DoubleChecker: Efficient Sound and Precise Atomicity Checking

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PLDI 2014

Impact of Concurrency Bugs

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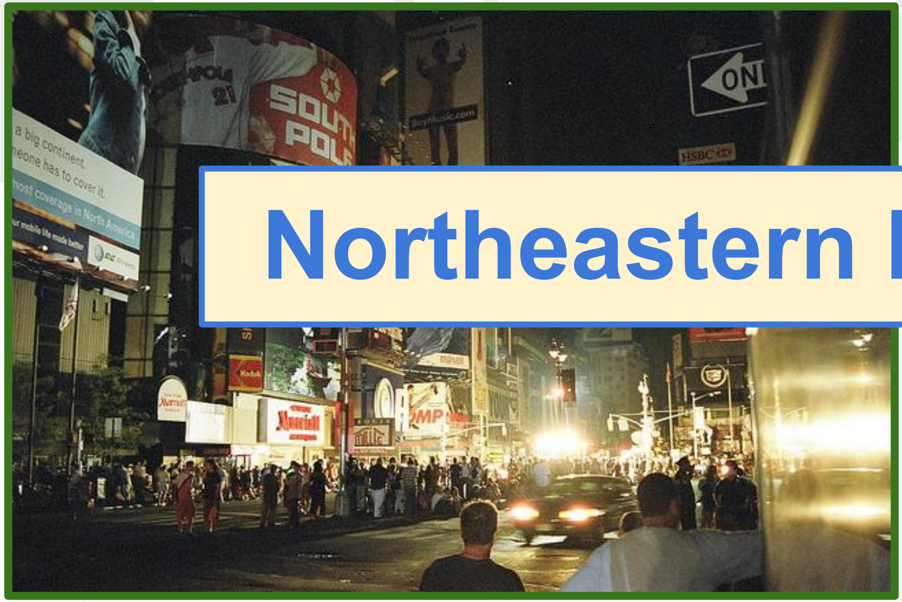


Northeastern blackout, 2003

Impact of Concurrency Bugs

BUSINESS SOFTWARE

business

BUSINESS READY

Nasdaq's Facebook Glitch Came From Race Conditions

Joab Jackson
@Joab_Jackson

May 21, 2012 12:30 PM

The Nasdaq computer system that delayed trade notices of the Facebook IPO on Friday was plagued by race conditions, the stock exchange announced Monday. As a result of this technical glitch in its Nasdaq OMX system, the market expects to pay out US$13 million or even more to traders.

A number of trading firms lost money due to mismatched Facebook share prices. About 30 million shares' worth of trading were affected, the exchange estimated.

On Friday, Nasdaq had delayed Facebook's IPO by 30 minutes. For about 20 minutes, the exchange stopped confirming trades placed by brokers, who were unable to see the results of their orders for more than two hours.

Atomicity Violations

- **Constitute 69%[1] of all non-deadlock concurrency bugs**

1. S. Lu et al. Learning from Mistakes: A Comprehensive Study on Real World Concurrency Bug Characteristics. In ASPLOS, 2008.

Atomicity

- Concurrency correctness property
- Synonymous with **serializability**
  - Program execution must be equivalent to some serial execution of the atomic regions

Thread 1

```
void execute() {

  while (...) {

    prepareList();
    . . . .
    processList();

    . . . .

    resetList();
  }

}
```

Thread 2

```
void execute() {

  while (...) {

    prepareList();
    . . . .
    processList();

    . . . .

    resetList();
  }

}
```

Atomicity Violation Example

Atomicity Violation Example

Thread 1

```
void prepareList() {
   synchronized (l1) {
        list.add(new Object());
   }
}

void processList() {
    synchronized (l1) {
        Object head = list.get(0);
    }
}
```

Thread 2

```
void resetList() {
  synchronized (l1) {
        list = null;
  }
}
```

Atomicity Violation Example

Thread 1

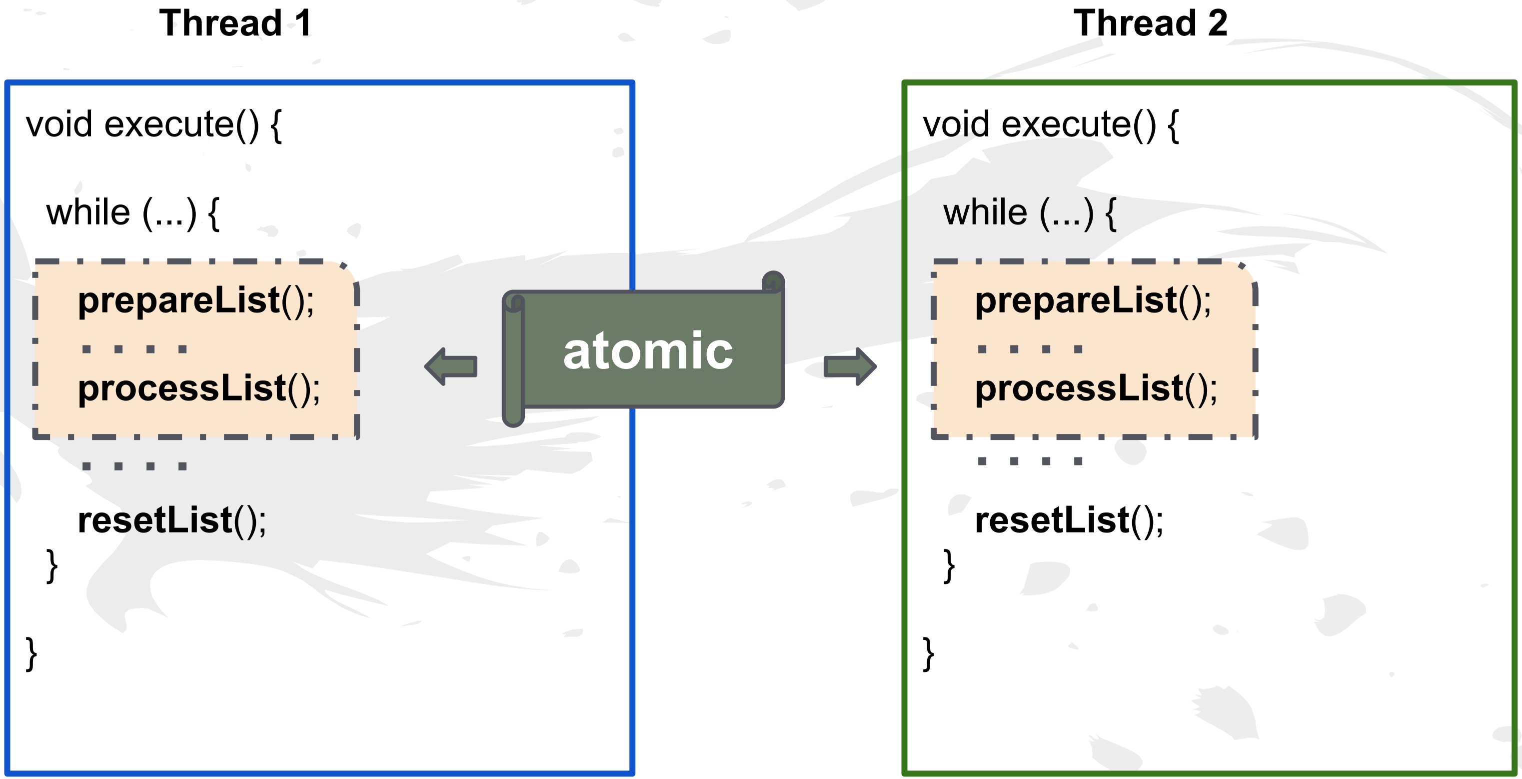
```
void prepareList() {
   synchronized (l1) {
        list.add(new Object());
   }
}

void processList() {
    synchronized (l1) {
        Object head = list.get(0);
    }
}
```

Null pointer dereference

Thread 2

```
void resetList() {
  synchronized (l1) {
        list = null;
  }
}
```

