Program Analysis

Analyzing Concurrent Programs (Part 4)

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Outline

1. **Introduction**
2. **Dynamic Data Race Detection**
3. **Testing Thread-Safe Classes**
4. **Exploring Interleavings** 

Mostly based on these papers:

- *Eraser: A Dynamic Data Race Detector for Multithreaded Programs*, Savage et al., ACM TOCS, 1997
- *Fully Automatic and Precise Detection of Thread Safety Violations*, Pradel and Gross, PLDI 2012
- *Finding and Reproducing Heisenbugs in Concurrent Programs*, Musuvathi et al., USENIX 2008

Scheduling Non-Determinism

- A single program executed with a single input may have many different interleavings
- Scheduler decides interleavings non-deterministically
- Some interleavings may expose bugs, others execute correctly ("Heisenbugs")
- Challenge: How to explore different interleavings? How to detect buggy interleavings?

CHESS in a Nutshell

- **A user mode scheduler that controls all scheduling non-determinism**
- **Guarantees:**
  - Every program run takes a new thread interleaving
  - Can reproduce the interleaving for every run
- **Systematic but non-exhaustive exploration of the set of possible interleavings**

Tree of Interleavings

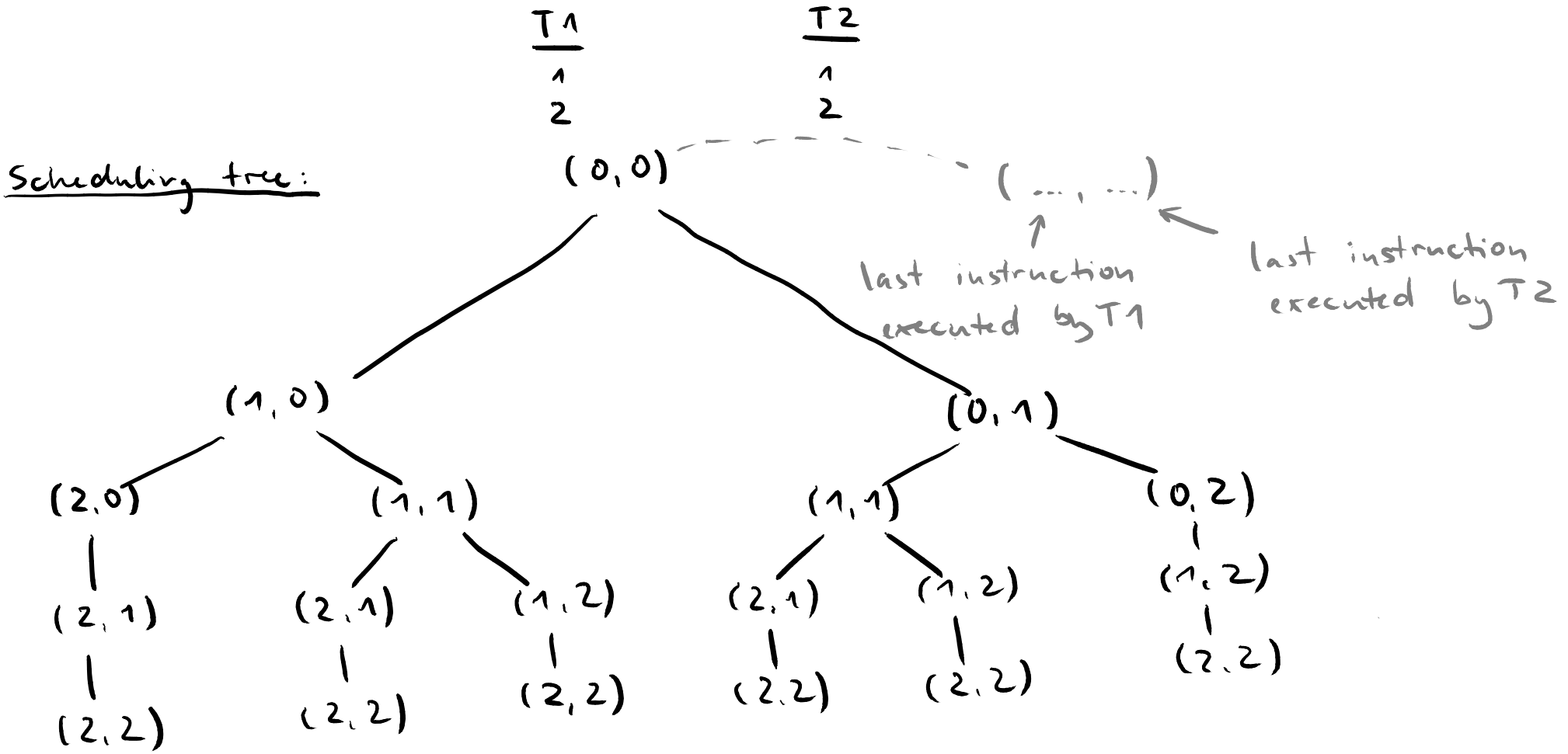
- **Search space** of possible interleavings: Represent as a **tree**
- Node = points of **scheduling decision**
- Edge = decisions taken
- Each **path** = one **possible schedule**

