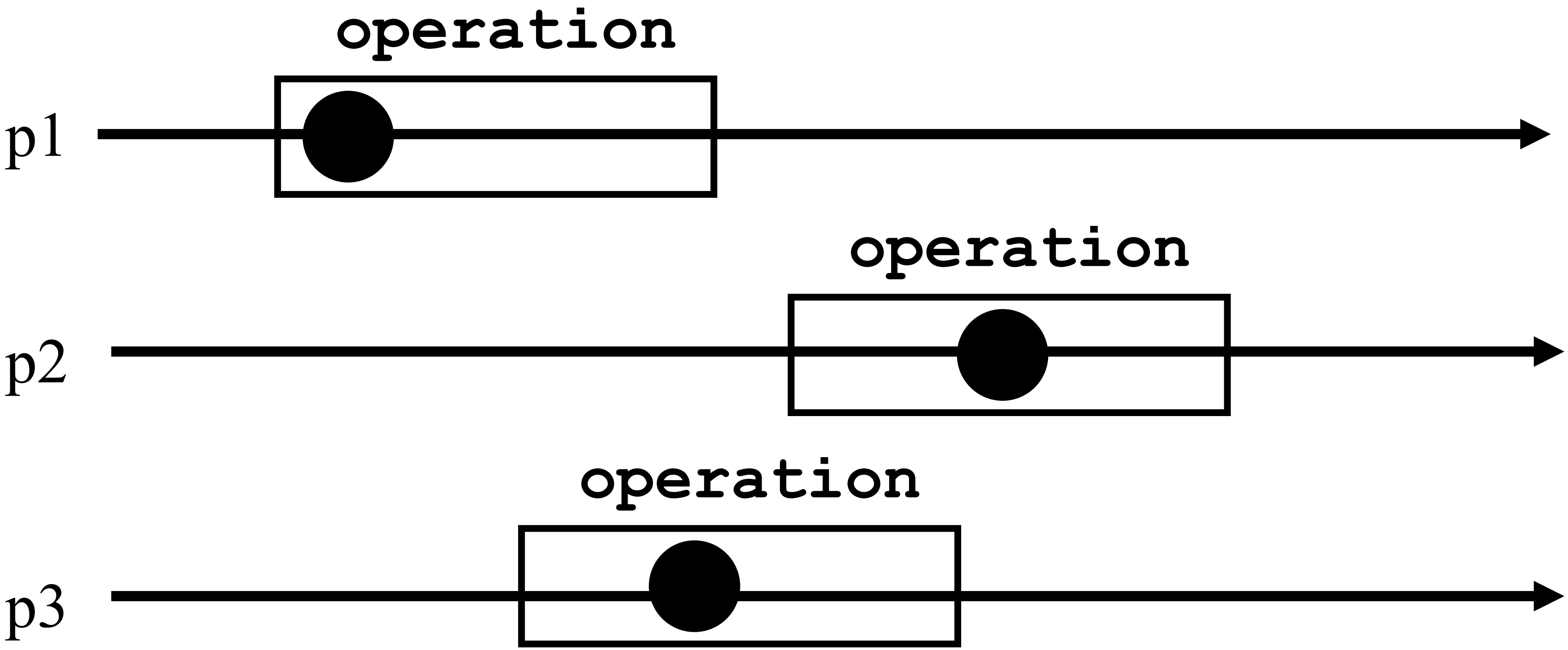
Atomicity

- Every operation appears to execute at some indivisible point in time (called linearization point) between the invocation and reply time events