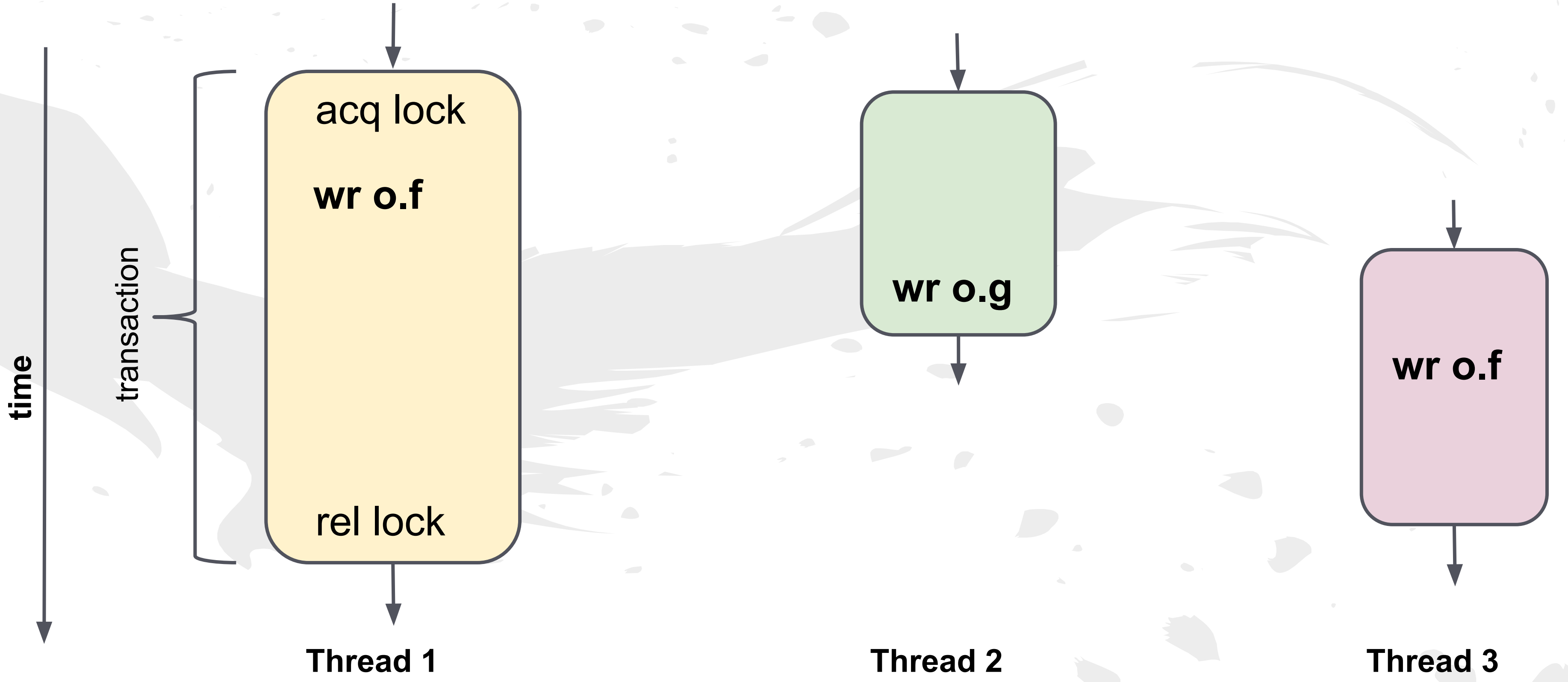
Data-race-free program



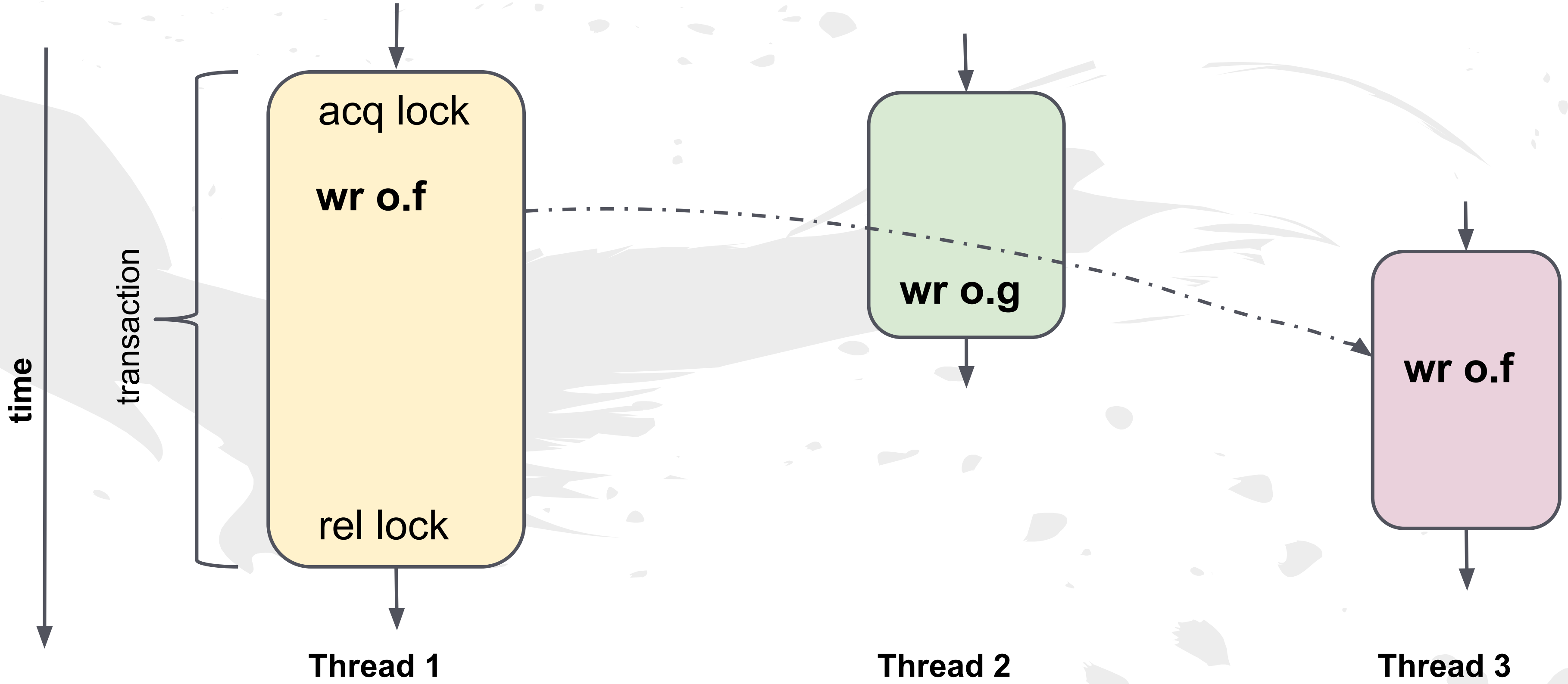
Atomicity Violation Example

Detecting Atomicity Violations

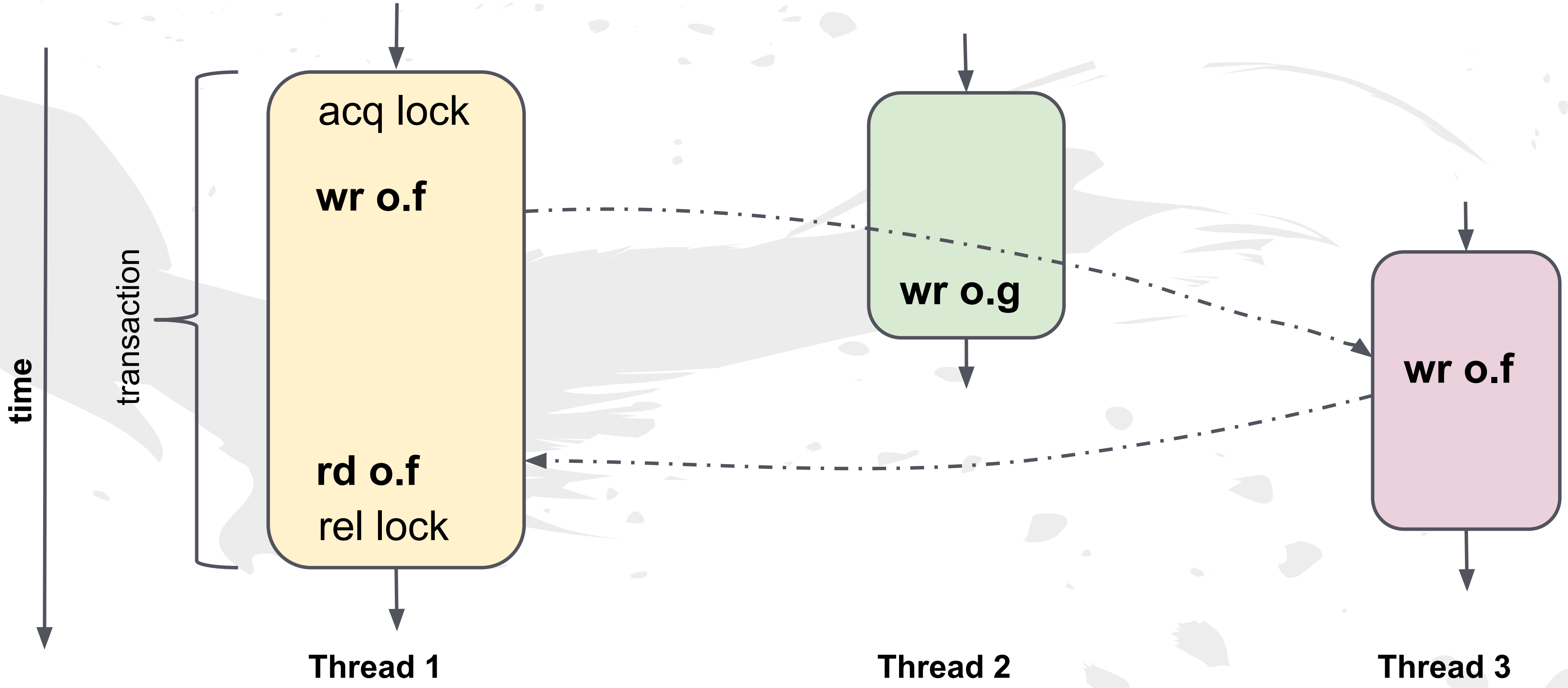
- Check for conflict serializability
  - Build a transactional dependence graph
  - Check for cycles
- Existing work
  - Velodrome, Flanagan et al., PLDI 2008
  - Farzan and Parthasarathy, CAV 2008



Transactional Dependence Graph



Transactional Dependence Graph



Cycle means Atomicity Violation

Velodrome[1]

- Paper reports 12.7X overhead
- 6.1X in our experiments

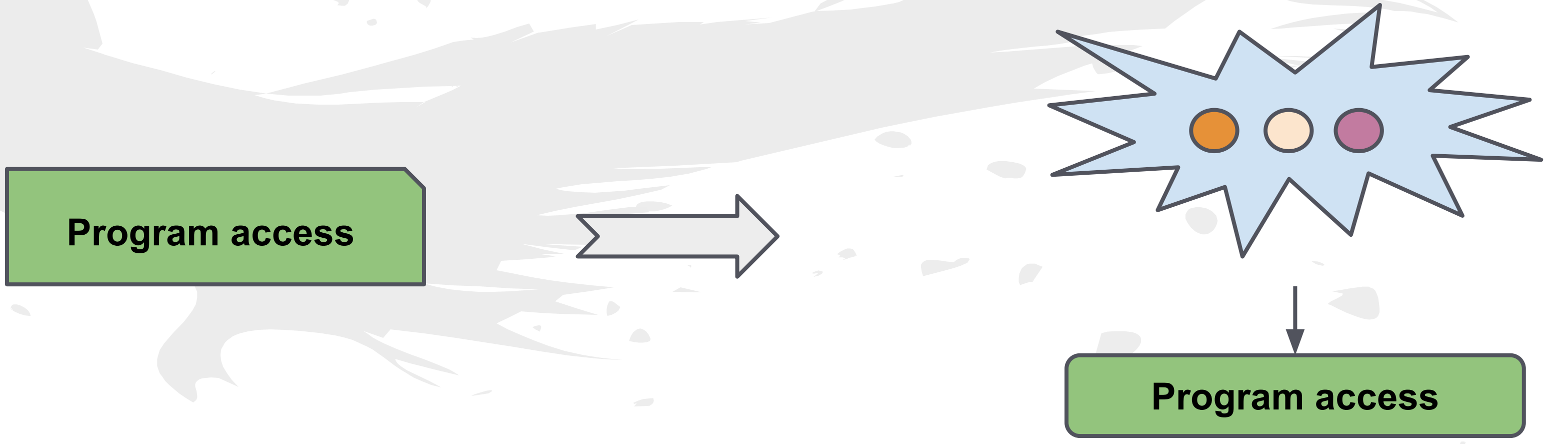
1. C. Flanagan et al. Velodrome: A Sound and Complete Dynamic Atomicity Checker for Multithreaded Programs. In PLDI, 2008.

Prior Work is Slow

High Overheads of Prior Work

- Precise tracking is expensive
  - "**last transaction(s) to read/write**" for every field
  - Need **atomic updates** in instrumentation

