Distributed Computing in Shared Memory and Networks

WEP 2018

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Human-machine future

« When people who can't think logically design large systems, those systems become incomprehensible. And we start thinking of them as biological systems. And since biological systems are too complex to understand, it seems perfectly natural that computer programs should be too complex to understand.

We should not accept this. »

Leslie Lamport, "Future of Computing: Logic or Biology", 2003

Roadmap

- Consistency: safety and liveness
- Consensus and universal construction
- Distributed services: Paxos, BFT, Blockchains

Slides and exercises:
https://perso.telecom-paristech.fr/kuznetso/WEP2018

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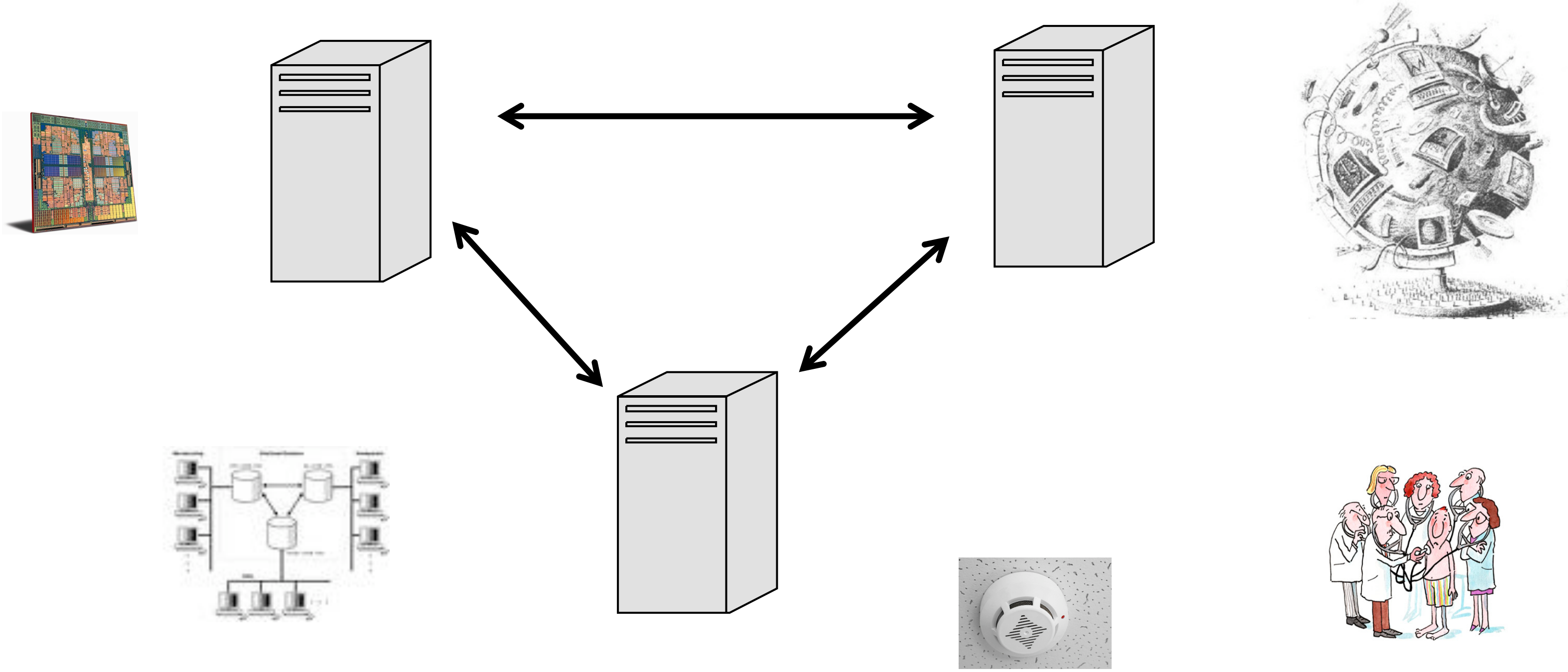
This course is about distributed computing:

independent sequential processes that communicate

Concurrency is everywhere!



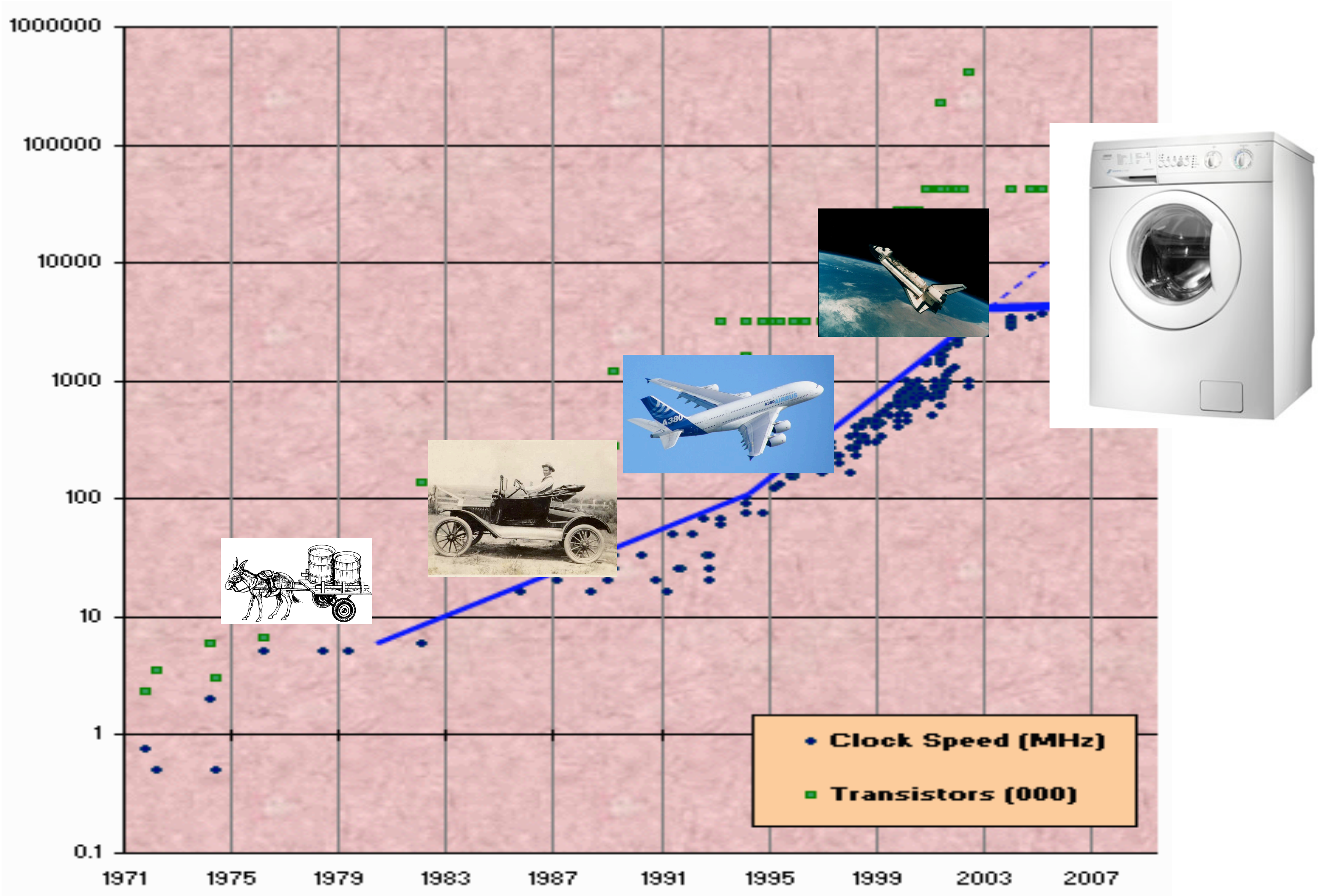
- Multi-core processors
- Sensor networks
- Internet
- …

Communication models

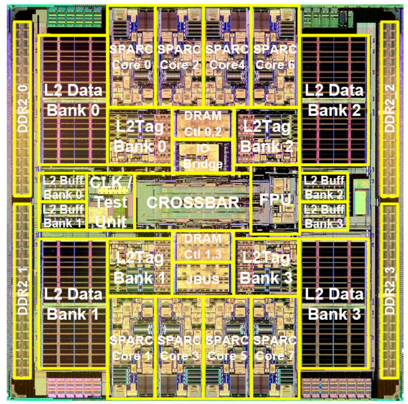
- Shared memory
  - ✓Processes apply operations on shared variables
  - ✓Failures and asynchrony

- Message passing
  - ✓Processes send and receive messages
  - ✓Communication graphs
  - ✓Message delays

Moore's Law and CPU speed



- Single-processor performance does not improve
- But we can add more cores
- Run concurrent code on multiple processors



Can we expect a proportional speedup? (ratio between sequential time and parallel time for executing a job)

Amdahl's Law

- p – fraction of the work that can be done in parallel (no synchronization)
- n - the number of processors
- Time one processor needs to complete the job = 1

$$S = \frac{1}{1 - p + p / n}$$

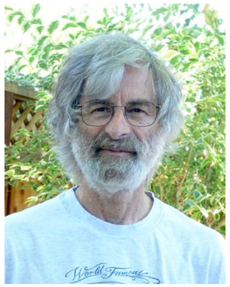
Challenges

- What is a correct implementation?
  - ✓Safety and liveness
- What is the cost of synchronization?
  - ✓Time and space lower bounds
- Failures/asynchrony
  - ✓Fault-tolerant concurrency?
- How to distinguish possible from impossible?
  - ✓Impossibility results

Distributed ≠ Parallel

- The main challenge is synchronization

- "you know you have a distributed system when the crash of a computer you've never heard of stops you from getting any work done" (Lamport)



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History

- Dining philosophers, mutual exclusion (Dijkstra)~60's
- Distributed computing, logical clocks (Lamport), distributed transactions (Gray) ~70's
- Consensus (Lynch) ~80's
- Distributed programming models, since ~90's
- Multicores and large-scale distributed services now

Real concurrency--in which one program actually continues to function while you call up and use another--is more amazing but of small use to the average person. How many programs do you have that take more than a few seconds to perform any task?

New York Times, 25 April 1989, in an article on new operating systems for IBM PC

Why synchronize ?

