Dynamic Data-Race Prediction

Fundamentals, Theory and Practice

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- The tutorial is recorded using Zoom
- Streamed on '**ACM SIGPLAN**' YouTube channel
- Multiple sections with Q&A breaks after each section
- Please be muted outside Q&A
- If your question can't wait, raise hand in zoom
    - Click "Reactions", then "raise hand" (✋)
- You can also ask questions in chat
    - Zoom chat is disabled – use the clowdr chat in our tutorial's room
- Tutorial slides & related material accessible on the tutorial's web-page (on `popl21.sigplan.org`)

Outline

Introduction

Concurrency : Software and Challenges

- Ubiquitous in modern software

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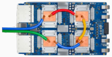
- Back-bone of big-data, AI revolutions



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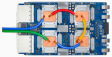

Challenging to write concurrent software

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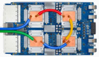

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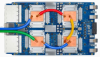
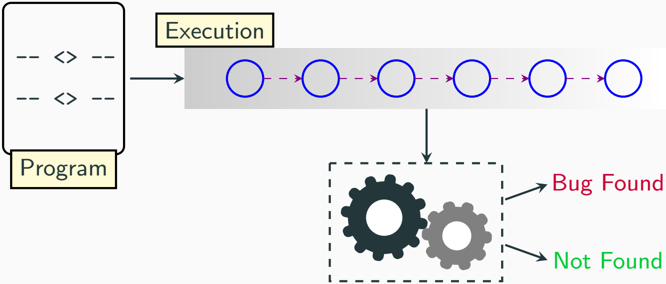


Challenging to write concurrent software

- Large interleaving space
- Concurrency bugs
  - data races, deadlocks, etc.,
  - manifest in production
  - despite rigorous testing
  - severe outcomes

Dynamic Analysis for Detecting Concurrency Bugs



What constitutes a good dynamic analysis?

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(3) High predictive power (not miss many bugs)

- high coverage.

This Tutorial

In this tutorial, we will discuss

- foundations of dynamic data race detection,
- recent algorithmic advances in effective race detection, and
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Preliminaries

Setting - Concurrent programs

```
public class Test extends Thread{

    static int x,y;
    static Object lock;
    public int id;

    @Override
    public void run() {
        if(id == 1){
            y = x + 5;
        }
        else{
            synchronized(lock){
                y = x + 10;
            }
        }
    }

    public static void main(String args[])
      throws Exception {
        final Test t1 = new Test();
        final Test t2 = new Test();
        t1.id = 1;
        t2.id = 2;
        t1.start();
        t2.start();
        t1.join();
        t2.join();
    }
}
```

Concurrent Program

- Threads
- Local variables
- Shared memory
- Synchronization constructs (locks)
- Sequential consistency

Setting: Execution Traces

- Sequences of events

	t_1	t_2
1	acq(ℓ)	
2	$r(x)$	
3	$w(y)$	
4		$r(x)$
5	rel(ℓ)	
6		acq(ℓ)
7		$w(y)$
8		acq(ℓ)

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- Event $e = \langle t, op \rangle$.

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Data Races

A data race in σ is a pair (e_1, e_2) of events such that

- e_1 and e_2 are conflicting
  - access same memory location x
  - at least one writes to x
- e_1 and e_2 are concurrent
  - e_1 and e_2 are simultaneously enabled in some prefix π of σ

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Execution σ'

Data race exists

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Execution σ'

Data race exists

Executions can be reordered to expose data races!

Which reorderings are allowed?

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Reordering 1 ✓

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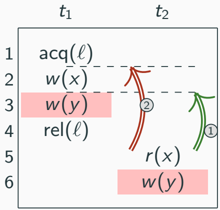

Reordering ① ✓

Reordering ② ✗

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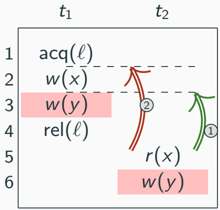


Reordering 1 ✓

Reordering 2 ✗

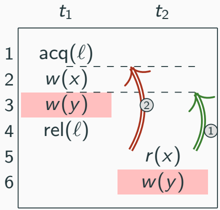
t_1	t_2

`synchronized(ℓ){`
`  x = 42;`
`  y = 1;`
`}`
	`if(x == 42){`
	`  y = 2;`
	`}`

Possible source program

(Initially, `x = 0`, `y = 0`)

Which reorderings are allowed?



Reordering 1 ✓

Reordering 2 ✗

t_1

```
synchronized(ℓ){
  x = 42;
  y = 1;
}
```

t_2

```
if(x == 42){
  y = 2;
}
```

Possible source program

(Initially, `x = 0`, `y = 0`)

Source agnostic analysis - some reorderings are not allowed

Formalizing Dynamic Predictive Analysis

Principle behind predictive analysis

A reordering σ^* of an observed execution σ is allowed if any program P that generates σ can also generate σ^*

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- Properties of concurrent objects and operations on them [HW90]
  - locks, shared variables, threads

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How do we formalize predictive analysis?

- Semantics of underlying programming language
- Properties of concurrent objects and operations on them [HW90]
  - locks, shared variables, threads
- Local determinism and prefix closedness [ŞCR13]

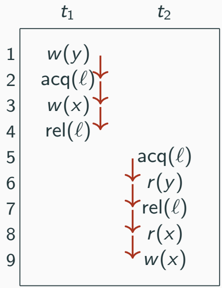
Some Notation

- Events_σ - set of events of σ.

	t_1	t_2
1	$w(y)$	
2	$\text{acq}(\ell)$	
3	$w(x)$	
4	$\text{rel}(\ell)$	
5		$\text{acq}(\ell)$
6		$r(y)$
7		$\text{rel}(\ell)$
8		$r(x)$
9		$w(x)$

Some Notation

- Events$_\sigma$ - set of events of σ.
- Thread order (a.k.a program order) $\leq^\sigma_{\mathsf{TO}}$



Some Notation

- Events_σ - set of events of σ.
- Thread order (a.k.a program order) $\leq^{\sigma}_{\mathsf{TO}}$
- Reads-from mapping $\mathcal{RF}_\sigma : \text{Reads}_\sigma \to \text{Writes}_\sigma$
  - $\mathcal{RF}_\sigma(e)$ is the last write event before e in σ that writes to the same memory location as x.
  - e reads the value written by $\mathcal{RF}_\sigma(e)$

	t_1	t_2
1	$w(y)$	
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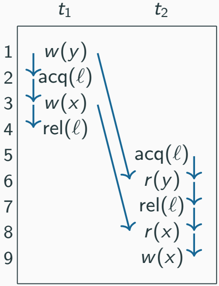
- $\leq^{\sigma}_{\text{TRF}} = (\leq^{\sigma}_{\text{TO}} \cup \mathcal{RF}^{-1}_\sigma)^+$



Correct Reordering

Correct Reordering [Sma+12]

A sequence σ^* is a correct reordering of trace σ if

1. σ^* is a well-formed trace
2. $\mathsf{Events}_{\sigma^*} \subseteq \mathsf{Events}_\sigma$
3. $\mathsf{Events}_{\sigma^*}$ is downward closed with respect $\leq^{\sigma}_{\mathsf{TRF}}$
4. $\leq^{\sigma^*}_{\mathsf{TO}} = \leq^{\sigma}_{\mathsf{TO}}|_{\mathsf{Events}_{\sigma^*}}$
5. $\mathcal{RF}_{\sigma^*} = \mathcal{RF}_\sigma|_{\mathsf{Events}_{\sigma^*}}$

Any program that can generate σ can generate all correct reorderings of σ

Data Race Prediction

A pair (e_1, e_2) in σ is a predictable data race if

- e_1 and e_2 are conflicting
- there is a correct reordering σ^* of σ, such that e_1 and e_2 are both σ-enabled in σ^*

	t_1	t_2
1	$r(x)$	
2	$\mathsf{acq}(\ell)$	
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If a program P has an execution with a predictable data race, then P has an execution with a data race

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Soundness and Completeness

Soundness

Completeness

Decision problem

$\mathcal{A}(\sigma) \in \{\text{YES}, \text{NO}\}$

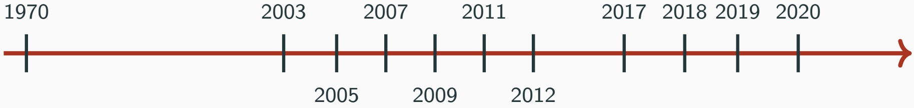
$\mathcal{A}$ is sound if

- whenever $\mathcal{A}(\sigma) = \text{YES}$, then σ has a predictable data race.