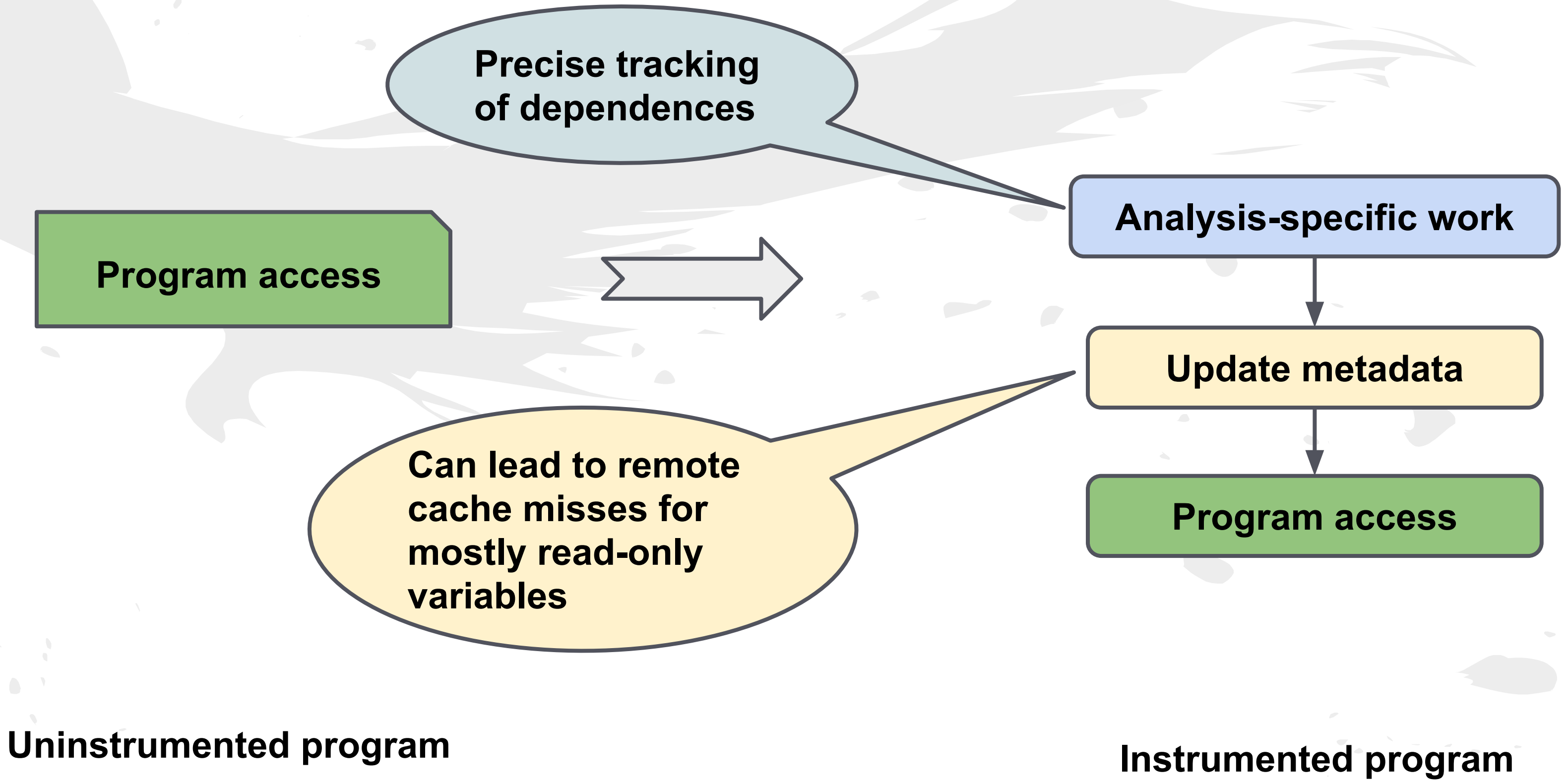
Instrumentation Approach



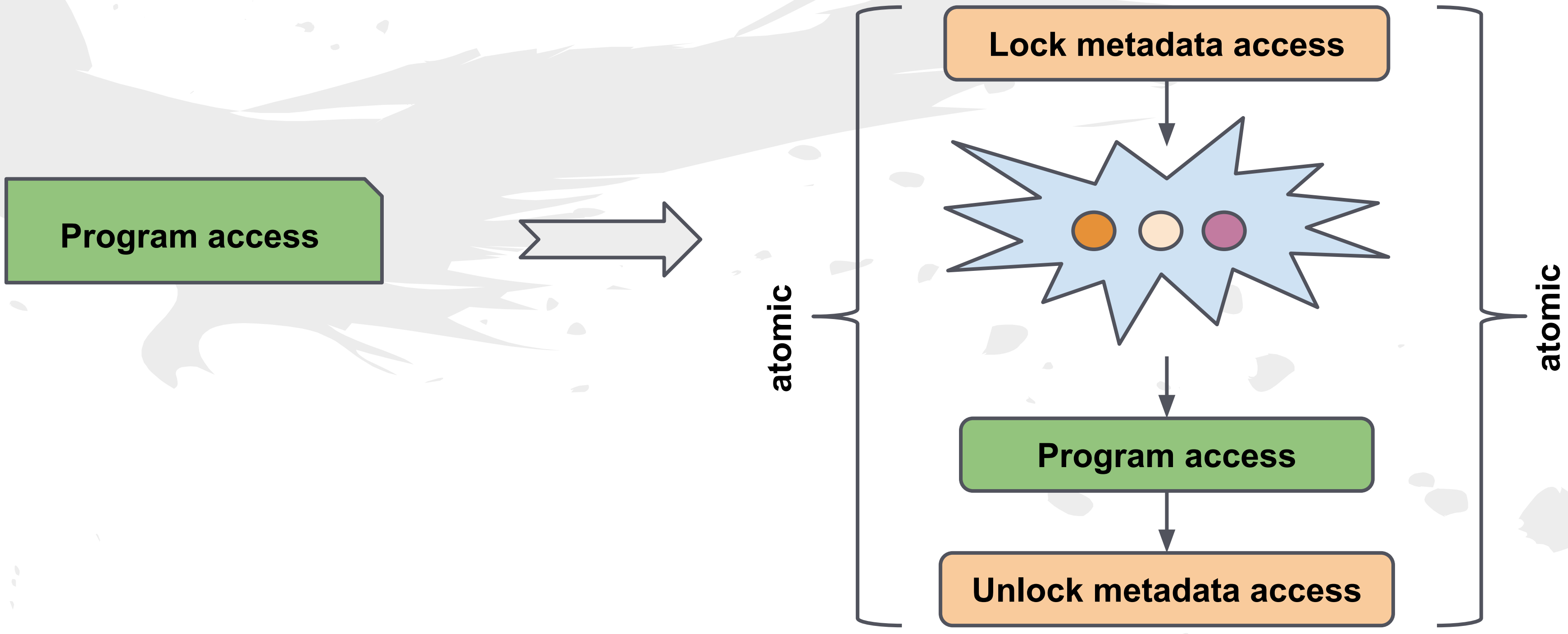
Uninstrumented program

Instrumented program

Precise Tracking is Expensive!



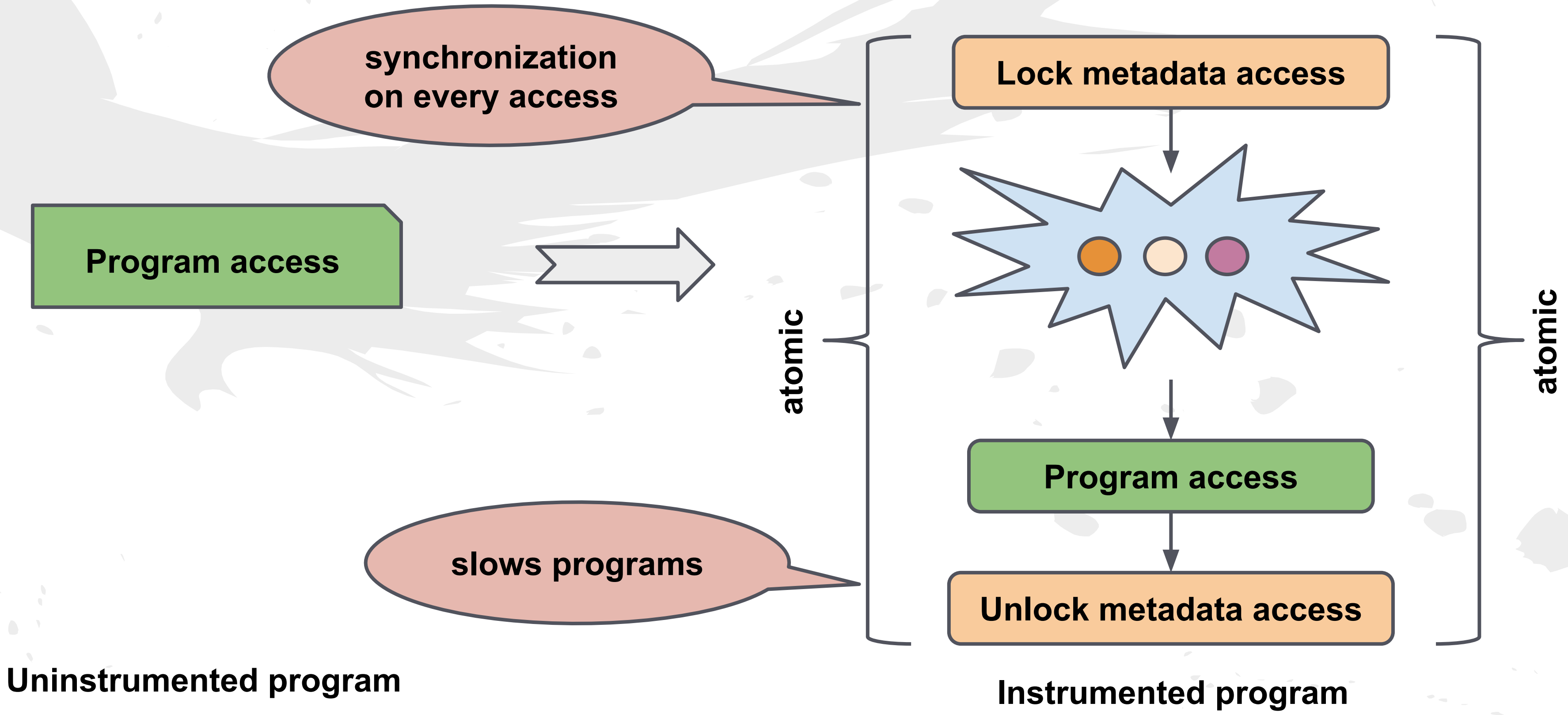
Synchronized Updates are Expensive!



Uninstrumented program

Instrumented program

Synchronized Updates are Expensive!



DoubleChecker

DoubleChecker’s Contributions

- Dynamic atomicity checker based on conflict serializability
- Precise
    - Sound and unsound operation modes
- Incurs 2-4 times lower overheads
- Makes dynamic atomicity checking more practical

Key Insights

- Avoid **high costs** of precise tracking of dependences at every access
  - Common case: no dependences
    - Most accesses are thread local

Key Insights

- Tracks dependences **imprecisely**
  - **Soundly over-approximates** dependences
  - Recovers precision when required
  - Turns out to be a lot **cheaper**

Staged Analysis

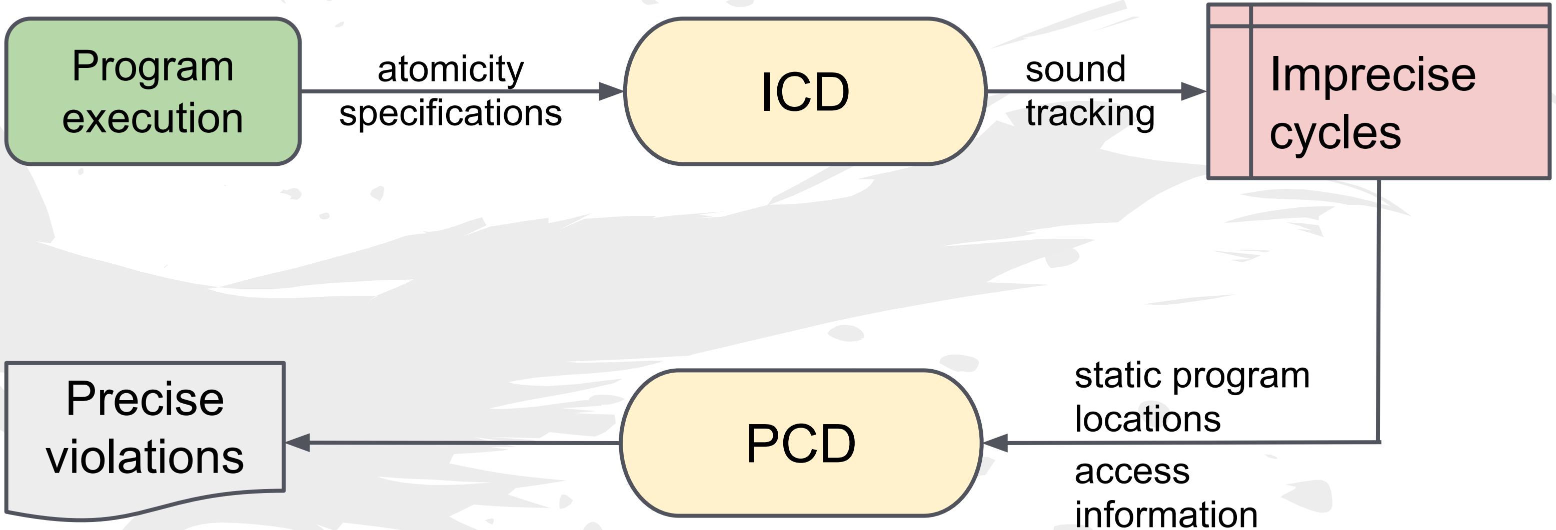
- Imprecise cycle detection (ICD)
- Precise cycle detection (PCD)