- Concurrent access to a shared resource may lead to an inconsistent state
  - ✓ E. g., concurrent file editing
  - ✓ Non-deterministic result (**race condition**): the resulting state depends on the scheduling of processes

- Concurrent accesses need to be **synchronized**
  - ✓ E. g., decide who is allowed to update a given part of the file at a given time

- Code leading to a race condition is called **critical section**
  - ✓ Must be executed sequentially

- **Synchronization problems**: mutual exclusion, readers-writers, producer-consumer, …

Edsger Dijkstra
1930-2002

Dining philosophers (Dijkstra, 1965)

- To make progress (to eat) each process (philosopher) needs two resources (forks)
- Mutual exclusion: no fork can be shared
- Progress conditions:
  - ✓Some philosopher does not starve (deadlock-freedom)
  - ✓No philosopher starves (starvation-freedom)

Mutual exclusion

- No two processes are in their critical sections (CS) at the same time

\+

- Deadlock-freedom: **at least one** process eventually enters its CS
- Starvation-freedom: **every** process eventually enters its CS
  - ✓ Assuming no process **blocks** in **CS** or **Entry section**

- Originally: implemented by reading and writing
  - ✓ Peterson's lock, Lamport's bakery algorithm
- Currently: in hardware (mutex, semaphores)

Peterson's lock: 2 processes

```
bool flag[0]   = false;
bool flag[1]   = false;
int turn;
```

```
P0:

flag[0] = true;
turn = 1;
while (flag[1] and turn==1)
{
          // busy wait
}
// critical section
…
// end of critical section
flag[0] = false;
```

```
P1:

flag[1] = true;
turn = 0;
while (flag[0] and turn==0)
{
          // busy wait
}
// critical section
…
// end of critical section
flag[1] = false;
```

Peterson's lock: N ≥ 2 processes

```
// initialization
level[0..N-1] = {-1};      // current level of processes 0...N-1
waiting[0..N-2] = {-1}; // the waiting process in each level
                           // 0...N-2

// code for process i that wishes to enter CS
for (m = 0; m < N-1; ++m) {
    level[i] = m;
    waiting[m] = i;
    while(waiting[m] == i &&(exists k ≠ i: level[k] ≥ m)) {
        // busy wait
    }
}
// critical section
level[i] = -1; // exit section
```

Bakery [Lamport'74,simplified]

```
// initialization
flag: array [1..N] of bool = {false};
label: array [1..N] of integer = {0}; //assume no bound

// code for process i that wishes to enter CS

flag[i] = true; //enter the “doorway”
label[i] = 1 + max(label[1], ..., label[N]); //pick a ticket
//leave the “doorway”
while (for some k ≠ i: flag[k] and (label[k],k)<<(label[i],i));
// wait until all processes “ahead” are served
…
// critical section
…
flag[i] = false; // exit section
```

Processes are served in the “ticket order”: first-come-first-serve

Bakery [Lamport'74,original]

```
// initialization
flag: array [1..N] of bool = {false};
label: array [1..N] of integer = {0}; //assume no bound

// code for process i that wishes to enter CS
flag[i] = true; //enter the doorway
label[i] = 1 + max(label[1], ..., label[N]); //pick a ticket
flag[i] = false; //exit the doorway
for j=1 to N do {
          while (flag[j]); //wait until j is not in the doorway
          while (label[j]≠0 and (label[j],j)<<(label[i],i));
          // wait until j is not "ahead"
}
…
// critical section
…
label[i] = 0; // exit section
```

Ticket withdrawal is "protected" with flags: a very useful trick: works with "safe" (non-atomic) shared variables

Black-White Bakery [Taubenfeld'04]

```
// initialization
color: {black,white};
flag: array [1..N] of bool = {false};
label[1..N]: array of type {0,…,N} = {0}  //bounded ticket numbers
mycolor[1..N]: array of type {black,white}

// code for process i that wishes to enter CS
flag[i] = true; //enter the "doorway"
mycolor[i] =color;
label[i] = 1 + max({label[j]| j=1,…,N: mycolor[i]=mycolor[j]});
flag[i] = false; //exit the "doorway"
for j=1 to N do
   while (flag[j]);
   if mycolor[j]=mycolor[i] then
      while (label[j]≠0 and (label[j],j)<<(label[i],i) and mycolor[j]=mycolor[i]  );
   else
      while (label[j]≠0 and mycolor[i]=color and mycolor[j] ≠ mycolor[i]);
// wait until all processes "ahead" of my color are served
…
// critical section
…
if mycolor[i]=black then color = white else color = black;
label[i] = 0; // exit section
```

Colored tickets => bounded variables!

Quiz 1.1

- What if we reverse the order of the first two lines the 2-process Peterson's algorithm

```
P0:                          P1:
turn = 1;                    turn = 0;
flag[0] = true;              flag[1] = true;
…                            …
```

Would it work?

- Prove that Peterson's N-process algorithm ensures:
  - ✓mutual exclusion: no two processes are in the critical section at a time
  - ✓starvation freedom: every process in the trying section eventually reaches the critical section (assuming no process fails in the trying, critical, or exit sections)

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Correctness: safety and liveness

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How to treat a (computing) system formally

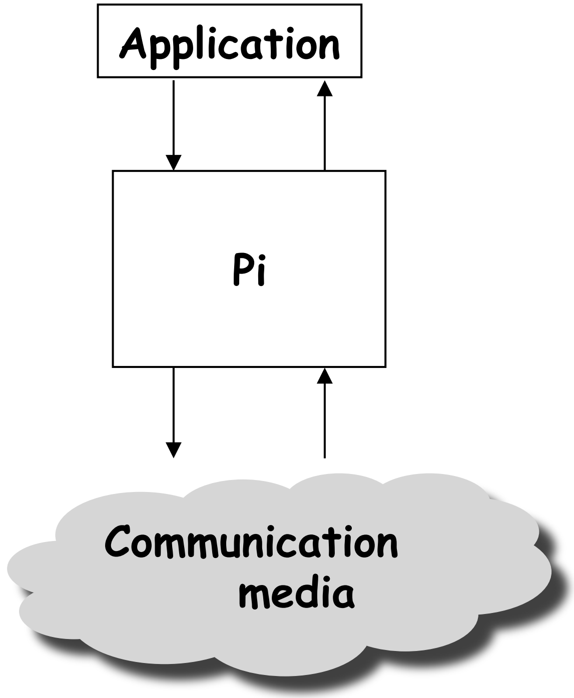
- Define models (tractability, realism)
- Devise abstractions for the system design (convenience, efficiency)
- Devise algorithms and determine complexity bounds

Basic abstractions

- *Process* abstraction – an entity performing independent computation
- Communication
  - ✓Message-passing: *channel* abstraction
  - ✓Shared memory: *objects*

Processes

- Automaton P_i (i=1,...,N):
  - ✓States
  - ✓Inputs
  - ✓Outputs
  - ✓Sequential specification

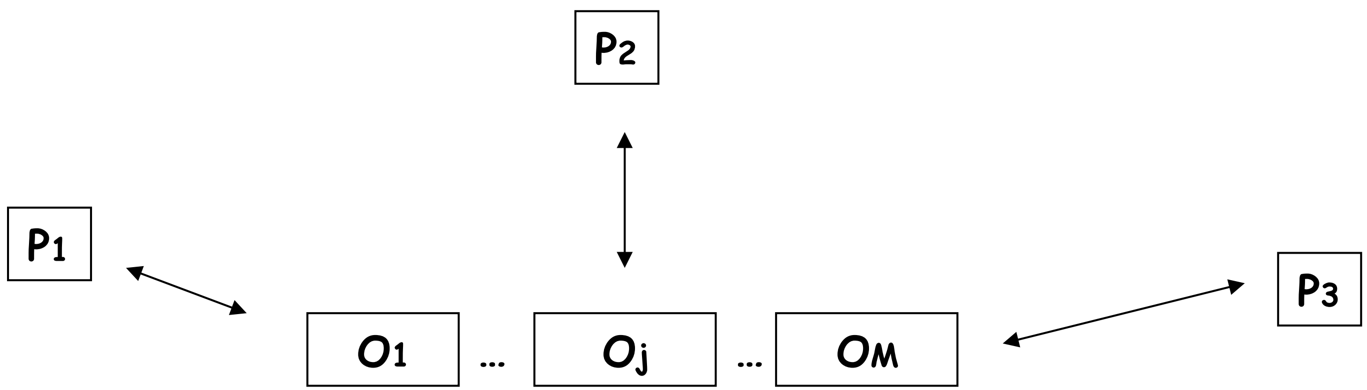


Algorithm = $\{P_1, \ldots, P_N\}$

- Deterministic algorithms
- Randomized algorithms

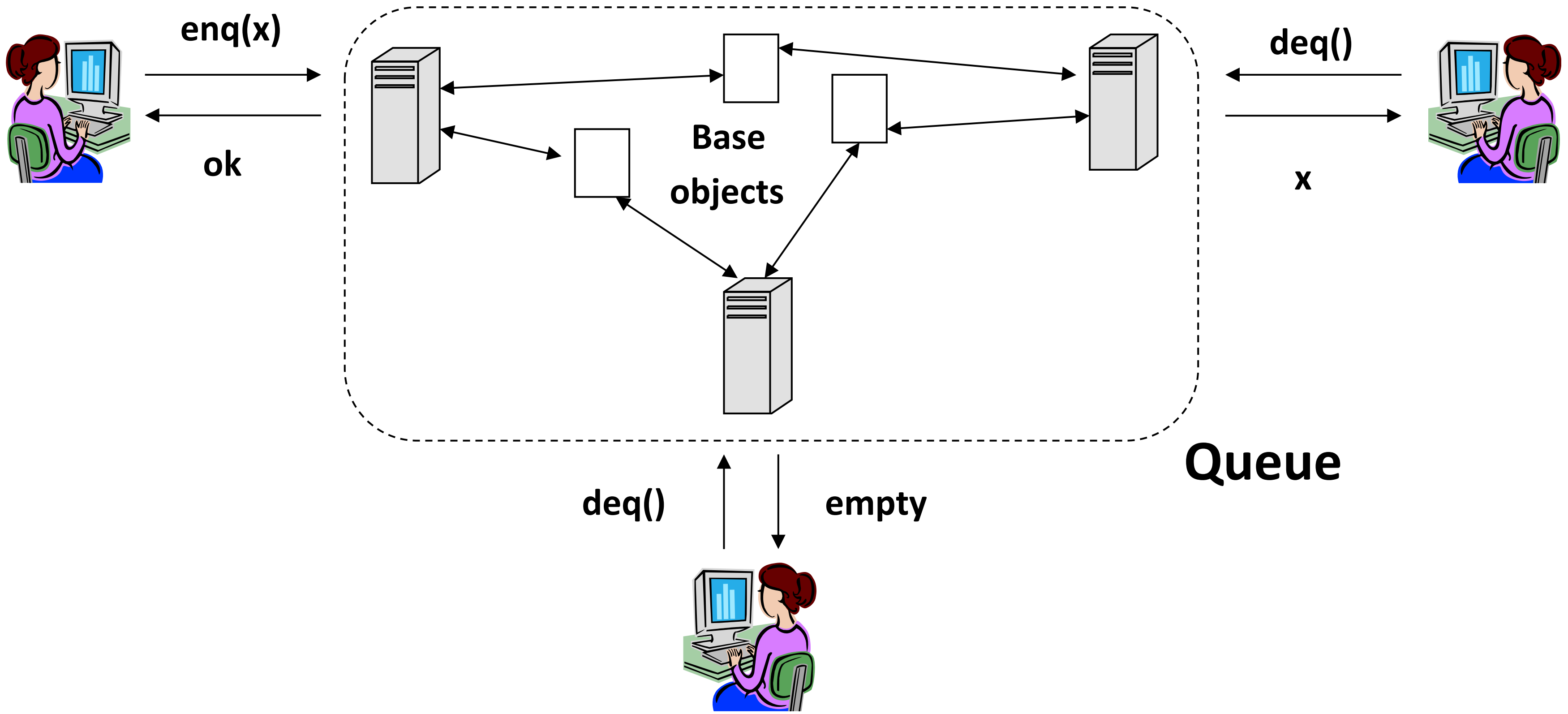
Shared memory

- Processes communicate by applying operations on and receiving responses from *shared objects*
- A shared object instantiates a state machine
  - ✓States
  - ✓Operations/Responses
  - ✓Sequential specification
- Examples: read-write registers, TAS,CAS,LL/SC,…



Implementing an object

Using *base* objects, create an illusion that an object O is available



Correctness

What does it mean for an implementation to be correct?