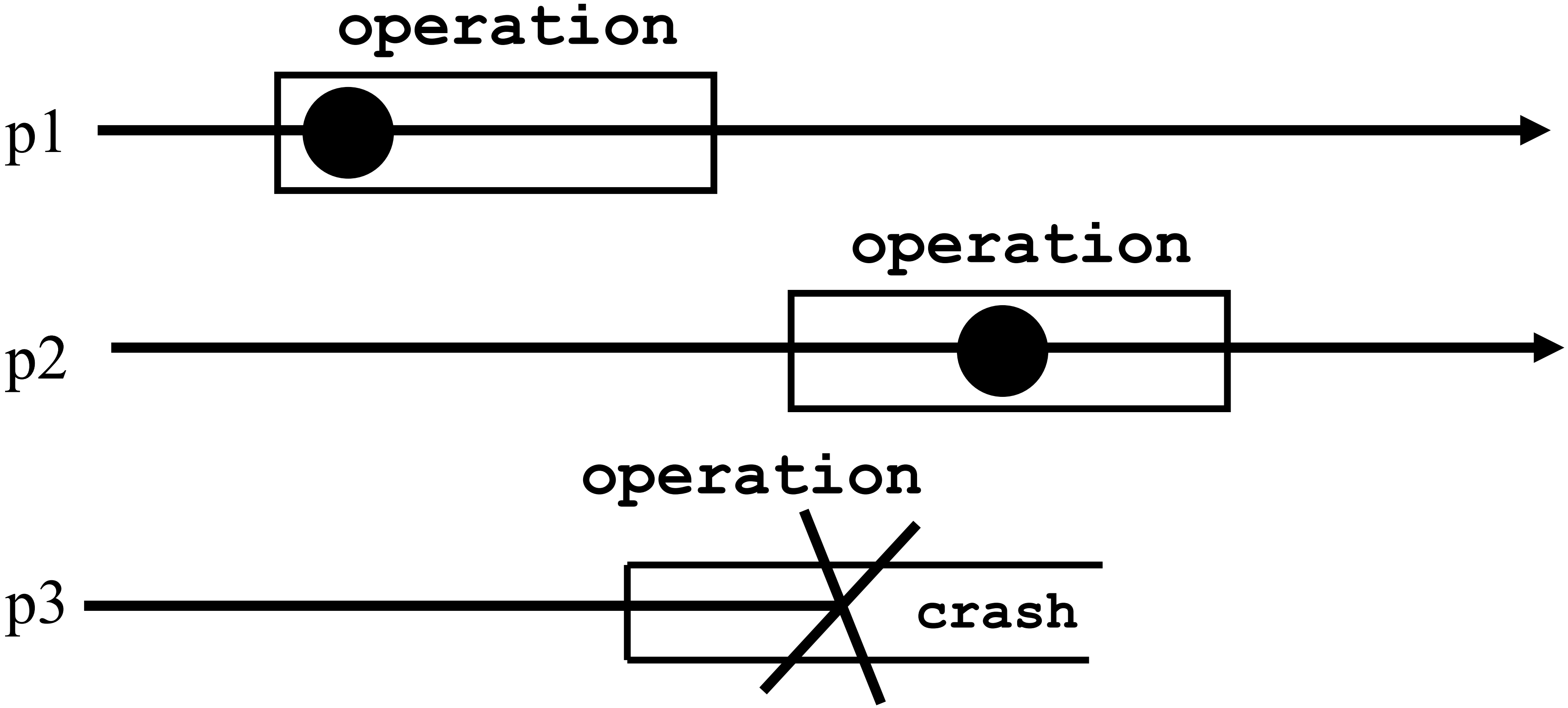
Atomicity



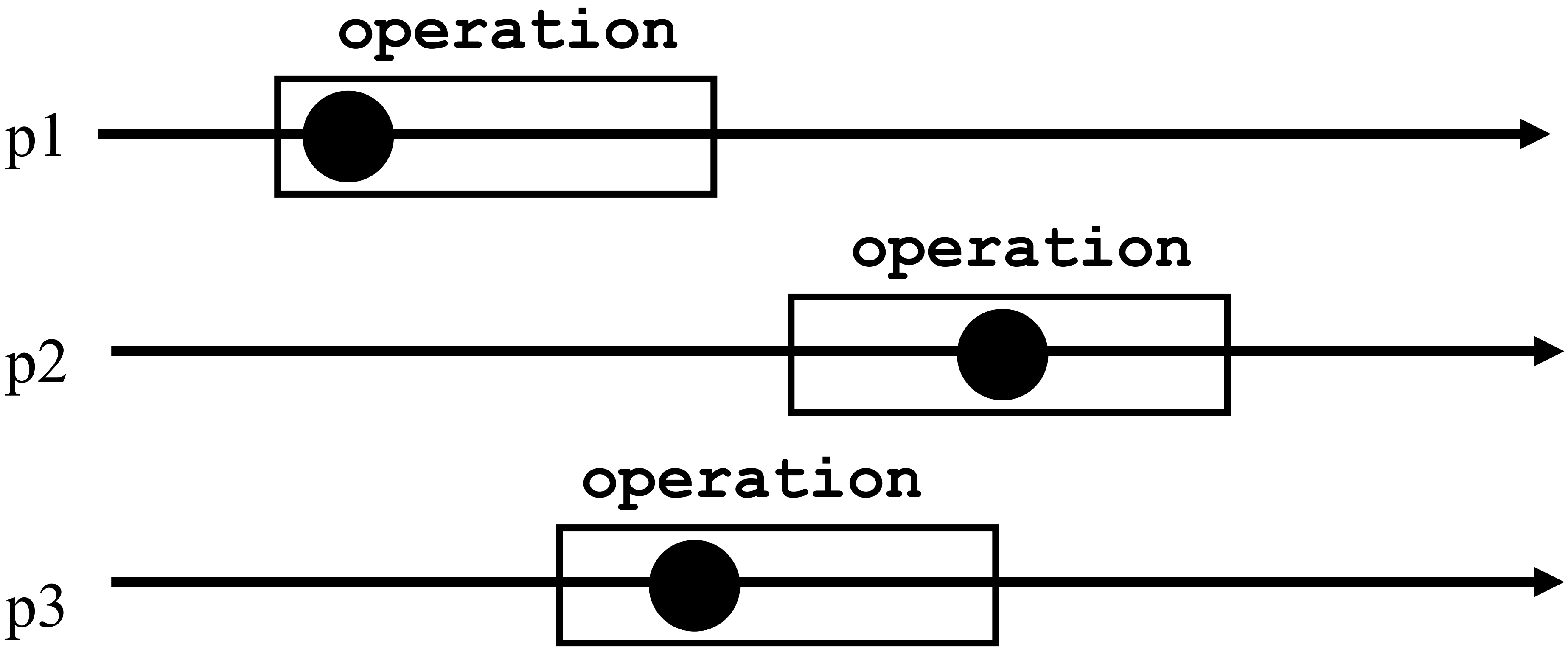
Atomicity



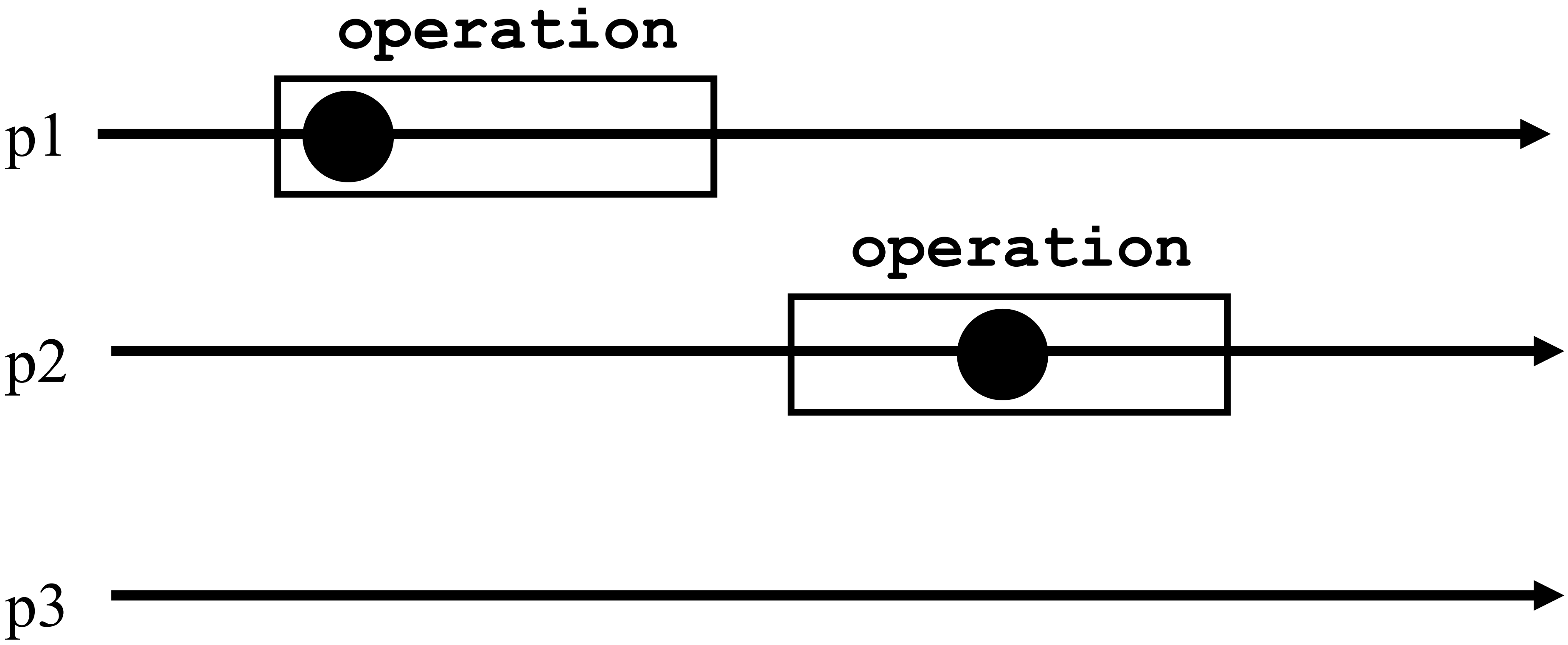
Atomicity (the crash case)



Atomicity (the crash case)



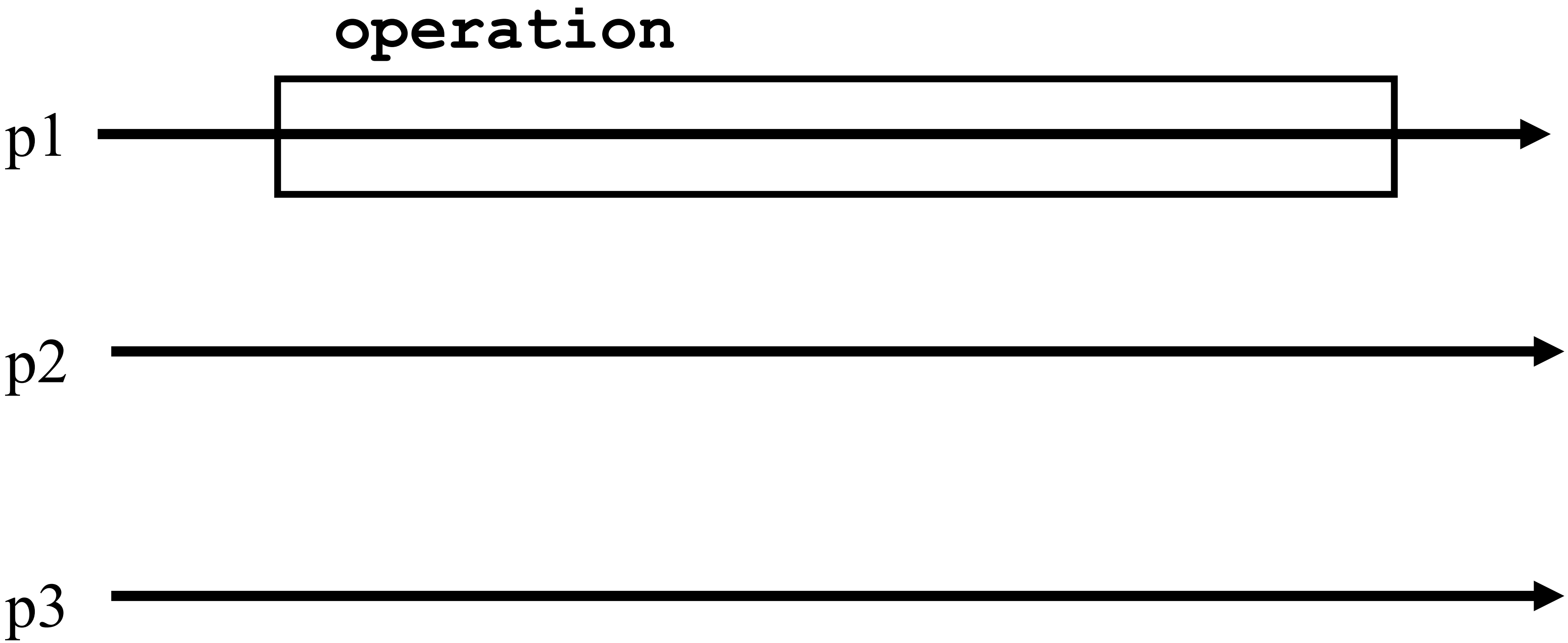
Atomicity (the crash case)



Wait-freedom

- Any correct process that invokes an operation eventually gets a reply, no matter what happens to the other processes (crash or very slow)

