Deterministic Process Groups in dOS

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A Nondeterministic Program

```
global x=0
```

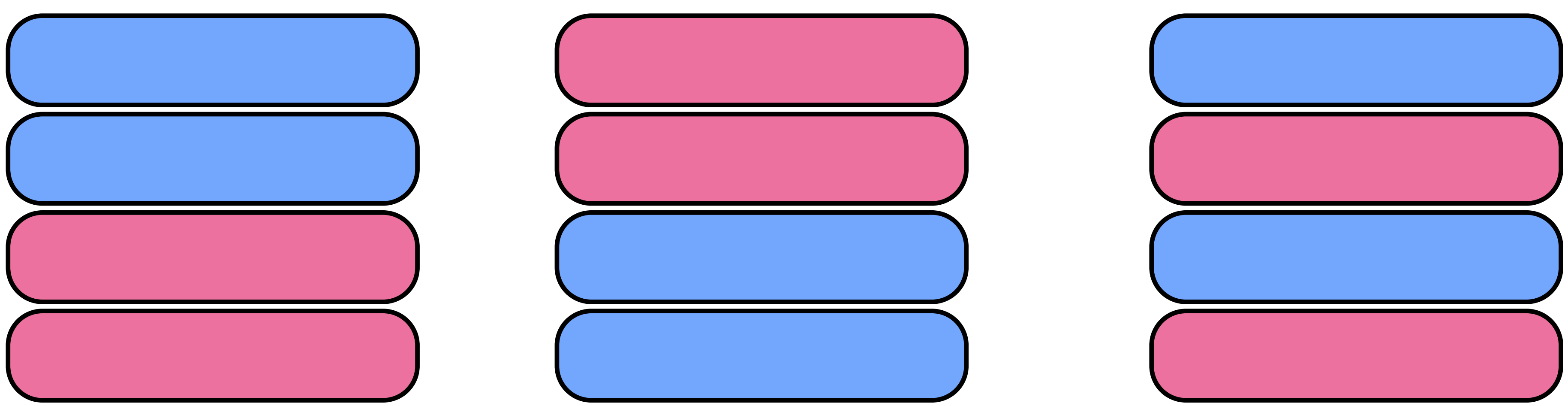
Thread 1

```
t := x
x := t + 1
```

Thread 2

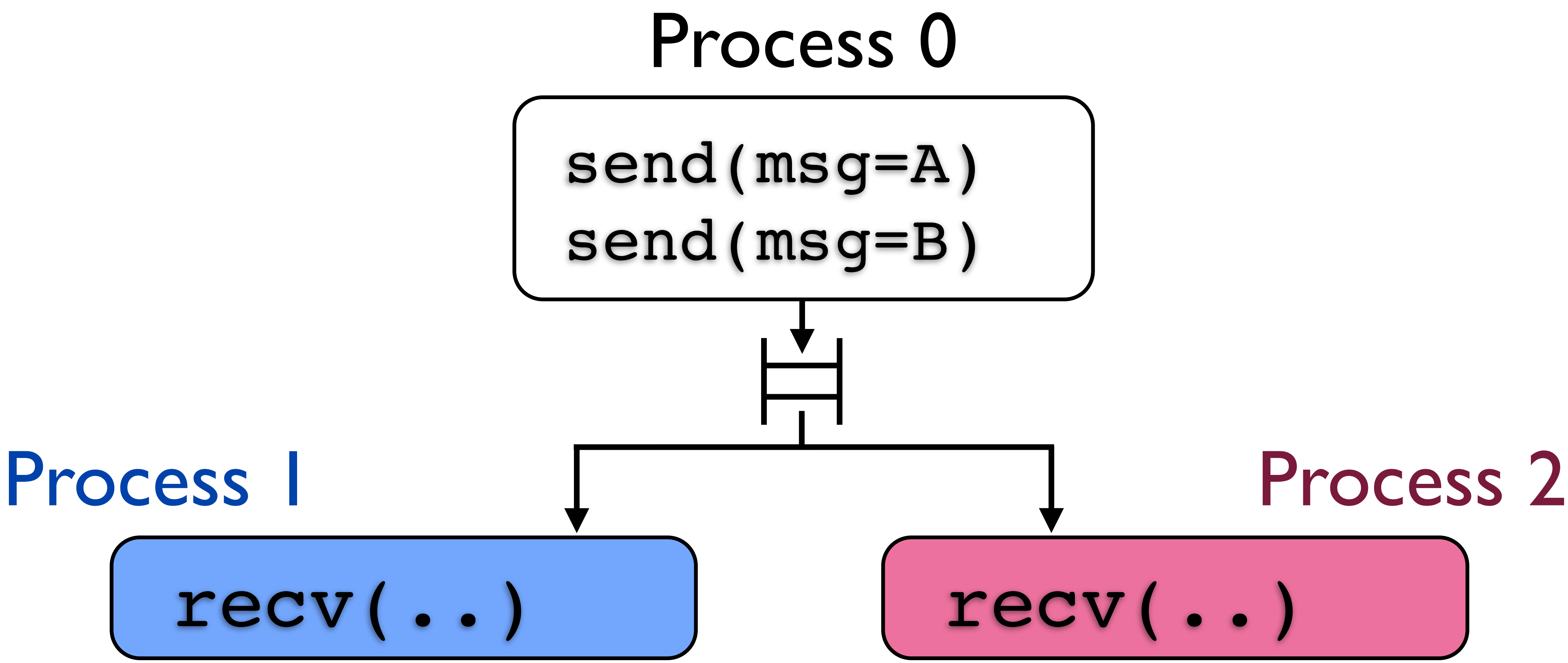
```
t := x
x := t + 1
```

What is x?

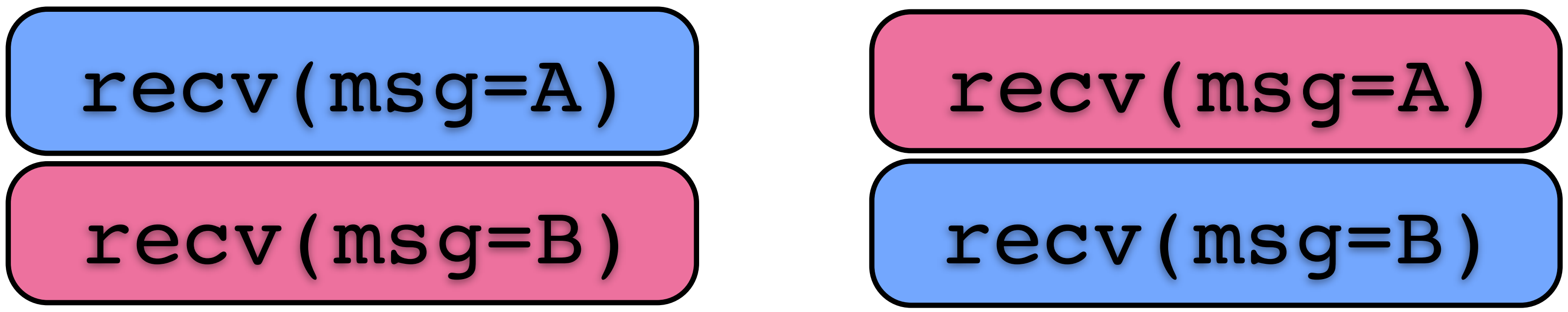


`x == 2` `x == 2` **`x == 1`**

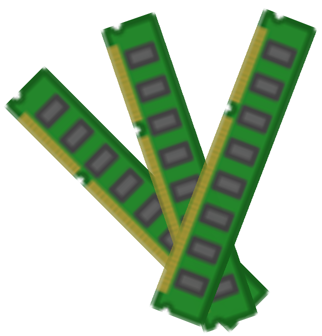
Nondeterministic IPC



Who gets msg A?



Nondeterminism In Real Systems

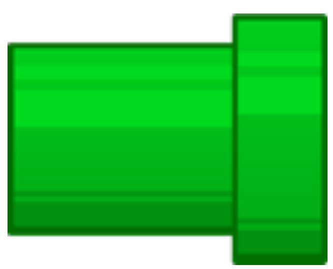


shared-memory

why nondeterministic:
multiprocessor hardware is unpredictable

disks

why nondeterministic:
drive latency is unpredictable

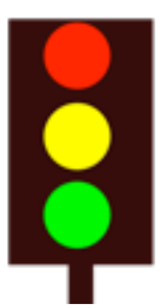


IPC (e.g. pipes)

why nondeterministic:
multiprocessor hardware is unpredictable

network

why nondeterministic:
packets arrive from external sources



posix signals

why nondeterministic:
unpredictable scheduling, also can be triggered by users

...

The Problem

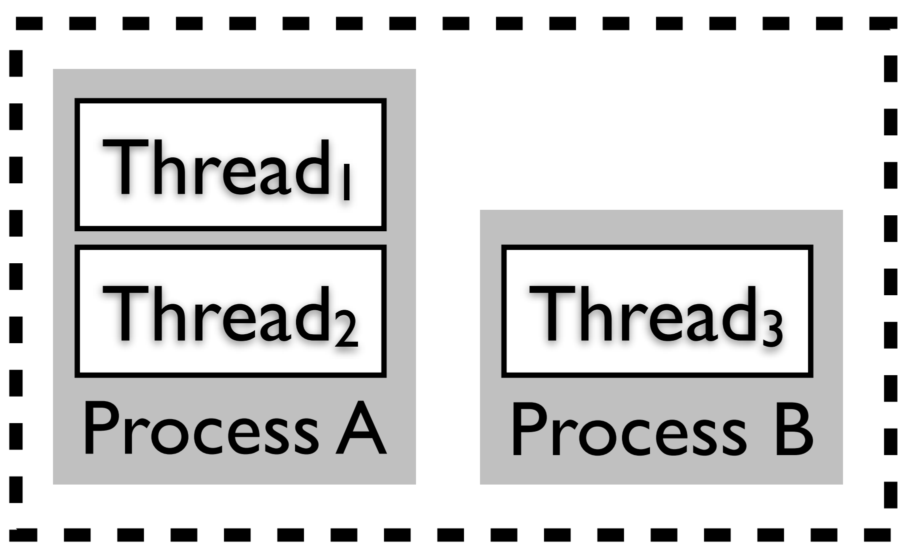
- Nondeterminism makes programs . . .
  - ➡ hard to test
    - same input, different outputs
  - ➡ hard to debug
    - leads to heisenbugs
  - ➡ hard to replicate for fault-tolerance
    - replicas get out of sync
- Multiprocessors make this problem much worse!

Our Solution

- OS support for deterministic execution
  - ➡ of arbitrary programs
  - ➡ attack *all* sources of nondeterminism (not just shared-memory)
  - ➡ even on multiprocessors

New OS abstraction:

Deterministic Process Group (DPG)



deterministic box

Key Questions

1. **What can be made deterministic?**

2. **What can we do about the remaining sources of nondeterminism?**

Key Questions

1 **What can be made deterministic?**

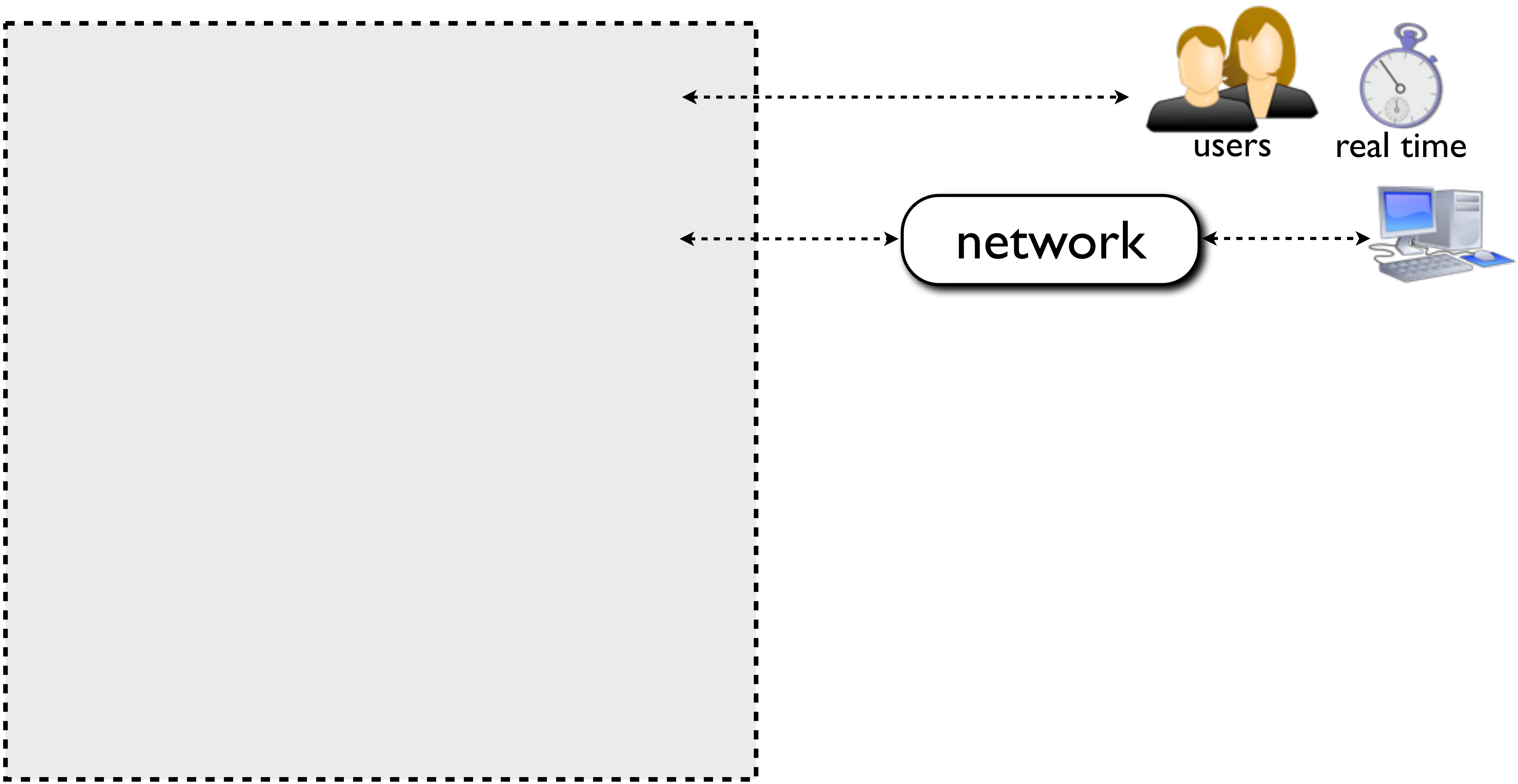
- distinguish *internal* vs. *external* nondeterminism