Imprecise Cycle Detection

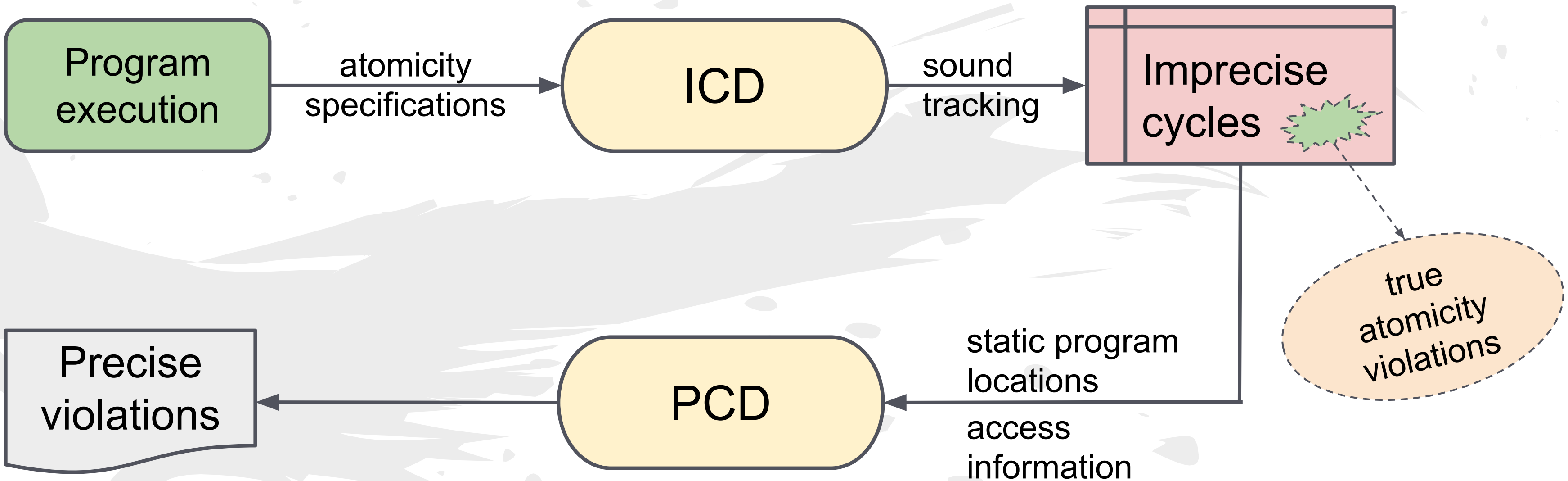
- **Processes every program access**
- Soundly overapproximates dependences, **is cheap**
- Could have false positives

Precise Cycle Detection

- **Processes a subset of program accesses**
- Performs precise analysis
- No false positives

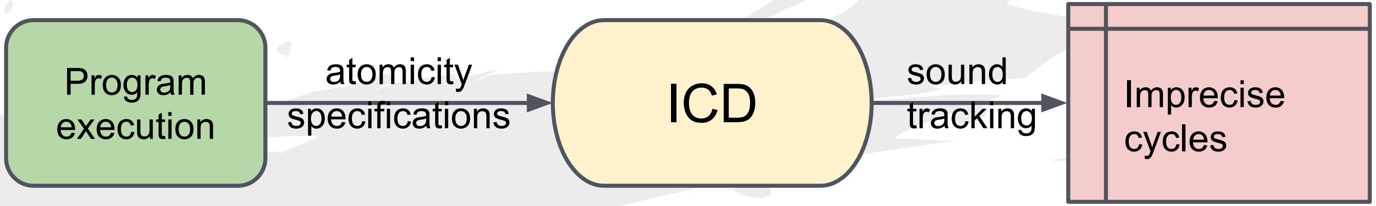


Staged Analyses: ICD and PCD


Program execution
atomicity specifications
ICD
sound tracking
Imprecise cycles
true atomicity violations
static program locations
access information
PCD
Precise violations

ICD is Sound

Role of ICD



- Most accesses in a program are thread-local
  - Uses **Octet**[1] for tracking cross-thread dependences
- Acts as a dynamically sound transaction filter

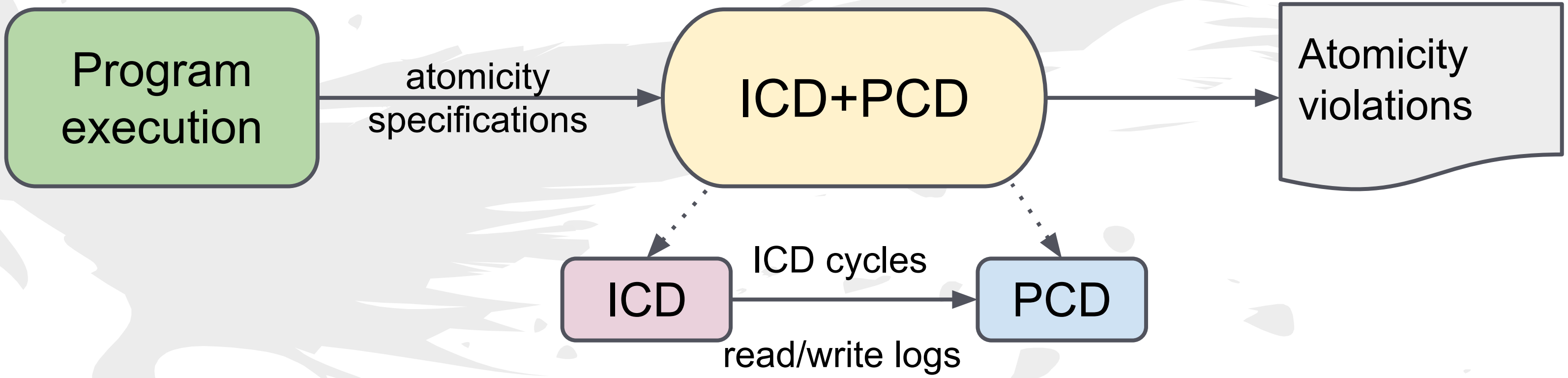
1. M. Bond et al. Octet: Capturing and Controlling Cross-Thread Dependences Efficiently. In OOPSLA, 2013.

Role of PCD

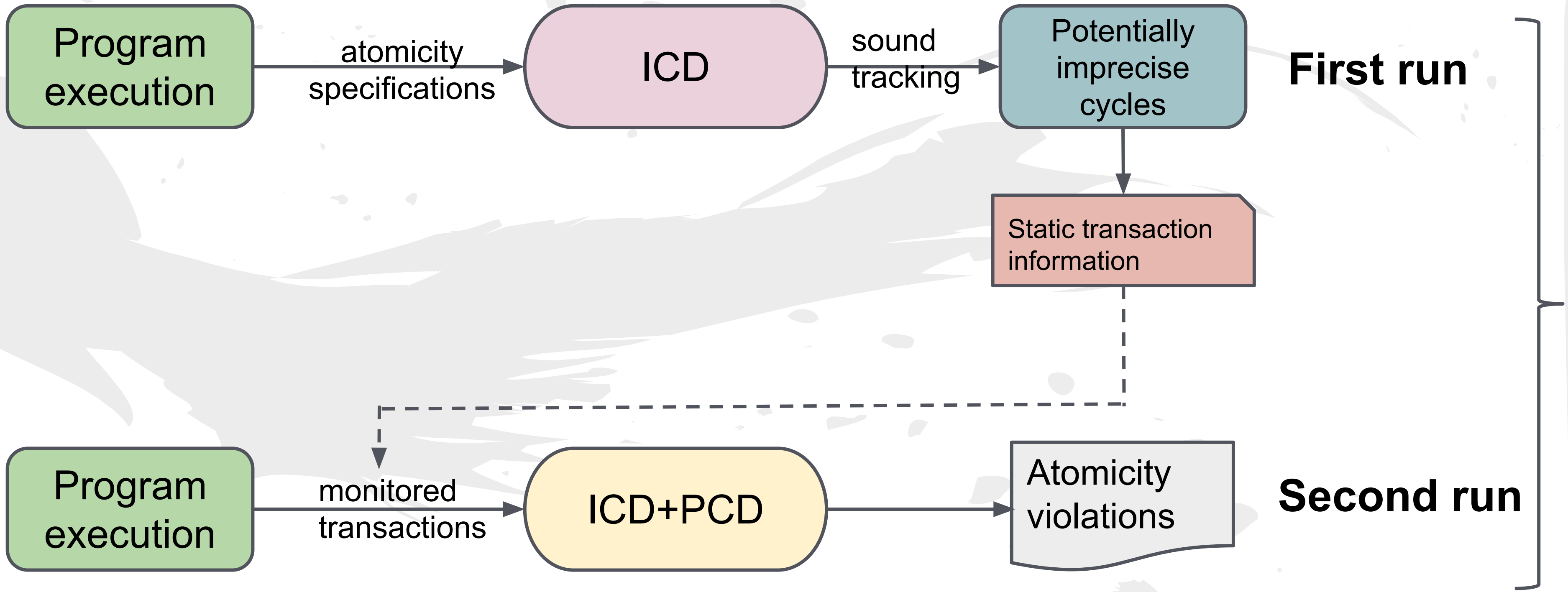
- Processes transactions involved in an ICD cycle
  - Performs precise serializability analysis
  - PCD has to do much less work
    - Program conforming to its atomicity specification will have very few cycles