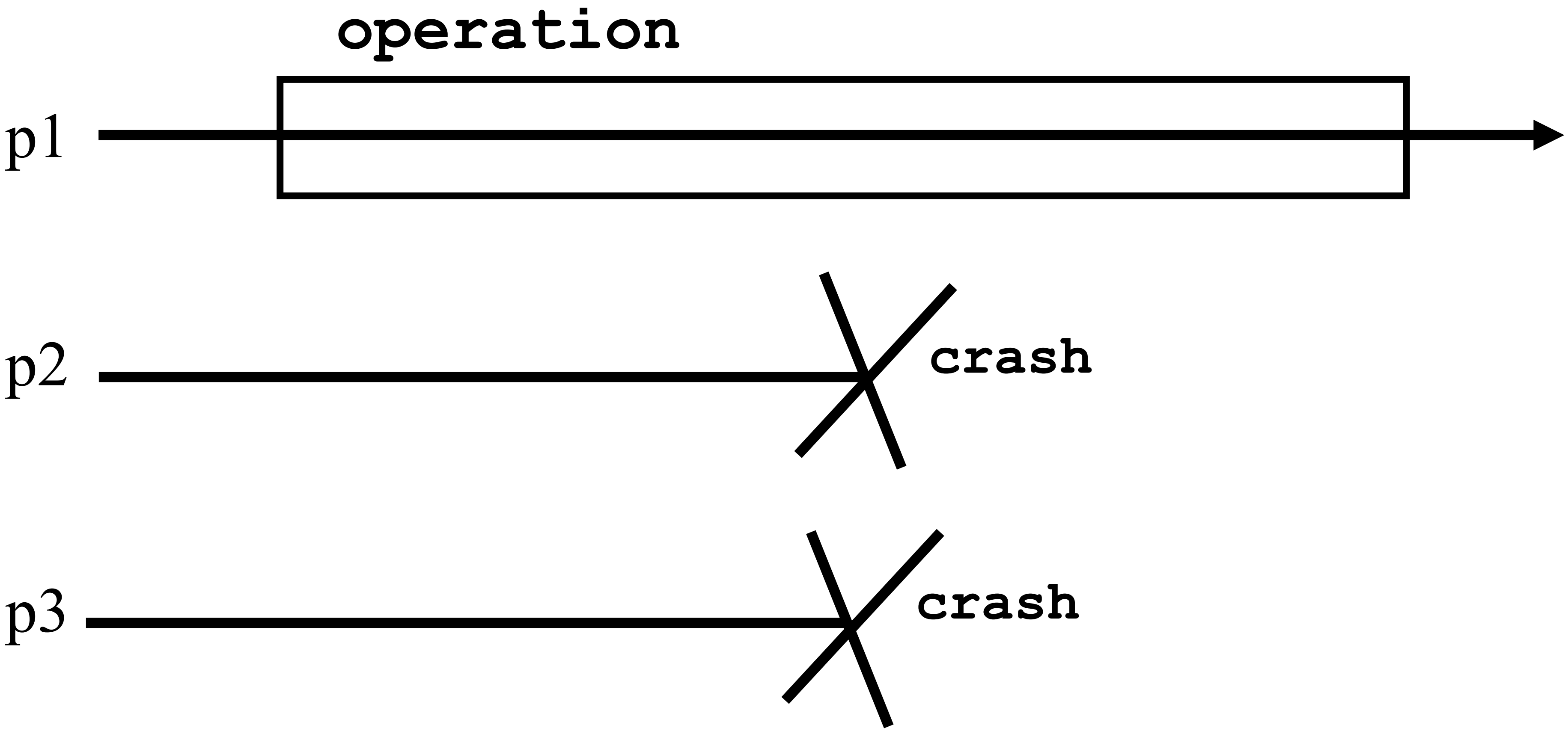
Wait-freedom



Wait-freedom

- Wait-freedom conveys the robustness of the implementation
- With a wait-free implementation, a process gets replies despite the crash of the n-1 other processes
- Note that this precludes implementations based on locks (mutual exclusion)

Wait-freedom



Roadmap

- *Model*
  - *Processes and objects*
  - *Atomicity and wait-freedom*
- *Examples*
- *Content*

Motivation

- Most synchronization primitives (problems) can be precisely expressed as atomic objects (implementations)

- Studying how to ensure robust synchronization boils down to studying wait-free atomic object implementations

Example 1

- The reader/writer synchronization problem corresponds to the ***register*** object
- Basically, the processes need to read or write a shared data structure such that the value read by a process at a time t, is the last value written before t

Register

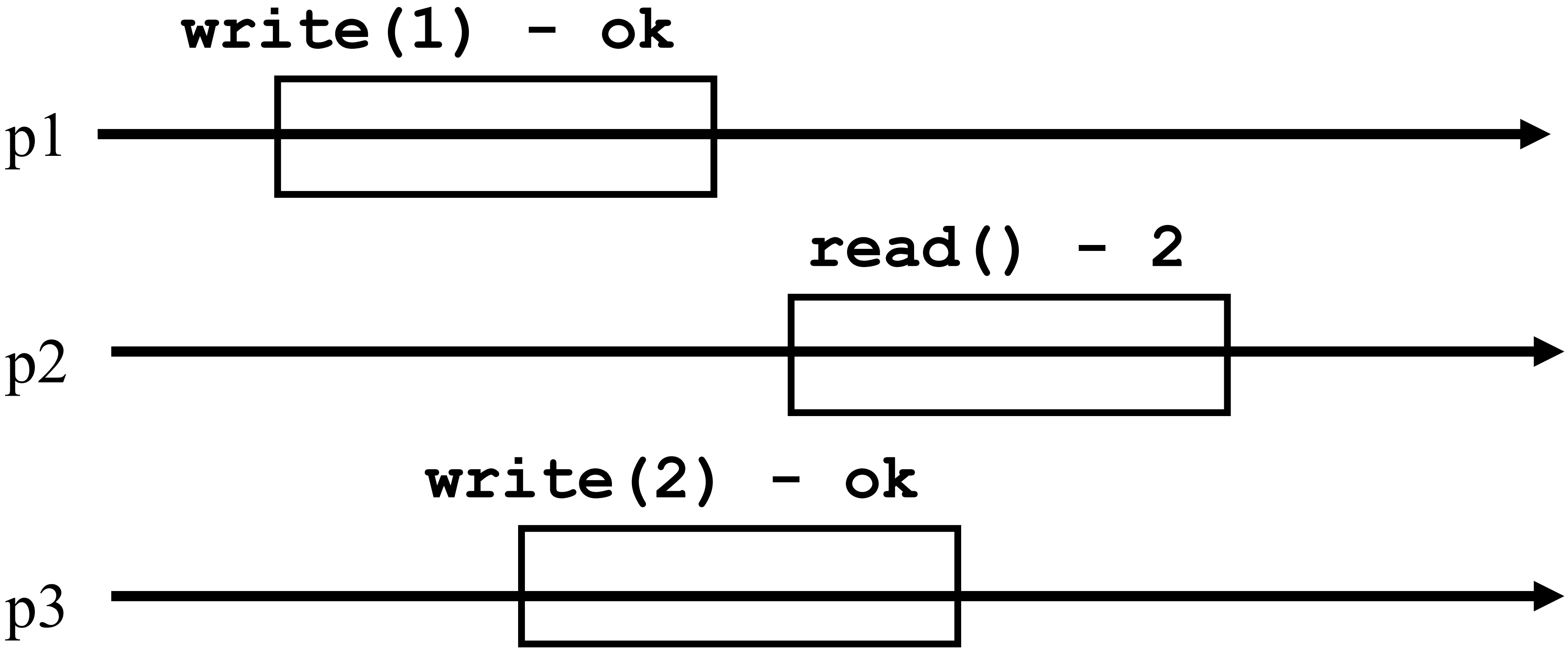
- A ***register*** has two operations: ***read()*** and ***write()***

- We assume that a ***register*** contains an integer for presentation simplicity, i.e., the value stored in the ***register*** is an integer, denoted by *x* (initially 0)

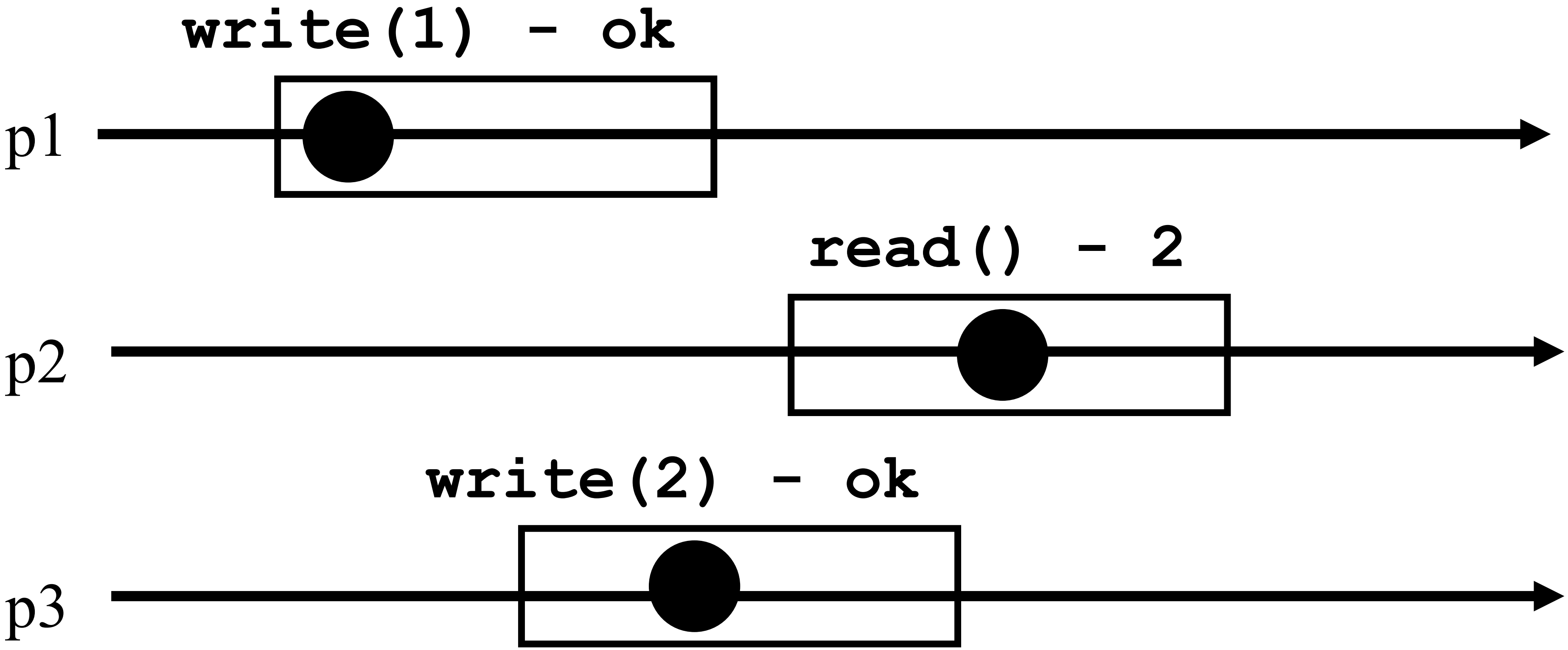
Sequential specification

- Sequential specification
  - ***read()***
    - return(x)
  - ***write(v)***
    - x <- v;
    - return(ok)