- Safety ≈ nothing bad ever happens
  - ✓Can be violated in a finite execution, e.g., by producing a wrong output or sending an incorrect message
  - ✓What the implementation is allowed to output
- Liveness ≈ something good eventually happens
  - ✓Can only be violated in an *infinite* execution, e.g., by never producing an expected output
  - ✓Under which condition the implementation outputs

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In our context

Processes access an (implemented) abstraction (e.g., read-write buffer, a queue, a mutex) by invoking operations

- An operation is implemented using a sequence of accesses to base objects
  - E.g.: a queue using reads, writes, TAS, etc.
- A process that never fails (stops taking steps) in the middle of its operation is called correct
  - We typically assume that a correct process invokes infinitely many operations, so a process is correct if it takes infinitely many steps

Runs

A system run is a sequence of events

- ✓E.g., actions that processes may take

Σ – event alphabet

- ✓ E.g., all possible actions

Σ^ω is the set all finite and infinite runs

A property P is a subset of Σ^ω

An implementation satisfies P if every its run is in P

Safety properties

P is a safety property if:

- P is prefix-closed: if σ is in P, then each prefix of σ is in P
- P is limit-closed: for each infinite sequence of traces σ_0, σ_1, σ_2,…, such that each σ_i is a prefix of σ_{i+1} and each σ_i is in P, the limit trace σ is in P

(Enough to prove safety for all finite traces of an algorithm)

Liveness properties

P is a liveness property if every finite σ (in Σ^*, the set of all finite histories) has an extension in P

(Enough to prove liveness for all infinite runs)

A liveness property is dense: intersects with extensions of every finite trace

Safety? Liveness?

- Processes propose *values* and decide on *values* (distributed tasks):

$\Sigma = \cup_{i,v}$ {propose$_i$(v),decide$_i$(v)} $\cup$ {base-object accesses}

✓Every decided value was previously proposed

✓No two processes decide differently

✓Every correct (taking infinitely many steps) process eventually decides

✓No two correct processes decide differently

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Quiz 1.2: safety

1. Let S be a safety property. Show that if all finite runs of an implementation I are safe (belong to S) then all runs of I are safe

2. Show that every unsafe run σ has an unsafe finite prefix σ': every extension of σ' is unsafe

3. Show that every property is an intersection of a safety property and a liveness property

How to distinguish safety and liveness: rules of thumb

Let P be a property (set of runs)

- If every run that violates P is infinite
  - ✓P is liveness
- If every run that violates P has a finite prefix that violates P
  - ✓P is safety
- Otherwise, P is a mixture of safety and liveness

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Example: implementing a concurrent queue

What *is* a concurrent FIFO queue?

- ✓FIFO means strict temporal order
- ✓Concurrent means ambiguous temporal order

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When we use a lock…

```
shared
     items[];
     tail, head := 0

deq()

  lock.lock();
    if (tail = head)
       x := empty;
    else
       x := items[head];
       head++;
  lock.unlock();
  return x;
```

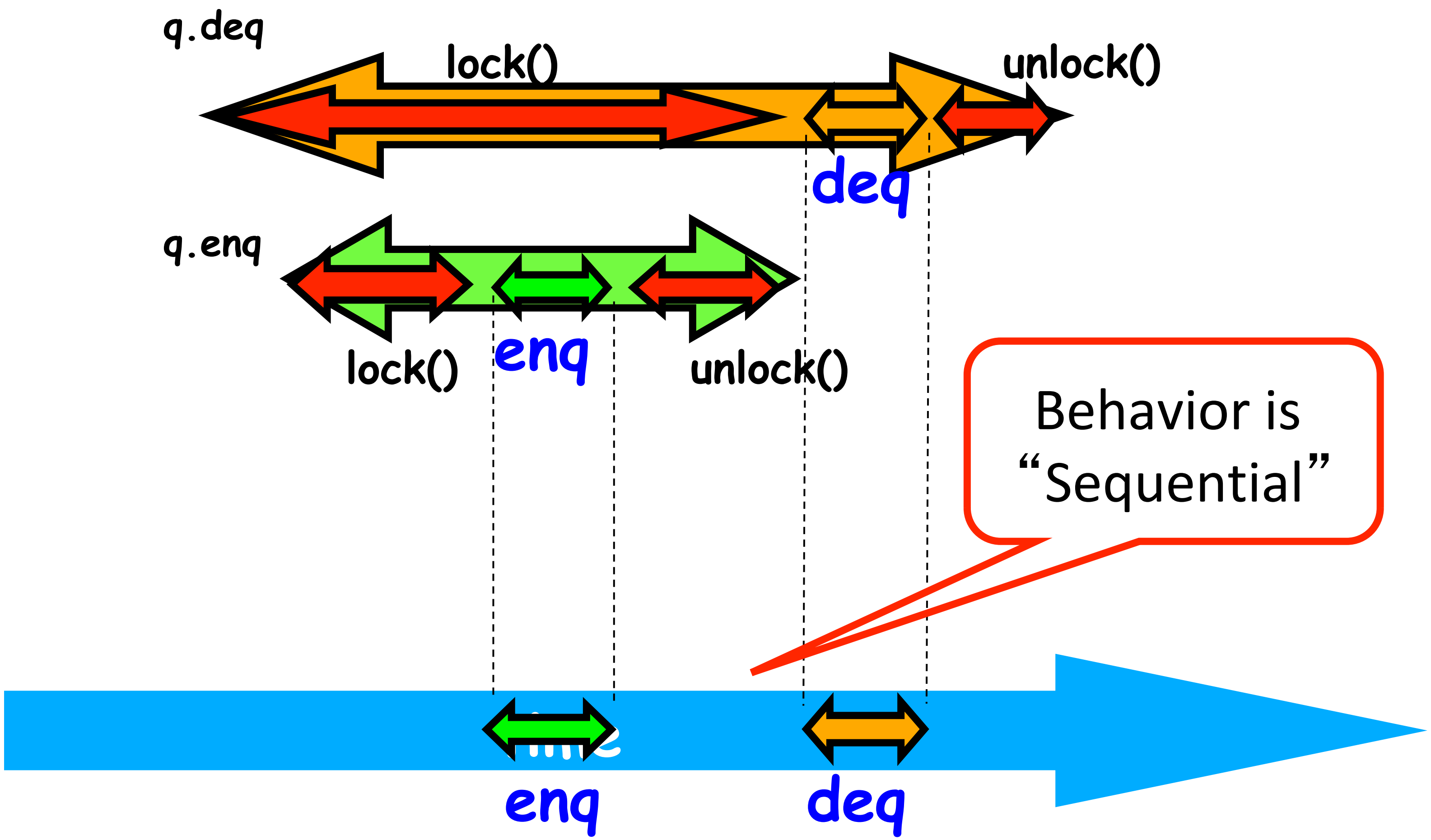
Intuitively…

```
deq()

  lock.lock();
    if (tail = head)
       x := empty;
    else
       x := items[head];
       head++;
  lock.unlock();
  return x;
```

All modifications of queue are done in mutual exclusion

We describe the concurrent via the sequential



Linearizability (atomicity): A Safety Property

- Each complete operation should
  - ✓ "take effect"
  - ✓ Instantaneously
  - ✓ Between invocation and response events

- The history of a concurrent execution is correct if its "sequential equivalent" is correct

- Need to define histories first

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Histories

A history is a sequence of invocation and responses

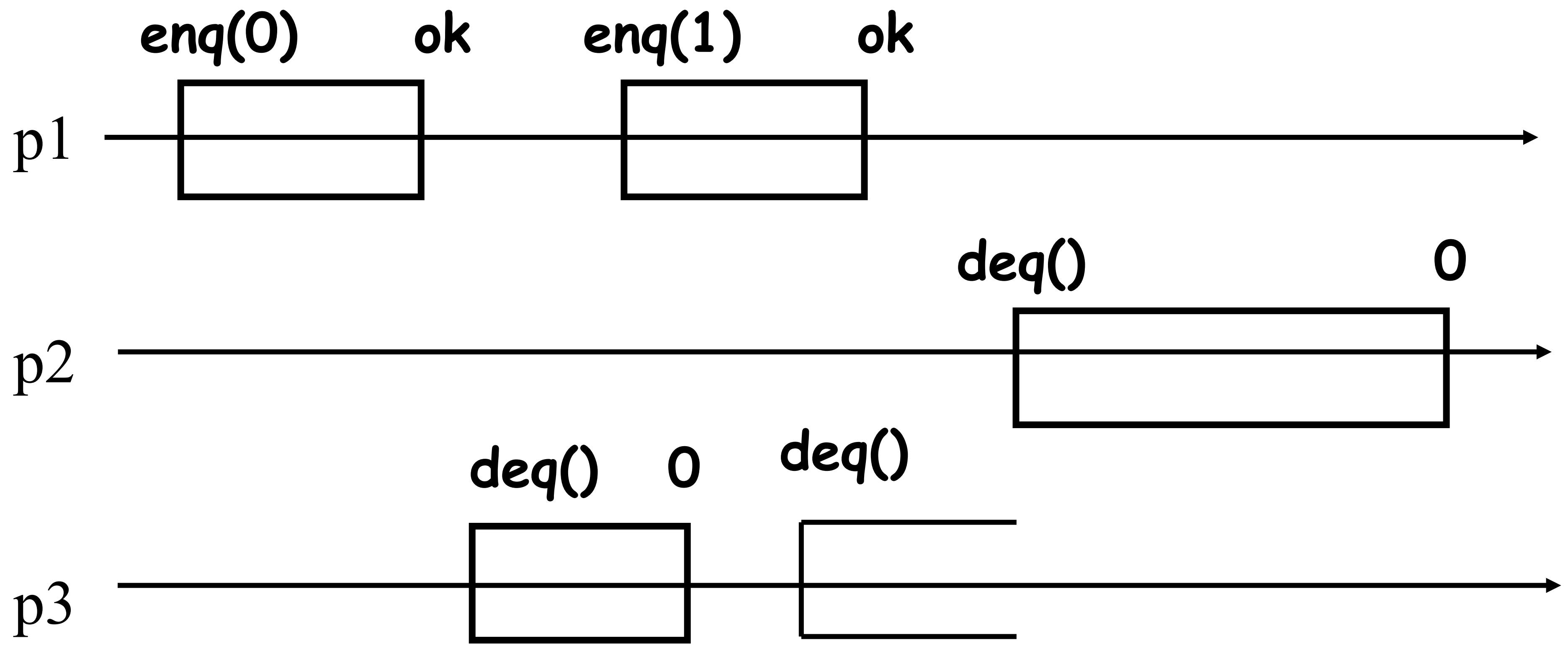
E.g., p1-enq(0), p2-deq(),p1-ok,p2-0,…

A history is sequential if every invocation is immediately followed by a corresponding response