2 **What can we do about the remaining sources of nondeterminism?**

Internal nondeterminism	External nondeterminism
• arises from scheduling artifacts (hw timing, etc)	• arises from interactions with the external world (networks, users, etc)
<u>NOT</u> Fundamental can be eliminated!	**Fundamental** can <u>not</u> be eliminated

Internal Determinism

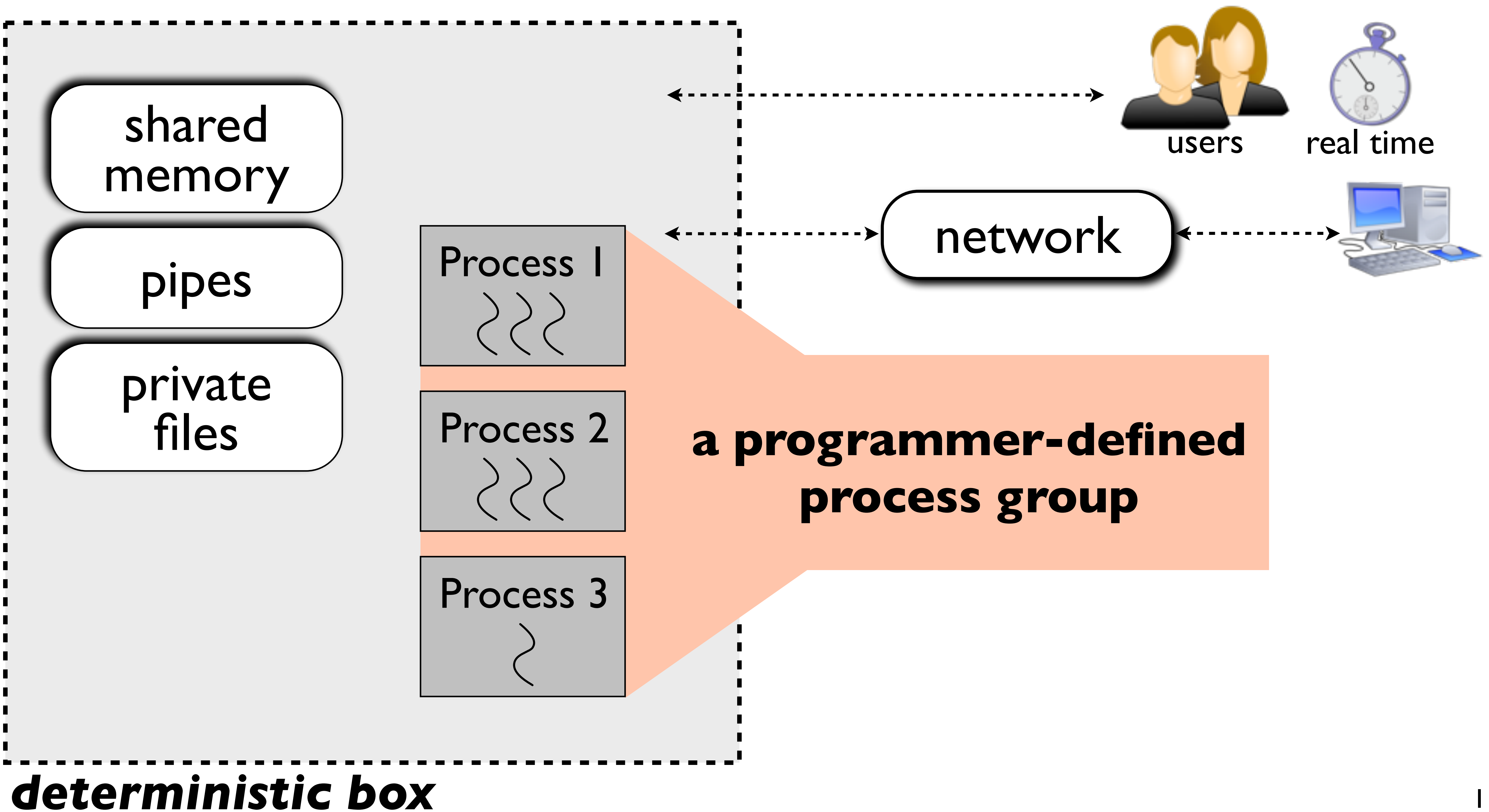
External Nondeterminism



deterministic box

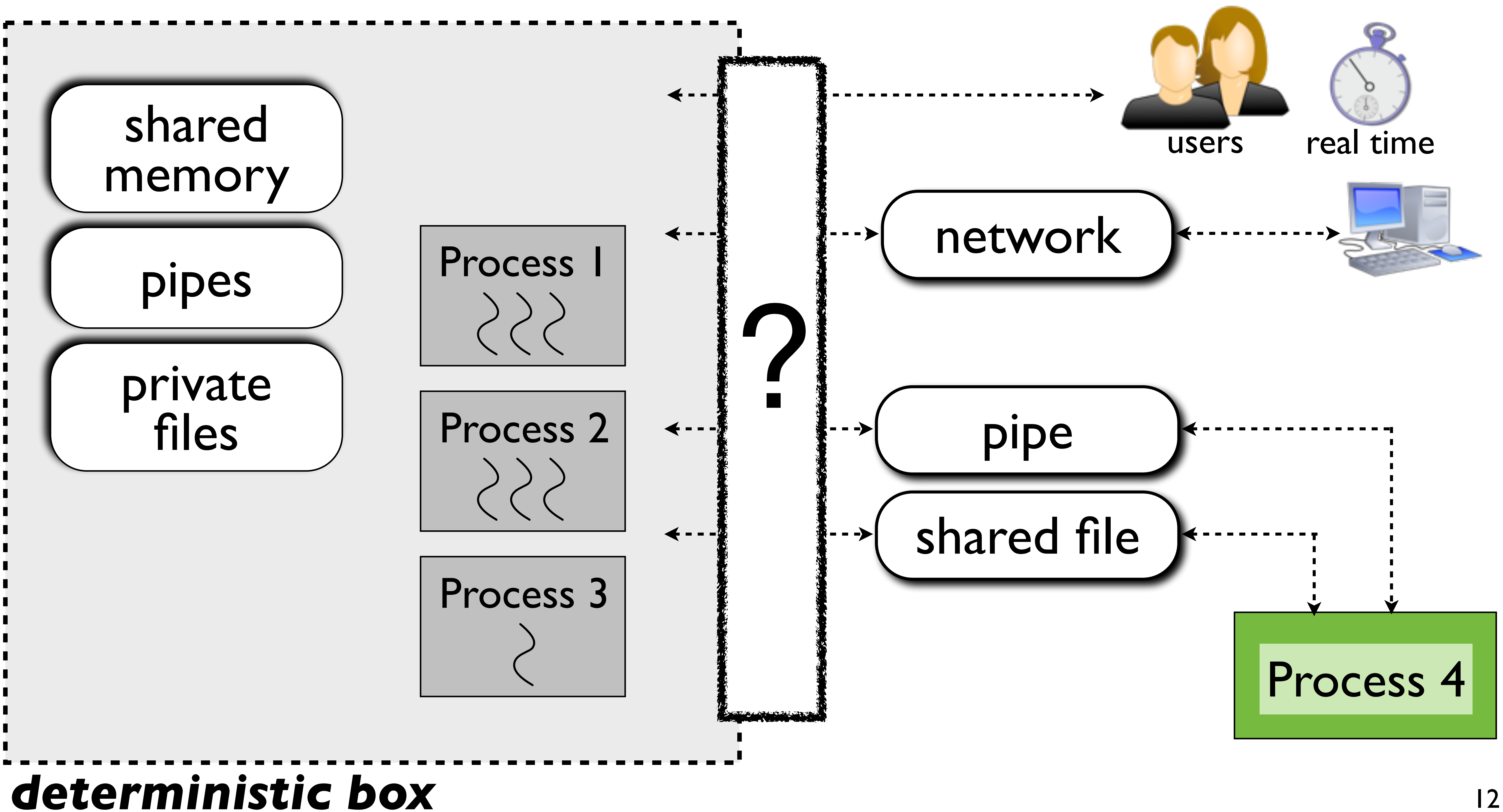
Internal Determinism

External Nondeterminism

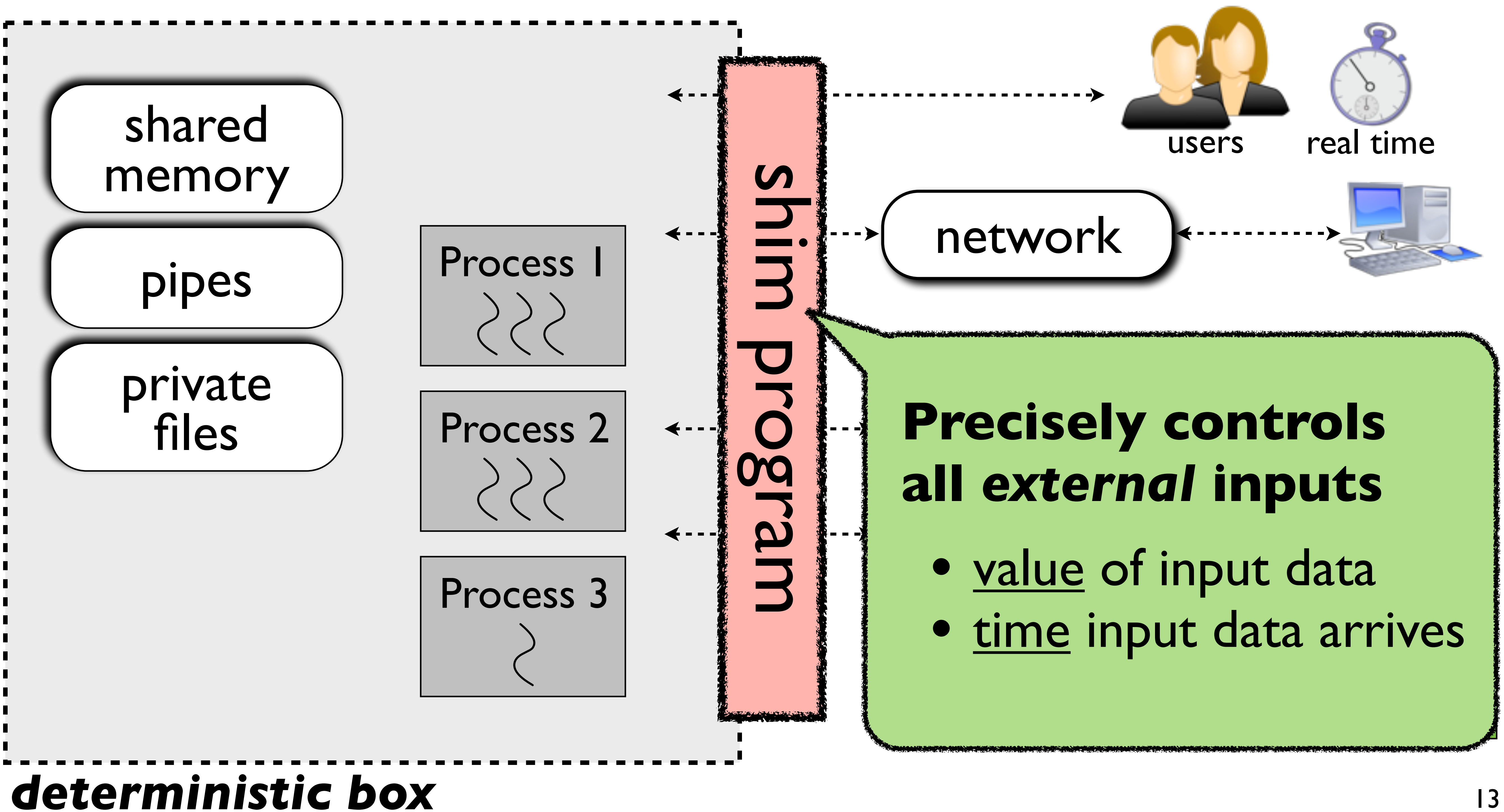


Internal Determinism

External Nondeterminism



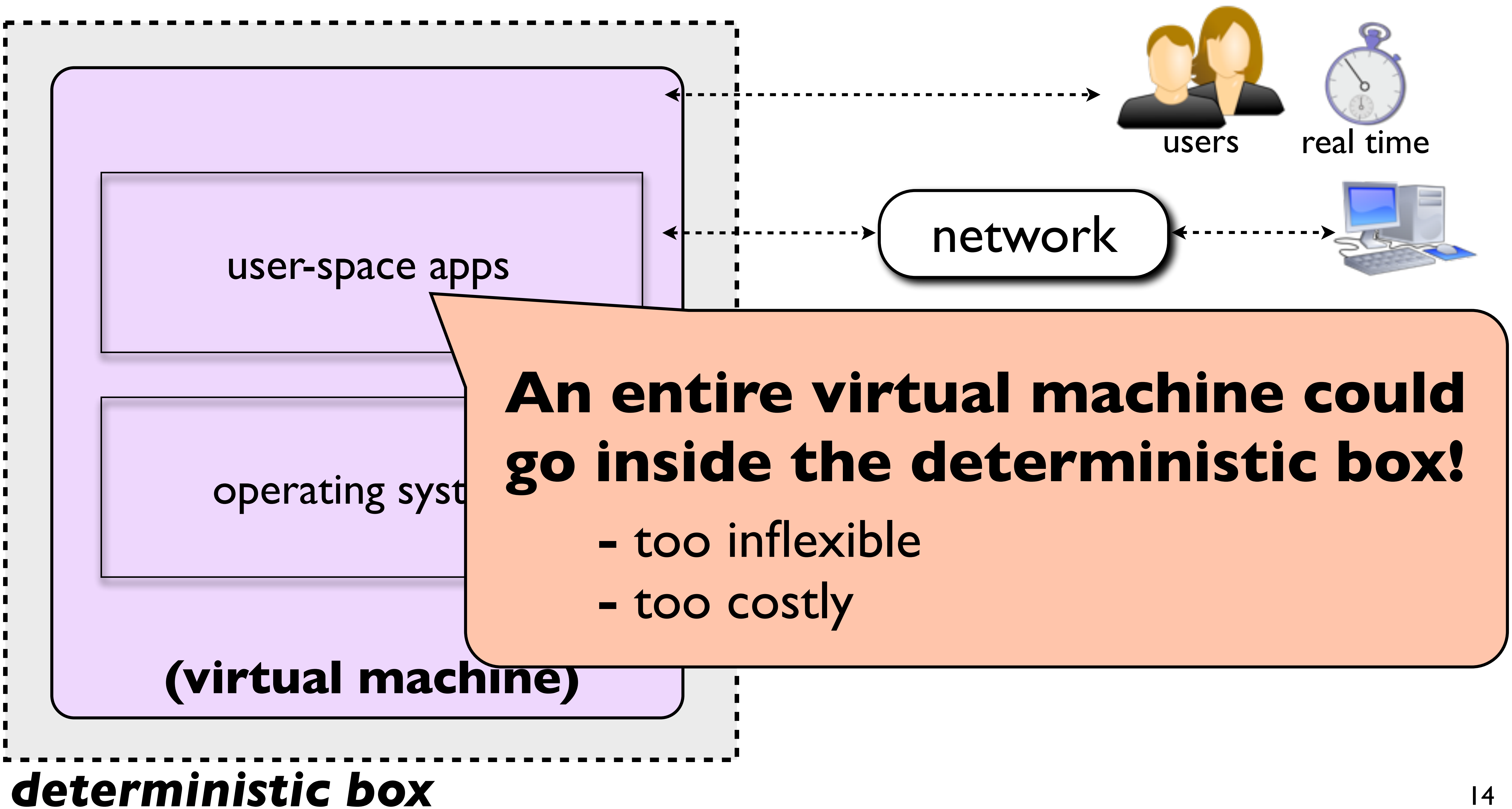
Internal Determinism | External Nondeterminism