Different Modes of Operation

- Single-run mode
- Multi-run mode



Single-Run Mode



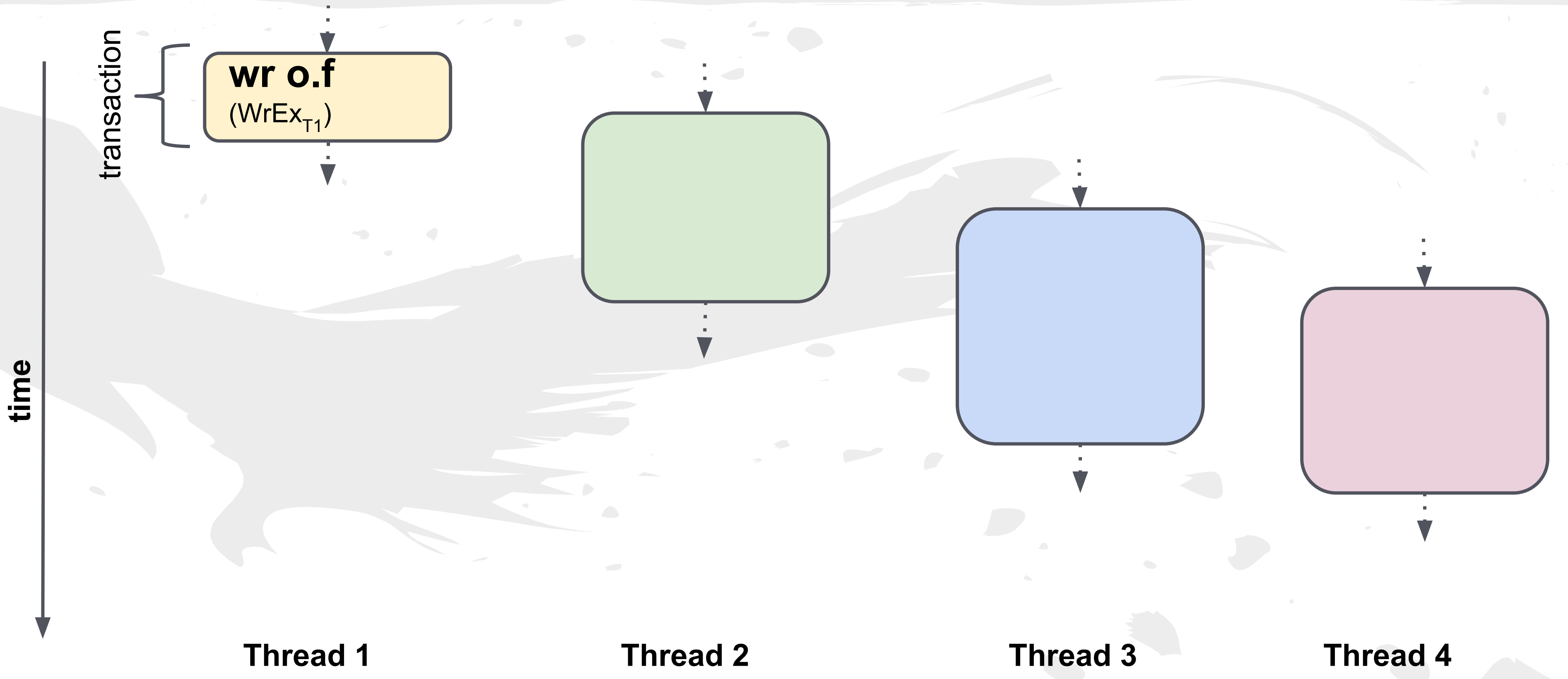
Multi-run Mode

Design Choices

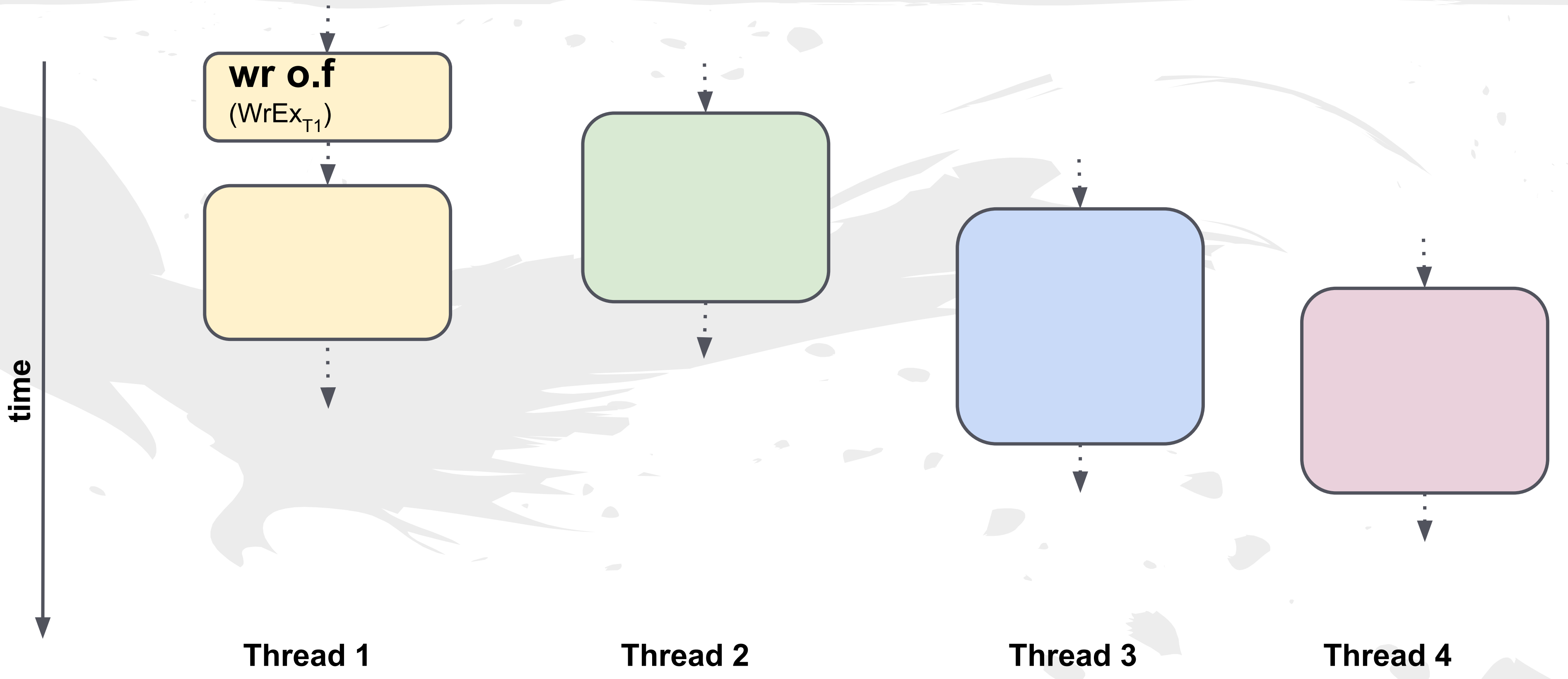
- Multi-run mode
    - Conditionally instruments non-transactional accesses
        - Otherwise overhead increases by 29%
    - Could use Velodrome for the second run
        - But performance is worse
            - Second run has to process many accesses
            - **ICD is still effective as a dynamic transaction filter**