E.g., p1-enq(0), p1-ok, p2-deq(),p2-0,…

(A sequential history has no concurrent operations)

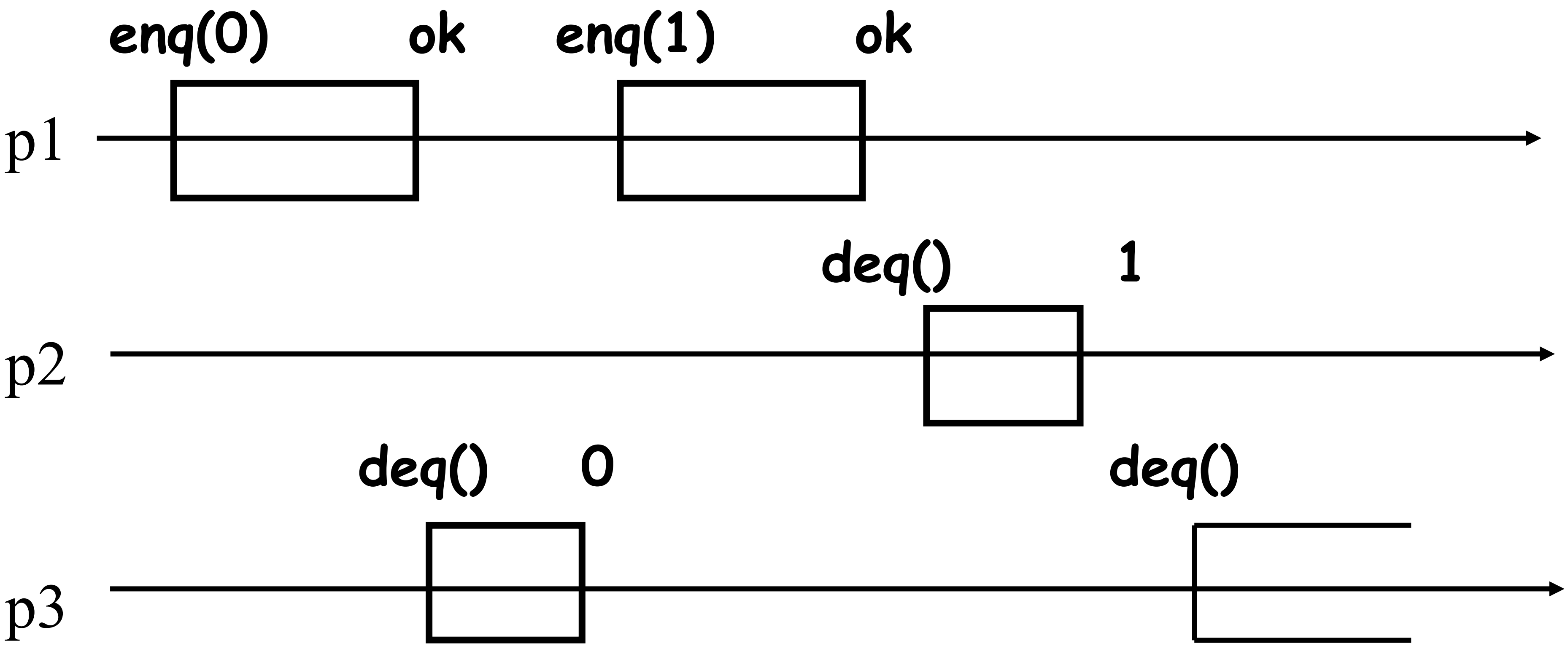
Histories



History:

p1-enq(0); p1-ok; p3-deq(); p1-enq(); p3-0; p3-deq(); p1-ok; p2-deq(); p2-0

Histories



History:

p1-enq(0); p1-ok; p3-deq(); p3-0; p1-enq(1); p1-ok; p2-deq(); p2-1; p3-deq();

Legal histories

A sequential history is *legal* if it satisfies the sequential specification of the shared object

- (FIFO) queues:
  Every deq returns the first not yet dequeued value

- Read-write registers:
  Every read returns the last written value

(well-defined for sequential histories)

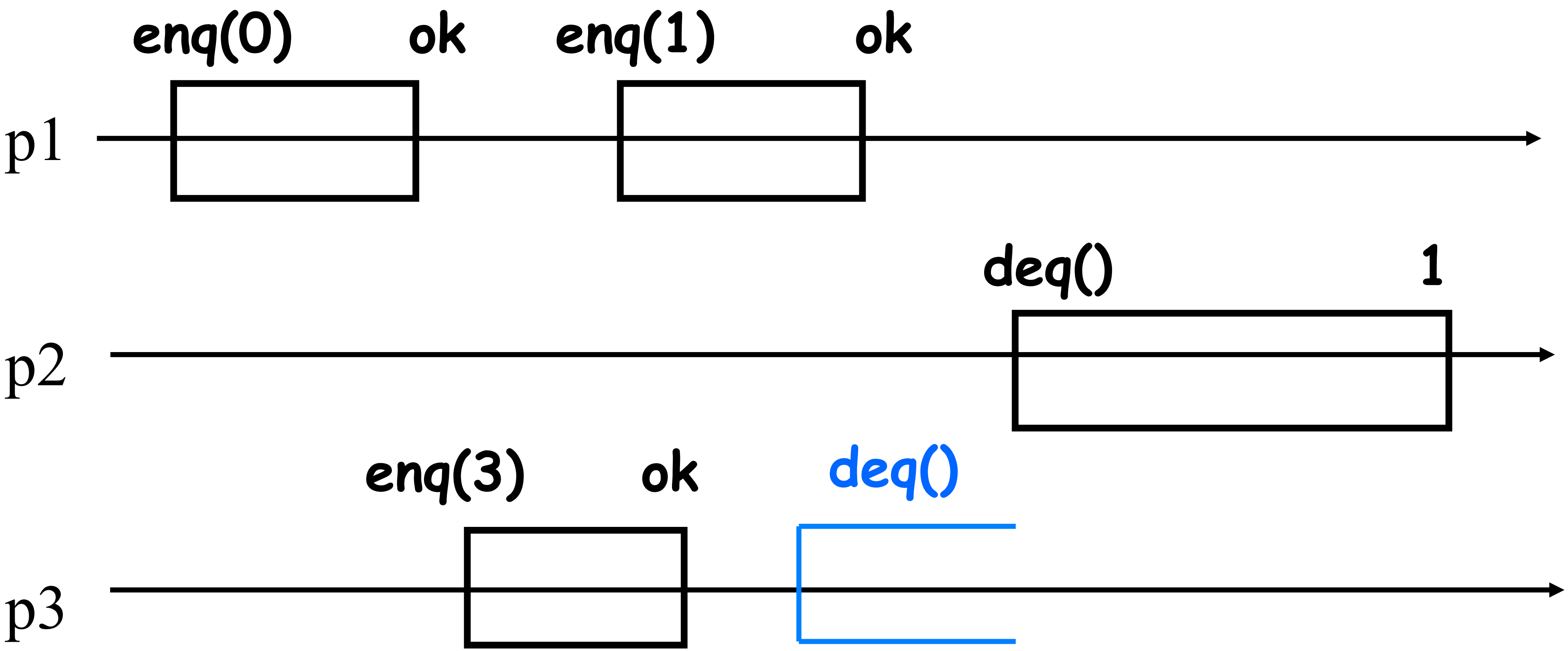
Complete operations and completions

Let H be a history

An operation op is *complete* in H if H contains both the invocation and the response of op

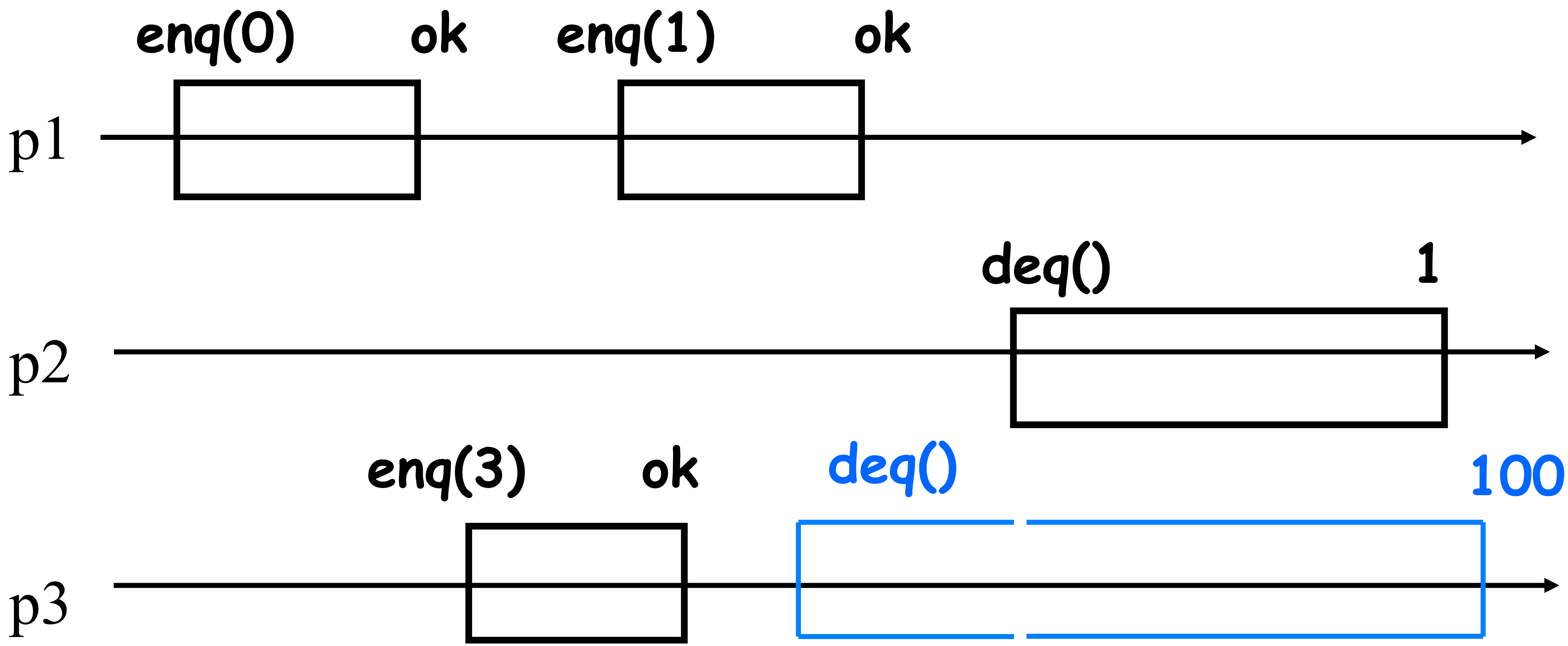
A *completion* of H is a history H' that includes all complete operations of H and a subset of incomplete operations of H followed with matching responses