$\mathcal{A}$ is complete if

- $\mathcal{A}(\sigma) = \text{YES}$ whenever σ has a predictable data race.

History of Data Race Prediction



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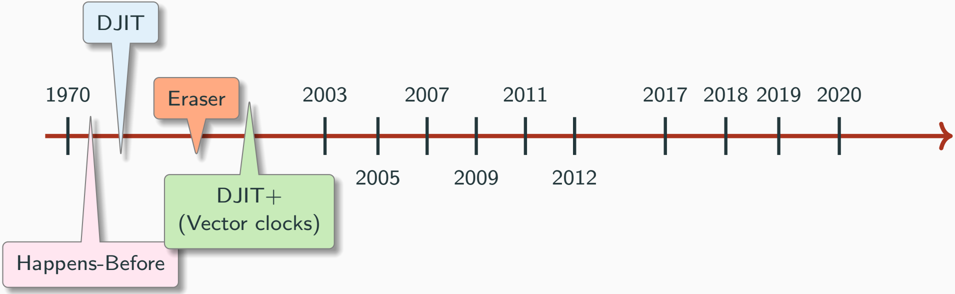

← Initial developments based on HB →

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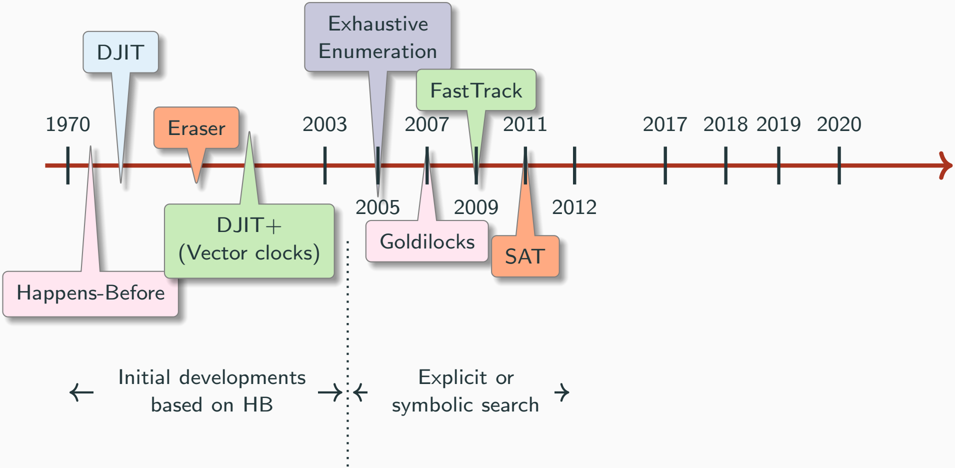

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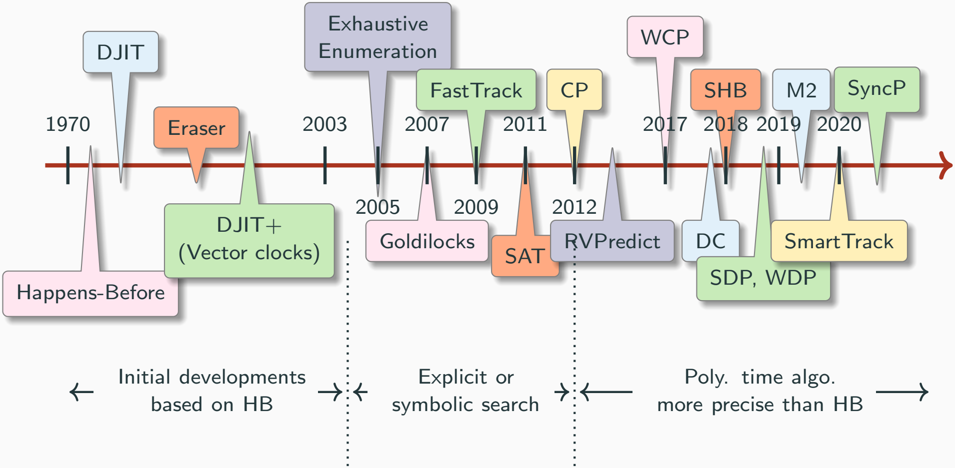

Eraser's lockset algorithm

Lockset principle (Eraser [Sav+97] style race detection):

Two events cannot be simultaneously enabled in any correct reordering if they are protected by a common lock.

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Unsound

Enumeration based techniques

- Data race prediction is in NP
    - Guess a sequence of events and check if it is a correct reordering having a race

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  - $O(\text{poly}(2^n))$

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- Symbolic techniques [Wan+09; Sai+11; HMR14]
  - Encode the existence of a correct reordering with race as a SAT/SMT constraint
  - $O(\text{SAT}(\text{poly}(n)))$

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  - Encode the existence of a correct reordering with race as a SAT/SMT constraint
  - $O(\text{SAT}(\text{poly}(n)))$
- Sound and complete, but don't scale

Happens-Before

For a trace σ, the happens-before relation on σ is the smallest partial order $\leq^{\sigma}_{\mathsf{HB}}$ such that

1. $\leq^{\sigma}_{\mathsf{TO}} \subseteq \leq^{\sigma}_{\mathsf{HB}}$,

	t_1	t_2	t_3
1	$\mathsf{acq}(\ell_1)$		
2	$w(x)$		
3	$\mathsf{rel}(\ell_1)$		
4		$\mathsf{acq}(\ell_1)$	
5		$\mathsf{acq}(\ell_2)$	
6		$\mathsf{rel}(\ell_2)$	
7			$\mathsf{acq}(\ell_2)$
8			$w(x)$
9		$\mathsf{rel}(\ell_1)$	
10			$\mathsf{rel}(\ell_2)$

For a trace σ, the happens-before relation on σ is the smallest partial order $\leq^{\sigma}_{\mathrm{HB}}$ such that

1. $\leq^{\sigma}_{\mathrm{TO}} \subseteq \leq^{\sigma}_{\mathrm{HB}}$,
2. for any lock ℓ and events $e_1 = \langle \cdot, \mathrm{rel}(\ell) \rangle$ and $e_2 = \langle \cdot, \mathrm{acq}(\ell) \rangle$ with $e_1 \leq^{\sigma}_{\mathrm{tr}} e_2$, $e_1 \leq^{\sigma}_{\mathrm{HB}} e_2$

	t_1	t_2	t_3
1	$\mathrm{acq}(\ell_1)$		
2	$w(x)$		
3	$\mathrm{rel}(\ell_1)$	HB	
4		$\mathrm{acq}(\ell_1)$	
5		$\mathrm{acq}(\ell_2)$	
6		$\mathrm{rel}(\ell_2)$	
7			$\mathrm{acq}(\ell_2)$
8			$w(x)$
9		$\mathrm{rel}(\ell_1)$	
10			$\mathrm{rel}(\ell_2)$

For a trace σ, the happens-before relation on σ is the smallest partial order $\leq_{\text{HB}}^{\sigma}$ such that

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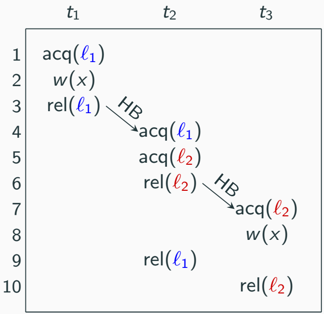

Happens-Before - Race Detection

HB-race : Pair of conflicting events (e_1, e_2) such that $e_1 \not\leq_{\mathsf{HB}} e_2$ and $e_2 \not\leq_{\mathsf{HB}} e_1$.