Precisely controls all *external* inputs

- value of input data
- time input data arrives

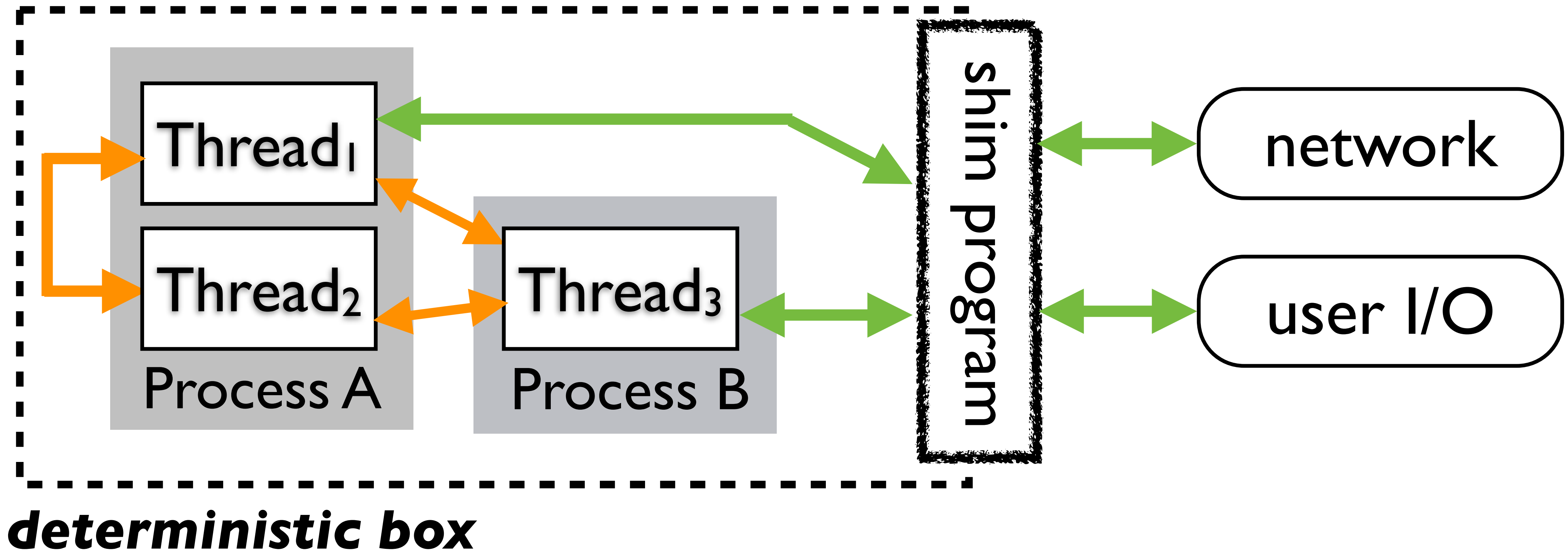
Internal Determinism | External Nondeterminism



An entire virtual machine could go inside the deterministic box!

- too inflexible
- too costly

Deterministic Process Groups



OS ensures:

- *internal* nondeterminism is eliminated
  (for shared-memory, pipes, signals, local files, ...)
- *external* nondeterminism funneled through *shim program*

Shim Program:

- user-space program that precisely *controls* all external nondeterministic inputs

Contributions

Conceptual:

- identify *internal* vs. *external* nondeterminism
- key: *internal* nondeterminism can be eliminated!

Abstraction:

- Deterministic Process Groups (DPGs)
- control *external* nondeterminism via a <u>shim program</u>

Implementation:

- dOS, a modified version of Linux
- supports arbitrary, unmodified binaries

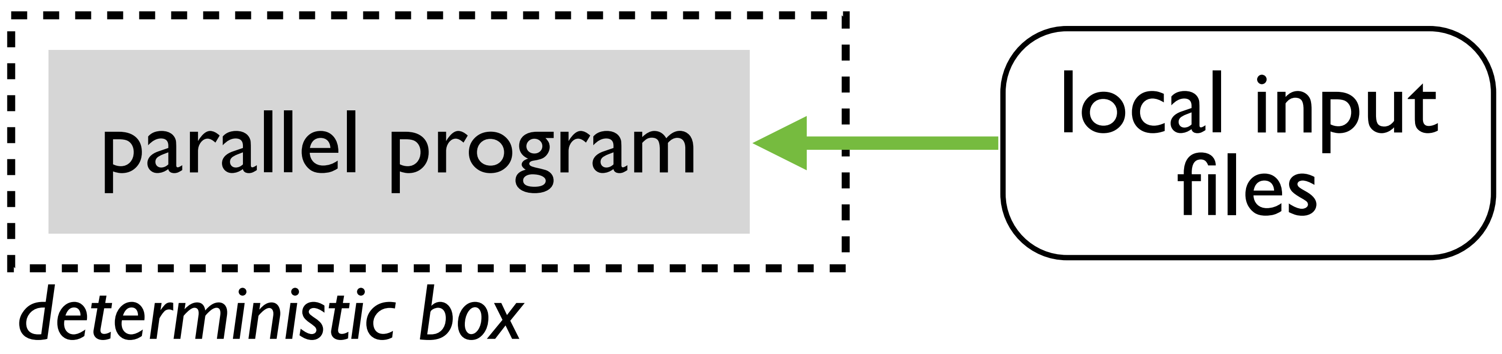
Applications:

- deterministic parallel execution
- record/replay
- replicated execution

Outline

- Example Uses
  - ➡ a parallel computation
  - ➡ a webserver
- Deterministic Process Groups
  - ➡ system interface
  - ➡ conceptual model
- dOS: our Linux-Based Implementation
- Evaluation

A Parallel Computation

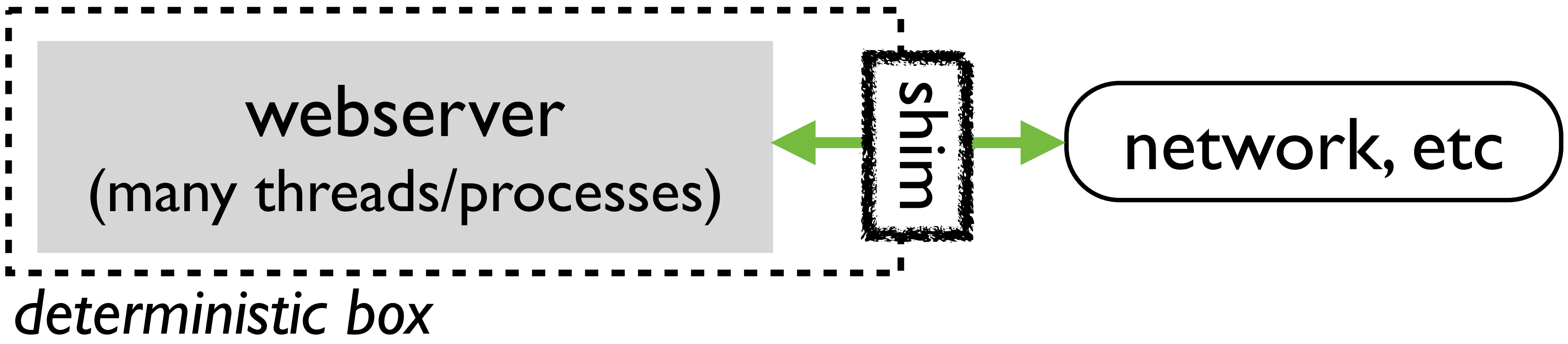


This program executes deterministically!

- even on a multiprocessor
- supports parallel programs written in *any* language

- no heisenbugs!
- test *input files*, not interleavings

A Webserver



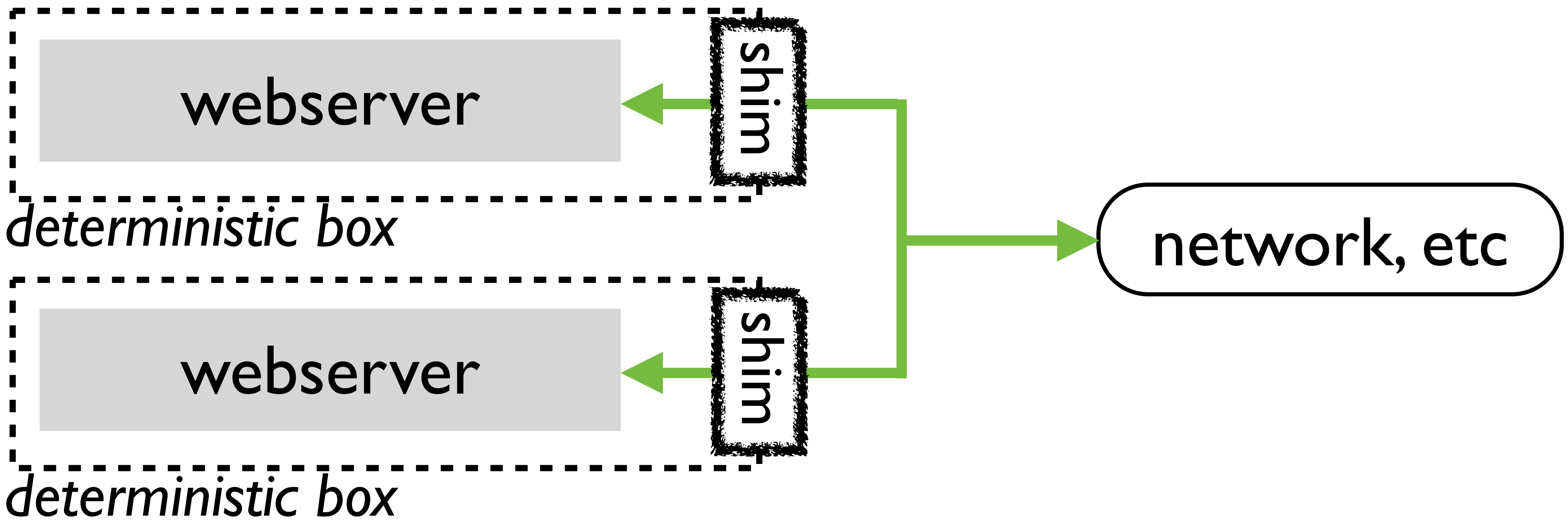
Deterministic Record/Replay

- implement in shim program
- requires no webserver modification

Advantages

- significantly less to log (*internal* nondeterminism is eliminated)
- log sizes 1,000x smaller!

A Webserver



Fault-tolerant Replication

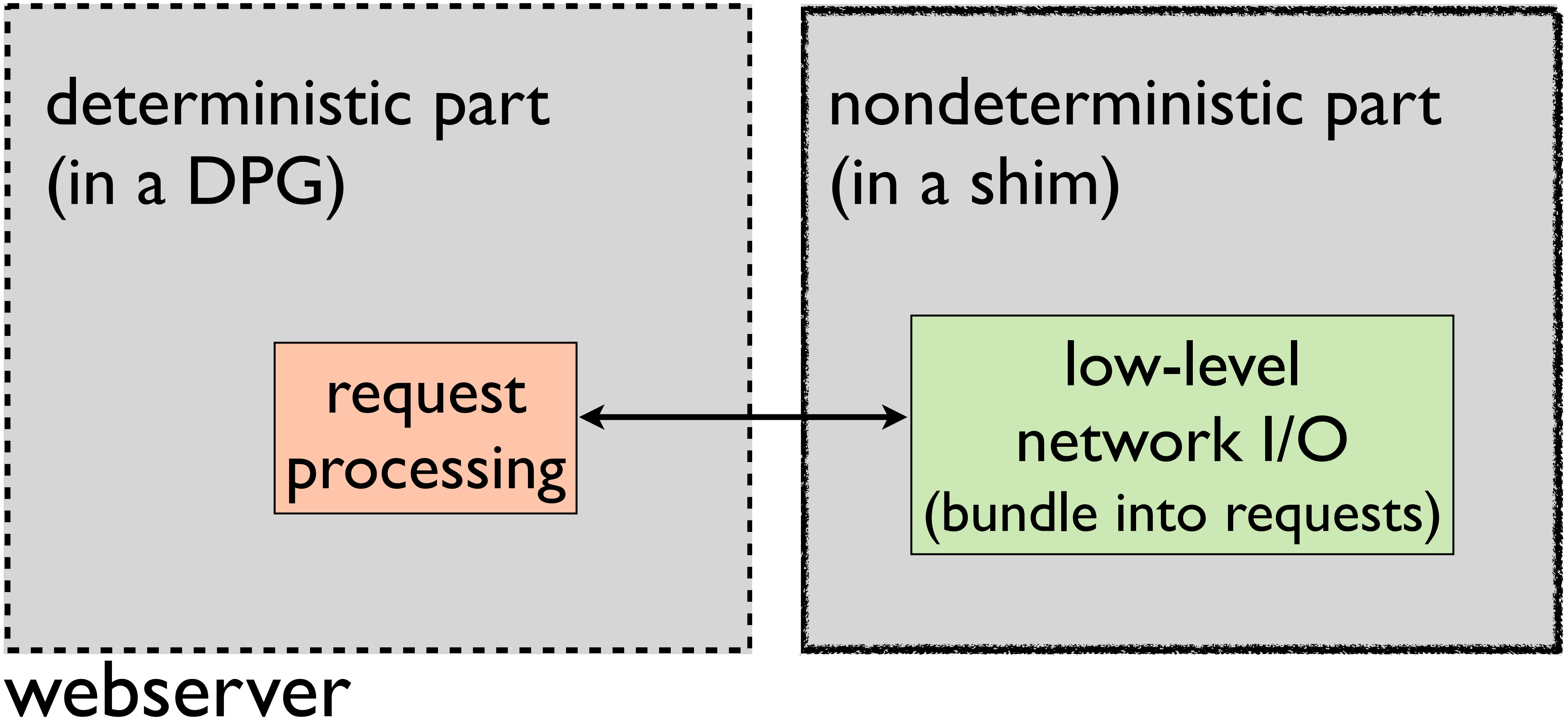
- implement replication protocol in <u>shim programs</u> (paxos, virtual synchrony, etc)