Examples

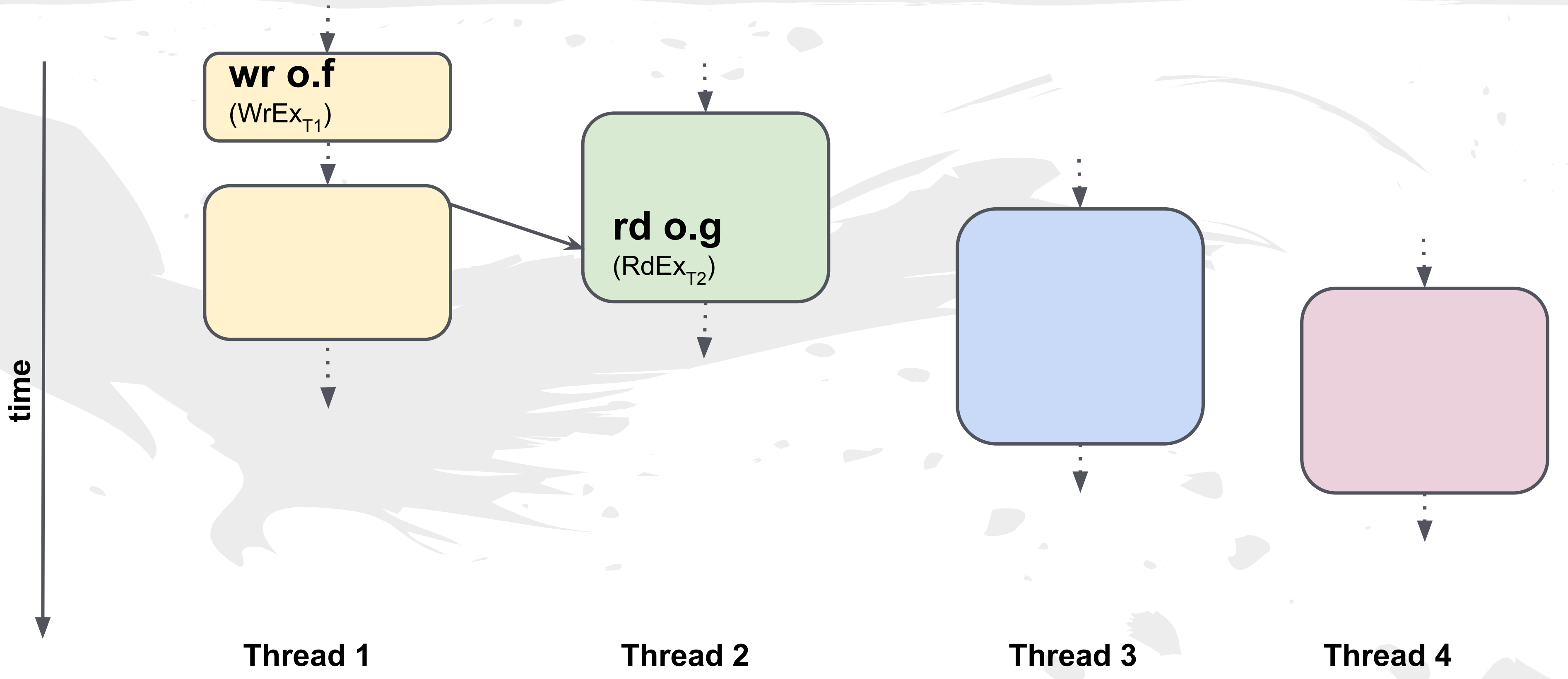
- Imprecise analysis
- Precise analysis



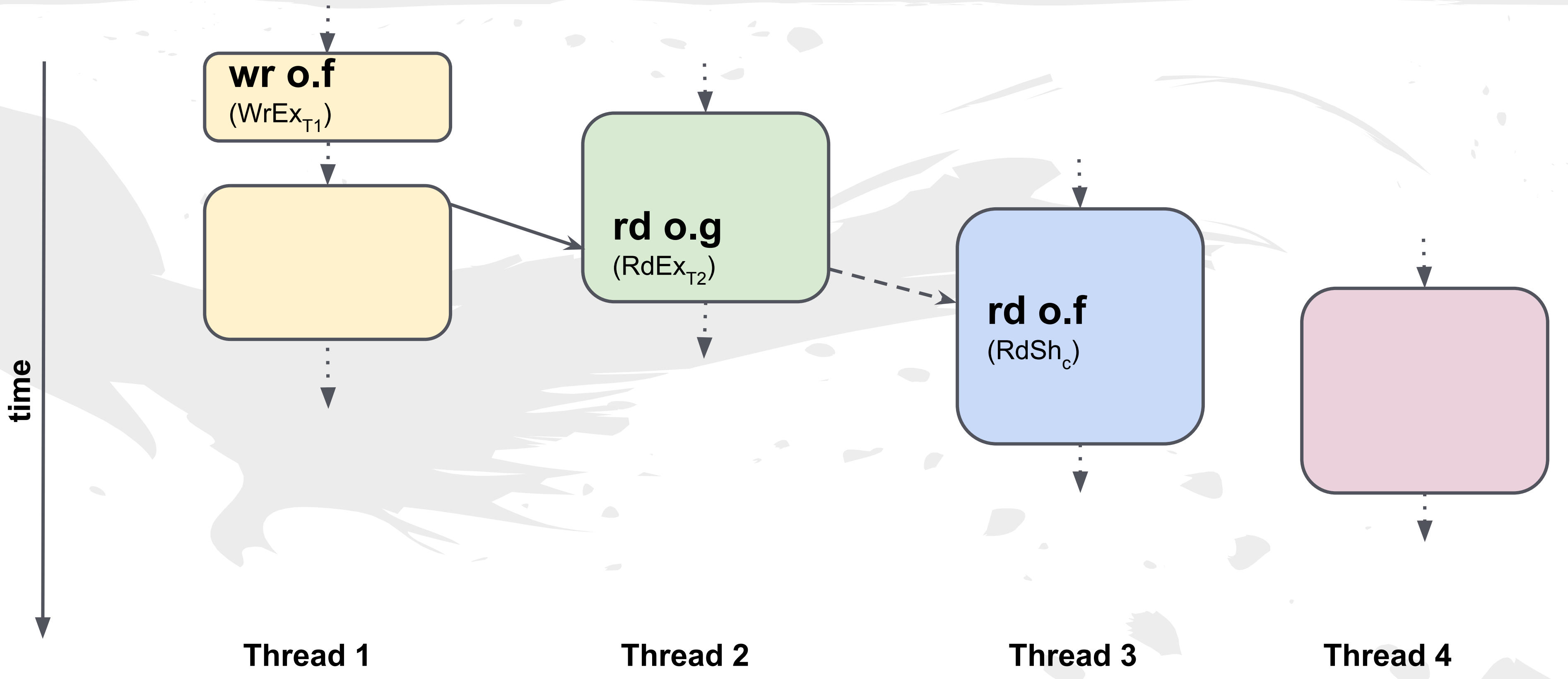
Imprecise Analysis



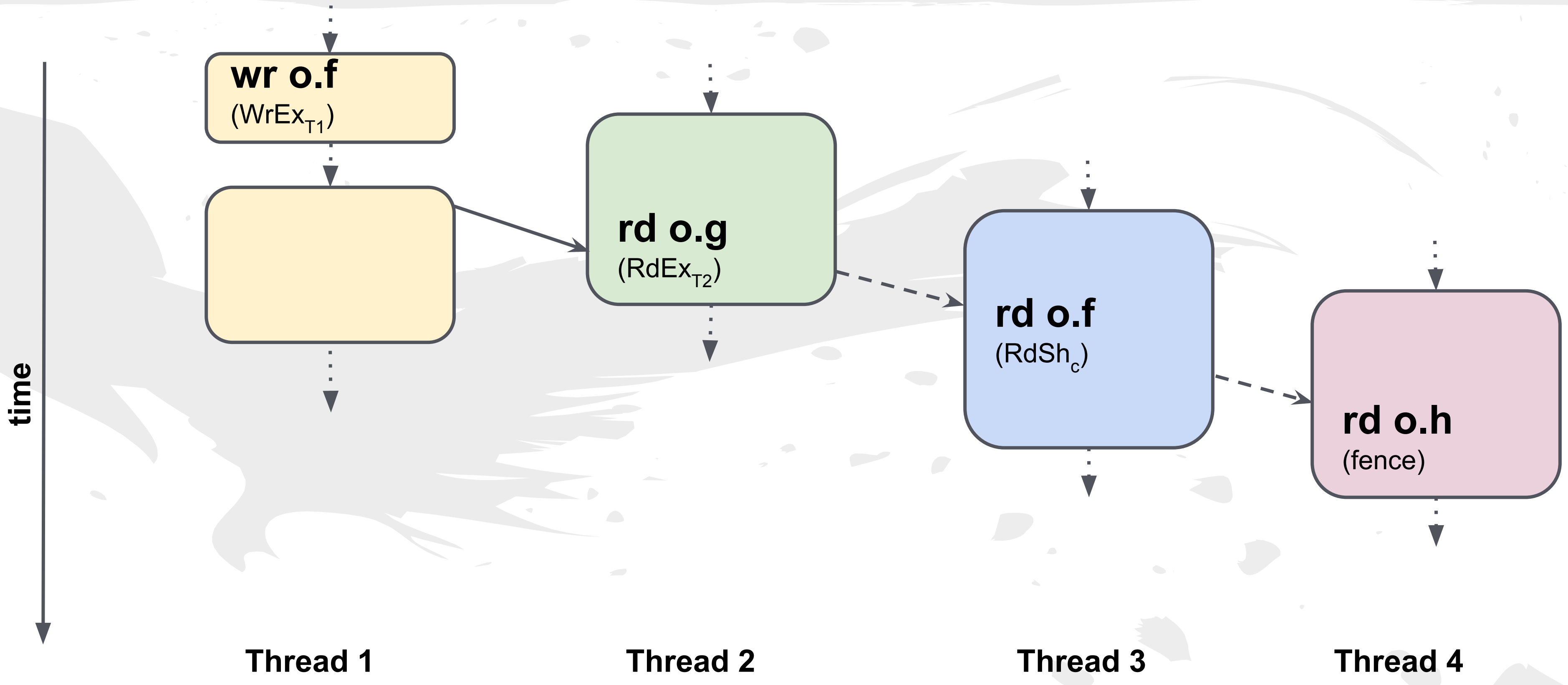
Imprecise Analysis



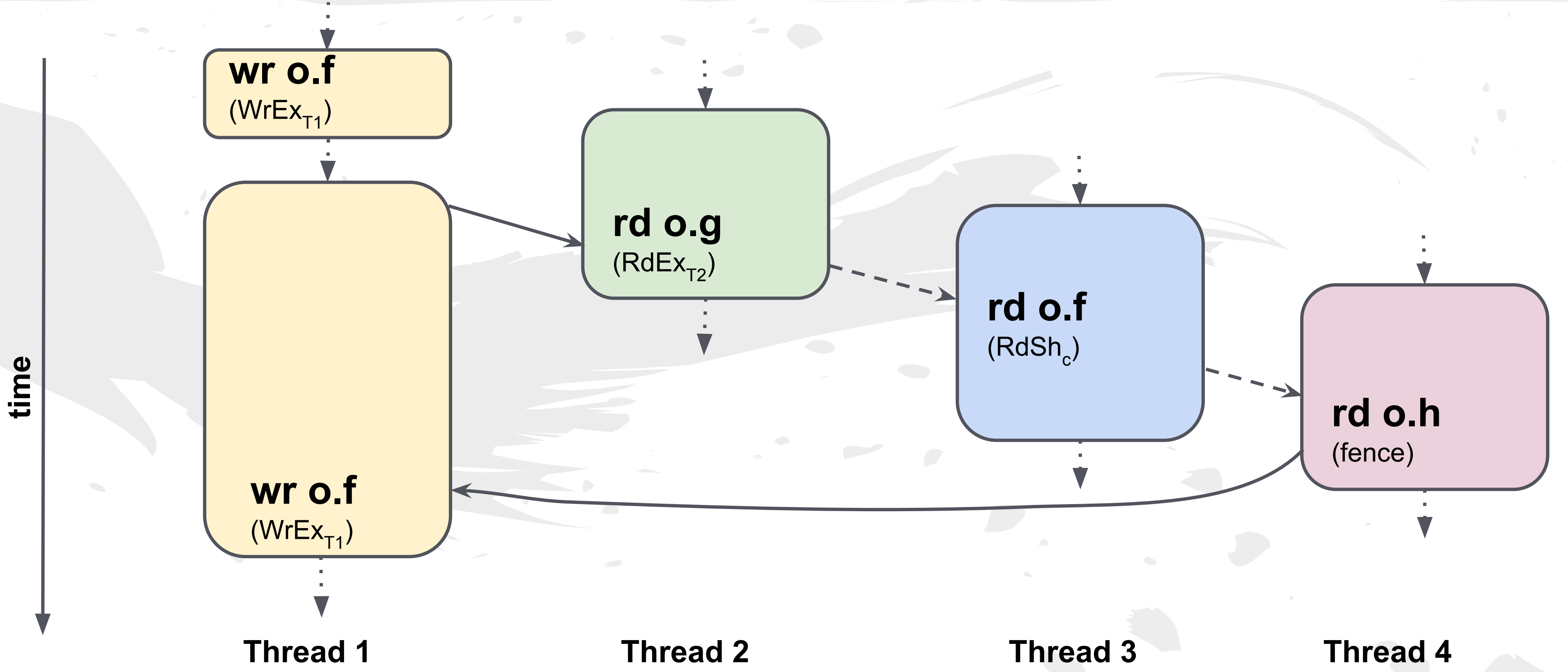
Imprecise Analysis



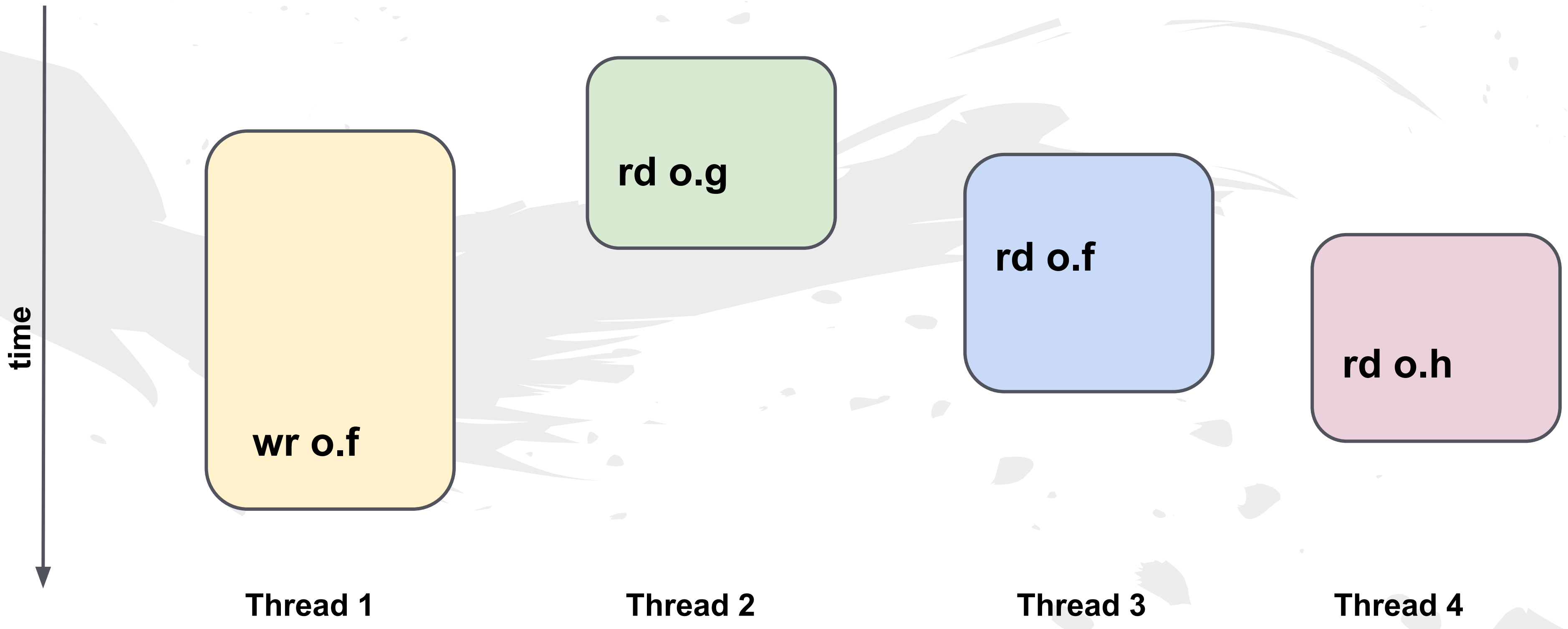
Imprecise Analysis



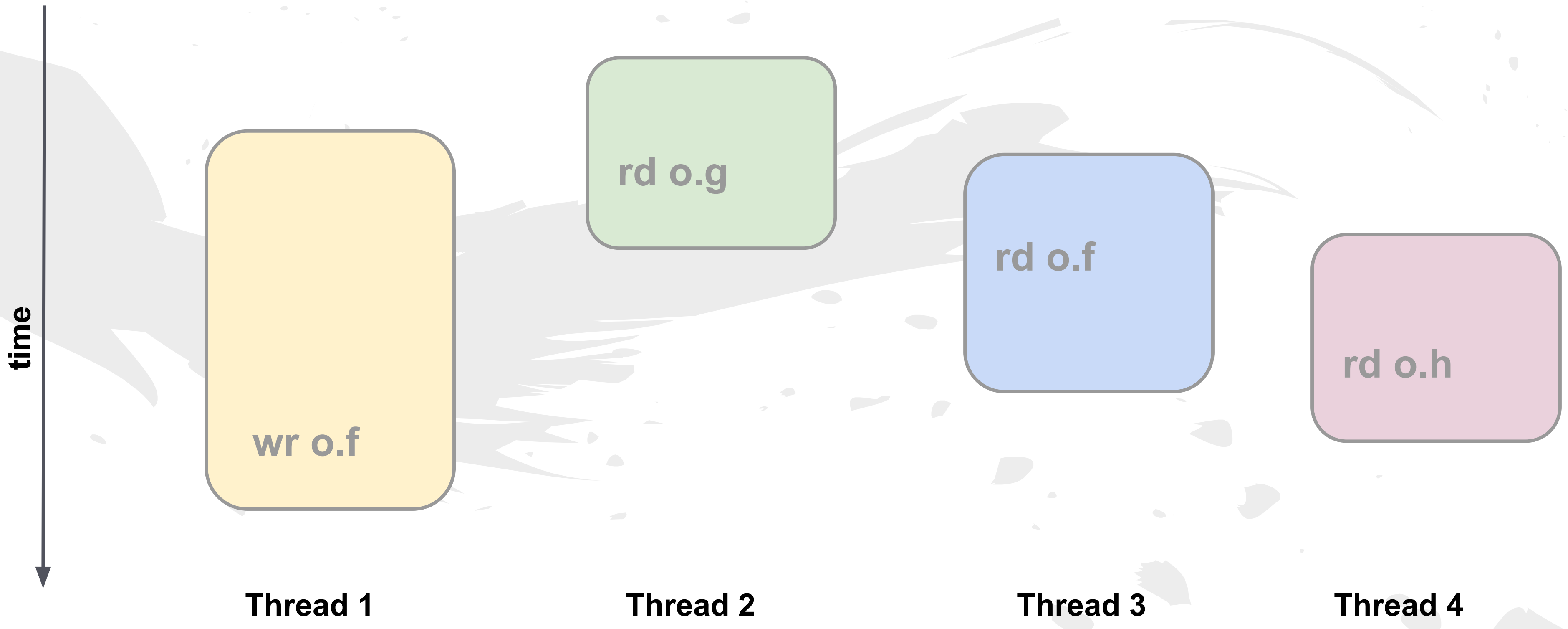