Complete operations and completions



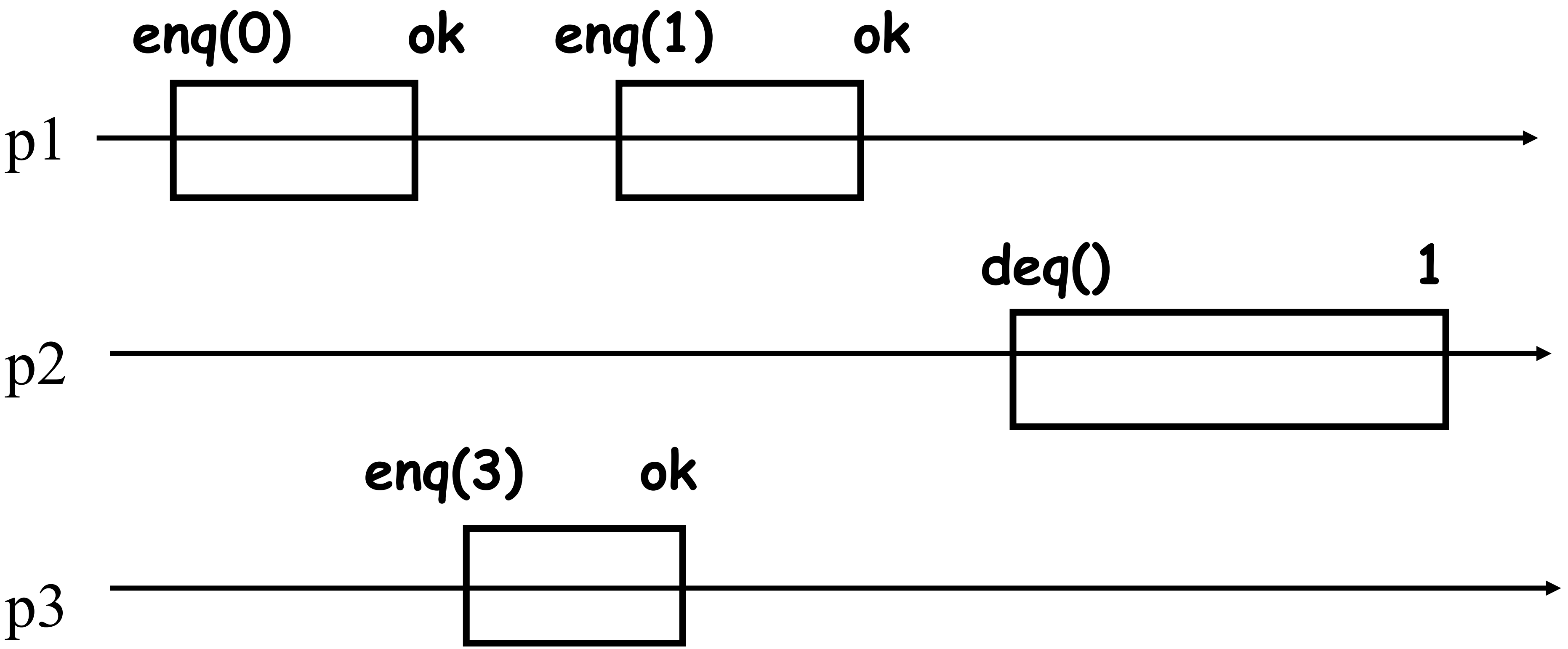
p1-enq(0); p1-ok; p3-enq(3); p1-enq(1); p3-ok;
p3-deq(); p1 –ok; p2-deq(); p2-1;

Complete operations and completions



p1-enq(0); p1-ok; p3-enq(3); p1-enq(1); p3-ok; p3-deq(); p1 –ok; p2-deq(); p2-1; p3-100

Complete operations and completions



p1-enq(0); p1-ok; p3-enq(3); p1-enq(1); p3-ok; p1 –ok; p2-deq(); p2-1;

Equivalence

Histories H and H' are *equivalent* if for all pi

$H \mid p_i = H' \mid p_i$

E.g.:

H=p_1-enq(0); p_1-ok; p3-deq(); p_3-3

H'=p_1-enq(0); p_3-deq(); p_1-ok; p_3-3

Linearizability (atomicity)

A history H is *linearizable* if there exists a sequential legal history S such that:

- S is equivalent to some completion of H
- S preserves the precedence relation of H:

op1 precedes op2 in H => op1 precedes op2 in S

What if: define a completion of H as any complete extension of H?

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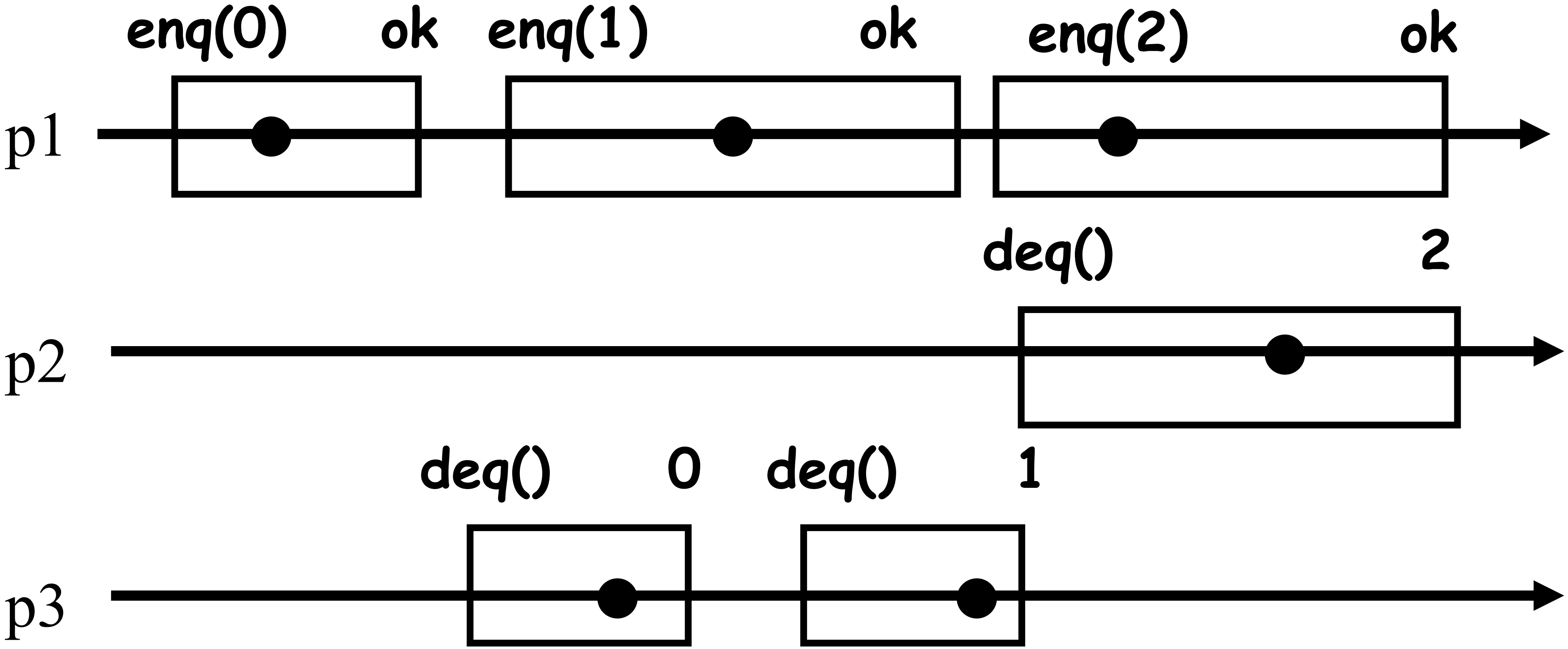
Linearization points

An implementation is *linearizable* if every history it produces is linearizable

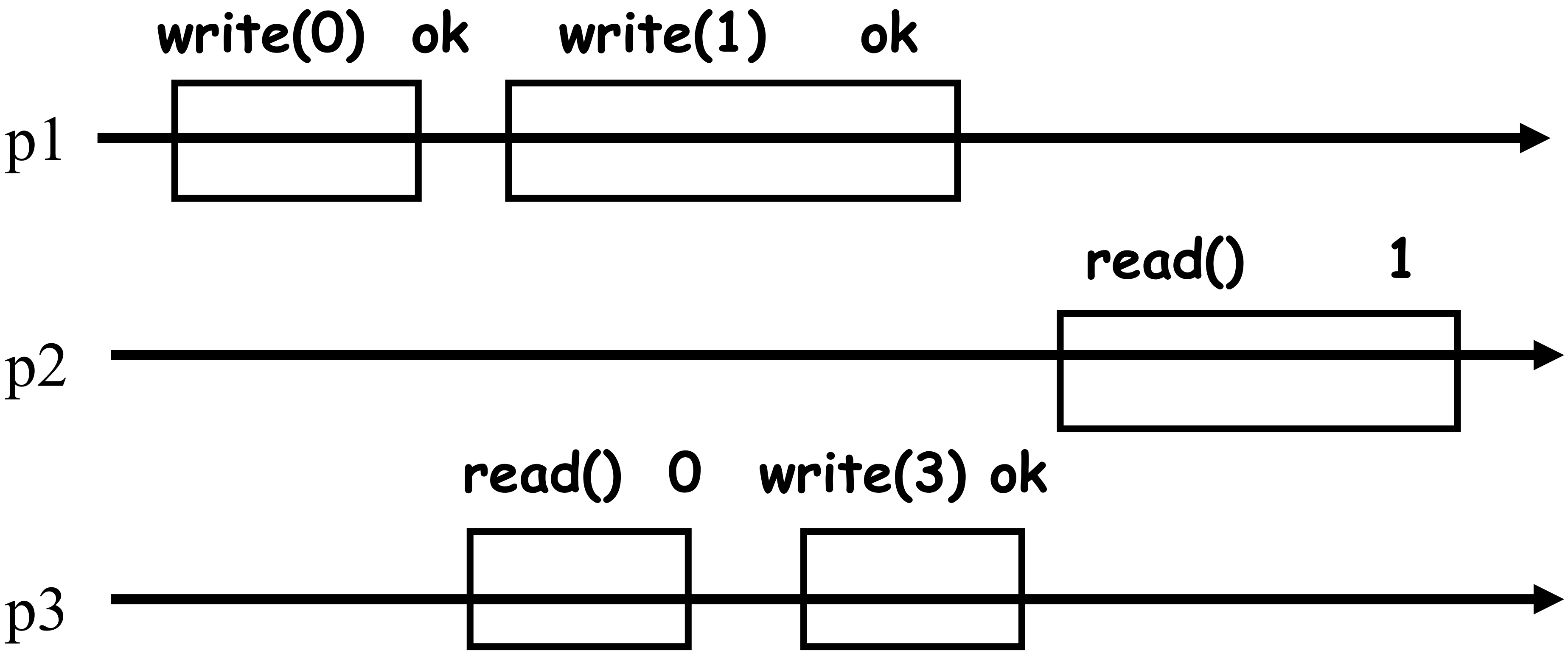
Informally, the complete operations (and some incomplete operations) in a history are seen as taking effect instantaneously at some time between their invocations and responses