Advantage

- easy to replicate multithreaded servers (*internal* nondeterminism is eliminated)

A Webserver

Using DPGs to construct applications



- behaves deterministically w.r.t. *requests* rather than *packets*

Shim program defines the nondeterministic interface

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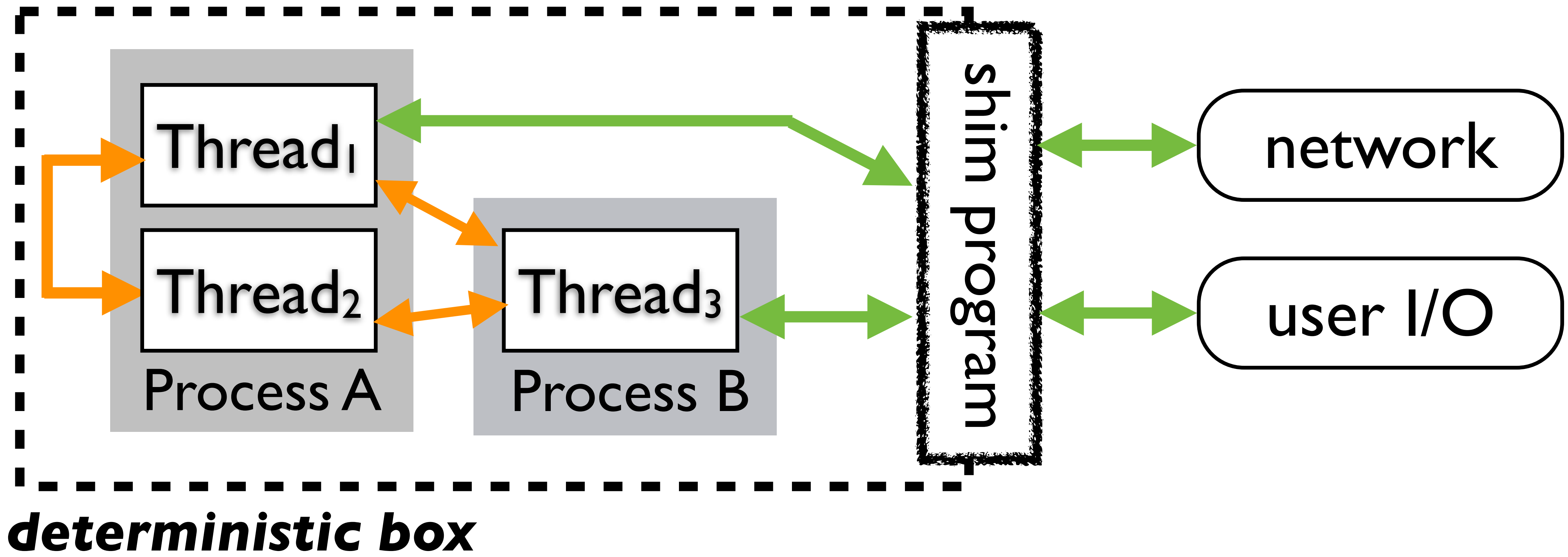
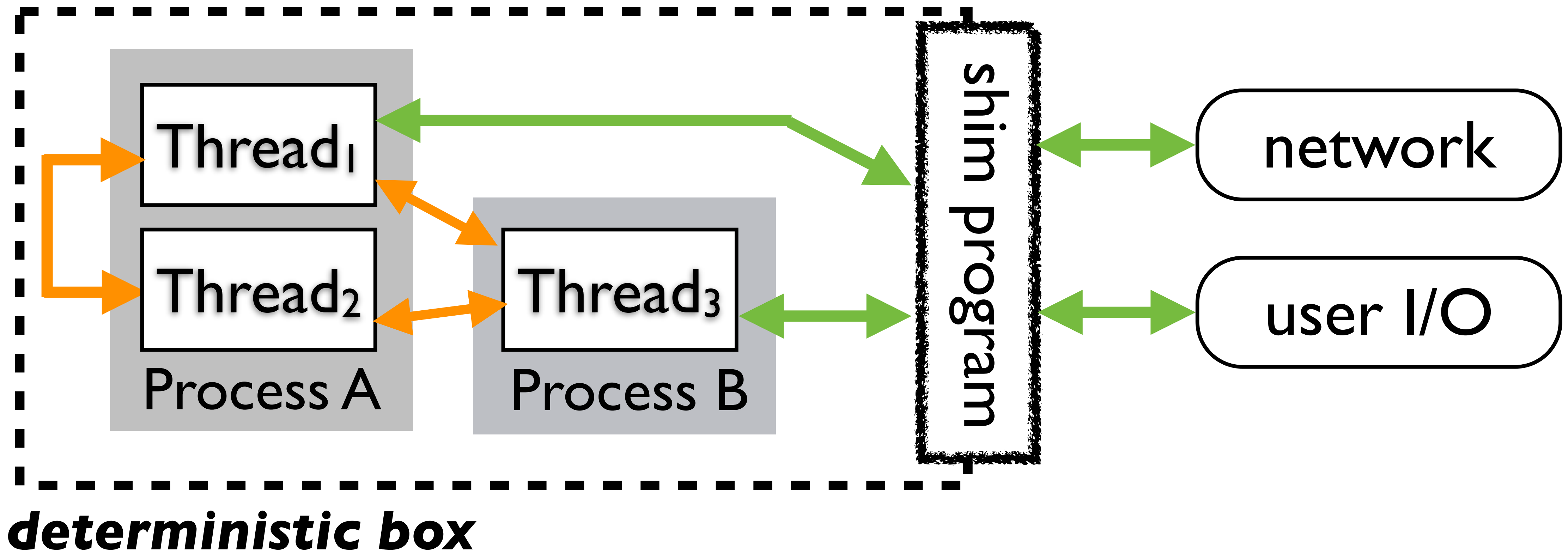
Deterministic Process Groups



System Interface

- New system call creates a new DPG: `sys_makedet()`
  - *DPG expands to include all child processes*
- Just like ordinary linux processes
  - *same system calls, signals, and hw instruction set*
  - *can be multithreaded*

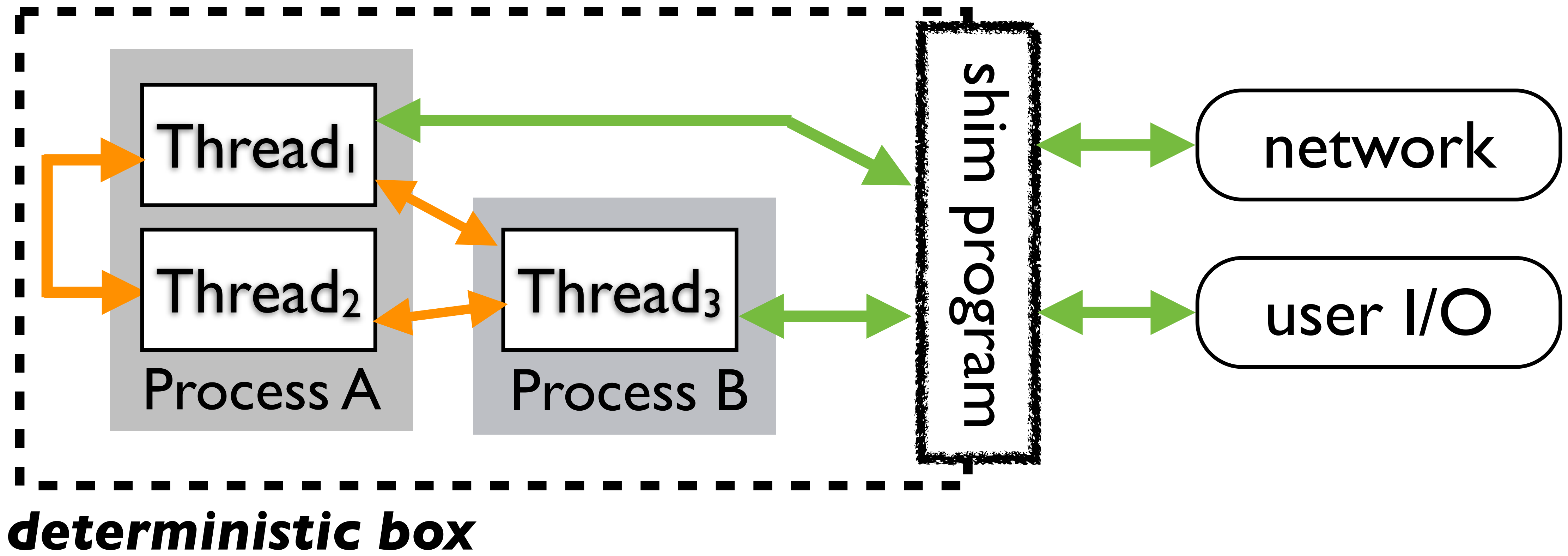
Deterministic Process Groups



Two questions:

- What are the semantics of *internal* determinism?
- How do shim programs work?

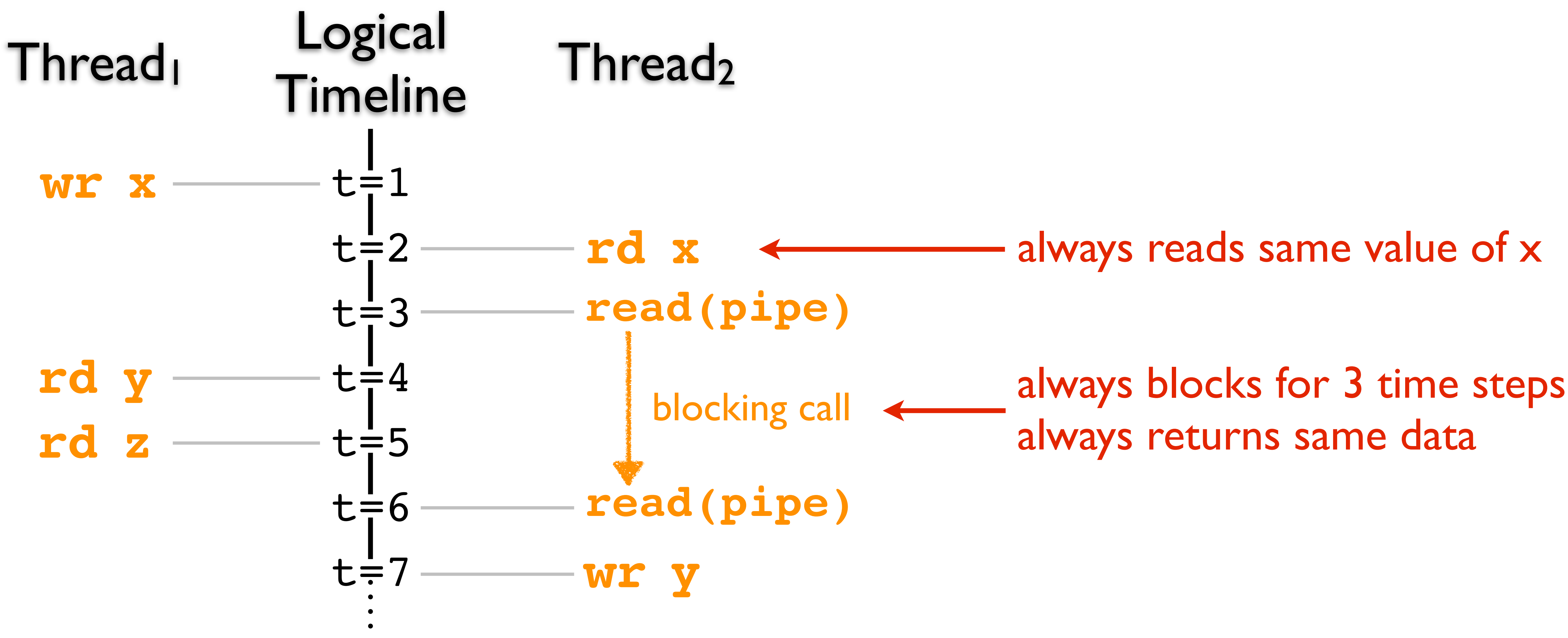
Deterministic Process Groups



Internal Determinism

- OS guarantees internal communication is scheduled *deterministically*
- Conceptually: executes as if serialized onto a *logical timeline*
  - *implementation is parallel*

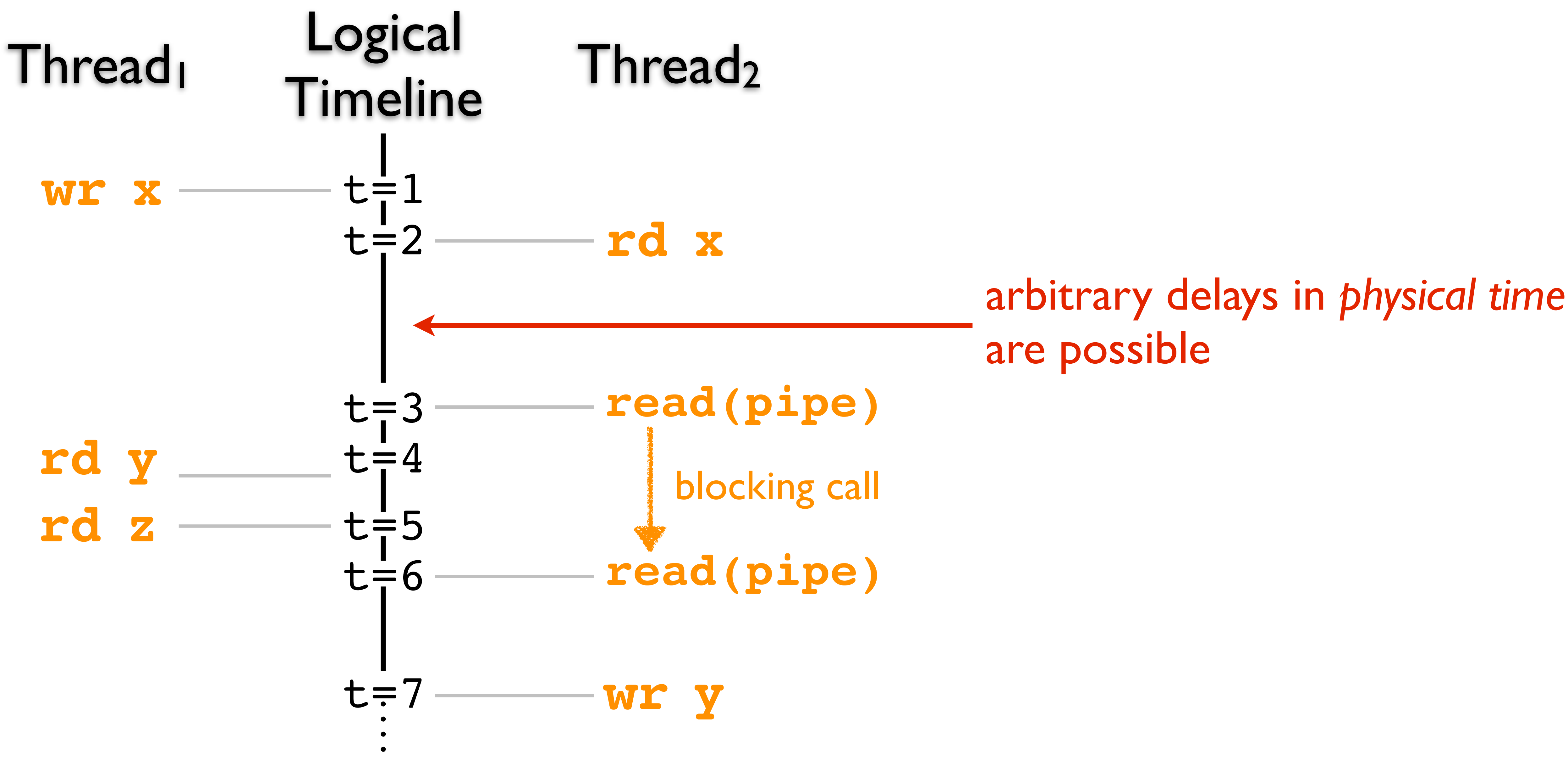
Internal Determinism



Each DPG has a *logical timeline*

- instructions execute as if serialized onto the logical timeline
- internal events are deterministic