Soundness of HB

If a trace σ has an HB-race, then σ has a predictable data race.

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Soundness of HB

If a trace σ has an HB-race, then σ has a predictable data race.

Algorithm:

- Vector clock algorithm, single pass, streaming
- Linear time and constant space
- Implemented by most commercial race detectors - TSan [SI09], FastTrack [FF09], Helgrind, Intel Inspector, etc.,

Happens-Before - Predictive Power

	t_1	t_2
1	$w(x)$	
2	acq(ℓ)	
3	rel(ℓ)	
4		acq(ℓ)
5		rel(ℓ)
6		$w(x)$

HB

Happens-Before - Predictive Power

	t_1	t_2
1	$w(x)$	
2	acq(ℓ)	
3	rel(ℓ)	
4		acq(ℓ)
5		rel(ℓ)
6		$w(x)$

	t_1	t_2
1		acq(ℓ)
2		rel(ℓ)
3		$w(x)$
4	$w(x)$	
5	acq(ℓ)	
6	rel(ℓ)	

Witness correct reordering

Happens-Before - Predictive Power

	t_1	t_2
1	$w(x)$	
2	acq(ℓ)	
3	rel(ℓ)	
4		acq(ℓ)
5		rel(ℓ)
6		$w(x)$

Predictable race missed by HB

	t_1	t_2
1		acq(ℓ)
2		rel(ℓ)
3		$w(x)$
4	$w(x)$	
5	acq(ℓ)	
6	rel(ℓ)	

Witness correct reordering

Happens-Before - Predictive Power

	t_1	t_2
1	$w(x)$	
2	acq(ℓ)	
3	rel(ℓ)	
4		acq(ℓ)
5		rel(ℓ)
6		$w(x)$

Predictable race missed by HB

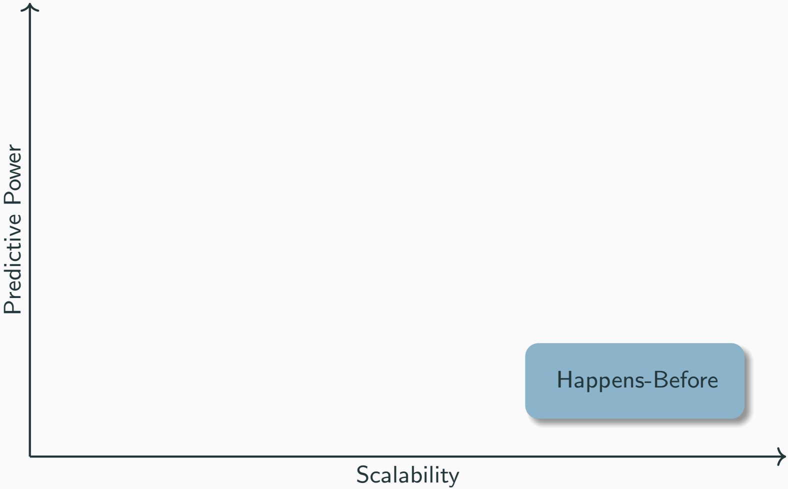
HB is conservative!

HB misses simple races
(Poor predictive power)

	t_1	t_2
1		acq(ℓ)
2		rel(ℓ)
3		$w(x)$
4	$w(x)$	
5	acq(ℓ)	
6	rel(ℓ)	

Witness correct reordering

Historical (Sound) Predictive Analysis



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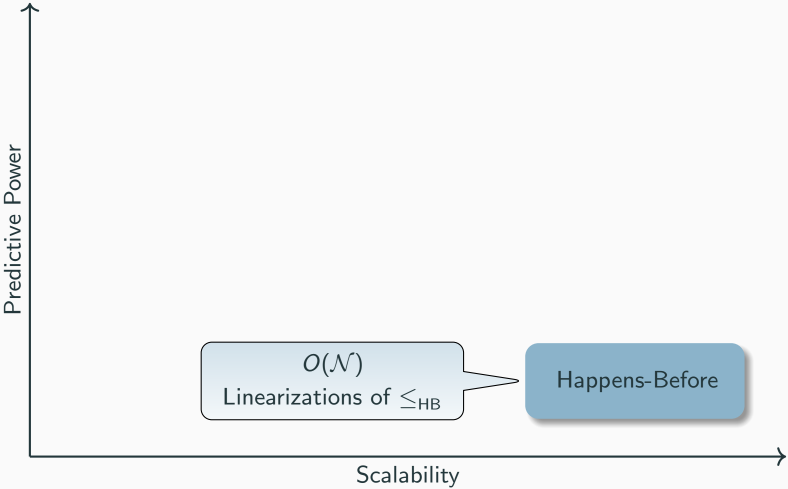

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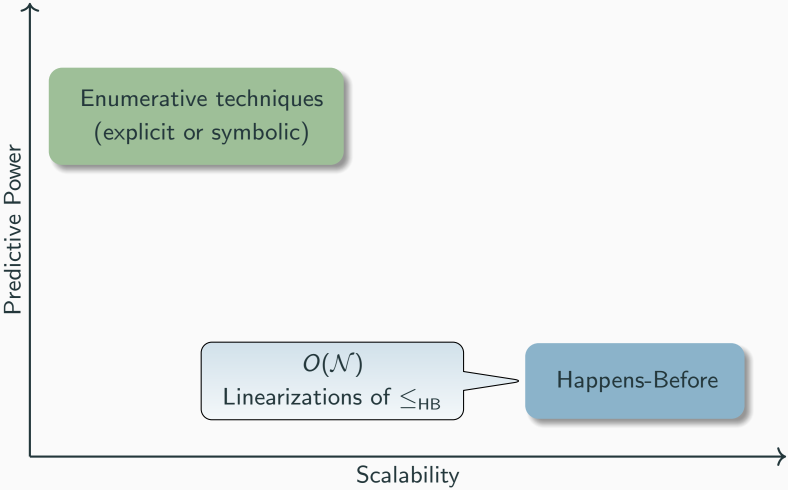

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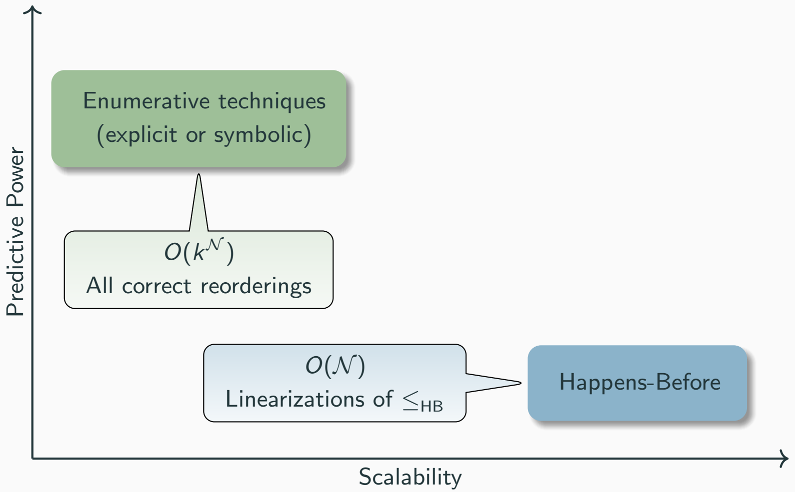

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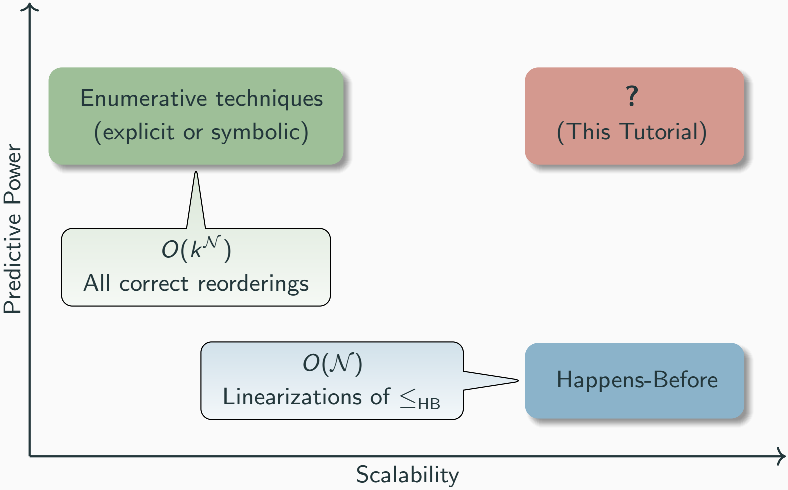

Schedulable Happens-Before

What happens after the first race?