Imprecise Analysis



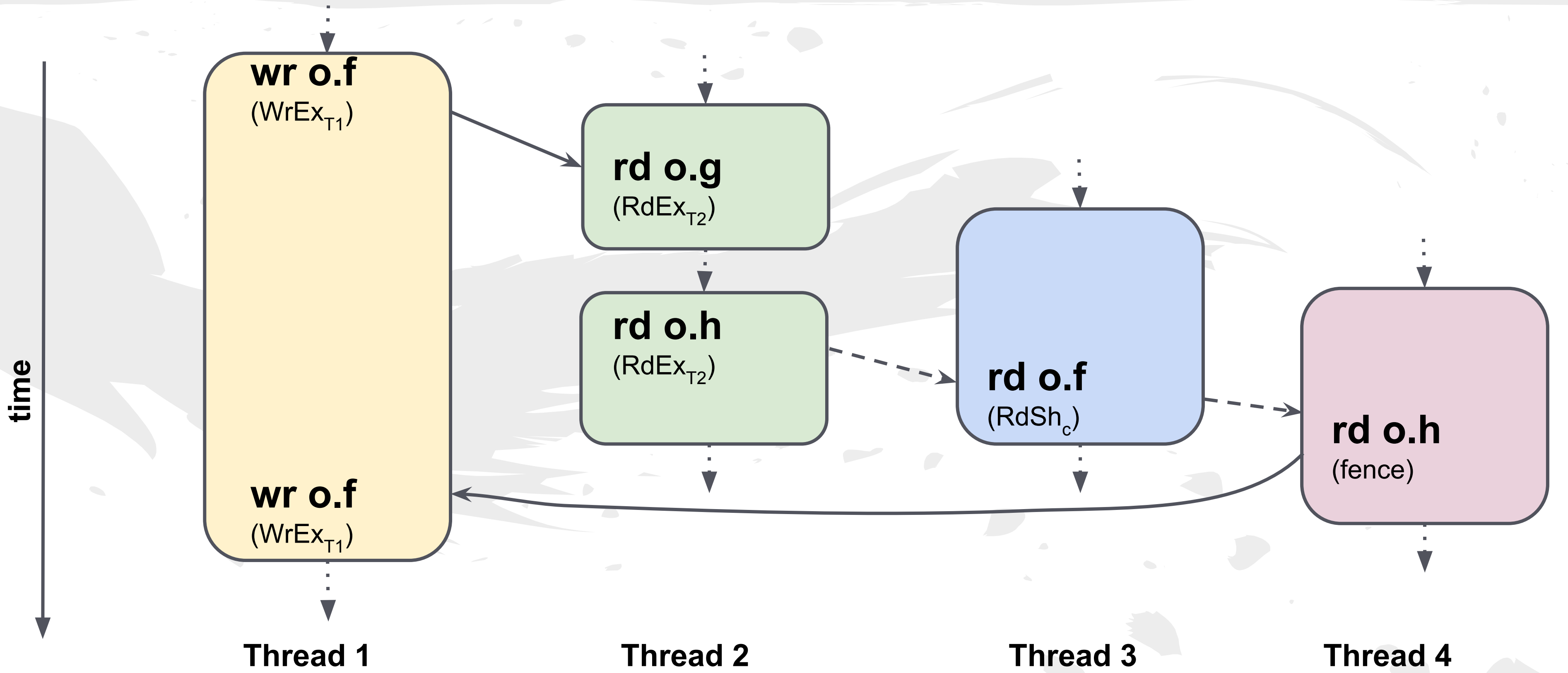
Imprecise Analysis



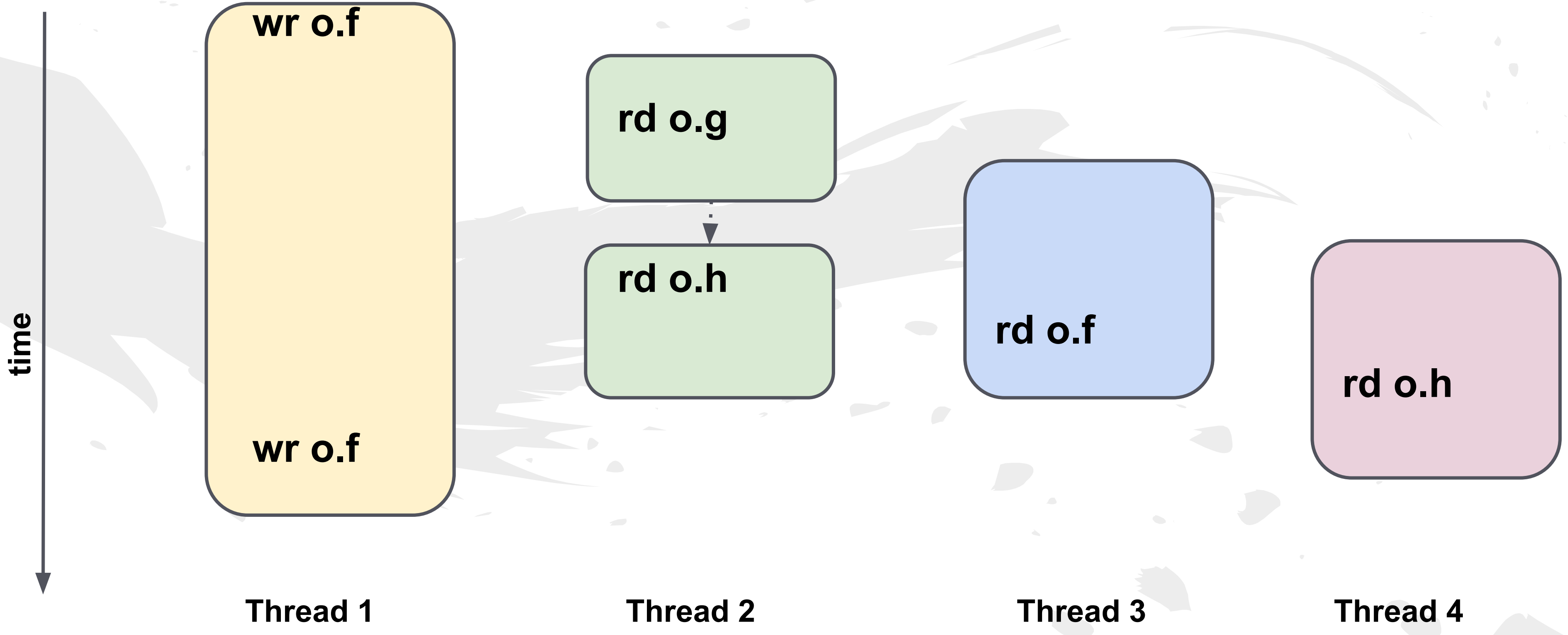
Precise Analysis



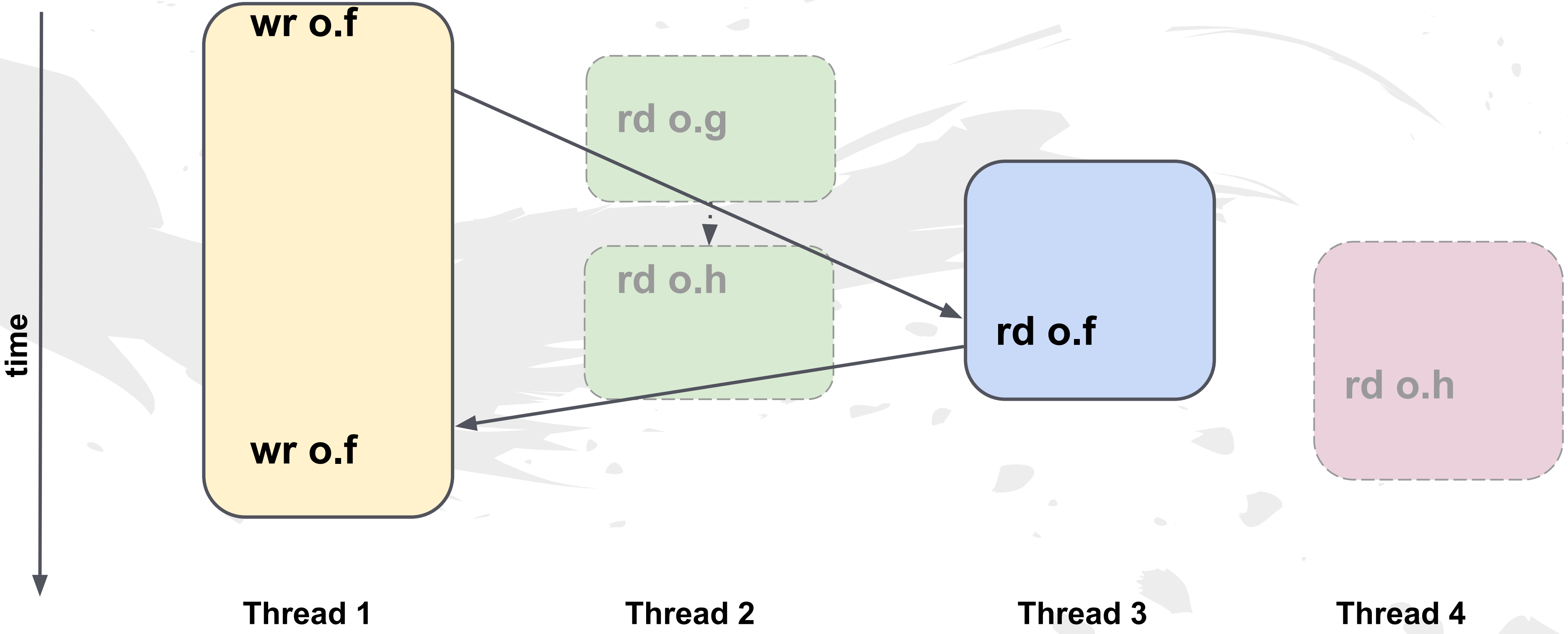
No Precise Violation


time
wr o.f
(WrEx T1)
rd o.g
(RdEx T2)
rd o.h
(RdEx T2)
rd o.f
(RdSh c)
rd o.h
(fence)
wr o.f
(WrEx T1)
Thread 1
Thread 2
Thread 3
Thread 4