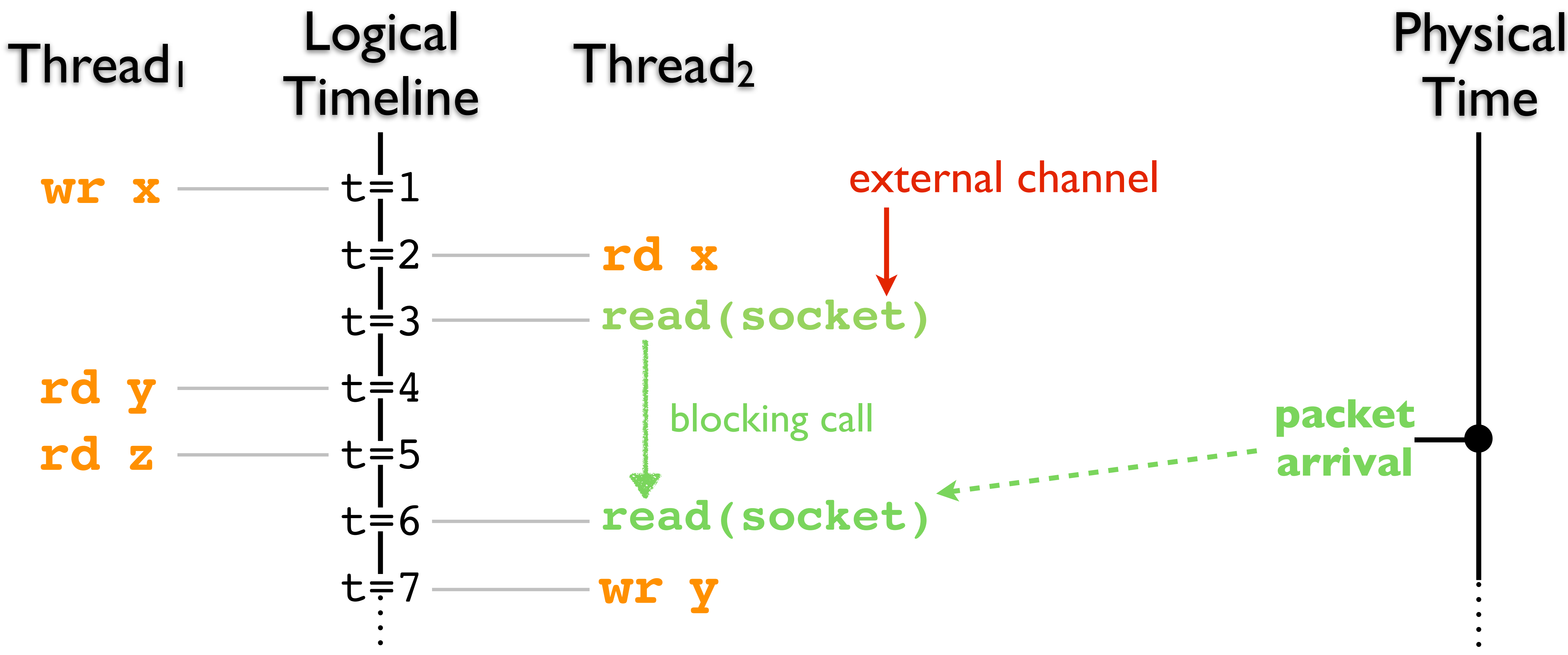
Internal Determinism



***Physical time* is <u>not</u> deterministic**

- deterministic *results*, but not deterministic *performance*

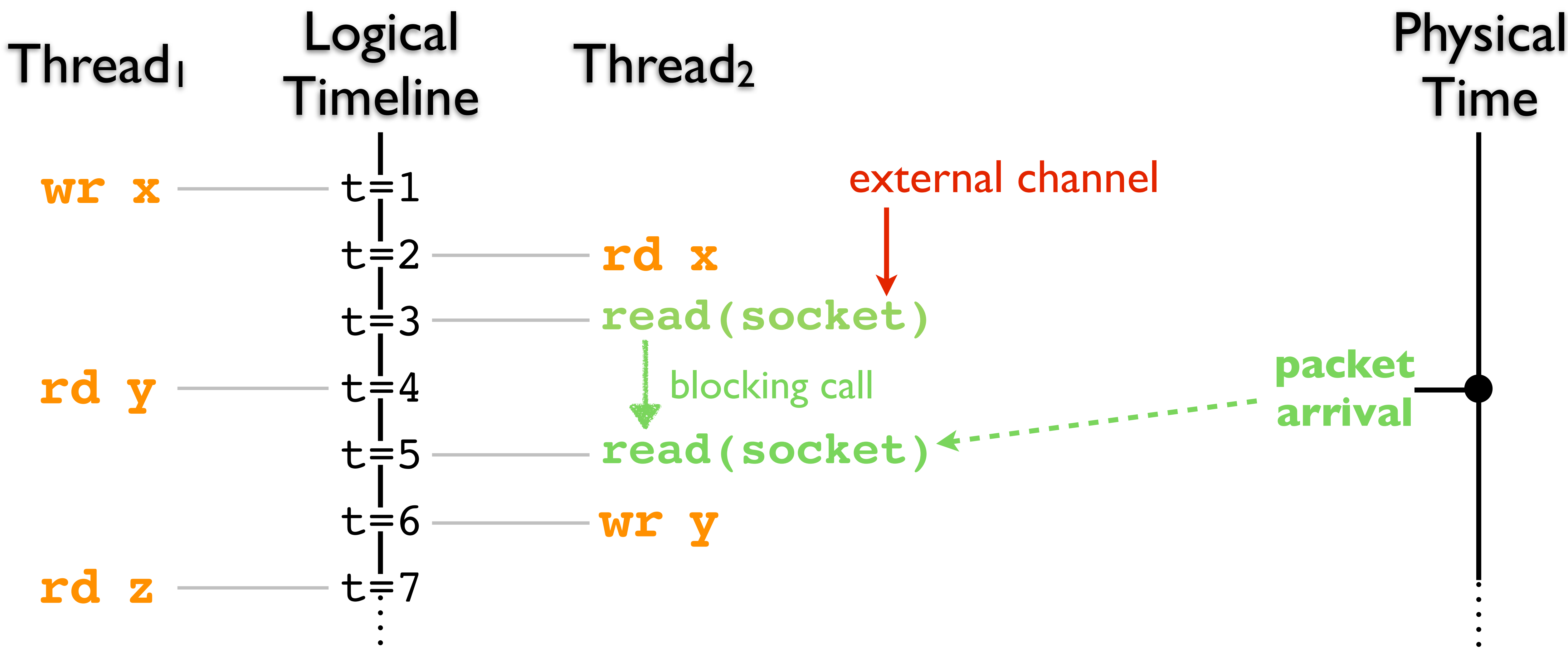
External Nondeterminism



Two sources of nondeterminism:

- data returned by `read()`
- blocking time of `read()`

External Nondeterminism



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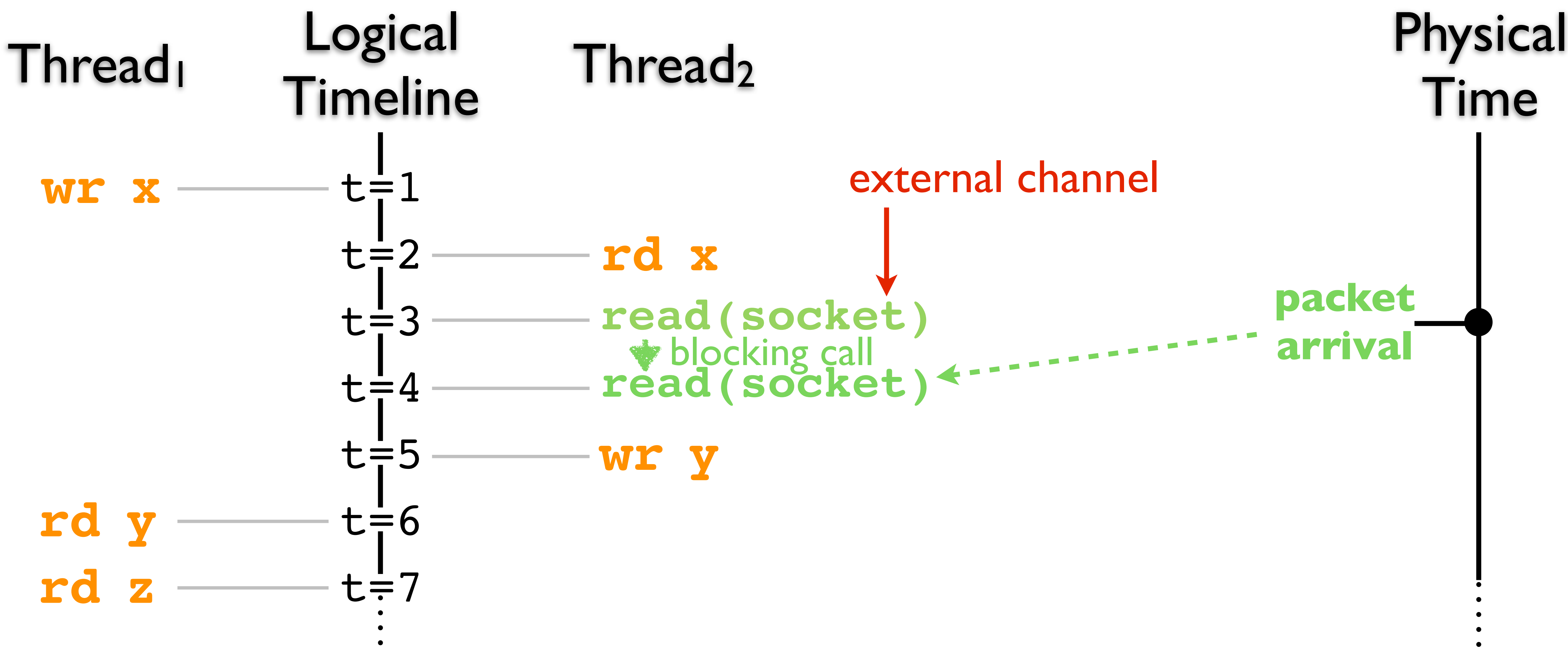