Operations ordered by their linearization points constitute a legal (sequential) history

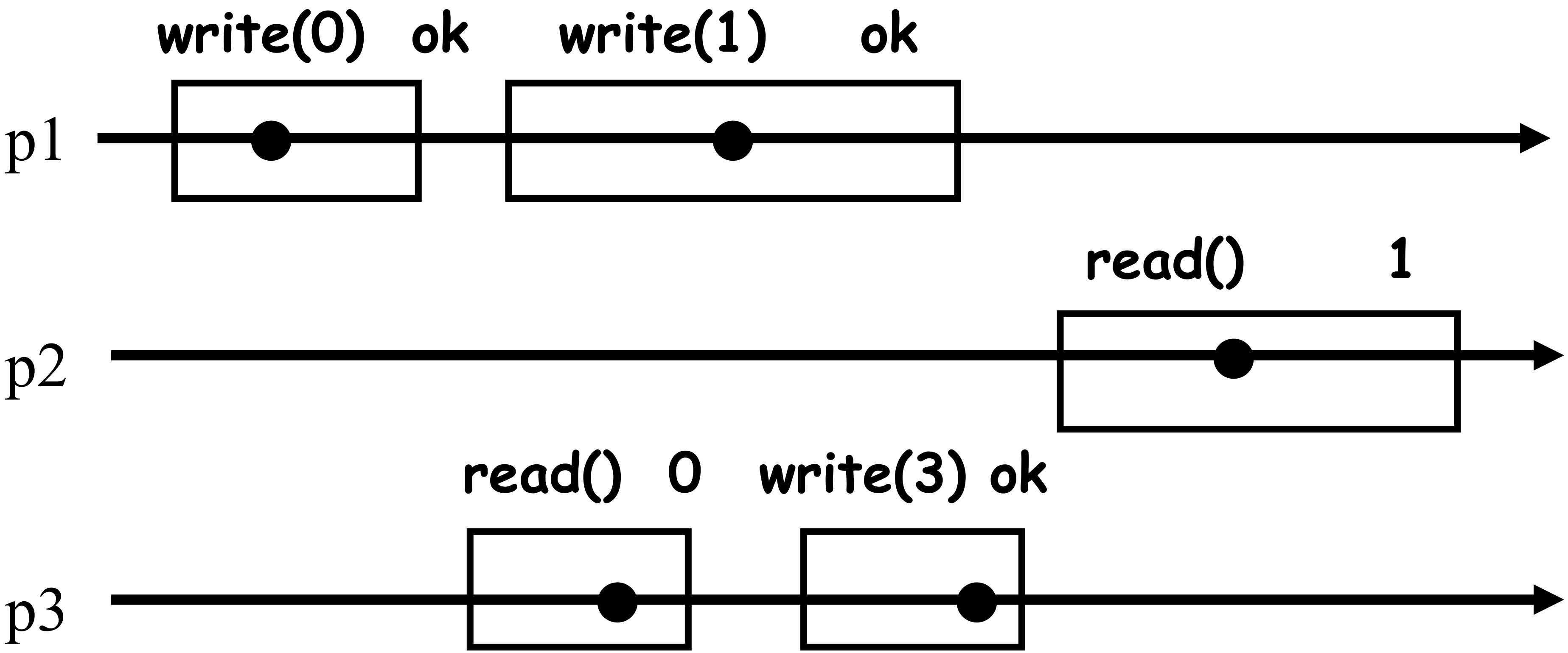
Linearizable?



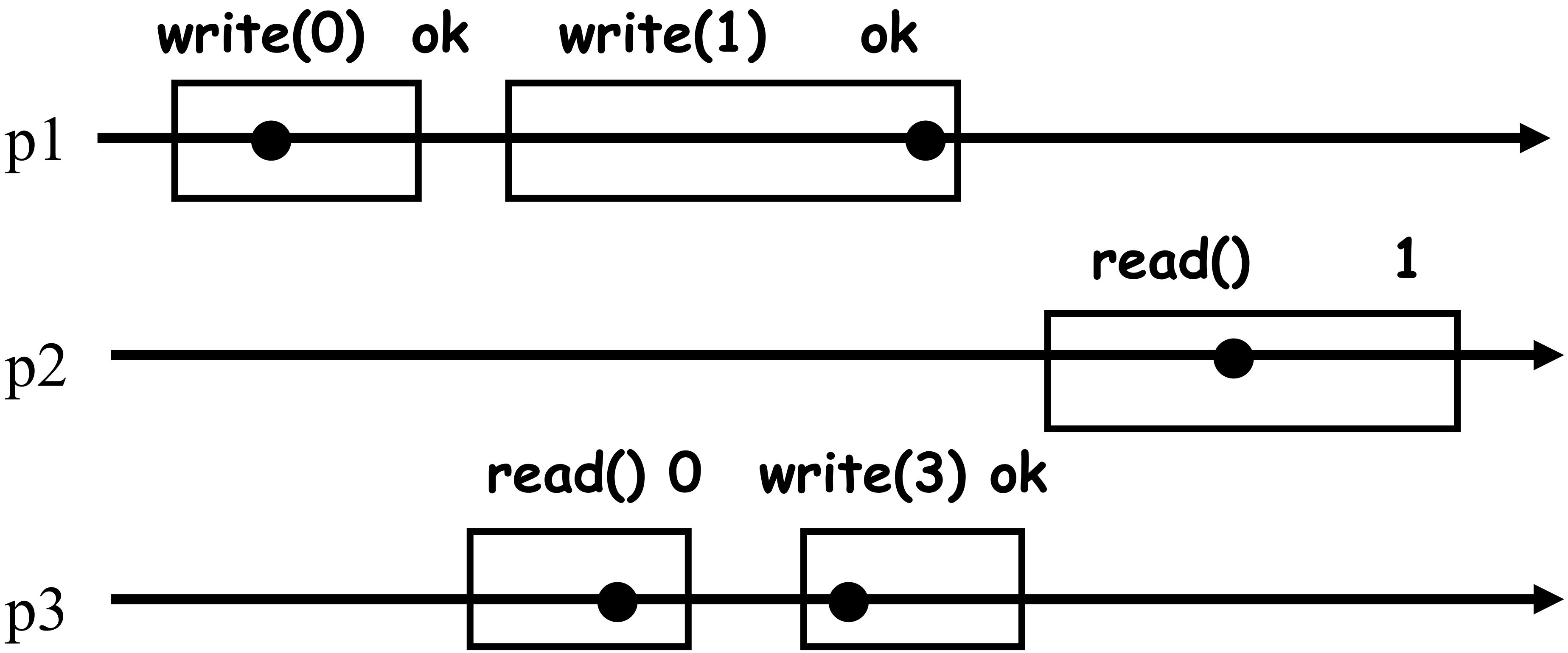
Linearizable?



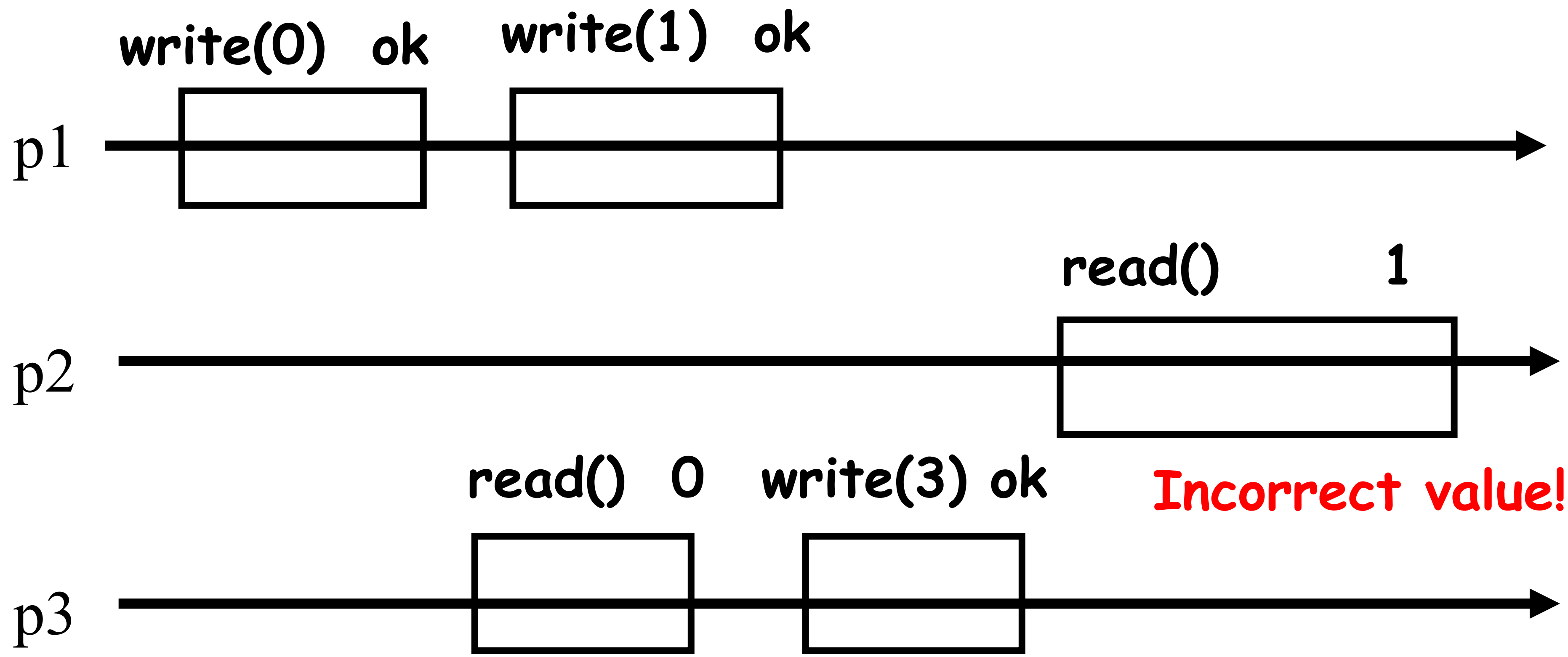
Linearizable?