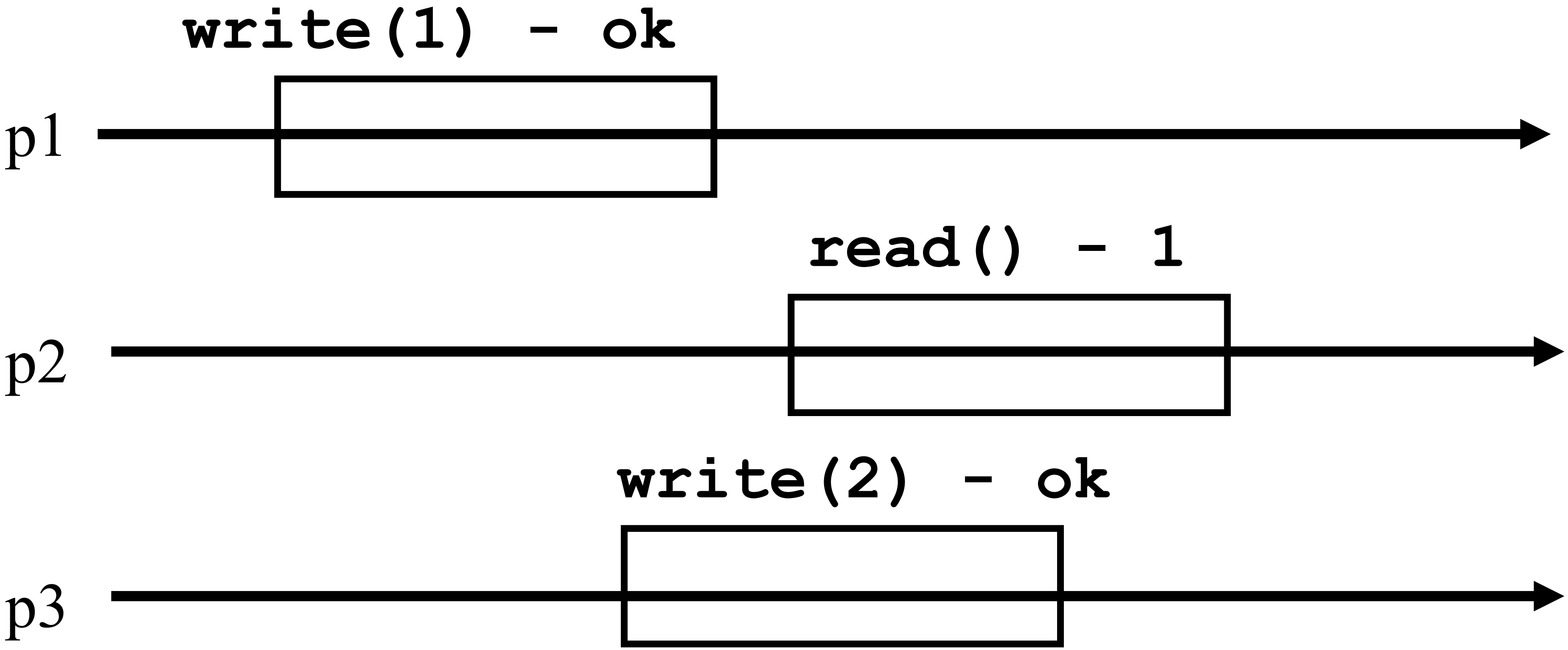
Atomicity?



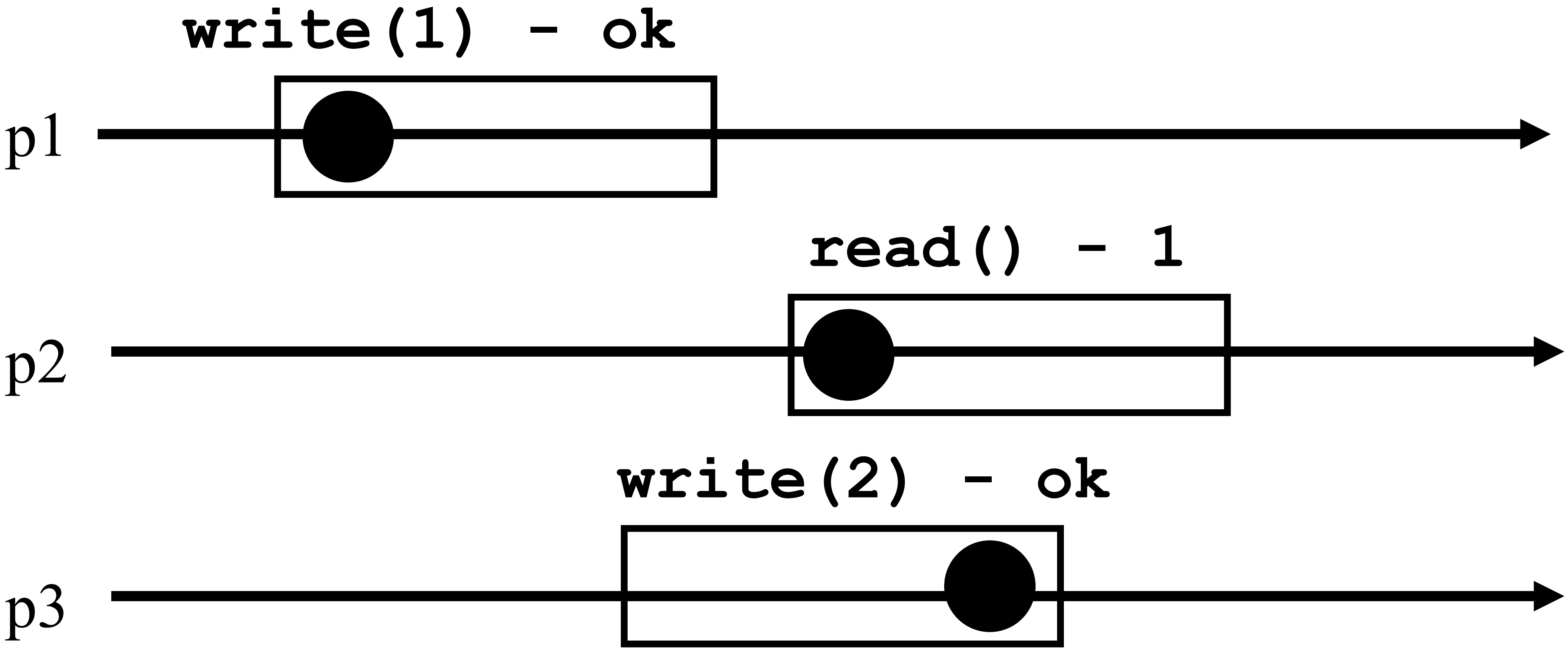
Atomicity?



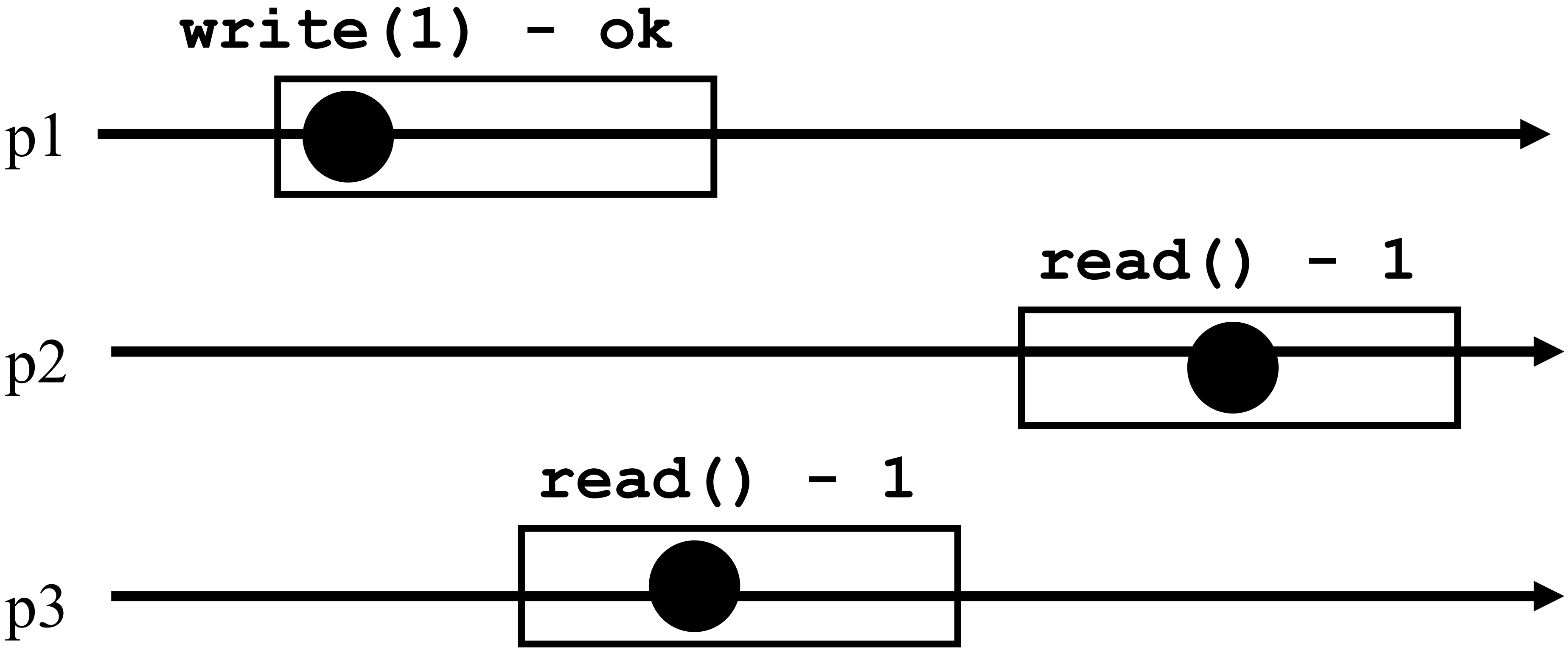
Atomicity?