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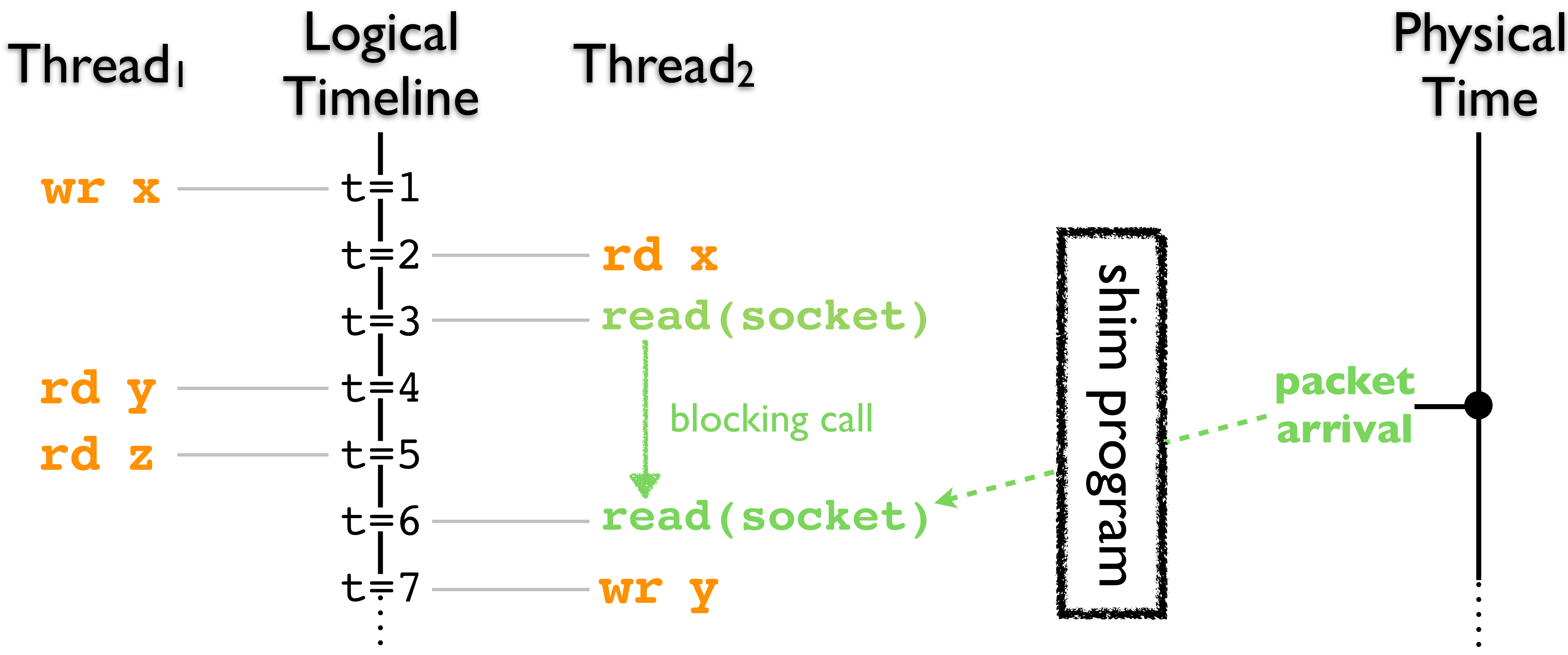
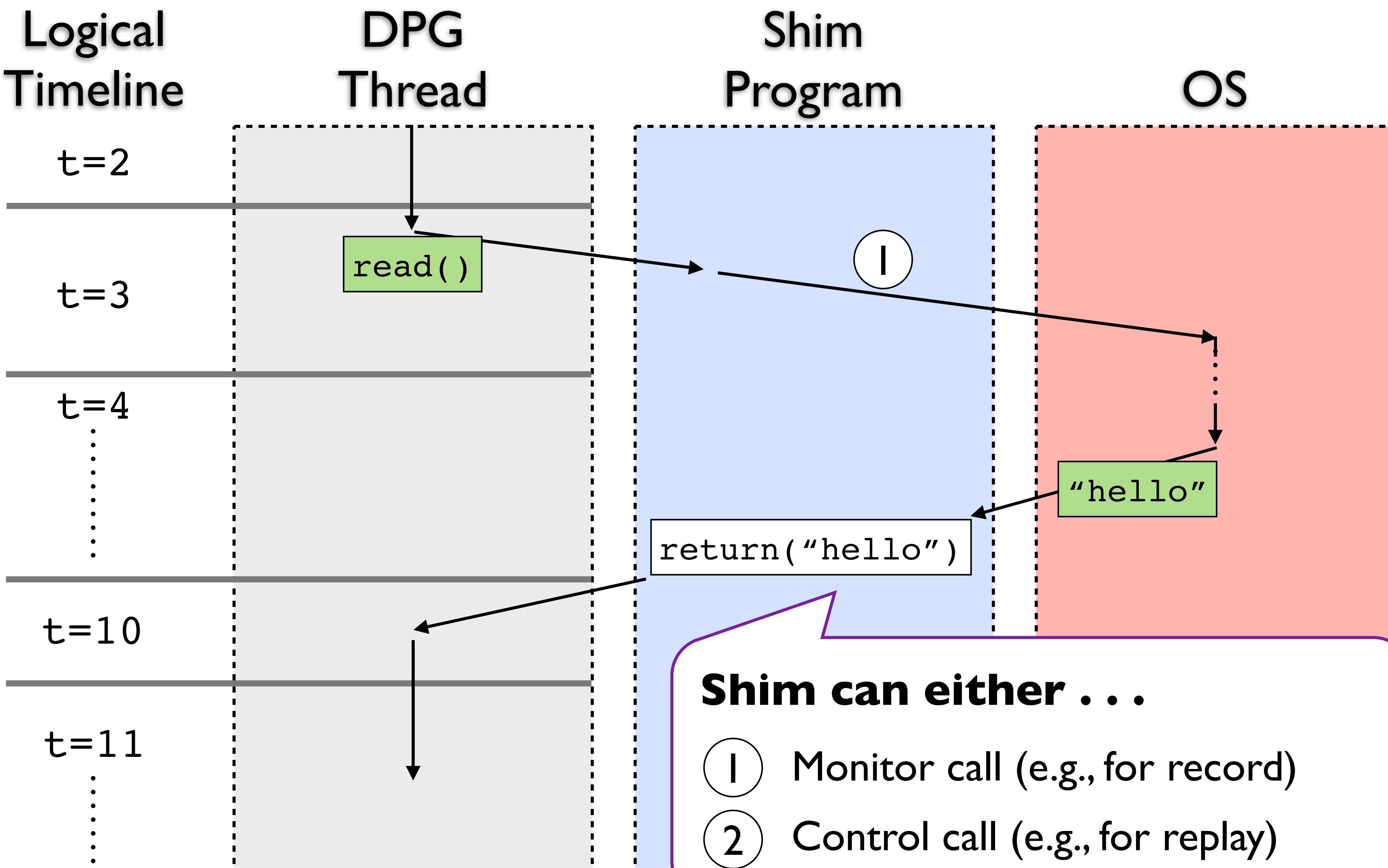


Two sources of nondeterminism:

- <u>data</u> returned by `read()` ‣ the <u>**what**</u>
- <u>blocking time</u> of `read()` ‣ the <u>**when**</u>

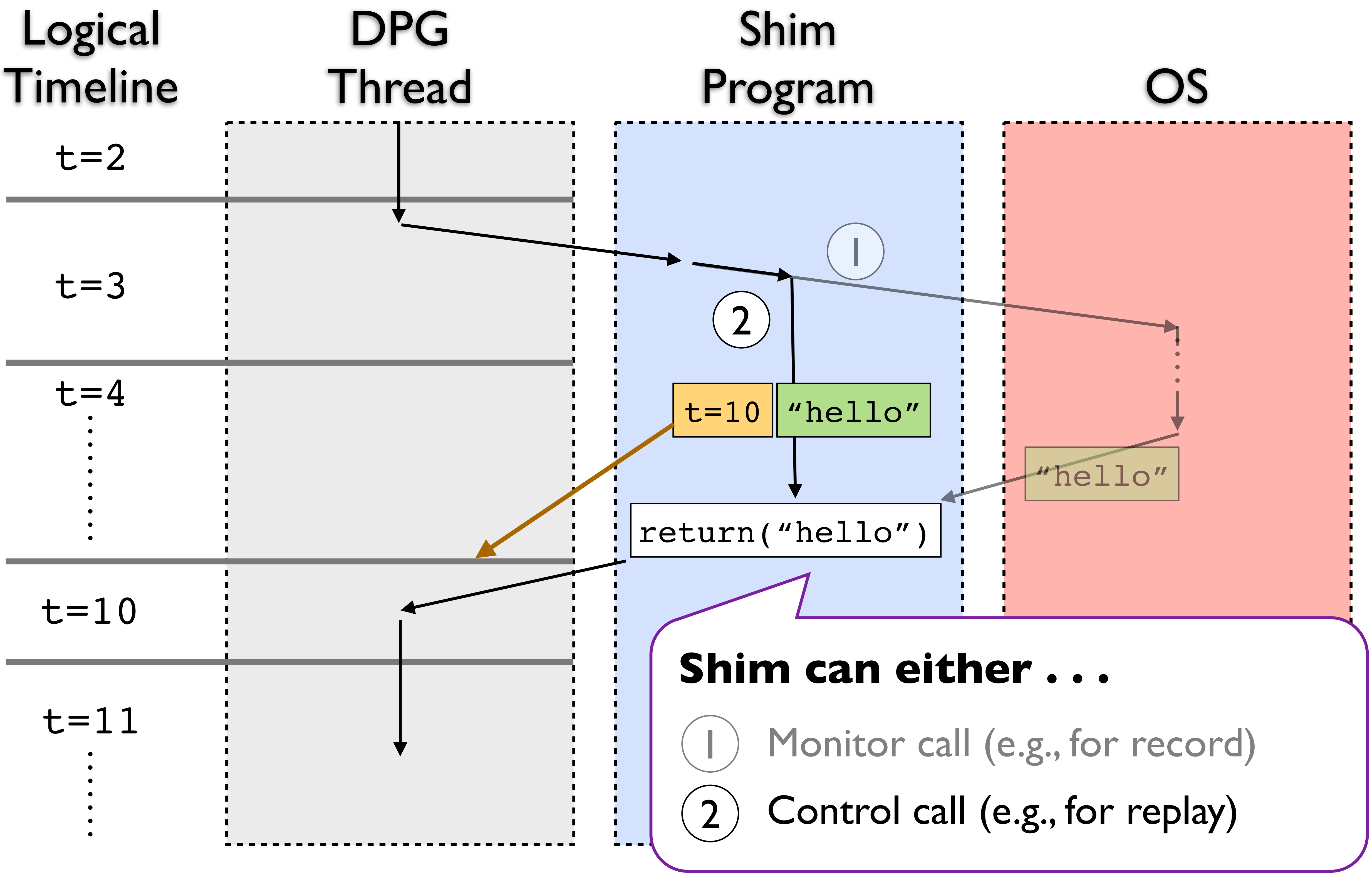
Shim Example: Read Syscall



Shim can either . . .

1. Monitor call (e.g., for record)
2. Control call (e.g., for replay)

Shim Example: Read Syscall

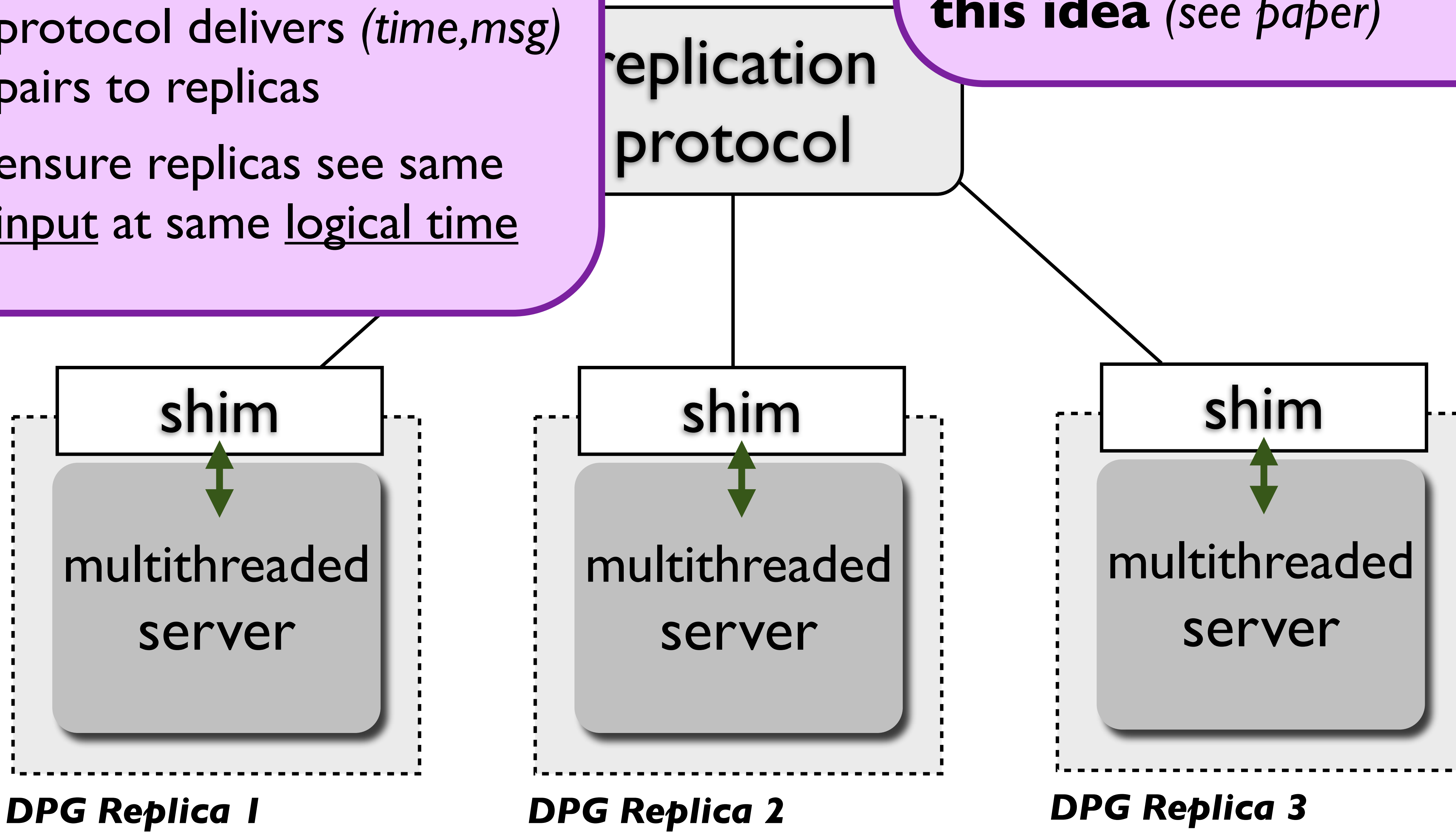


Shim Example: Replication

Key idea:

- protocol delivers *(time,msg)* pairs to replicas
- ensure replicas see same <u>input</u> at same <u>logical time</u>

We have implemented this idea *(see paper)*



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dOS Overview

Modified version of Linux 2.6.24/x86_64

- ~8,000 lines of code added or modified
- ~50 files changed or modified
- transparently supports unmodified binaries

Support for DPGs:

- implement a deterministic scheduler
- implement an API for writing shim programs
- subsystems modified:
  - thread scheduling
  - virtual memory
  - system call entry/exit

talk focus

Paper describes challenges in depth

dOS: Deterministic Scheduler

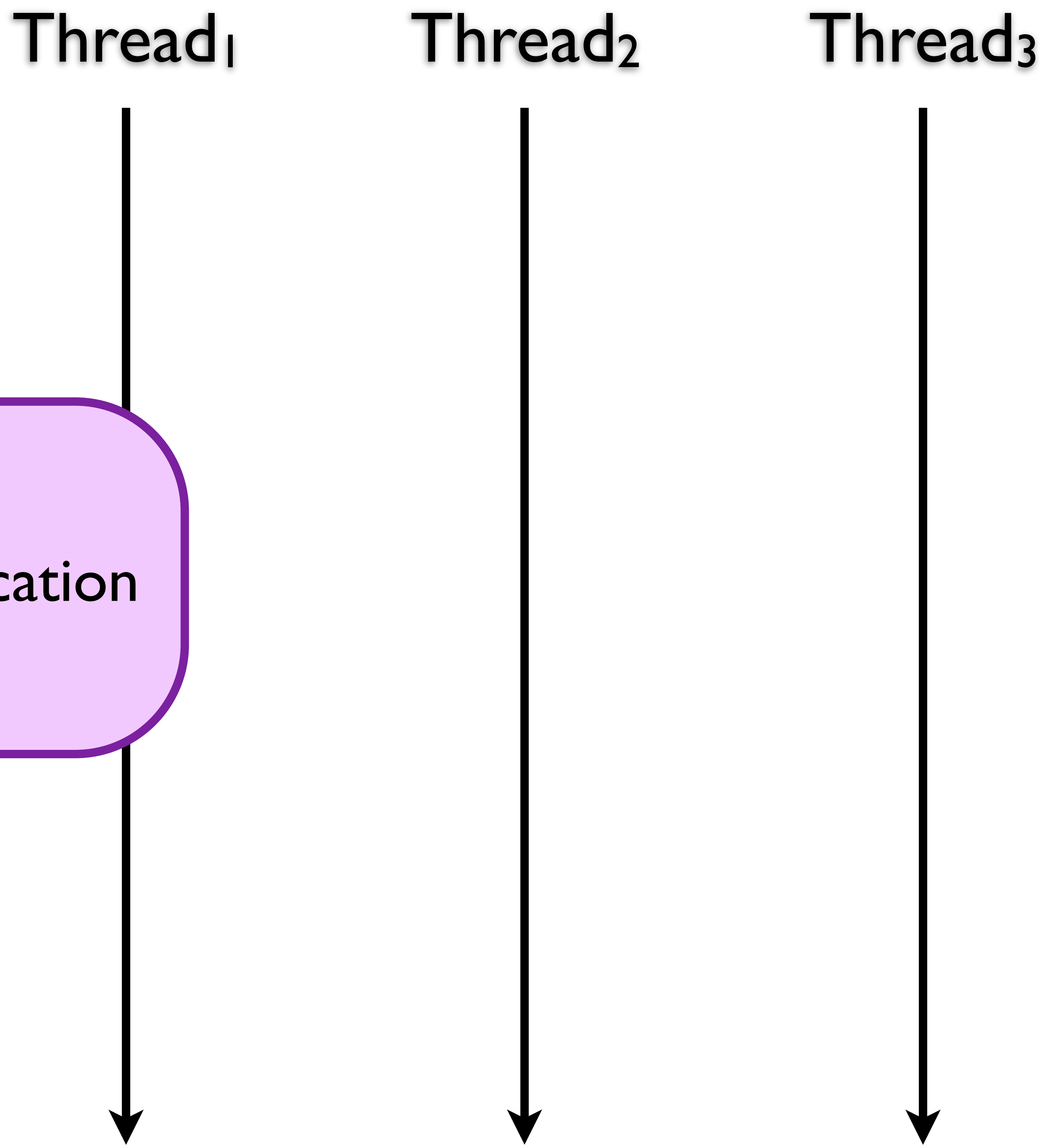
Which deterministic execution algorithm?