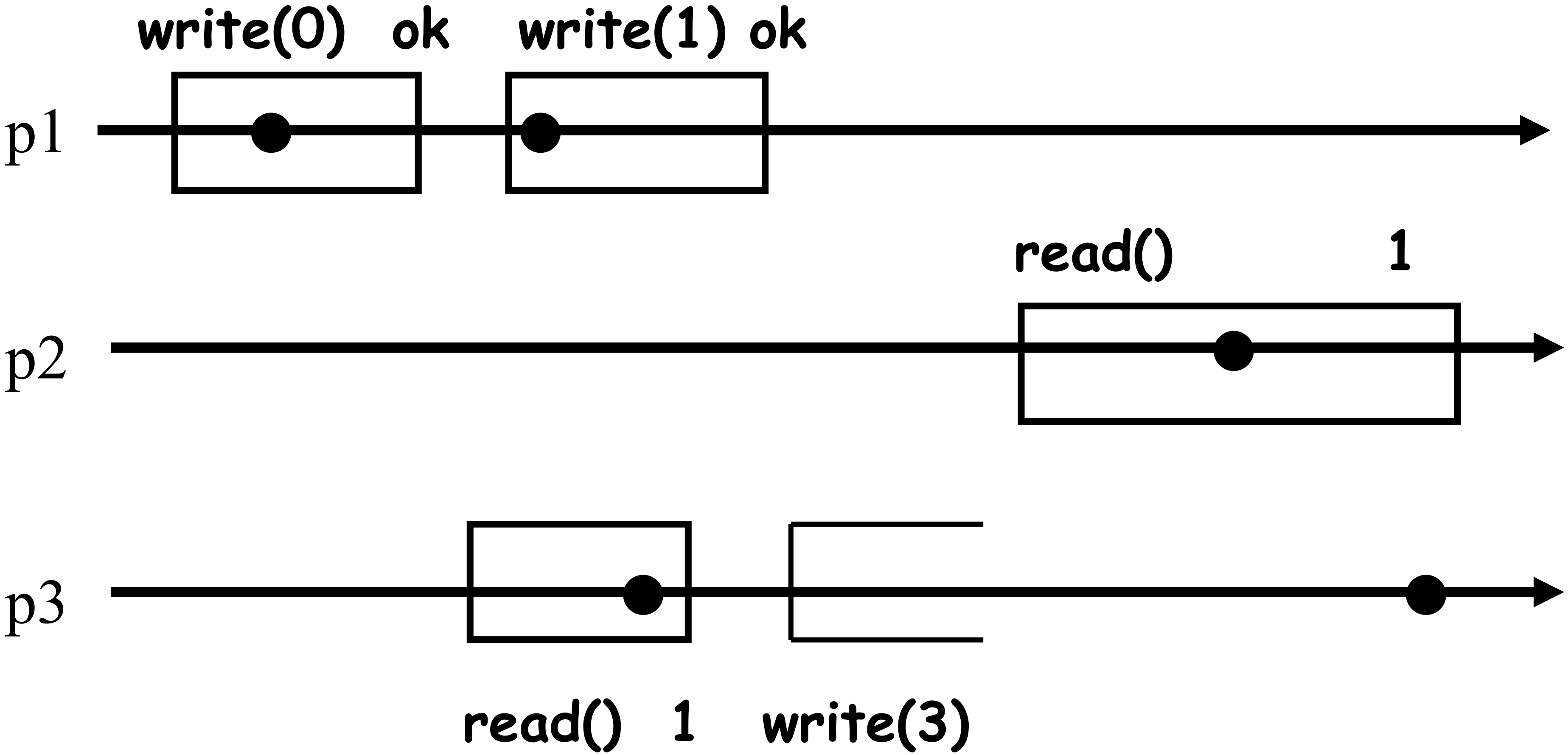
Linearizable?



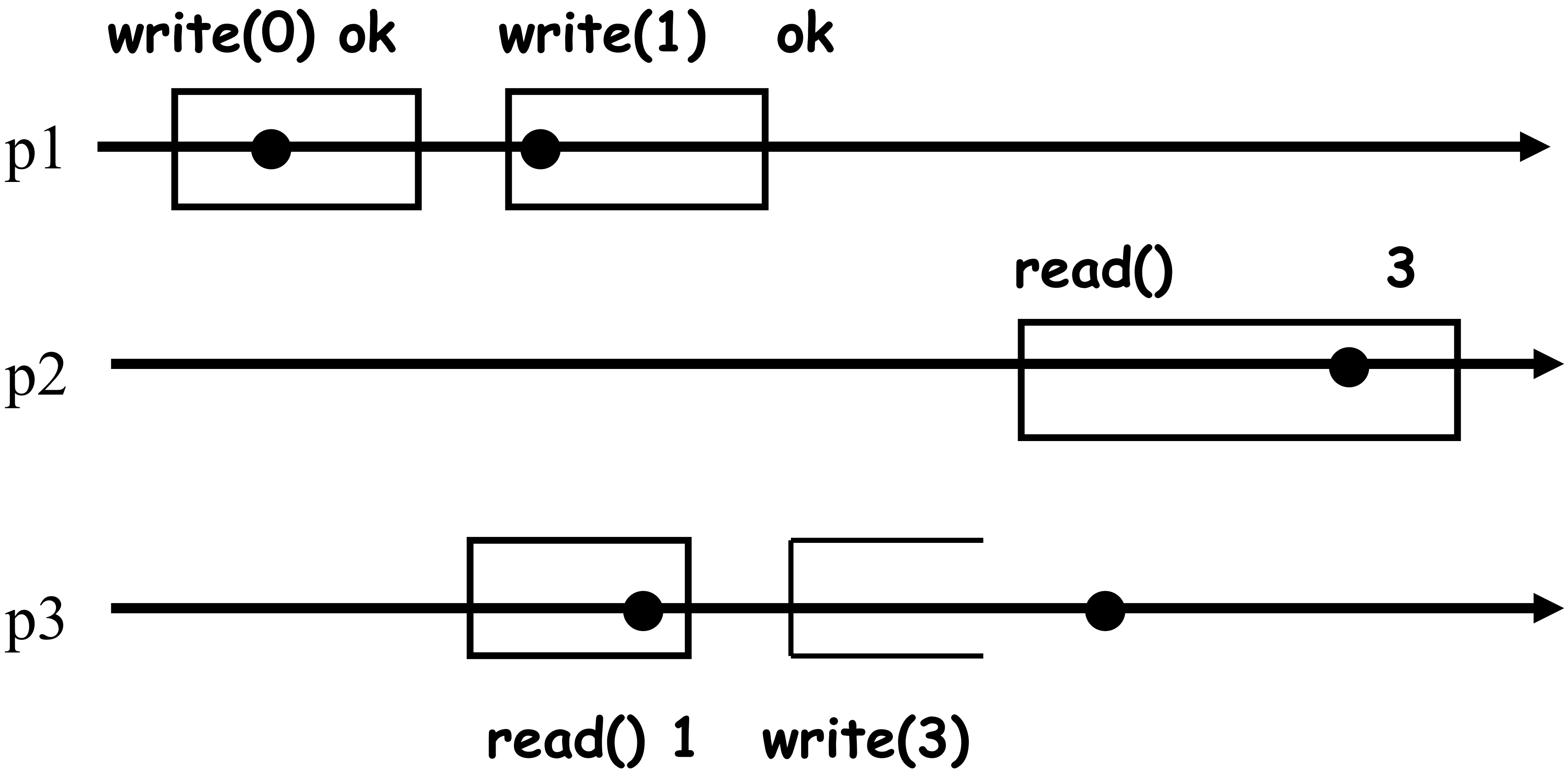
Linearizable?



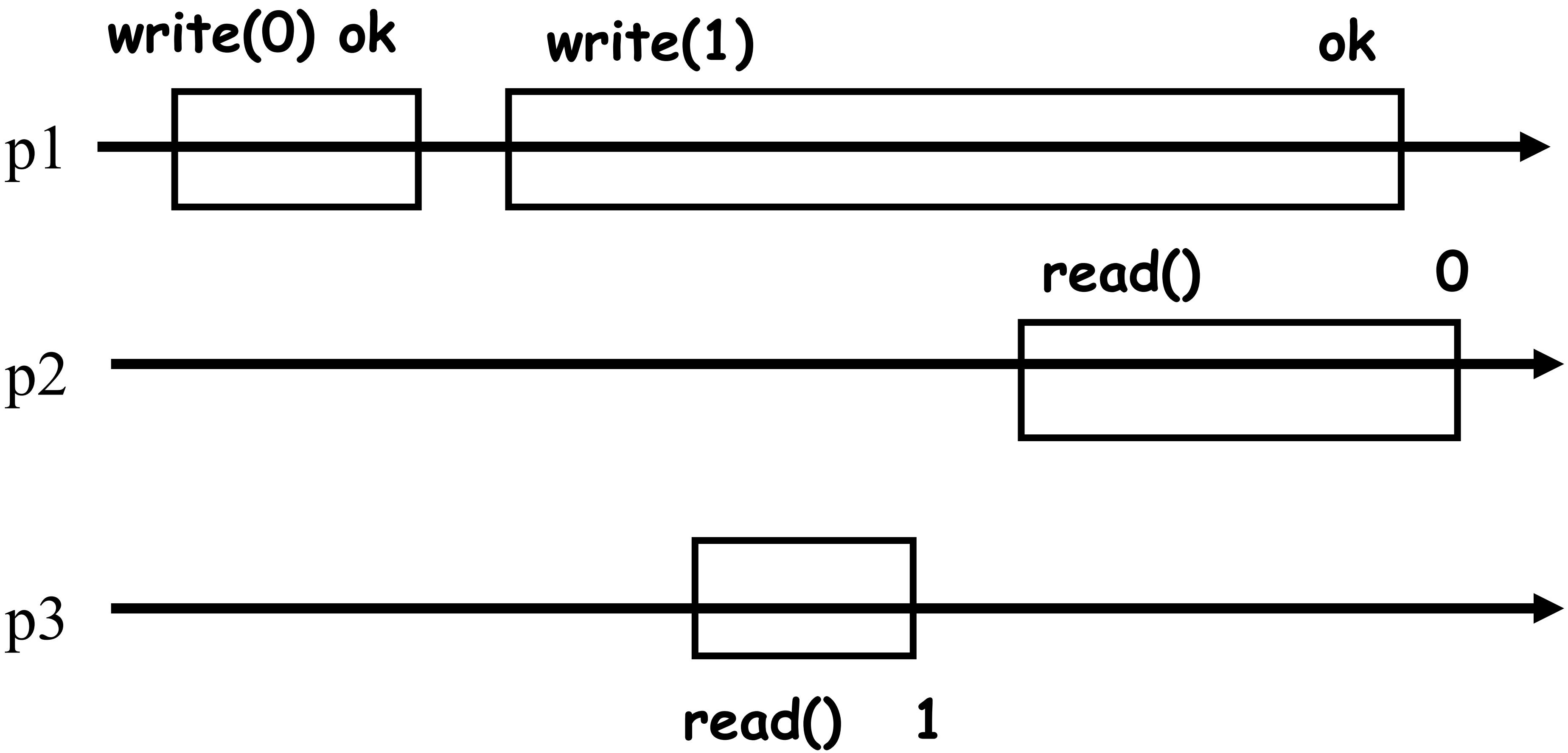
Linearizable?



