Parallel Bug-finding in Concurrent Programs via Reduced Interleaving Instances*

Truc L. Nguyen[1], **Peter Schrammel**[2],
Salvatore La Torre[4], Gennaro Parlato[1] Bernd Fischer[3]

[1] University of Southampton, United Kingdom
[2] University of Sussex, United Kingdom
[3] Stellenbosch University, South Africa
[4] Universita degli Studi di Salerno, Italy

* published at ASE'17

UNIVERSITY OF Southampton

UNIVERSITY OF SUSSEX

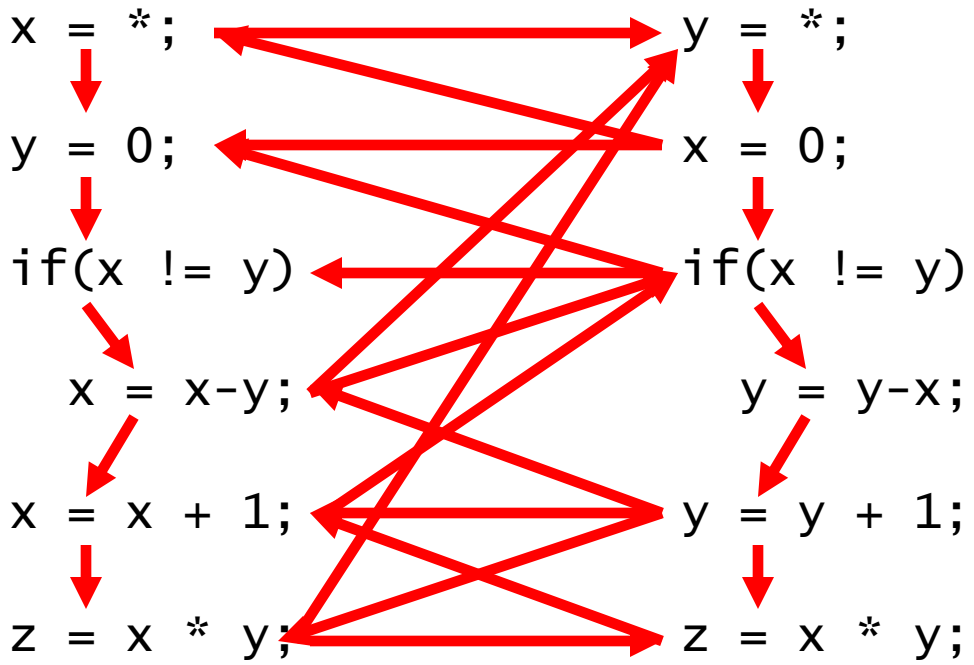
UNIVERSITÀ DEGLI STUDI DI SALERNO

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

Concurrency makes bug finding harder.

UNIVERSITY OF SUSSEX

State space explosion (i.e., large number of interleavings):



(… and many more)