ICD Cycle



Precise analysis



Precise Violation

Evaluation Methodology

- Implementation
- Atomicity specifications
- Experiments

Implementation

- DoubleChecker and Velodrome
  - Developed in **Jikes RVM 3.1.3**
  - Artifact successfully evaluated
  - Code shared on Jikes RVM Research Archive

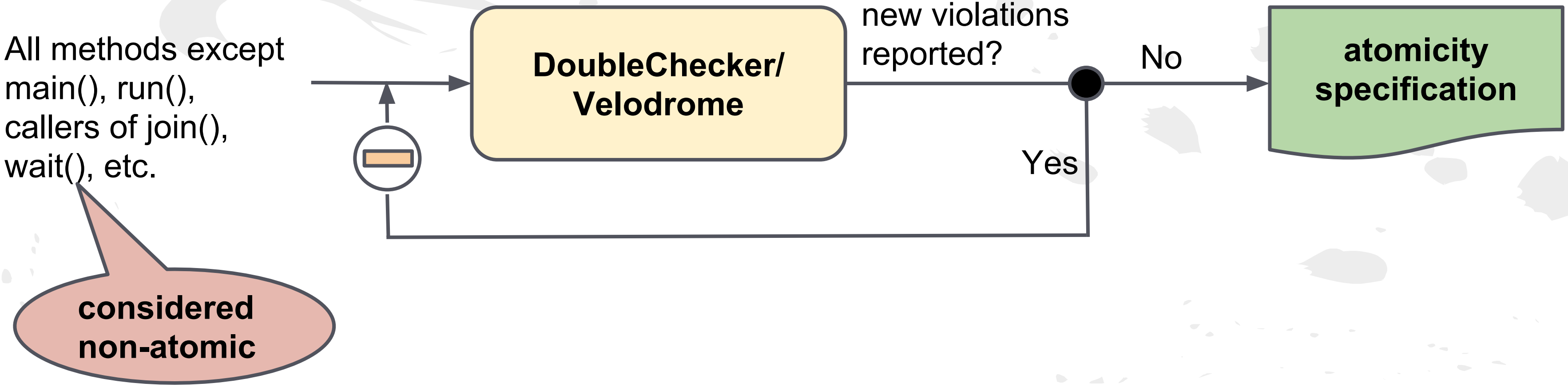
Experimental Methodology

- Benchmarks
  - DaCapo 2006, 9.12-bach, Java Grande, other benchmarks used in prior work[1]
- Platform: 3.30 GHz 4-core Intel i5 processor

1. C. Flanagan et al. Velodrome: A Sound and Complete Dynamic Atomicity Checker for Multithreaded Programs. In PLDI, 2008.

Atomicity Specifications

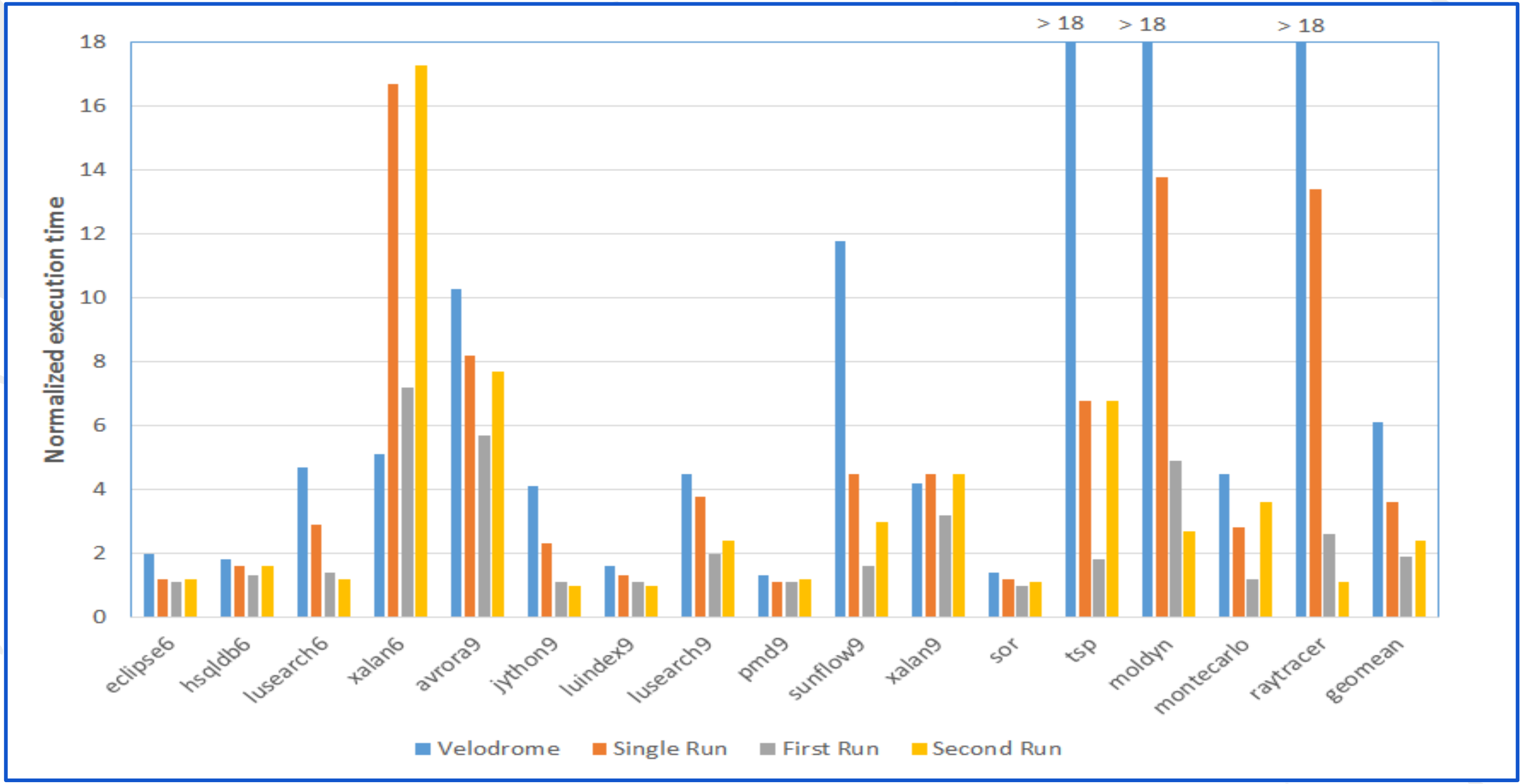
- Assume provided by the programmers
- We reuse prior work's approach to infer the specifications



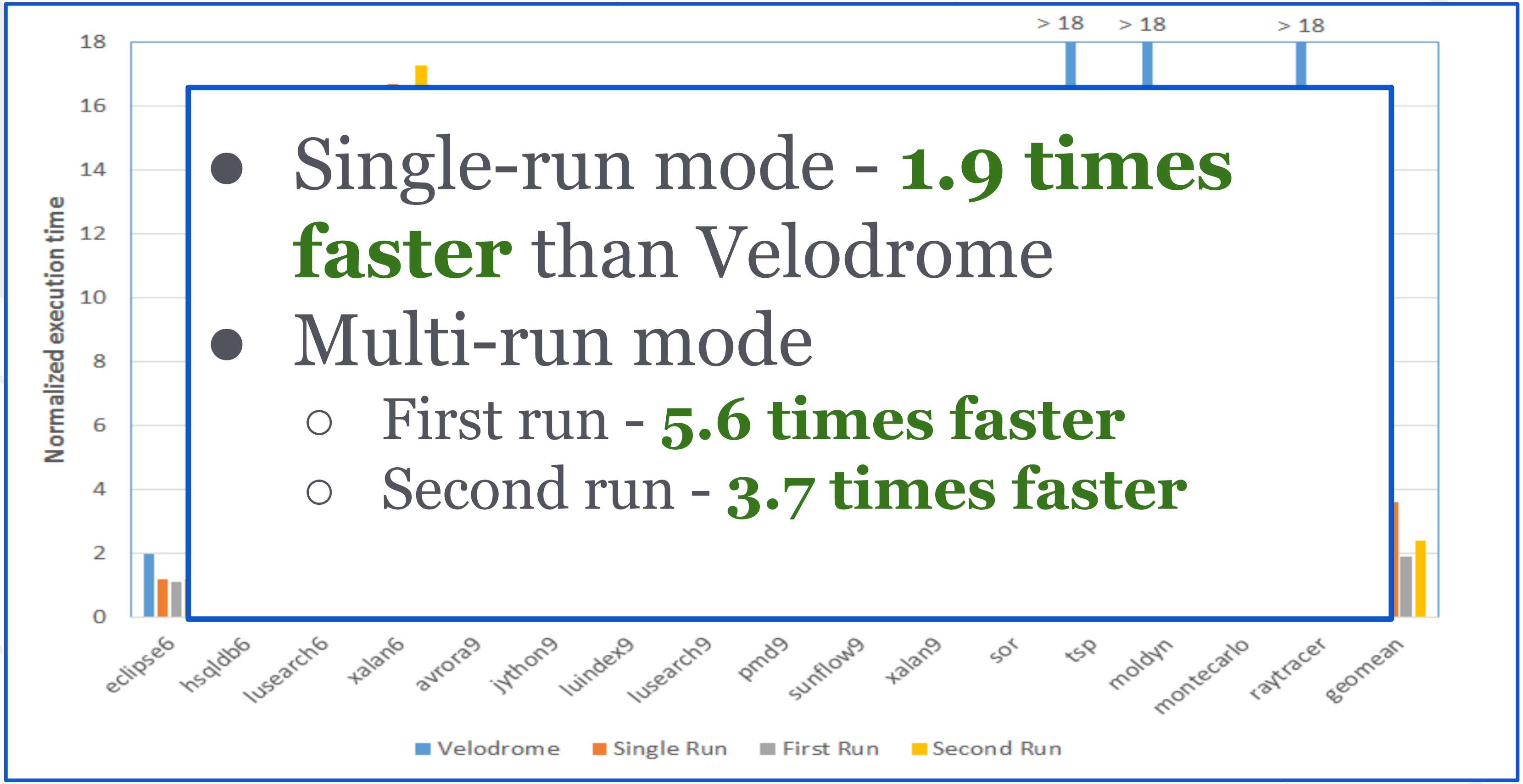
Soundness Experiments

- Generated atomicity violations with
  - Velodrome - sound and precise
  - DoubleChecker
    - Single-run mode - sound and precise
    - Multi-run mode - unsound
- Results match closely for Velodrome and the single-run mode
  - Multi-run mode finds 83% of all violations

Performance Experiments



Performance Experiments



- Single-run mode - **1.9 times faster** than Velodrome
- Multi-run mode
  - First run - **5.6 times faster**
  - Second run - **3.7 times faster**

DoubleChecker

- 2-4 times lesser overhead than current state-of-art
- Makes dynamic atomicity checking **more practical**

Related Work

- Type systems
  - Flanagan and Qadeer, PLDI 2003
  - Flanagan et al., TOPLAS 2008
- Model checking
  - Farzan and Madhusudan, CAV 2006
  - Flanagan, SPIN 2004
  - Hatcliff et al., VMCAI 2004

Related Work

- Dynamic analysis
  - Conflict-serializability-based approaches
    - Flanagan et al., PLDI 2008; Farzan and Madhusudan, CAV 2008
  - Inferring atomicity
    - Lu et al., ASPLOS 2006; Xu et al., PLDI 2005; Hammer et al., ICSE 2008
  - Predictive approaches
    - Sinha et al., MEMOCODE 2011; Sorrentino et al., FSE 2010
  - Other approaches
    - Wang and Stoller, PPoPP 2006; Wang and Stoller, TSE 2006

What Has DoubleChecker Achieved?

- **Improved overheads** over current state-of-art
  - Makes dynamic atomicity checking more practical
- **Cheaper to over-approximate dependences**
  - Showcases a judicious separation of tasks to recover precision