Soundness Guarantee of HB

Soundness of HB

If a trace σ has an HB-race, then σ has a predictable data race.

Soundness Guarantee of HB

Soundness of HB

If a trace σ has an HB-race, then σ has a predictable data race.

	t_1	t_2
1	$r(x)$	
2	$w(y)$	
3		$r(y)$
4		$w(x)$

Execution

Soundness Guarantee of HB

Soundness of HB

If a trace σ has an HB-race, then σ has a predictable data race.

	t_1	t_2
1	$r(x)$	
2	$w(y)$	
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Execution

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1	$r(x)$	
2	$w(y)$	
3		$r(y)$
4		$w(x)$

Execution

Soundness of HB

If a trace σ has an HB-race, then σ has a predictable data race.

	t_1	t_2
1	$r(x)$	
2	$w(y)$	
3		$r(y)$
4		$w(x)$

Execution

t_1

```
y = x + 5;
```

t_2

```
if(y == 5){
  x = 10;
} else {
  while (true);
}
```

Possible Program
(Initially, `x = 0`, `y = 0`)

Soundness Guarantee of HB

Soundness of HB

If a trace σ has an HB-race, then σ has a predictable data race.

What it is

If σ has
an HB-race,
then σ has some
predictable race

Soundness Guarantee of HB

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If a trace σ has an HB-race, then σ has a predictable data race.

What it is

If σ has an HB-race, then σ has some predictable race

What it is NOT

If (e_1, e_2) is an HB-race in σ, then (e_1, e_2) is a predictable race

(More precise) Soundness Guarantee of HB

First HB-race : HB-race (e_1, e_2) such that there is no earlier HB-race in σ:

- for every HB-race (e_1', e_2'), either $e_2 \leq_{\text{tr}}^{\sigma} e_2'$, or $(e_2 = e_2'$ and $e_1' \leq_{\text{tr}}^{\sigma} e_1)$.

	t_1	t_2
1	$r(x)$	
2	$w(y)$	
3		$r(y)$
4		$w(x)$

More Precise Soundness of HB

If a trace σ has an HB-race, then the first HB-race in σ is a predictable data race.

What about other HB races?

- Not every HB-race is predictable.
- Deciding whether an arbitrary HB-race (e_1, e_2) is predictable is intractable
- What if we restrict to HB-respecting orderings?

Schedulable Happens-Before

For a trace σ, the **schedulable-happens-before** relation on σ is the smallest partial order $\leq^{\sigma}_{\mathsf{SHB}}$ such that

1. $\leq^{\sigma}_{\mathsf{HB}} \subseteq \leq^{\sigma}_{\mathsf{SHB}}$,
2. for events e_1, e_2 such that $\mathcal{RF}_{\sigma}(e_2) = e_1$, then $e_1 \leq^{\sigma}_{\mathsf{SHB}} e_2$

	t_1	t_2	t_3
1	acq(ℓ)		
2	rel(ℓ)		
3	$w(z)$		
4		acq(ℓ)	
5		rel(ℓ)	
6		$w(x)$	
7			$r(x)$
8			$w(z)$

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7			$r(x)$
8			$w(z)$

Beyond the First Race - Soundness of SHB

Soundness of SHB

Let (e_1, e_2) be an HB-race of σ. Then,

(e_1, e_2) is a predictable race witnessed by a HB-respecting correct reordering of σ

iff

there is no e_3 for which $e_1 \leq^{\sigma}_{\mathsf{SHB}} e_3 \leq^{\sigma}_{\mathsf{SHB}} e_2$ or $e_2 \leq^{\sigma}_{\mathsf{SHB}} e_3 \leq^{\sigma}_{\mathsf{SHB}} e_1$.

SHB Algorithm and Evaluation

Algorithm

- One pass, streaming algorithm
- Vector clock algorithm, similar to HB
- Can be easily implemented in existing HB-based race detectors.
- Linear time and constant space (like HB)

Evaluation

SHB Algorithm and Evaluation

Algorithm

- One pass, streaming algorithm
- Vector clock algorithm, similar to HB
- Can be easily implemented in existing HB-based race detectors.
- Linear time and constant space (like HB)

Evaluation

- Implemented in RAPID (`github.com/umangm/rapid`)
- Evaluated on standard benchmarks
- 50% fewer race reports than HB
- Most others were confirmed to be false positives
- Scales linearly (like HB)

Weak Causal Precedence

Predicting races beyond HB in linear time

Conservativeness of HB

	t_1	t_2
1	$w(x)$	
2	acq(ℓ)	
3	rel(ℓ) $\xrightarrow{\text{HB}}$	
4		acq(ℓ)
5		rel(ℓ)
6		$w(x)$

HB is conservative!

- HB orders all critical sections on the same lock

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	t_1	t_2
1	$w(x)$	
2	$\mathrm{acq}(\ell)$	
3	$\mathrm{rel}(\ell) \xrightarrow{\text{HB}}$	
4		$\mathrm{acq}(\ell)$
5		$\mathrm{rel}(\ell)$
6		$w(x)$

HB is conservative!

- HB orders all critical sections on the same lock
- Space of correct reorderings = linearizations of $\leq_{\mathrm{HB}}$
  - Linear time (scalability)
  - No false positives (soundness)

Conservativeness of HB

	t_1	t_2
1	$w(x)$	
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- Space of correct reorderings = linearizations of $\leq_{\text{HB}}$
  - Linear time (scalability)
  - No false positives (soundness)
- Does not reflect any 'hard' orderings
- Misses simple races

Tackling HB's Conservativeness

Can we relax some HB-orderings?

Tackling HB's Conservativeness

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- Naively $\implies$ infeasible reorderings

	t_1	t_2
1	$w(x)$	
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Can reorder critical sections

Tackling HB's Conservativeness

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Can reorder critical sections

	t_1	t_2
1	acq(ℓ)	
2	$w(x)$	
3	rel(ℓ)	
4		acq(ℓ)
5		$r(x)$
6		rel(ℓ)

Cannot reorder critical sections

Tackling HB's Conservativeness

Can we relax some HB-orderings?