- DMP-O, from prior work [Asplos09, Asplos10]
    - other algorithms have better scalability, but
    - … Dmp-O is easiest to implement

How does DMP-O work?

How does dOS implement DMP-O?

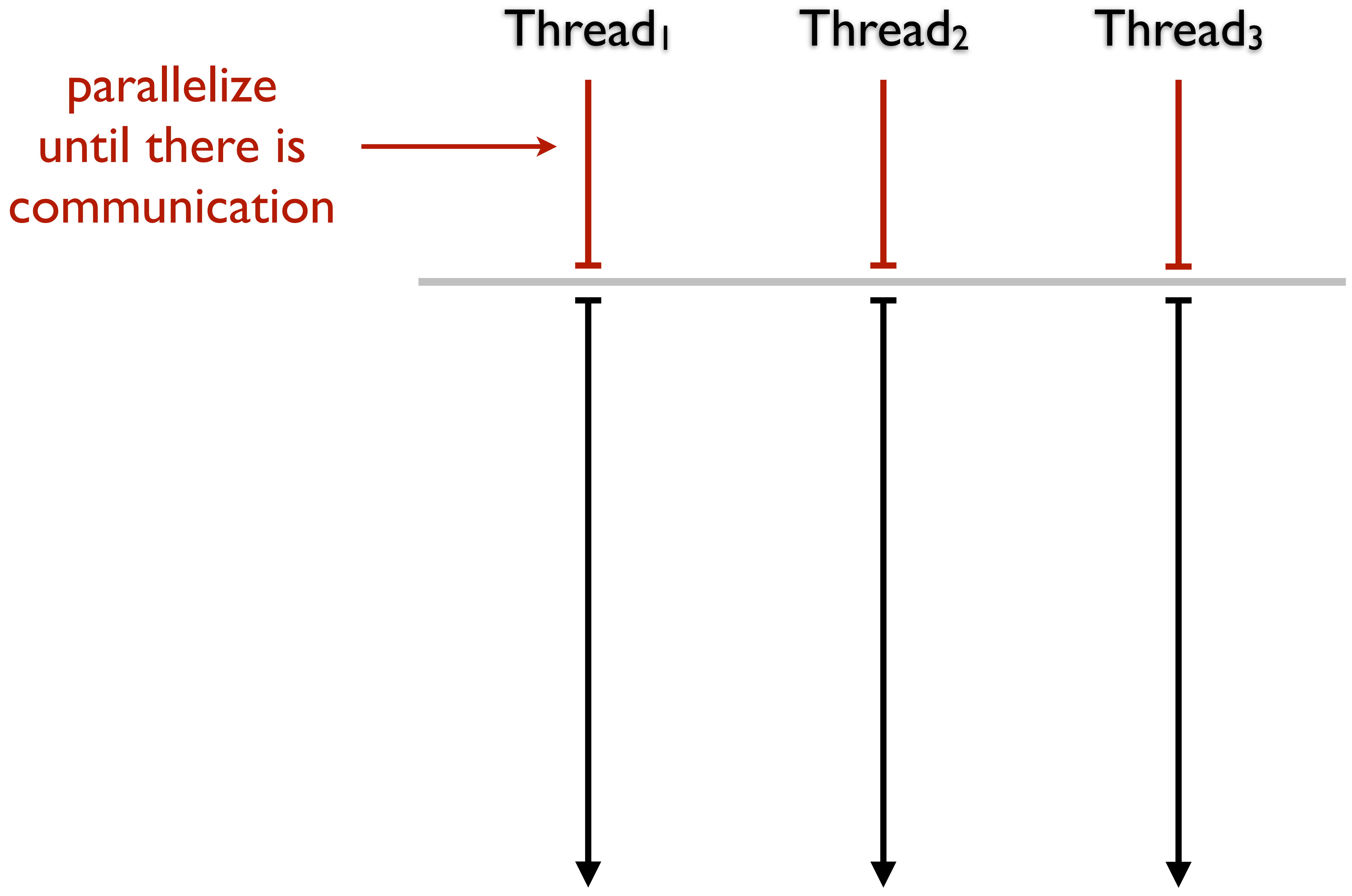
Deterministic Execution with DMP-O



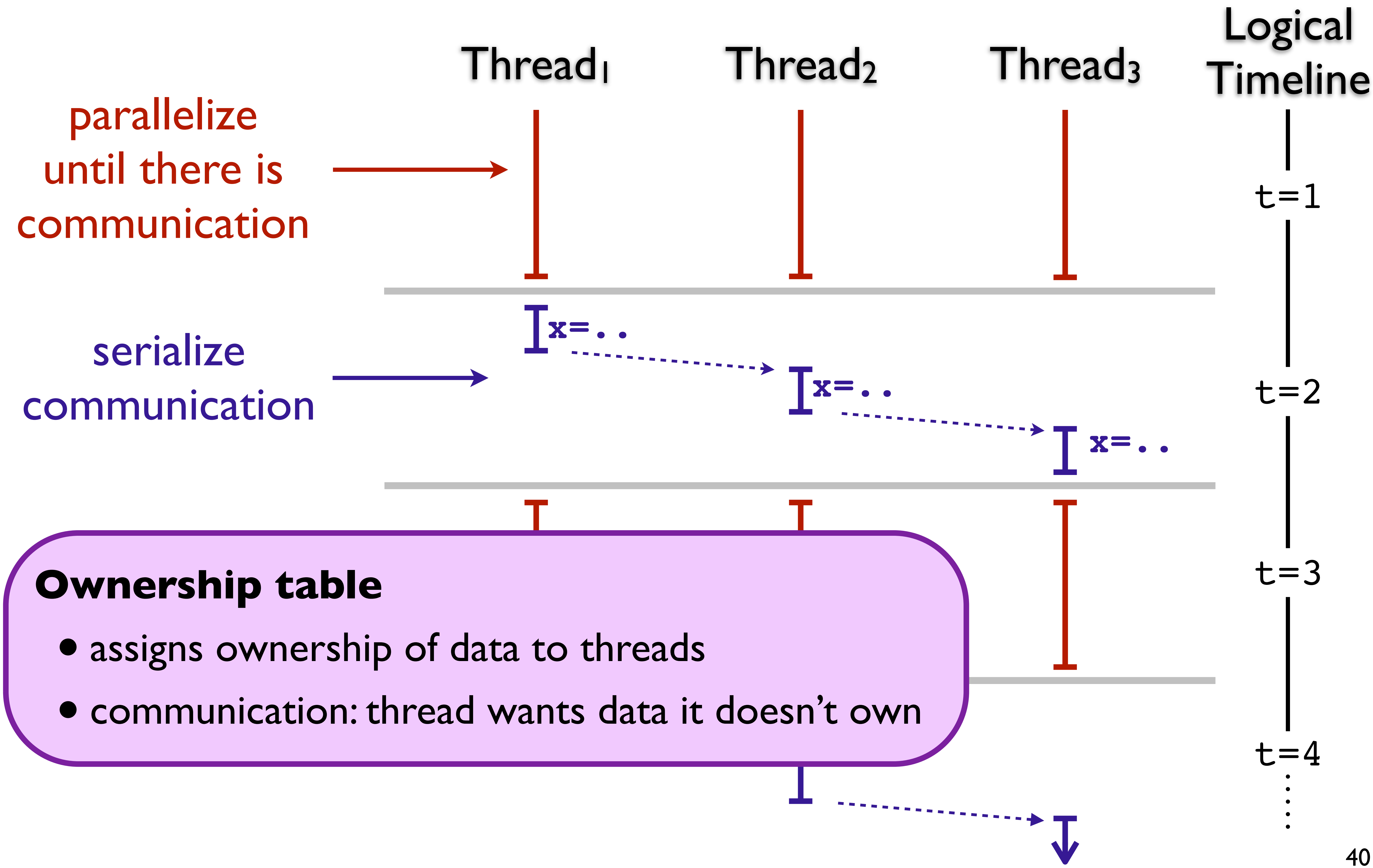
Key idea:

- *serialize* all communication deterministically

Deterministic Execution with DMP-O



Deterministic Execution with DMP-O



Ownership table

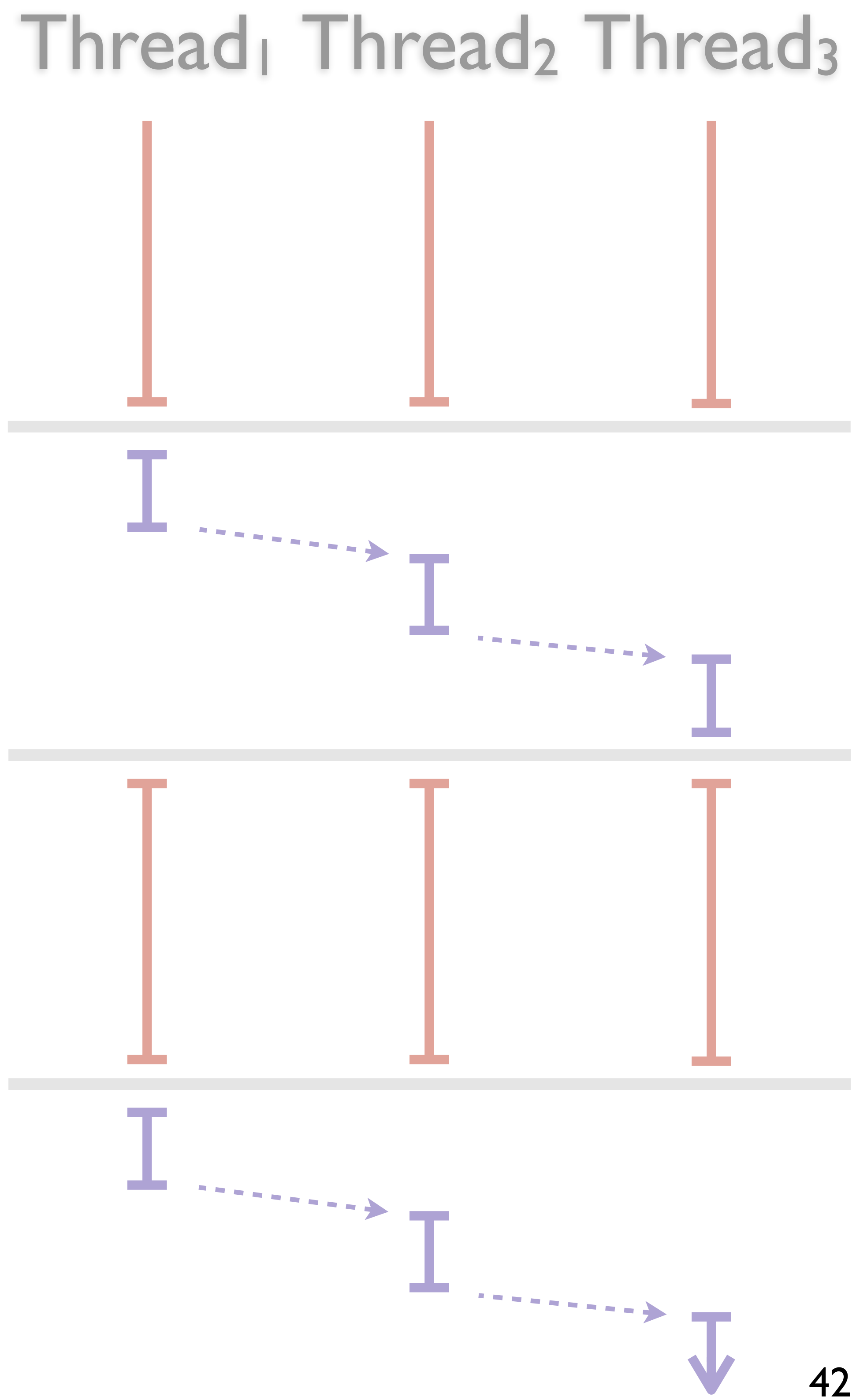
- assigns ownership of data to threads
- communication: thread wants data it doesn't own

dOS: Changes for DMP-O

Ownership Table

<u>must instrument the system interface</u>

- *loads/stores*
  - for shared-memory
- *system calls*
  - for in-kernel channels
  - *explicit*: pipes, files, signals, ...
  - *implicit*: address space, file descriptor table, ...