Example

```
// bank account
int balance = 10;
```


```
// deposit money
int tmp1 = balance;
balance = tmp1 + 5;
```

```
// withdraw money
int tmp2 = balance;
balance = tmp2 - 7;
```


T1
1
2
T2
1
2
Scheduling tree:
(0,0)
(..., ...)
last instruction executed by T1
last instruction executed by T2
(1,0)
(0,1)
(2,0)
(1,1)
(1,1)
(0,2)
(2,1)
(2,1)
(1,2)
(2,1)
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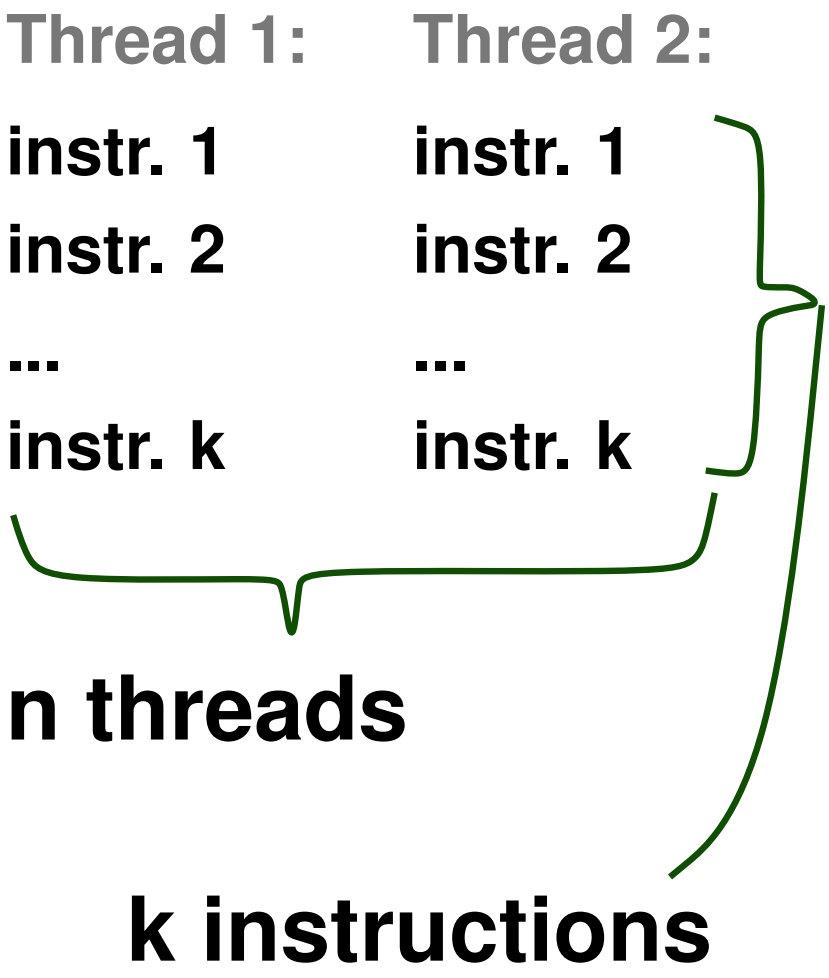
State Space Explosion



- Number of interleavings: $\mathcal{O}(n^{n \cdot k})$
- Exponential in both n and k
  - Typically: $n < 10$, $k > 100$
- Exploring all interleavings does not scale to large programs (i.e., large k)

Preemption Bounding

- Limit exploration to schedules with a small number c of preemptions
  - Preemption = Context switches forced by the scheduler
- Number of schedules: $\mathcal{O}((n^2 \cdot k)^c \cdot n!)$
  - Exponential in c and n, but not in k
- Based on empirical observation: Most concurrency bugs can be triggered with few (< 2) preemptions

Implementation and Results

- Implemented via binary instrumentation
- Applied to eight mid-size and large systems (up to 175K lines of code),
- Found a total of 27 bugs
- Major benefit over stress testing: Once a failure is detected, can easily reproduce and debug it

Other Ways to Control Scheduling

- **Randomly** delay concurrency-related operations
- **Heuristics**, e.g., based on known bug patterns or programmer annotations
- **Active testing**: Find potential bugs and then bias scheduler toward confirming them