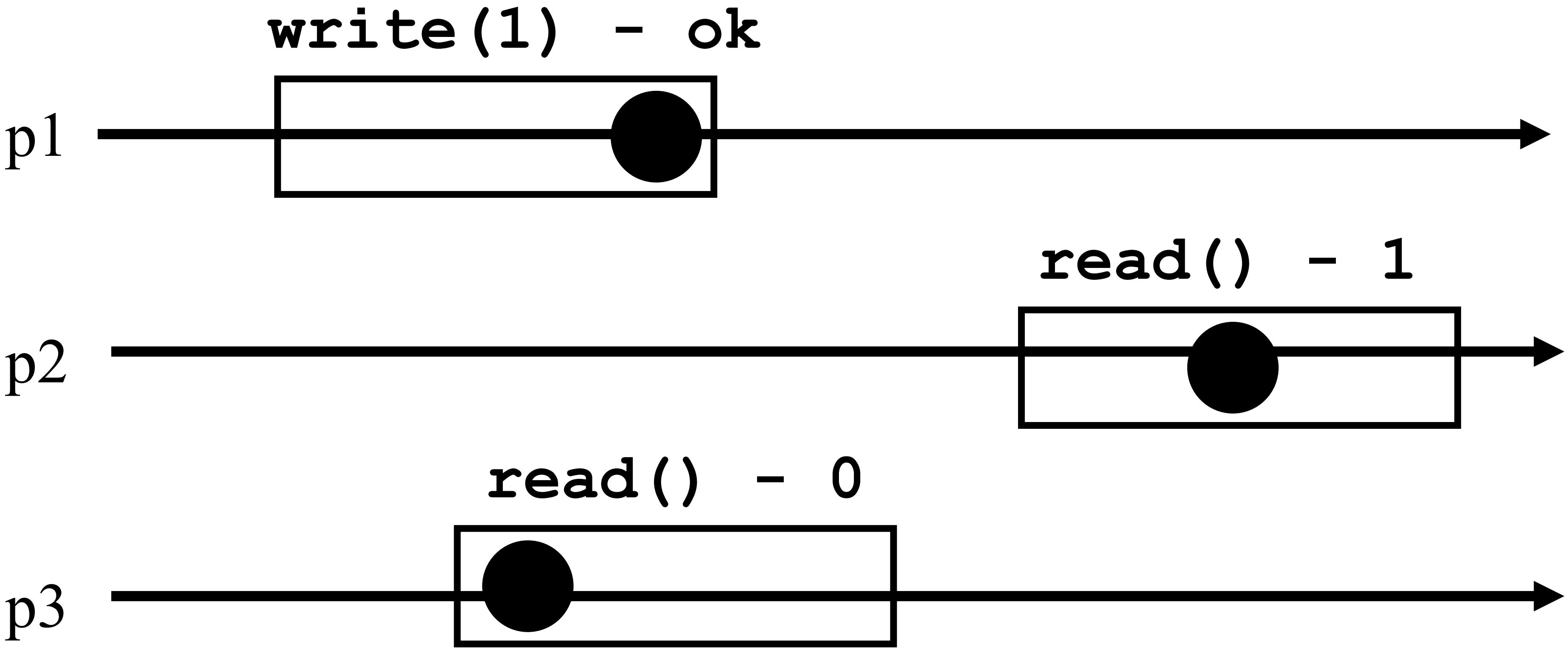
Atomicity?



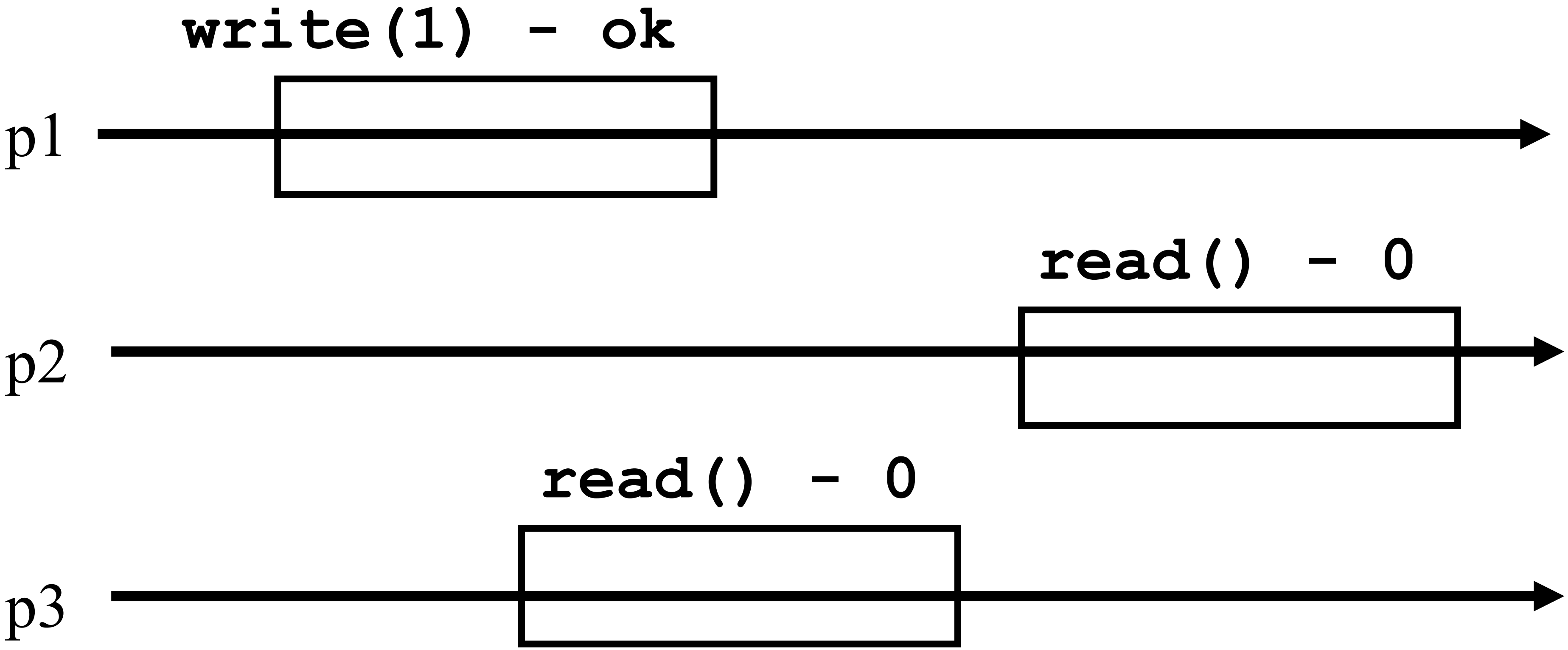
Atomicity?