- Naively $\implies$ infeasible reorderings
- Carefully $\implies$ expensive (?)

	t_1	t_2
1	$w(x)$	
2	acq(ℓ)	
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5		rel(ℓ)
6		$w(x)$

Can reorder critical sections

	t_1	t_2
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- Carefully $\implies$ expensive (?)

	t_1	t_2
1	$w(x)$	
2	$\mathsf{acq}(\ell)$	
3	$\mathsf{rel}(\ell)$	
4		$\mathsf{acq}(\ell)$
5		$\mathsf{rel}(\ell)$
6		$w(x)$

Can reorder critical sections

	t_1	t_2
1	$\mathsf{acq}(\ell)$	
2	$w(x)$	
3	$\mathsf{rel}(\ell)$	
4		$\mathsf{acq}(\ell)$
5		$r(x)$
6		$\mathsf{rel}(\ell)$

Cannot reorder critical sections

WCP effectively identifies when to (not) order critical sections

Weak Causal Precedence (WCP)

For a trace σ, $\prec^{\sigma}_{\mathsf{WCP}}$ is the smallest transitive order with the following properties:

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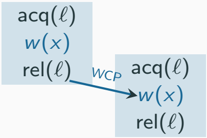

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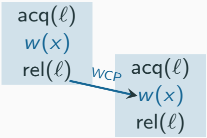

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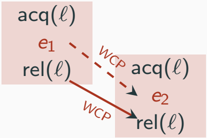

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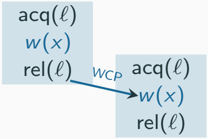

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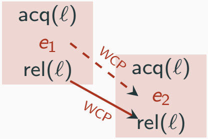
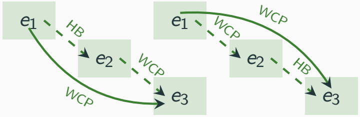


3. $\prec^{\sigma}_{\mathrm{WCP}}$ is closed under composition with $\leq^{\sigma}_{\mathrm{HB}}$:
   - $\leq^{\sigma}_{\mathrm{HB}} \circ \prec^{\sigma}_{\mathrm{WCP}} \subseteq \prec^{\sigma}_{\mathrm{WCP}}$
   - $\prec^{\sigma}_{\mathrm{WCP}} \circ \leq^{\sigma}_{\mathrm{HB}} \subseteq \prec^{\sigma}_{\mathrm{WCP}}$



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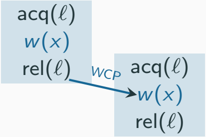

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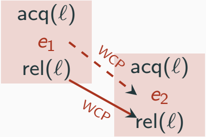

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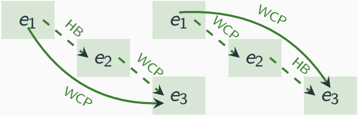

Finally, $\leq^{\sigma}_{\mathrm{WCP}} = \prec^{\sigma}_{\mathrm{WCP}} \cup \leq^{\sigma}_{\mathrm{TO}}$

Soundness of WCP

WCP-race : Pair of conflicting events (e_1, e_2) such that $e_1 \not\leq_{\mathsf{WCP}} e_2$ and $e_2 \not\leq_{\mathsf{WCP}} e_1$.

Soundness of WCP

If a trace σ has an WCP-race, then σ either has a **predictable data race** or a **predictable deadlock**.

WCP versus HB

Comparison with HB

WCP is strictly more predictive than HB:

- For every trace σ, $\leq^{\sigma}_{\mathsf{WCP}} \subseteq \leq^{\sigma}_{\mathsf{HB}}$. Thus, every HB-race is also a WCP-race.
- There is a trace σ for which $\leq^{\sigma}_{\mathsf{WCP}} \subsetneq \leq^{\sigma}_{\mathsf{HB}}$. Thus, WCP can catch races that HB can miss.

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Critical sections can be swapped
Race detected by WCP, missed by HB

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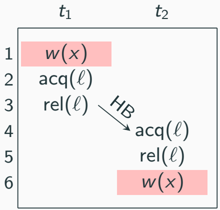

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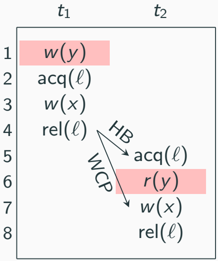

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WCP is strictly more predictive than HB:

- For every trace σ, $\leq^{\sigma}_{\mathrm{WCP}} \subseteq \leq^{\sigma}_{\mathrm{HB}}$. Thus, every HB-race is also a WCP-race.
- There is a trace σ for which $\leq^{\sigma}_{\mathrm{WCP}} \subsetneq \leq^{\sigma}_{\mathrm{HB}}$. Thus, WCP can catch races that HB can miss.

	t_1	t_2
1	$w(x)$	
2	acq(ℓ)	
3	rel(ℓ)	
4		acq(ℓ)
5		rel(ℓ)
6		$w(x)$

Critical sections can be swapped
Race detected by WCP, missed by HB

	t_1	t_2
1	$w(y)$	
2	acq(ℓ)	
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No predictable race

Race prediction using WCP

- Vector Clock algorithm
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> **WCP** detects more races than **HB** and runs in **linear time** (like HB)

Evaluating WCP

RAPID dynamic analysis framework

github.com/umangm/rapid

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Benchmarks [KMV17]

- 18 benchmark programs (Dacapo, Apache projects, IBM Contest suite, Java Grande Forum)
- Trace sizes- 50 to 216M

RAPID dynamic analysis framework

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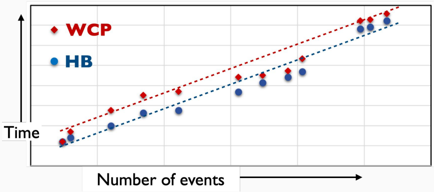

WCP scales linearly, like HB

Benchmarks [KMV17]

- 18 benchmark programs (Dacapo, Apache projects, IBM Contest suite, Java Grande Forum)
- Trace sizes- 50 to 216M

Technique	Races	Avg. Time
HB	182	144 s
WCP	**190**	**198 s**
SMT*	51	2258 s

* RVPREDICT (commercial race detector)

Fundamentals

What is the cost of a sound and complete algorithm?

Approaches So Far

- Existing sound and complete techniques take exponential time
- Search over the exponential space of correct reorderings
  - Explicit (enumerate all correct reorderings)
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Is exponential time necessary?

What Is The Search Space?

Recall our definition of a correct reordering

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3	rel(ℓ)	
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Subset trace

$\rightarrow$

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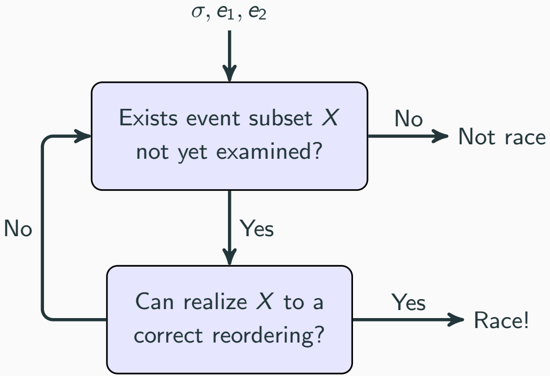
Witness = Choose event set + choose ordering

General Approach In Data Race Prediction



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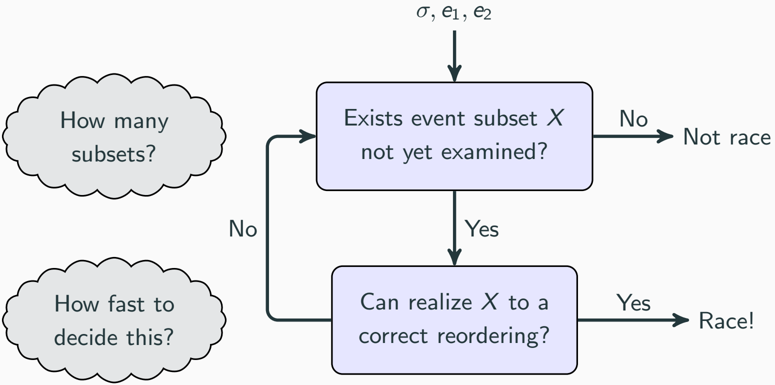