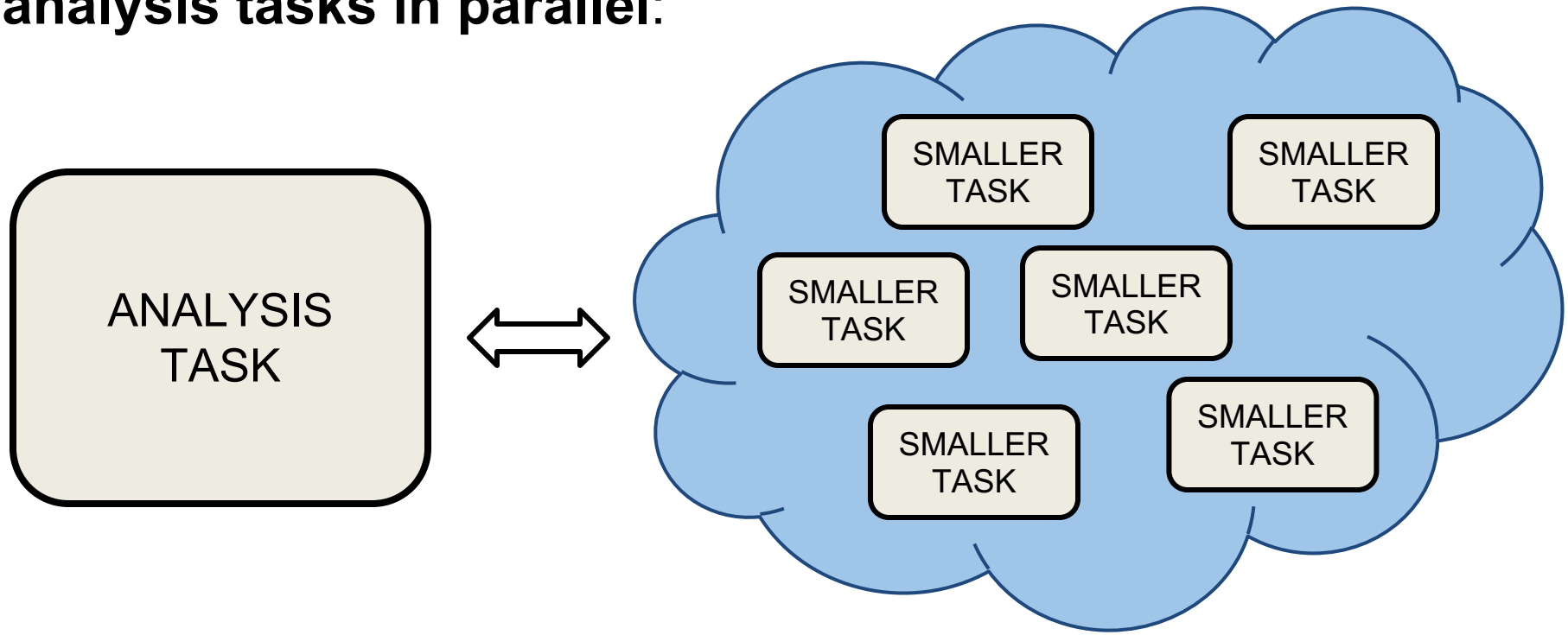
Problem: modern hardware means concurrency is everywhere

$\Rightarrow$ software is increasingly concurrent

Concurrency makes bug finding *easier*.