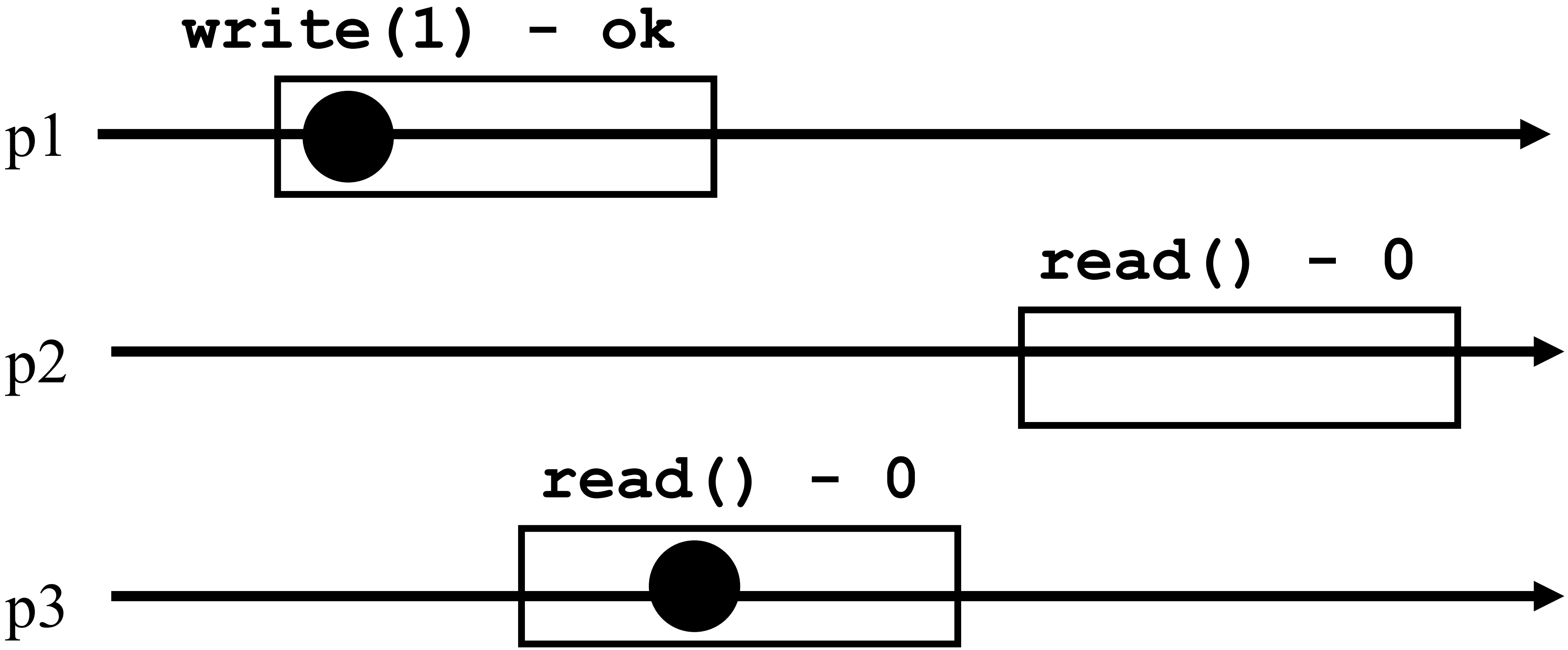
Atomicity?



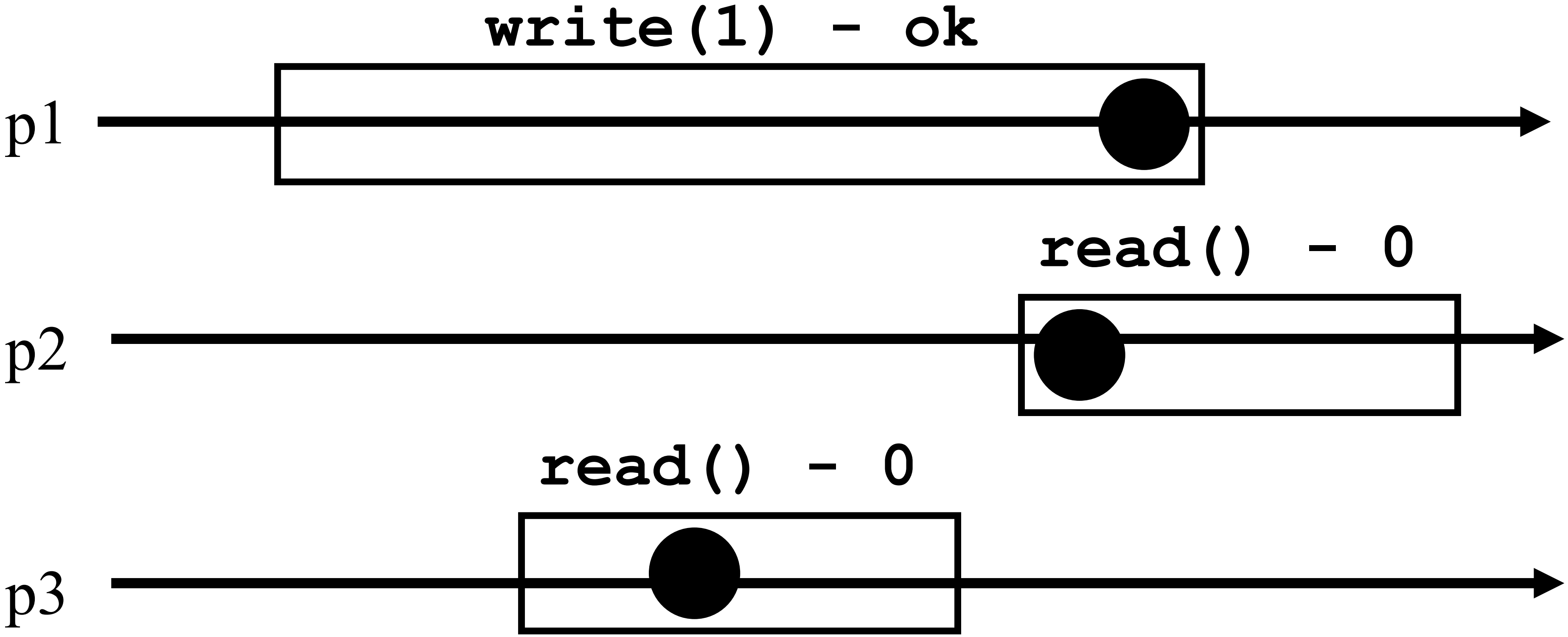
Atomicity?



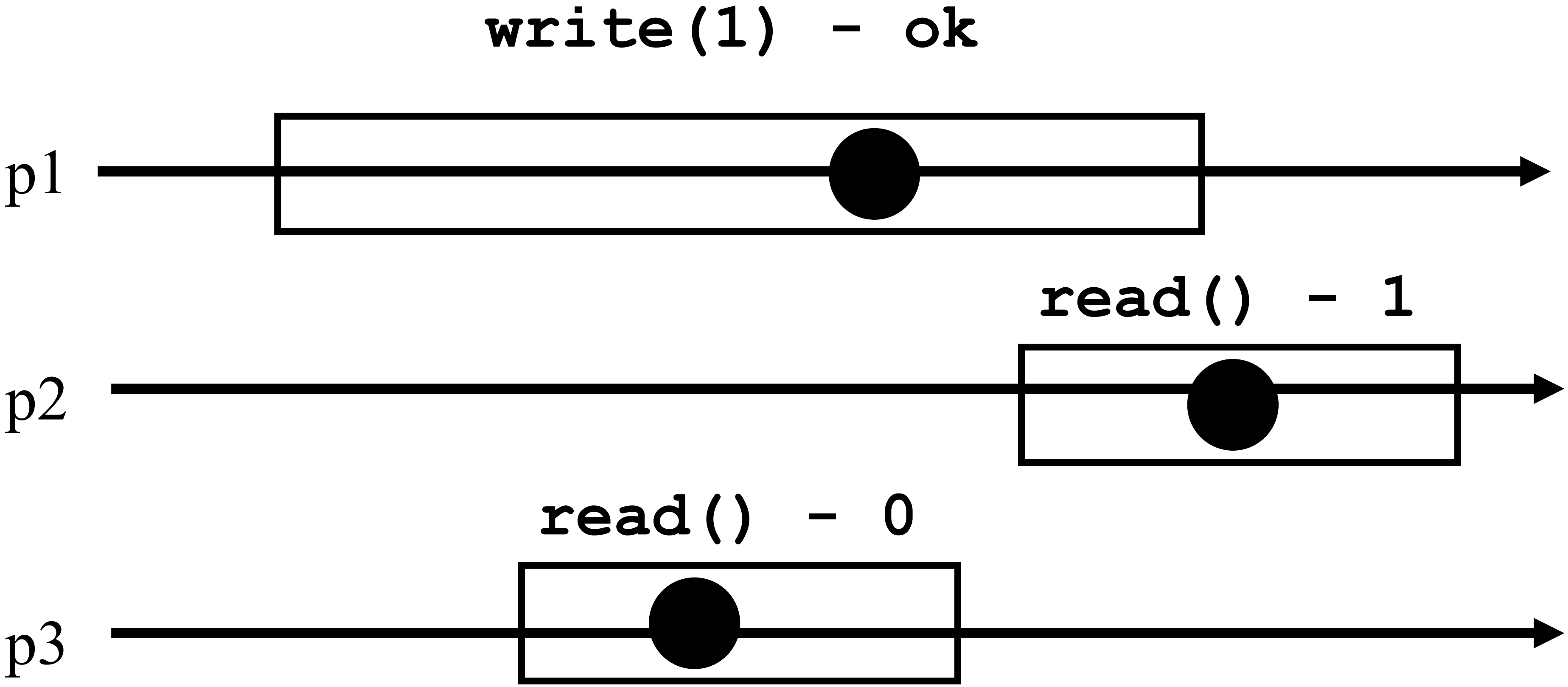
Atomicity?