Linearizable?



Linearizable?



Sequential consistency

A history H is *sequentially consistent* if there exists a sequential legal history S such that:

- S is equivalent to some completion of H
- S preserves the per-process order of H:

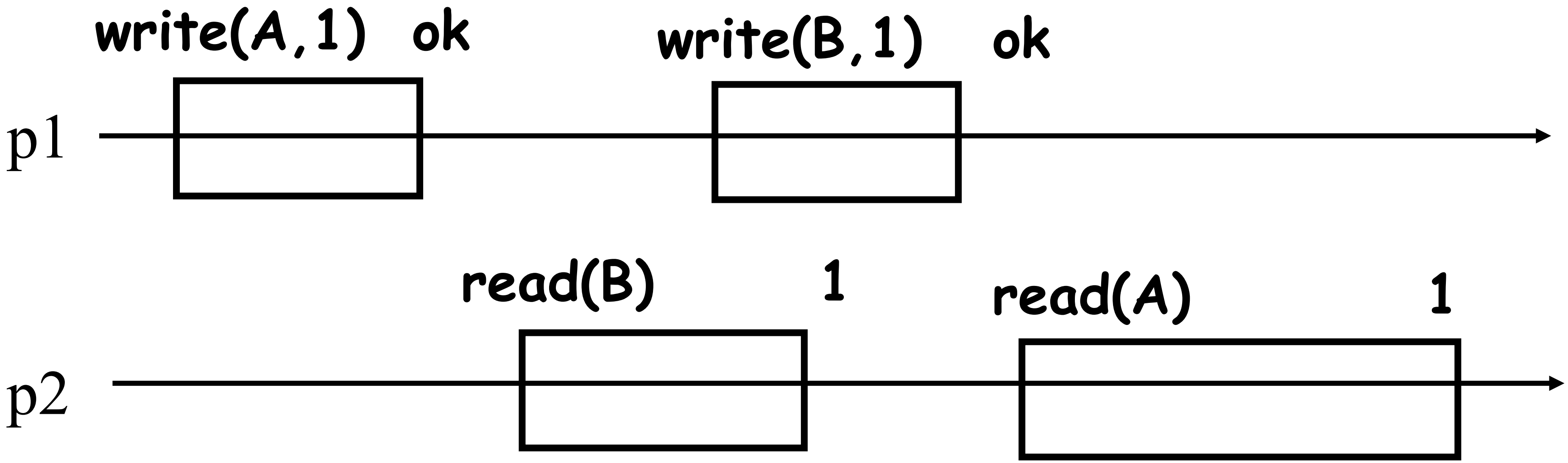
  pi executes op1 before op2 in H => pi executes op1 before op2 in S

Why (strong) linearizability and not (weak) sequential consistency?

Linearizability is compositional!

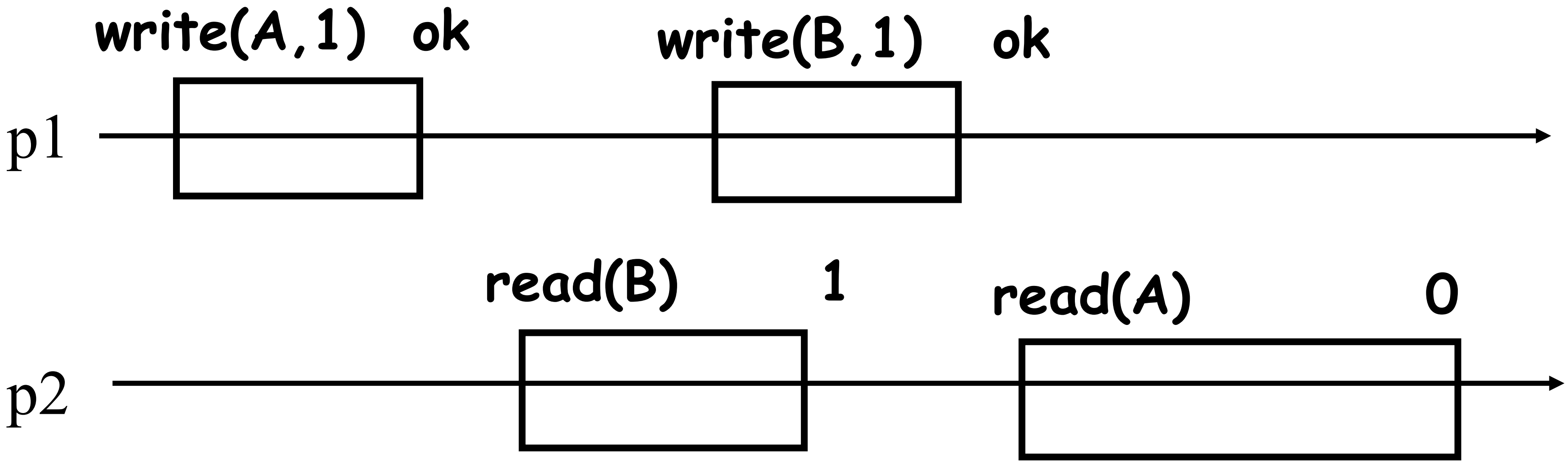
- Any history on two linearizable objects A and B is a history of a linearizable composition (A,B)

- A composition of two registers A and B is a two-field register (A,B)



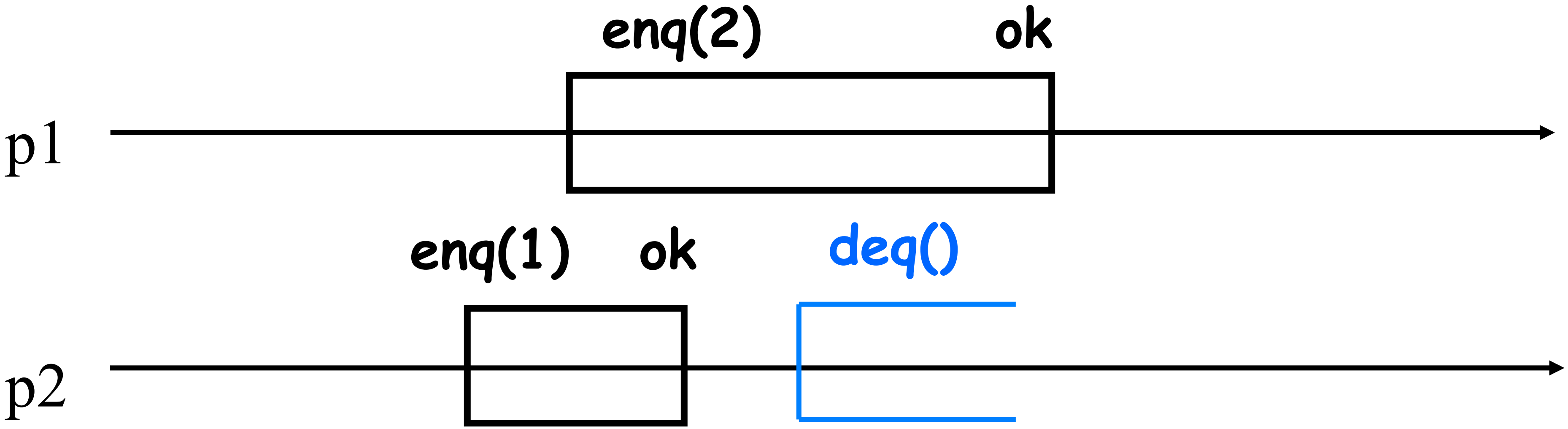
Sequential consistency is not!

- A composition of sequential consistent objects is not always sequentially consistent!



Linearizability is nonblocking

Every incomplete operation in a finite history can be independently completed



What safety property is blocking?

Linearizability as safety

- Prefix-closed: every prefix of a linearizable history is linearizable
- Limit-closed: the limit of a sequence of linearizable histories is linearizable

(see Chapter 2 of the lecture notes)

An implementation is linearizable if and only if all its finite histories are linearizable

Why not using one lock?

- Simple – automatic transformation of the sequential code
- Correct – linearizability for free
- In the best case, starvation-free: if the lock is "fair" and every process cooperates, every process makes progress
- Not robust to failures/asynchrony
  - ✓ Cache misses, page faults, swap outs
- Fine-grained locking?
  - ✓ Complicated/prone to deadlocks

Liveness properties

- *Deadlock-free:*
  - ✓ If every process is correct*, some process makes progress**
- *Starvation-free:*
  - ✓ If every process is correct, every process makes progress

- *Lock-free (*sometimes called *non-blocking):*
  - ✓ Some correct process makes progress
- *Wait-free:*
  - ✓ Every correct process makes progress
- *Obstruction-free:*
  - ✓ Every process makes progress if it executes in isolation (it is the only correct process)

* A process is correct if it takes infinitely many steps.

** Completes infinitely many operations.

Periodic table of liveness properties
[© 2013 Herlihy&Shavit]

	independent non-blocking	**dependent non-blocking**	**dependent blocking**
every process makes progress	wait-freedom	obstruction-freedom	starvation-freedom
some process makes progress	lock-freedom	?	deadlock-freedom

What are the relations (weaker/stronger) between these progress properties?

Quiz 1.3: liveness

- Show how the elements of the "periodic table of progress" are related to each other

  ✓Hint: for each pair of properties, A and B, check if any run of A is a run of B (A is stronger than B), or if there exists a run of A that is not in B (A is not stronger than B)

  ✓Can be shown by transitivity: if A is stronger than B and B is stronger than C, then A is stronger than C

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Liveness properties: relations

Property A is stronger than property B if every run satisfying A also satisfies B (A is a subset of B).

A is strictly stronger than B if, additionally, some run in B does not satisfy A, i.e., A is a proper subset of B.

For example:

- WF is stronger than SF

Every run that satisfies WF also satisfies SF: every correct process makes progress (regardless whether processes cooperate or not).

WF is actually strictly stronger than SF. Why?

- SF and OF are incomparable (none of them is stronger than the other)

There is a run that satisfies SF but not OF: the run in which p1 is the only correct process but does not make progress.

There is a run that satisfies OF but not SF: the run in which every process is correct but no process makes progress

Quiz 1.4: linearizability

- Show that the sequential queue implementation considered before is linearizable and wait-free *as is* if used by two processes: one performing only enqueue operations and one performing only dequeue operations

- Devise a simple queue implementation shared by any number of processes in which enqueue and dequeue operations can run concurrently (data races between these operations are allowed)