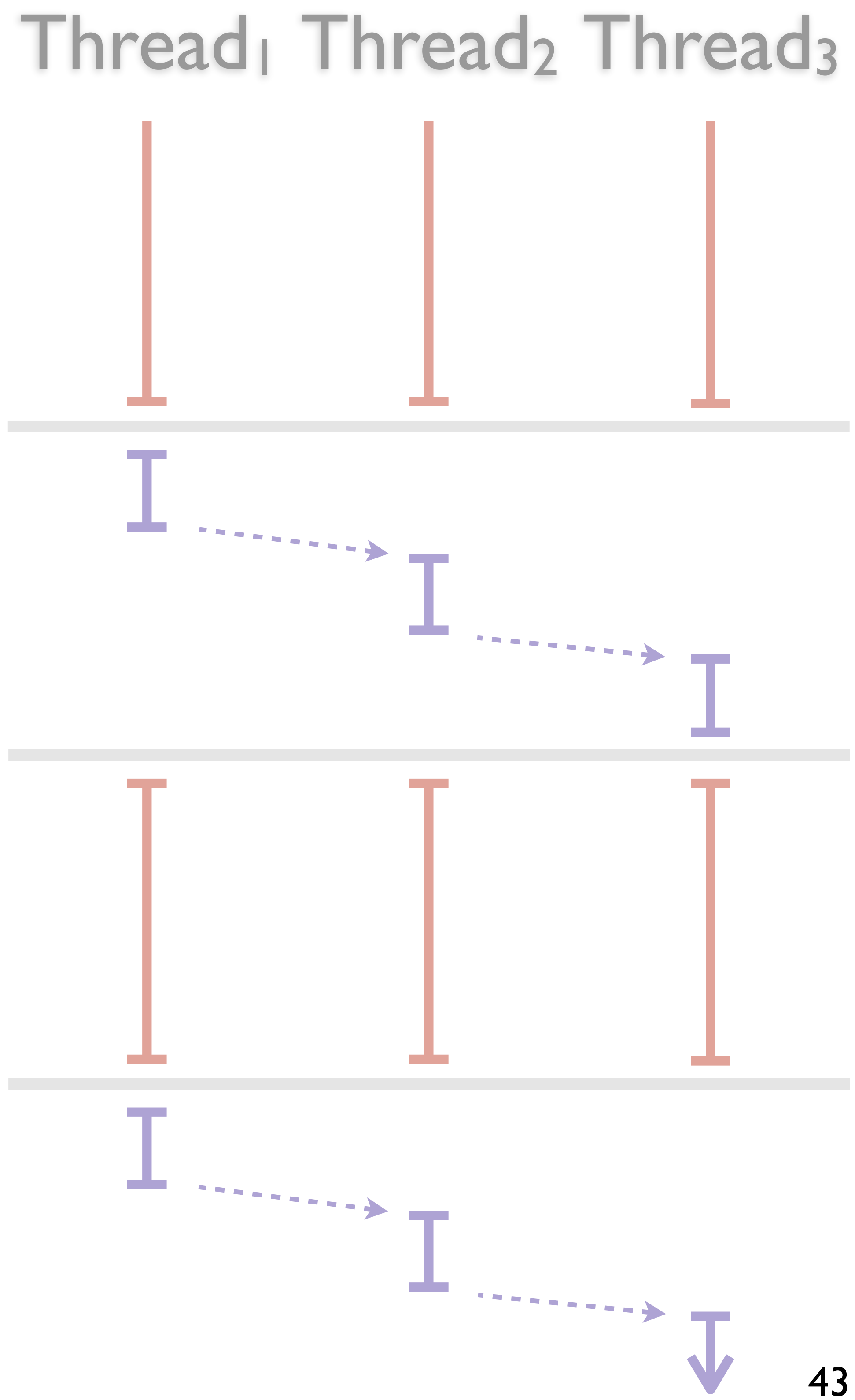


dOS: Changes for DMP-O

Ownership Table

<u>for shared-memory</u>

- must instrument loads/stores
  - use page-protection hw
- each thread has a *shadow page table*
  - permission bits denote ownership
  - page faults denote communication
  - *page granularity* ownership



dOS: Changes for DMP-O

Ownership Table

<u>for in-kernel channels (pipes, etc.)</u>

- must instrument *system calls*
- on syscall entry:
  - decide what channels are used

    `read()`: pipe or file being read

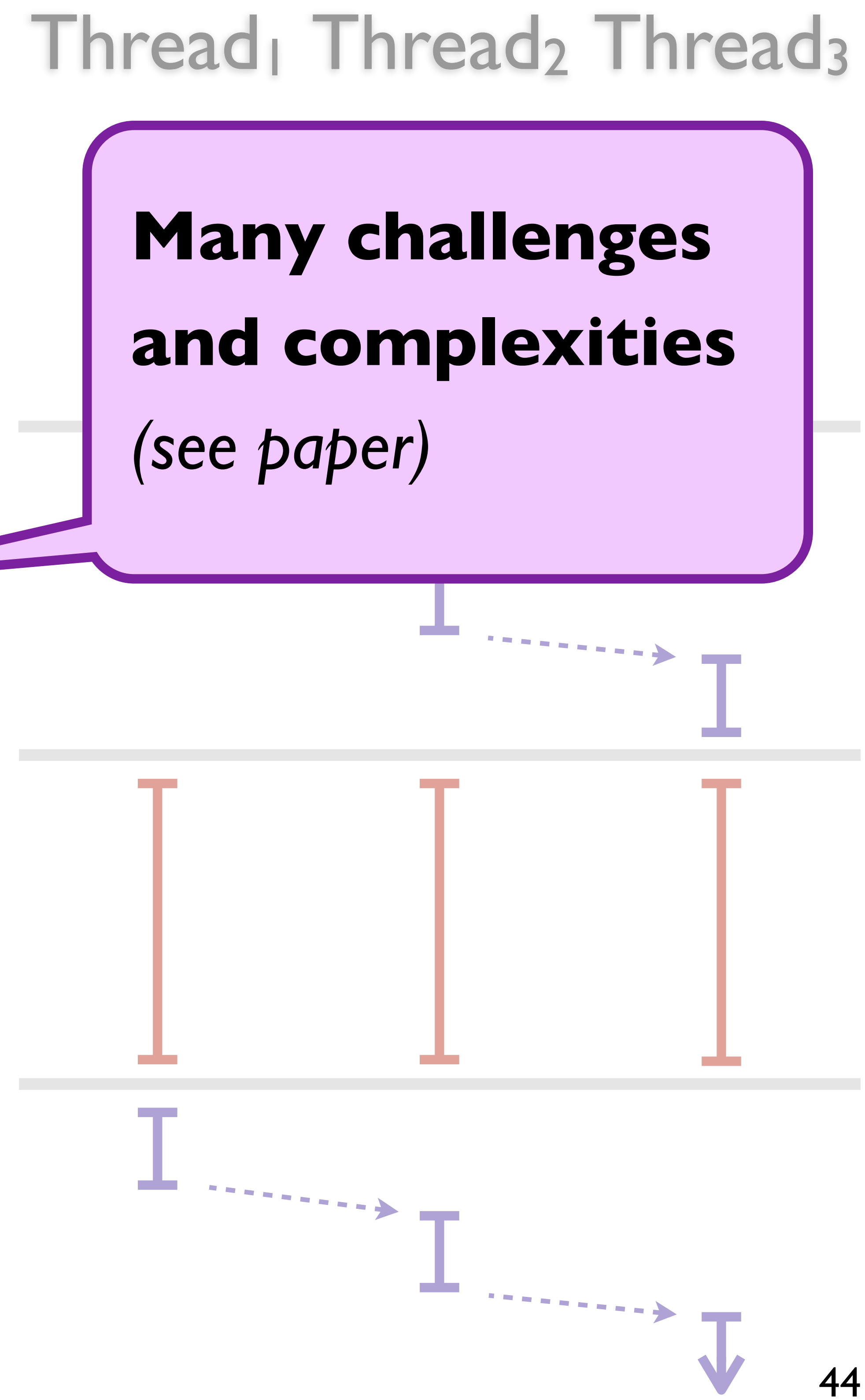
    `mmap()`: the thread's address space
  - acquire ownership

    ownership table is just a hash-table
  - any external channels?

    if yes: forward to shim program

Many challenges and complexities

(see paper)



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Evaluation Overview

Setup

- ➡ 8-core 2.8GHz Intel Xeon, 10GB RAM
- ➡ Each application ran in its own DPG

Verifying determinism

- ➡ used the racey deterministic stress test [ISCA02, MarkHill]

Key questions

- ➡ How much internal nondeterminism is eliminated? (log sizes for record/replay)
- ➡ How much overhead does dOS impose?
- ➡ How much does dOS affect parallel scalability?

Eval: Record Log Sizes

dOS

- ➡ implemented an "execution recorder" shim

SMP-ReVirt (a hypervisor) [VEE 08]

- ➡ also uses page-level ownership-tracking
- ➡ . . . but has to record *internal* nondeterminism

Log size comparison

	dOS	SMP-ReVirt	
`fmm`	1 MB	83 GB	*(log size per day)*
`lu`	11 MB	11 GB	
`ocean`	1 MB	28 GB	
`radix`	1 MB	88 GB	8,800x bigger!
`water`	5 MB	58 GB	

Eval: dOS Overheads

Possible sources of overhead

- deterministic scheduling
- shim program interposition

Ran each benchmark in three ways:

- without a DPG (ordinary, nondeterministic)

scheduling overheads

- with a DPG only

shim overheads

- with a DPG and an "execution recorder" shim program

Eval: dOS Overheads

Apache

- 16 worker threads
- serving 100KB static pages

  DPGs saturate 1 gigabit network

- serving 10 KB static pages

  Nondet (no DPG) *saturates 1 gigabit network*
  DPG (no shim): 26% throughput drop
  DPG (with record shim): 78% throughput drop (over Nondet)

Chromium

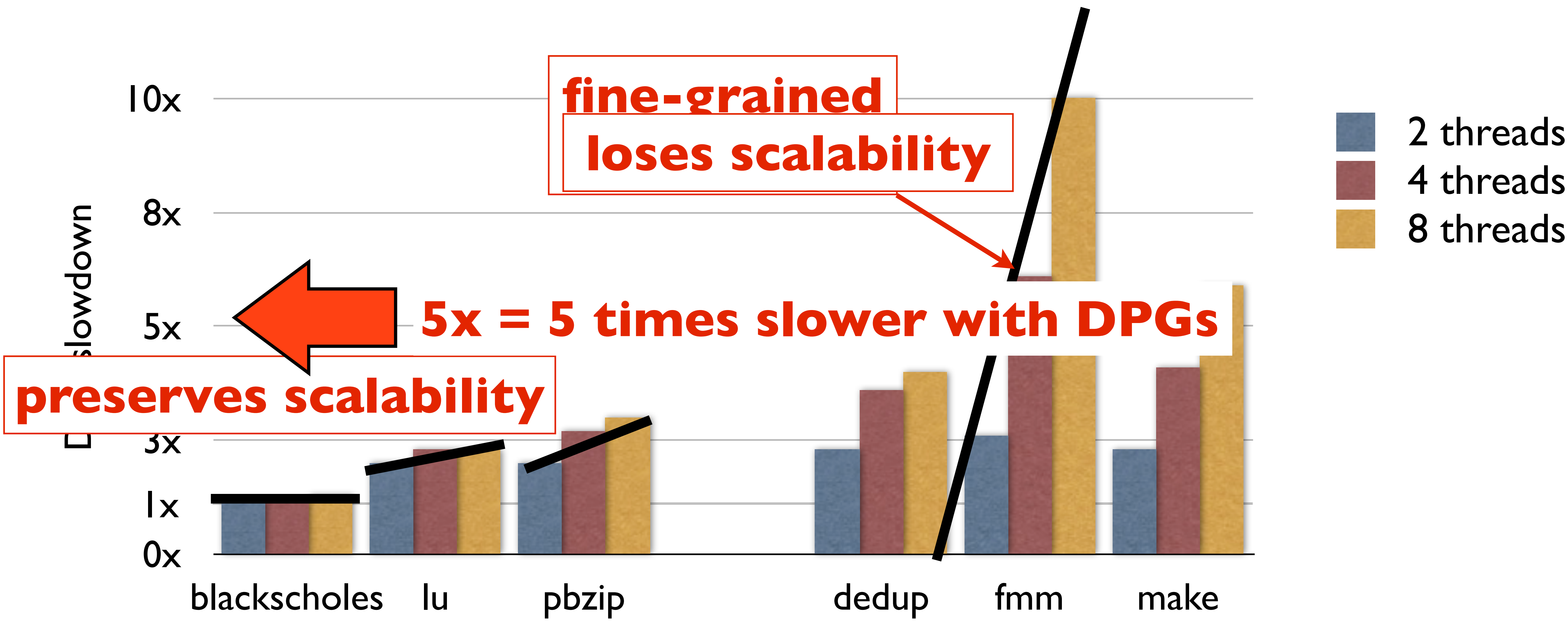
- process per tab
- scripted user session (5 tabs, 12 urls)

  DPG (no shim): 1.7x slowdown
  DPG (with record shim): 1.8x slowdown (over Nondet)

Eval: dOS Overheads

Parallel application slowdowns

- DPG only
- relative to nondeterministic execution



Wrap Up

Deterministic Process Groups

- ➡ new OS abstraction
- ➡ *eliminate* or *control* sources of nondeterminism

dOS

- ➡ Linux-Based implementation of DPGs
- ➡ use cases demonstrated: deterministic execution, record/ replay, and replicated execution

Also in the paper . . .

- ➡ many more implementation details
- ➡ a more thorough evaluation
- ➡ thoughts on a "from scratch" implementation

Thank you!

Questions?

http://sampa.cs.washington.edu

```
C:\DOS
C:\DOS\RUN
C:\DOS\RUN\DETERM~1.EXE
```

Discussion

How can we "constructively" make use of DPG?

Is OS the right place to provide determinism? How else can we provide deterministic program execution? Language, Compiler, Hardware? What are the pros and cons of each approach?

ewm87: *"each source of non-determinism should handle itself"*

wysem: *"do we really want/need deterministic execution for everything?"*

danyangz: *"the cost of making the scheduling deterministic is quite large...better to use some invariance reasoning"*

Why do we need deterministic processes?

bornholt: *"The demand for determinism seems like a side effect of terrible abstractions for concurrency."*

Is DPG a perfect solution for debugging/testing?

osandov: *"make data race bugs harder to find"*

naveenks: *"since many multi-threaded bugs are due to race-conditions and concurrency, how does debugging inside a DPG help catch those bugs?"*

lijl: "when customers encouter a bug, the developers should be able to reproduce the bug even on a completely different machine"

How robust is the determinism enforced inside a DPG? What if the programmer add a single debug print statement?

billzorn: *"It's like not getting the best of either world: the determinism is fragile and complicated."*

What are the preconditions to use DPG for your application? What are the properties that are not compulsory but good to have?

unmodified

performance-insensitive

no randomness

share as few things as possible

have a small number of external communications

Are there any constraints/assumptions that can be relaxed in DPG to give us better performance?

antoinek *“the false-sharing problem technically is the exact same thing as for cache lines, but with two major differences:*

1) *the 4K pages on x86 are generally 64x larger than cache lines*
2) *even false sharing at a relatively low rate can quickly become really expensive, because execution has to switch to serialized”*