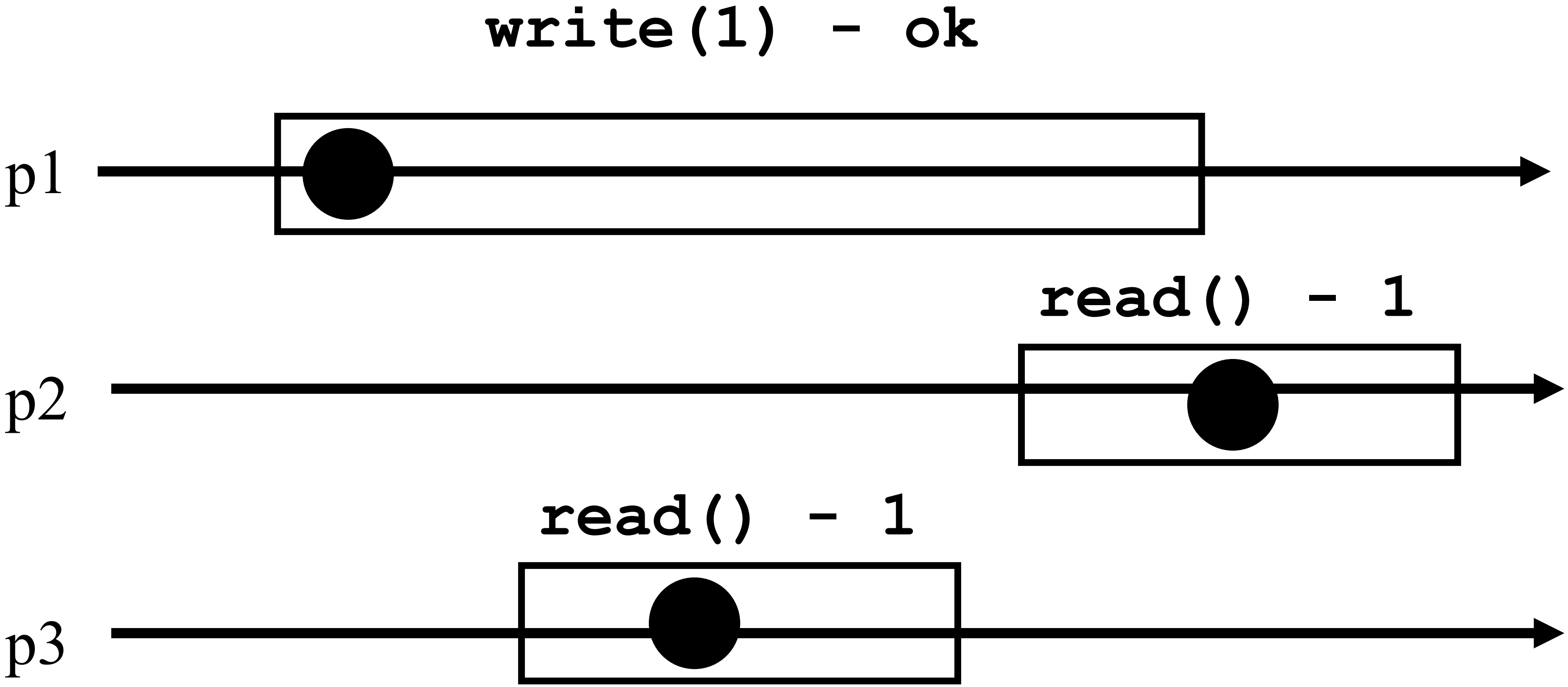
Atomicity?



Atomicity?



Atomicity?



Example 2

- The producer/consumer synchronization problem corresponds to the ***queue*** object
- Producer processes create items that need to be used by consumer processes
- An item cannot be consumed by two processes and the first item produced is the first consumed

Queue

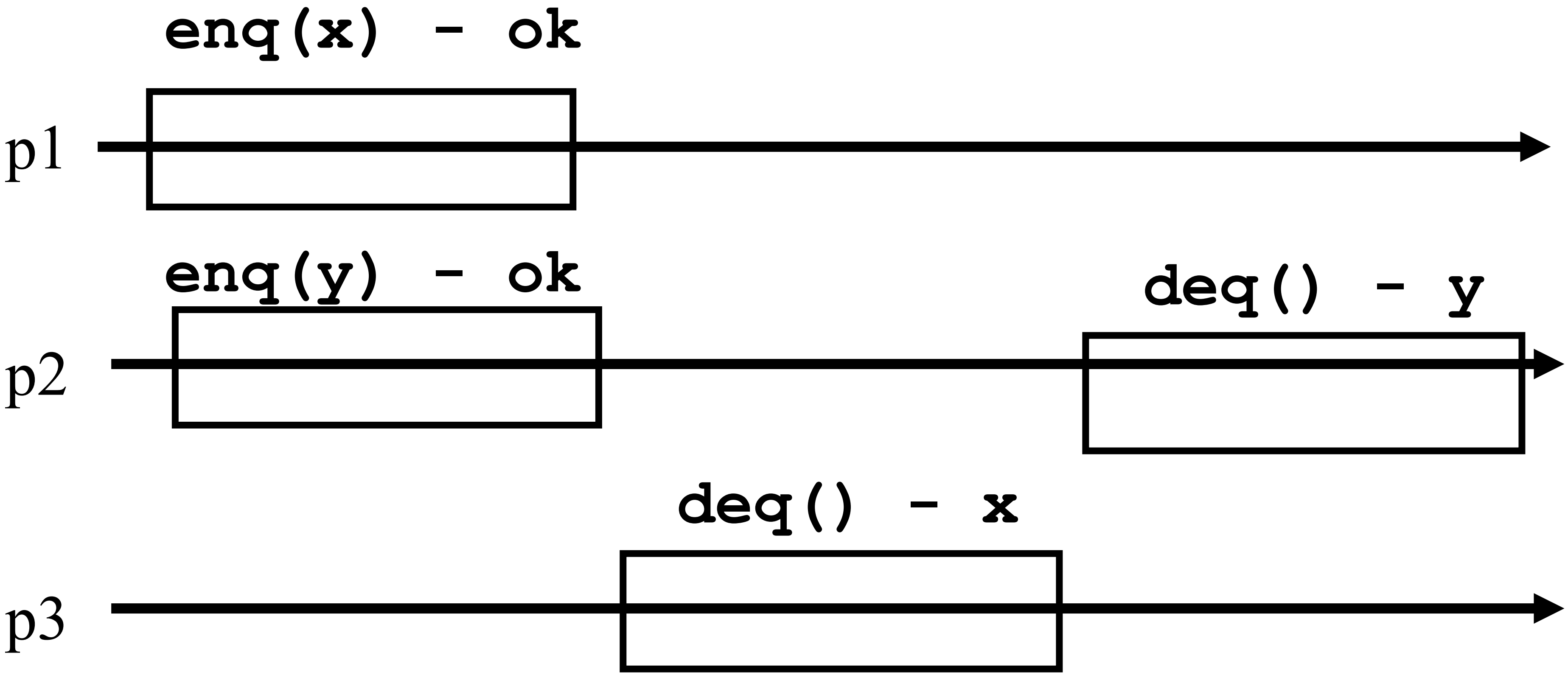
- A ***queue*** has two operations: ***enqueue()*** and ***dequeue()***

- We assume that a ***queue internally*** maintains a list *x* which exports operation *appends()* to put an item at the end of the list and *remove()* to remove an element from the head of the list