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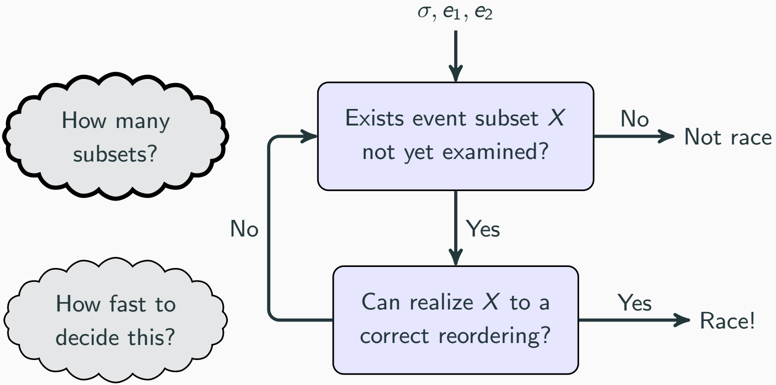

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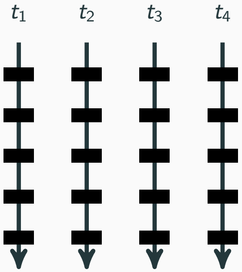
$\mathcal{N}$ events, $\mathcal{T}$ threads

- $2^{\mathcal{N}}$ subsets in general



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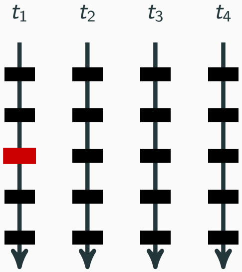

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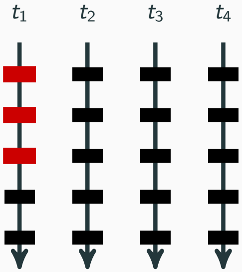

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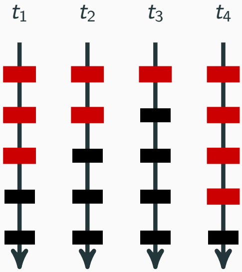

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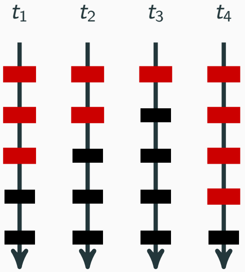
- $\mathcal{N}^{\mathcal{T}}$ event subsets suffice
- Polynomial for small $\mathcal{T}$



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How Much Time To Decide Realizability?

Realizability of RF-Posets

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Decide: Can we linearize $(X, <_P)$ to a trace σ^* such that $\mathcal{RF}_{\sigma^*} = \mathcal{RF}$?

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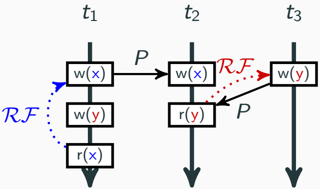

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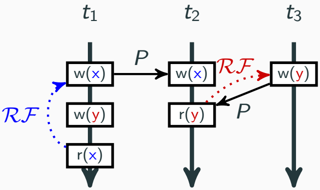

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Lemma

RF-Poset realizability can be decided in $O(\mathcal{T} \cdot \mathcal{N}^{\mathcal{T}})$.

Upper-bound

Theorem

Dynamic data-race prediction can be solved in $O(\mathcal{T} \cdot \mathcal{N}^{2 \cdot \mathcal{T}})$ time.

- $\mathcal{N}$ *events,* $\mathcal{T}$ *threads*

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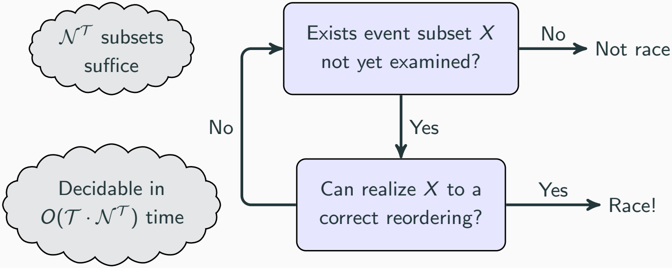

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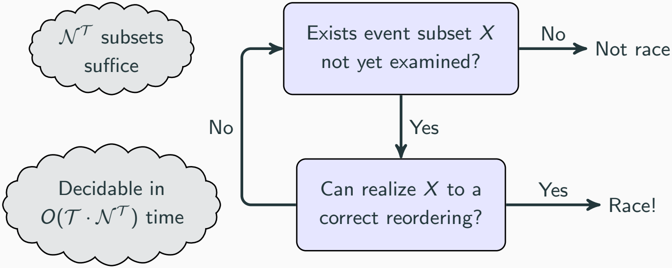

Can we do better? $O(\mathcal{N}^{O(1)})$? $O(2^{\mathcal{T}} \cdot \mathcal{N}^{O(1)})$?

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Data-race prediction is W[1]*-hard parameterized by the number of threads* $\mathcal{T}$.

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- NP-hard when $\mathcal{T} = \Omega(\mathcal{N})$
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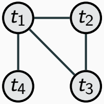
Other meaningful parameterizations that make race prediction tractable?

Acyclic Communication Topologies

Communication Topology

An undirected graph $G = (V, E)$

- $V = \{t_1, \ldots, t_T\}$ is the set of threads
- $(t_i, t_j) \in E$ if t_i, t_j communicate over shared variables/locks



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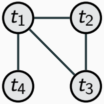

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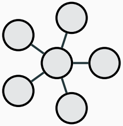
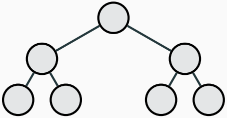
Focus on acyclic topologies



Sever-clients

Pipeline



Divide and concquer

RF-Poset Closure

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1. For every read r and conflicting write w
   - if $w <_P r$ then $w <_P \mathcal{RF}(r)$
   - if $\mathcal{RF}(r) <_P w'$ then $r <_P w'$

$$\begin{tikzcd}
\mathcal{RF}(r) \arrow[dd] & \\
& w \arrow[dl] \arrow[ul, dashed] \\
r &
\end{tikzcd}
\qquad\qquad
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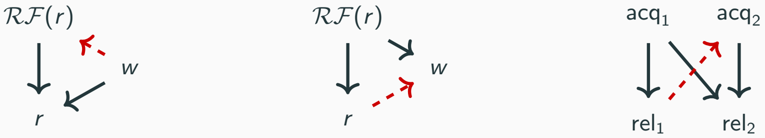
2. For every two critical sections $\mathrm{acq}_1 \ldots \mathrm{rel}_1$ and $\mathrm{acq}_2 \ldots \mathrm{rel}_2$ on the same lock
   - if $\mathrm{acq}_1 <_P \mathrm{rel}_2$ then $\mathrm{rel}_1 <_P \mathrm{acq}_2$



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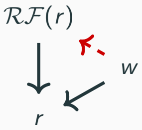

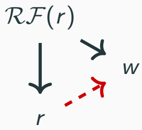

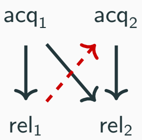

How fast can we compute the closure?

Complexity of Closure

Lemma

The closure of an RF-Poset can be computed in $O(\mathcal{T}^2 \cdot V \cdot \mathcal{N}^2 \cdot \log \mathcal{N})$ *time.*

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Acyclic Topology

Upper-Bound On Acyclic Topologies

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Dynamic data-race prediction over acyclic communication topologies can be solved in $O(\mathcal{T}^2 \cdot V \cdot \mathcal{N}^2 \cdot \log \mathcal{N})$ time.