UNIVERSITY OF SUSSEX

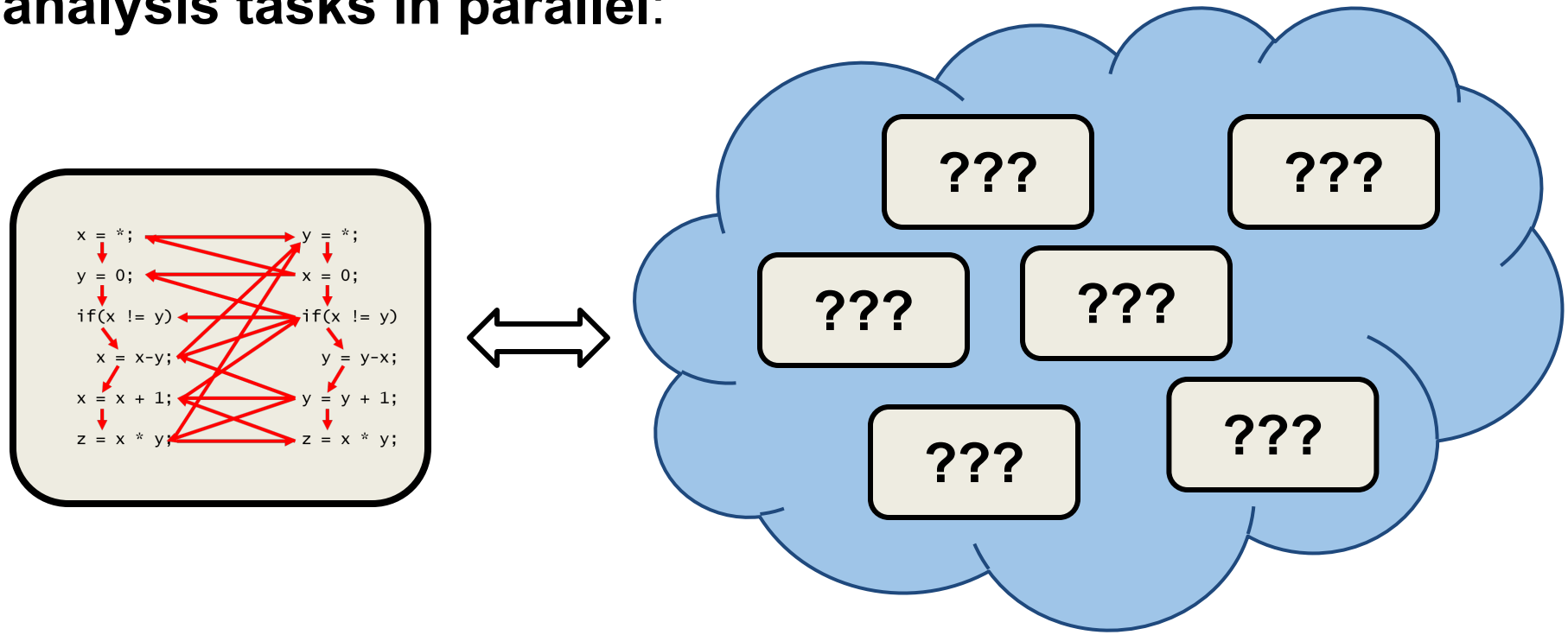
Concurrent hardware allows us to **run many (smaller) analysis tasks in parallel**:



Concurrency makes bug finding *easier*.

UNIVERSITY OF SUSSEX

Concurrent hardware allows us to **run many (smaller) analysis tasks in parallel**:



How can we partition a task into **independent smaller** tasks?

Strategy competition vs. task competition

UNIVERSITY OF SUSSEX

Strategy competition: run **different settings** on **same task**

(**first counterexample** "wins" and aborts other tasks)

Swarm Verification Techniques

Gerard J. Holzmann, Rajeev Joshi, and Alex Groce

"anticipate the appearance of systems with large numbers of CPU cores, but without matching increases in clock speeds… describe a model checking strategy that leverages this trend"

Abs
the
bene
in p
systems. For the near-term future, we can anticipate the appearance of systems with large numbers of CPU cores, but without matching increases in clockspeeds. We will describe a model checking strategy that can allow us to leverage this trend, and that allows us to tackle significantly larger problem sizes than before.

Index Terms—software engineering tools and techniques, logic model checking, distributed algorithms, software verification.

This talk:

Task competition: run **same prover** (setting) on **different tasks**

⇒ How can we partition a task into **independent smaller** tasks?

Problem decomposition

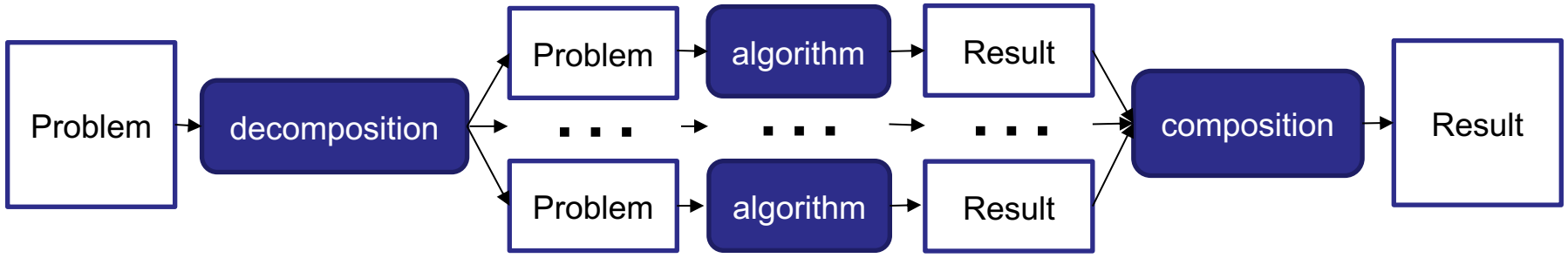
UNIVERSITY OF SUSSEX

Compositional Safety Refutation Techniques

Kumar Madhukar[1,3], Peter Schrammel[2], and Mandayam Srivas[3]