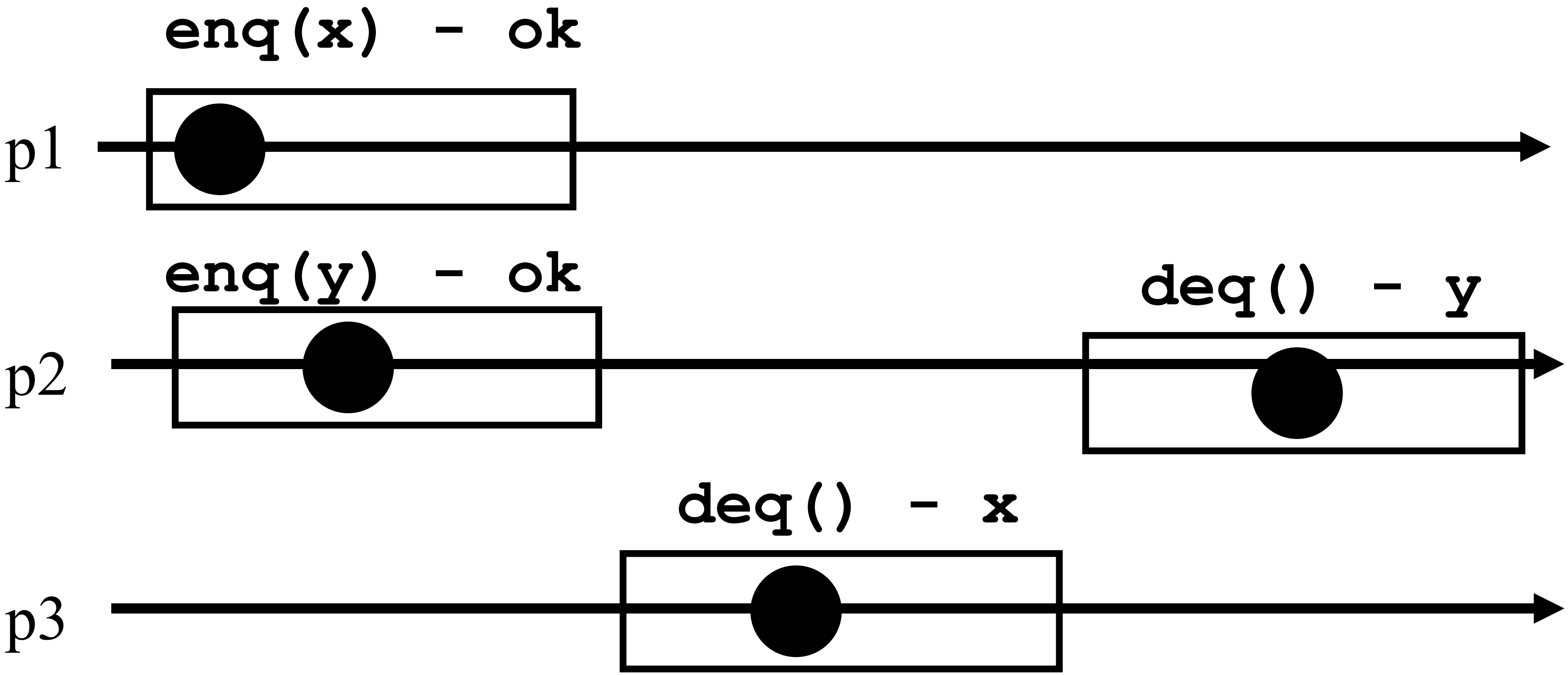
Sequential specification

- ***dequeue()***
  - if(x=0) then return(nil);
  - else return(x.remove())
- ***enqueue(v)***
  - x.append(v);
  - return(ok)

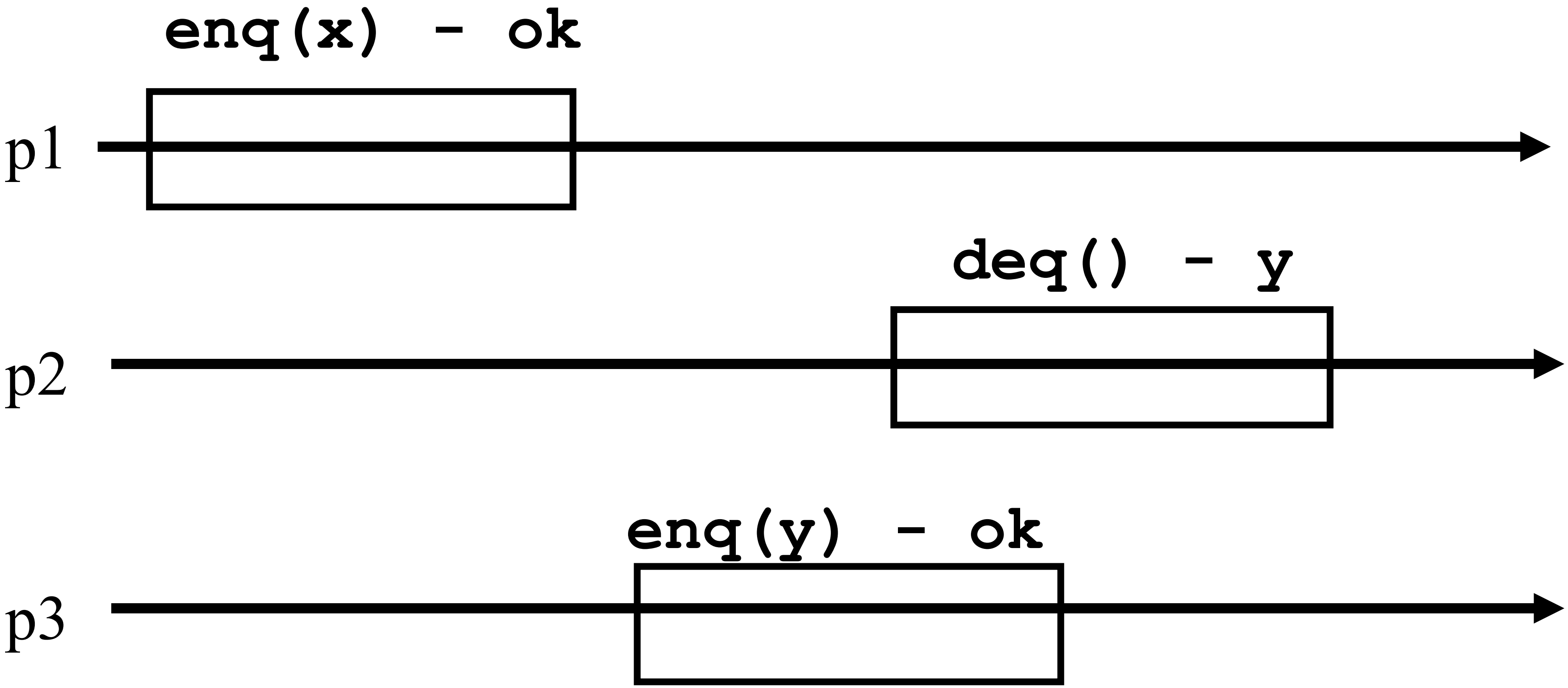
Atomicity?



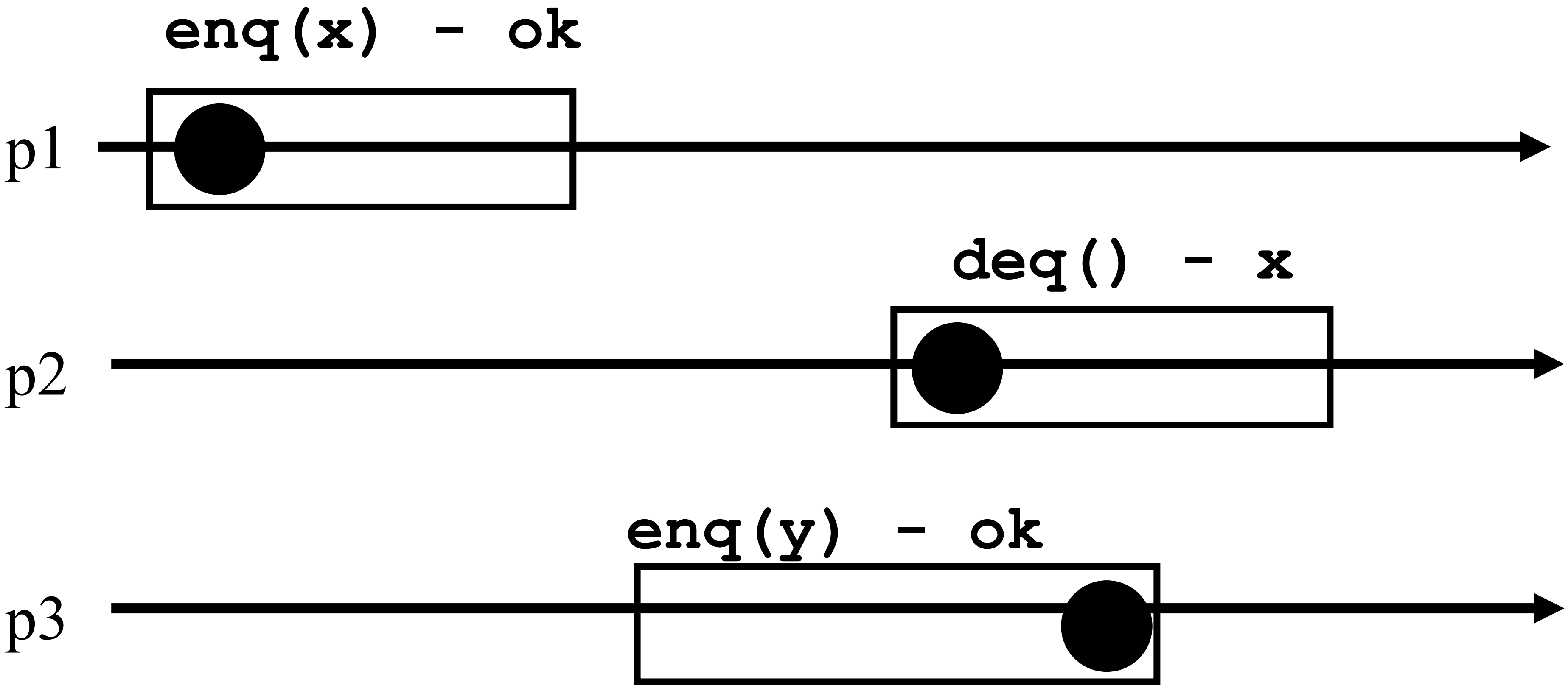
Atomicity?



Atomicity?



Atomicity?



Roadmap

- *Model*
  - *Processes and objects*
  - *Atomicity and wait-freedom*
- *Examples*
- *Content*

Content

- (1) Implementing ***registers***
- (2) The power & limitation of ***registers***
- (3) ***Universal*** objects & synchronization number
- (4) The power of ***time*** & failure detection
- (5) Tolerating ***failure*** prone objects
- (6) ***Anonymous*** implementations
- (7) ***Transaction*** memory

In short

This course shows how to wait-free implement high-level atomic objects out of basic objects

Remark. Unless explicitly stated otherwise, objects mean atomic objects and implementations are wait-free