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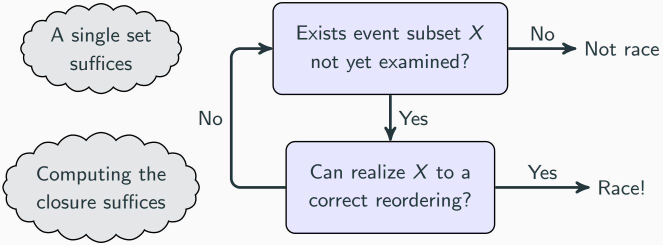

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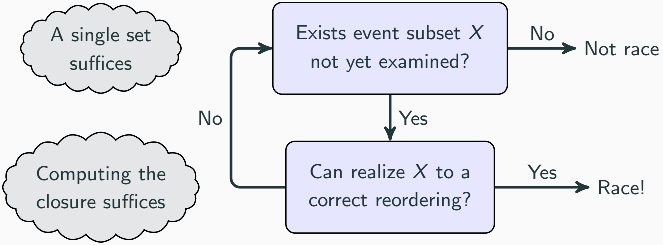

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Lower-Bound On Acyclic Topologies

Theorem (Quadratic hardness of race prediction)

Consider traces σ over

- $\mathcal{T} = 2$ *threads*
- $V = 8$ *variables*
- *a single lock*

For any fixed $\epsilon > 0$, data race prediction over σ has no $O(\mathcal{N}^{2-\epsilon})$ algorithm.

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Optimality for acyclic topologies

- Recall our bound $O(\mathcal{T}^2 \cdot V \cdot \mathcal{N}^2 \cdot \log \mathcal{N})$
- Nearly optimal for moderate number of threads and variables ($\mathcal{T}, V = \text{polylog}(\mathcal{N})$)

In Summary

	General	Acyclic Topologies
Upper-bound	$O(\mathcal{T} \cdot \mathcal{N}^{2 \cdot \mathcal{T}})$	$O(\mathcal{T}^2 \cdot V \cdot \mathcal{N}^2 \cdot \log \mathcal{N})$
Lower-bound	W[1]-hard	No $O(\mathcal{N}^{2-\epsilon})$

- $\mathcal{N}$ events
- $\mathcal{T}$ threads
- V variables/locks

M2

Turning complete theory into (almost) complete practice

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	t_1	t_2	t_3
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2	$\mathsf{acq}(\ell)$		
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7		$r(y)$	
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9			$w(x)$
10			$w(y)$
11			$\mathsf{rel}(\ell)$
12		$r(x)$	
13		$\mathbf{e_2}$	

Choosing The Event Set

Witness = **Choose event set** + choose ordering

Heuristic: close all critical sections not containing e_1 and e_2

Choose X as the smallest set so that

1. X contains all $<_{\mathsf{TO}}$ predecessors of e_1, e_2
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Only 1 event subset

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3	$w(x)$		
4	$\mathbf{e_1}$		
5	$\mathsf{rel}(\ell)$		
6		$w(y)$	
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3. No open critical sections except those containing e_1, e_2

Only 1 event subset

If $\{e_1, e_2\} \cap X \neq \varnothing$ report "No race"

	t_1	t_2	t_3
1	$w(y)$		
2	$\mathrm{acq}(\ell)$		
3	$w(x)$		
4	$\mathbf{e_1}$		
5	$\mathrm{rel}(\ell)$		
6		$w(y)$	
7		$r(y)$	
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9			$w(x)$
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Constructing The Witness

Witness = Choose event set + **choose ordering**

Constructing The Witness

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Recall our solution for rf-poset realizability on acyclic topologies

Lemma

The closure of an RF-Poset can be computed in $O(\mathcal{T}^2 \cdot V \cdot \mathcal{N}^2 \cdot \log \mathcal{N})$ *time.*

Cycle

Not realizable

No Cycle

May be realizable

Realizable under extra conditions

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Cycle → Not realizable

No Cycle → May be realizable → Realizable under extra conditions

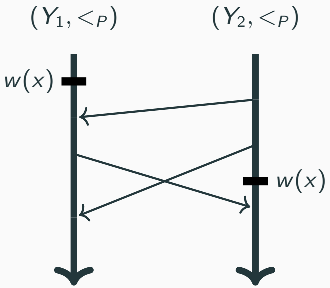
MaxMin **Linearizations**

Theorem (MaxMin **Linearizations)**

Take a closed rf-poset $(X, P, \mathcal{RF})$ where X is partitioned into Y_1, Y_2, where

1. $(Y_1, <_P)$ *is a total order*
2. $(Y_2, <_P)$ *orders all conflicting writes.*

Then $(X, P, \mathcal{RF})$ is realizable.



M2

Algorithm: M2

Input: A trace σ, a conflicting pair (e_1, e_2)

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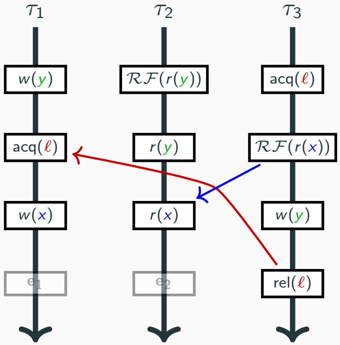
Start with a partial order $\rightarrow$

(a) $\mathcal{RF}_\sigma(r) \rightarrow r$ for every read r

(b) $\mathsf{rel}_1 \rightarrow \mathsf{acq}_2$ if acq_2 does not close



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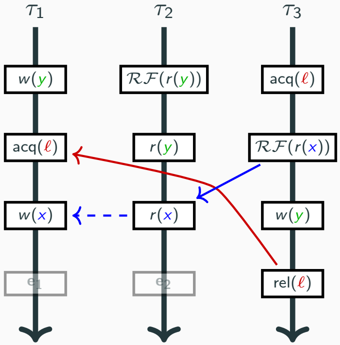
Close $\rightarrow$



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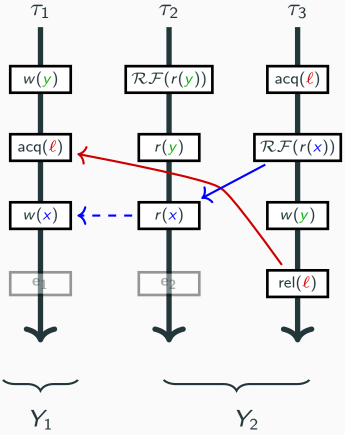
Close $\rightarrow$

Let Y_1 be all events in the thread of e_1

and Y_2 all other events



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Close $\rightarrow$

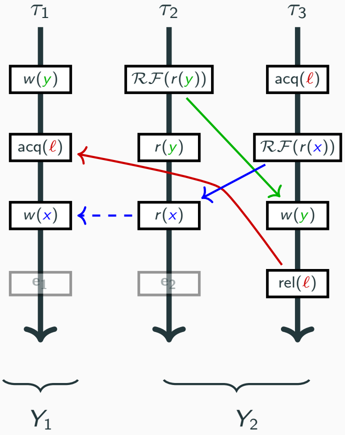
Let Y_1 be all events in the thread of e_1

and Y_2 all other events

while $\exists \overline{w}_1, \overline{w}_2 \in Y_{\neq i}$ *conflicting and unordered* **do**

| Order $\overline{e}_1, \overline{e}_2$ in σ as in σ, then close $\rightarrow$

end



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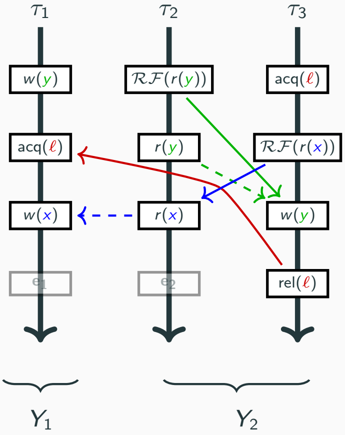


Algorithm: M2

Input: A trace σ, a conflicting pair (e_1, e_2)

Start with a partial order $\to$

(a) $\mathcal{RF}_\sigma(r) \to r$ for every read r

(b) $\mathsf{rel}_1 \to \mathsf{acq}_2$ if acq_2 does not close

Close $\to$

Let Y_1 be all events in the thread of e_1

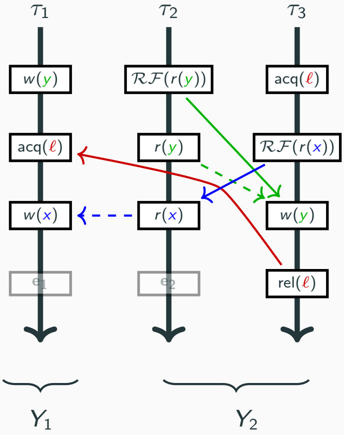
and Y_2 all other events

while $\exists \overline{w}_1, \overline{w}_2 \in Y_{\neq i}$ *conflicting and unordered* **do**