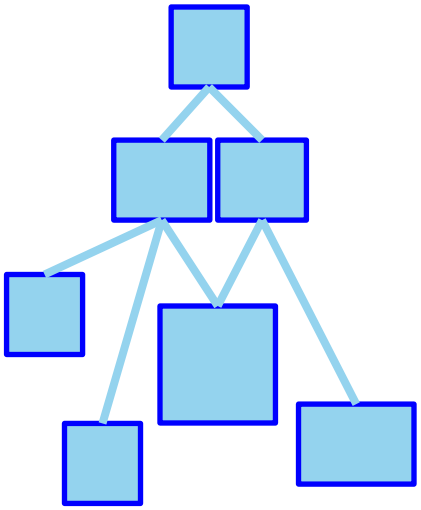
[1] TCS Research, Pune, India
[2] University of Sussex, School of Engineering and Informatics, Brighton, UK
[3] Chennai Mathematical Institute, Chennai, India

Abstract. One of the most successful techniques for refuting safety properties is to find counterexamples by bounded model checking. However, for large programs, bounded model checking instances often exceed the limits of resources available. Generating such counterexamples in a modular way could speed up refutation, but it is challenging because of the inherently non-compositional nature of these counterexamples. We start from the monolithic safety verification problem and present a step



Problem decomposition

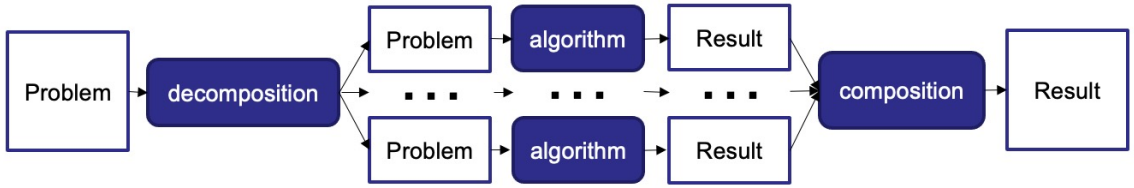
UNIVERSITY OF SUSSEX



Compositional Safety Refutation Techniques

Kumar Madhukar[1,3], Peter Schrammel[2], and Mandayam Srivas[3]

[1] TCS Research, Pune, India
[2] University of Sussex, School of Engineering and Informatics, Brighton, UK
[3] Chennai Mathematical Institute, Chennai, India

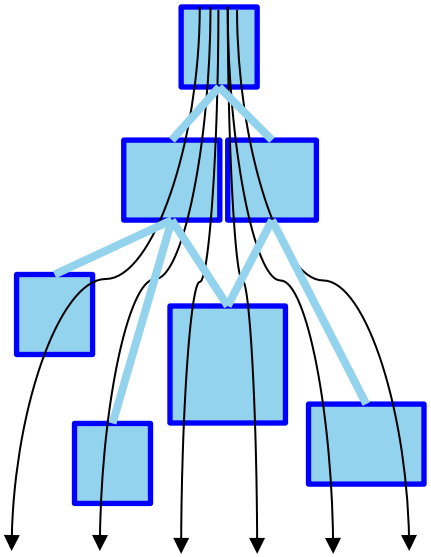


Horizontal/hierarchical decomposition, i.e. component-wise:

- E.g. Rely-guarantee, etc
- Easy for verification, difficult for refutation

Problem decomposition

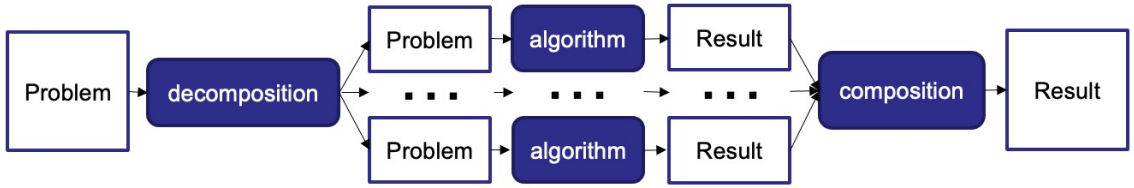
UNIVERSITY OF SUSSEX



Compositional Safety Refutation Techniques

Kumar Madhukar[1,3], Peter Schrammel[2], and Mandayam Srivas[3]

[1] TCS Research, Pune, India
[2] University of Sussex, School of Engineering and Informatics, Brighton, UK
[3] Chennai Mathematical Institute, Chennai, India

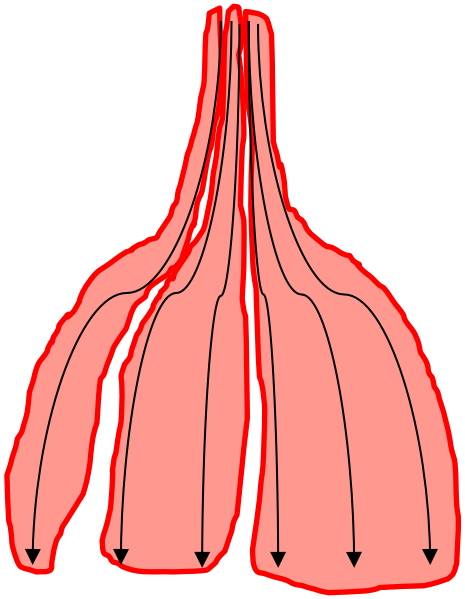


Horizontal/hierarchical decomposition, i.e. component-wise:

- E.g. Rely-guarantee, etc
- Easy for verification, difficult for refutation

Problem decomposition

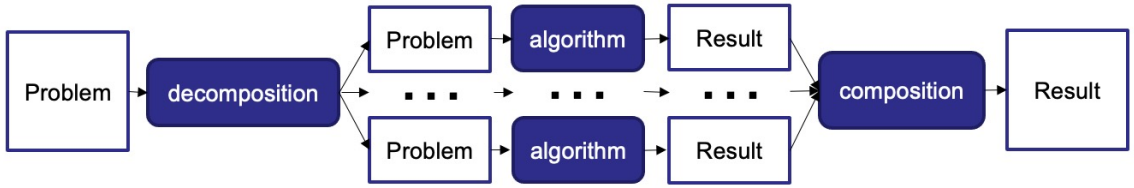
UNIVERSITY OF SUSSEX



Compositional Safety Refutation Techniques

Kumar Madhukar[1,3], Peter Schrammel[2], and Mandayam Srivas[3]

[1] TCS Research, Pune, India
[2] University of Sussex, School of Engineering and Informatics, Brighton, UK
[3] Chennai Mathematical Institute, Chennai, India



Horizontal/hierarchical decomposition, i.e. component-wise:

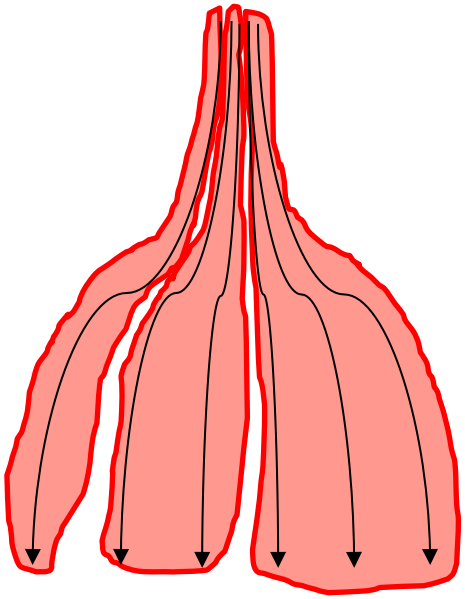
- E.g. Rely-guarantee, etc
- Easy for verification, difficult for refutation