Order $\overline{e}_1, \overline{e}_2$ in σ as in σ, then close $\to$

end

Use MaxMin to linearize $\to$ to a witness σ^*



M2 **Illustration**

	t_1	t_2	t_3
1	$w(y)$		
2	$\mathrm{acq}(\ell)$		
3	$w(x)$		
4	$\mathbf{e_1}$		
5	$\mathrm{rel}(\ell)$		
6		$w(y)$	
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Input trace

$\longrightarrow$ M2 $\longrightarrow$

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11	$\mathbf{e_1}$	$\mathbf{e_2}$	

Correct reordering

	t_1	t_2	t_3
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10	$w(x)$		
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Correct reordering

Theorem

M2 *makes sound predictions of data races with complexity* $O(\mathcal{T}^2 \cdot V \cdot \mathcal{N}^4 \cdot \log \mathcal{N})$.

- *For* $\mathcal{T} = 2$ *threads,* M2 *is also complete.*

Experiments

Benchmark	Size	HB	WCP	DC	SHB	**M2**
		Races	**Races**	**Races**	**Races**	**Races**
`critical`	49	3	3	3	8	
`airtickets`	116	3	3	3	4	
`account`	125	1	1	1	1	
`pingpong`	126	2	2	2	2	
`bbuffer`	322	2	2	2	2	
`mergesort`	3K	1	1	1	1	
`bubblesort`	4K	4	4	5	6	
`raytracer`	16K	3	3	3	3	
`ftpserver`	48K	23	23	24	23	
`moldyn`	164K	2	2	2	2	
`derby`	1M	12	12	12	12	
`jigsaw`	3M	8	10	10	9	
`bufwriter`	11M	2	2	2	2	
`hsqldb`	18M	4	4	5	9	
`cryptorsa`	57M	5	5	7	5	
`eclipse`	86M	33	34	39	54	
`xalan`	122M	7	7	9	11	
`lusearch`	216M	30	30	30	52	
Total	**514M**	**145**	**148**	**160**	**206**	

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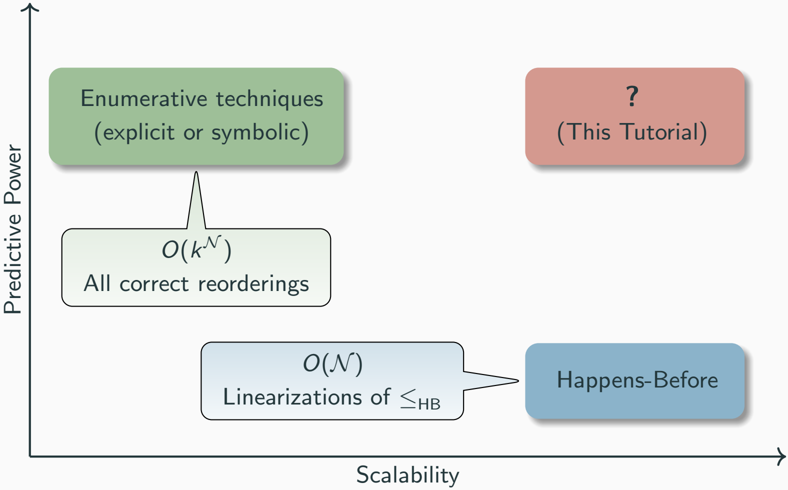
Times	HB	WCP	DC	SHB	**M2**
Total	42m0s	34m14s	3h39m	40m31s	1h15m

Conclusion

Wrap-up and a small teaser

Advances in Predictive Analysis (This Tutorial)



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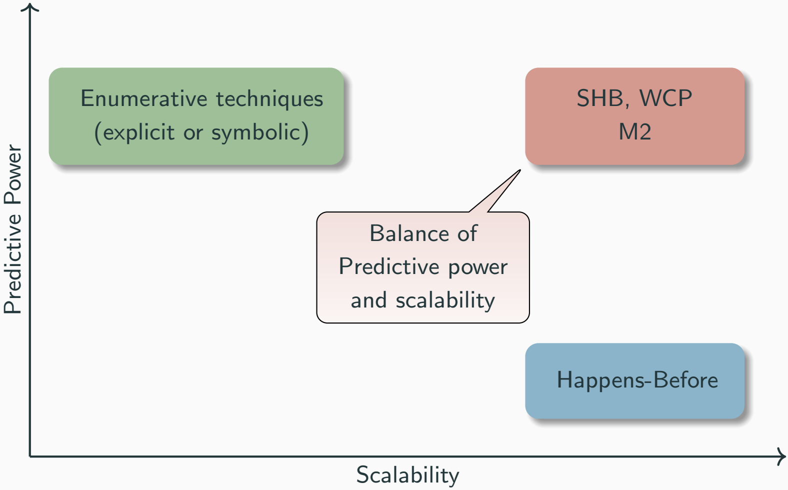

Other Recent Works

- Doesn't commute (DC) [RGB18]
- SDP, WDP [Gen+19]
- WDC [RGB20]
- DigHR [Luo+18]
- All unsound - soundness is a challenge

Open Challenges

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1. Most efficient race detection

- The most efficient detectors must operate in linear time
- Challenge: Sound, linear-time + as precise as possible

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- Relax the $\mathcal{RF}$ function to be based on values

Open Challenges

1. Most efficient race detection

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- Challenge: Sound, linear-time + as precise as possible

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- Relax the $\mathcal{RF}$ function to be based on values

3. Other Violations

- Data races are the most well studied
- Deadlocks?
- Atomicity?
- ...

Open Challenges (Cont.)

4. Relaxed Memory Models

More permissive reorderings $\rightarrow$ more data races

Open Challenges (Cont.)

4. Relaxed Memory Models

More permissive reorderings $\rightarrow$ more data races

5. Mixing Paradigms

- Mixing shared memory and message passing becomes the norm
  - E.g., in Go lang
- Concurrent data structures

Open Challenges (Cont.)

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More permissive reorderings $\rightarrow$ more data races

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  - E.g., in Go lang
- Concurrent data structures

6. More benchmarks

- DaCapo
- JavaGrande
- SIR
- ...
- new?

Synchronization-Preserving Races

- HB principle: "do not reorder critical sections"
- Not complete for this principle
- Here a race is missed
- Exposed without reordering critical sections

	t_1	t_2
1	$\mathbf{w}(\mathbf{x})$	
2	acq(ℓ)	
3	rel(ℓ)	
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6		$\mathbf{w}(\mathbf{x})$

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6		$\mathbf{w}(\mathbf{x})$

HB

What is the cost of a complete algorithm for this principle?

U. Mathur, A. Pavlogiannis, and M. Viswanathan. "Optimal Prediction of Synchronization-Preserving Races". In: POPL '21. To Appear. 2021

Tune in for the POPL talk!

- Watch the talk https://app.clowdr.org/conference/popl2021/item/6709324c-cd56-4d26-b2b3-266fa5e668f5
- Q&A on Thu 21 Jan 16:00 - 17:00 (CET): Concurrency (Shared Memory) at POPL-B

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U. Mathur, A. Pavlogiannis, and M. Viswanathan. "Optimal Prediction of Synchronization-Preserving Races". In: POPL '21. To Appear. 2021.

Other Related Literature II

- J. Roemer, K. Genç, and M. D. Bond. "High-coverage, Unbounded Sound Predictive Race Detection". In: *Proceedings of the 39th ACM SIGPLAN Conference on Programming Language Design and Implementation*. PLDI 2018. ACM, 2018, pp. 374–389.
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Thank You!