Vertical decomposition, i.e. partition of execution traces:

- E.g. testing, path-wise symbolic execution, etc
- Easy for refutation, difficult for verification

Problem decomposition

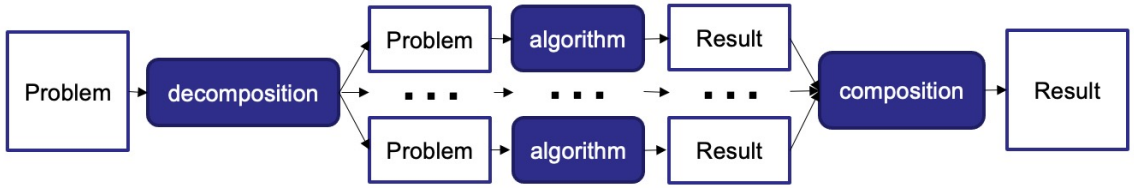
UNIVERSITY OF SUSSEX



Compositional Safety Refutation Techniques

Kumar Madhukar[1,3], Peter Schrammel[2], and Mandayam Srivas[3]

[1] TCS Research, Pune, India
[2] University of Sussex, School of Engineering and Informatics, Brighton, UK
[3] Chennai Mathematical Institute, Chennai, India



Horizontal/hierarchical decomposition, i.e. component-wise:

- E.g. Rely-guarantee, etc
- Easy for verification, difficult for refutation

Vertical decomposition, i.e. partition of execution traces:

- E.g. testing, path-wise symbolic execution, etc
- Easy for **refutation**, difficult for verification

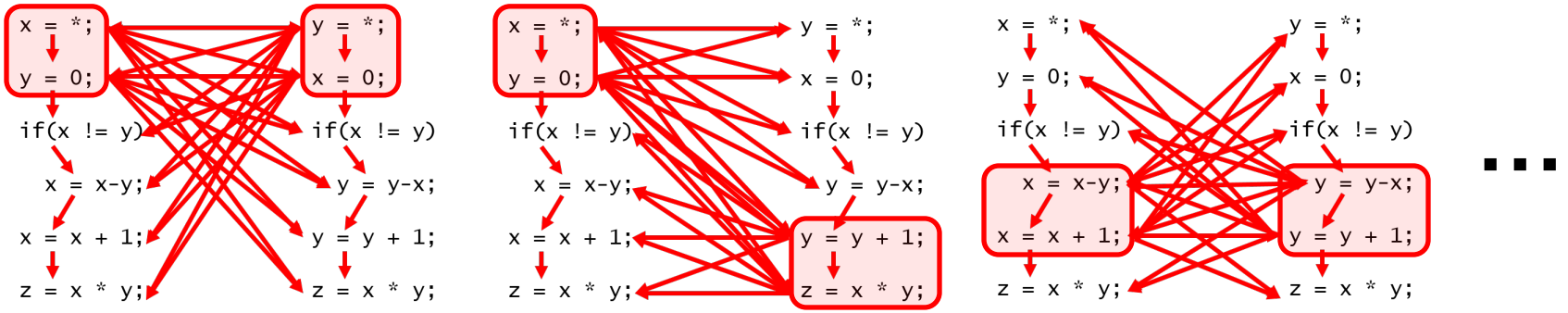
⬅ **This talk**

Reduced interleaving instances

UNIVERSITY OF SUSSEX

Our goal:

Split set of **interleavings** $\mathcal{I}_k(P)$ into **subsets** that can be **analyzed symbolically** and **independently**.



Our solution:

Derive program **variants** P_ϑ that **allow context switches only** in **subsets** of statements (**tiles**) s.t. $\mathcal{I}_k(P) = \mathrm{U}_\vartheta\ \mathcal{I}_k(P_\vartheta)$.

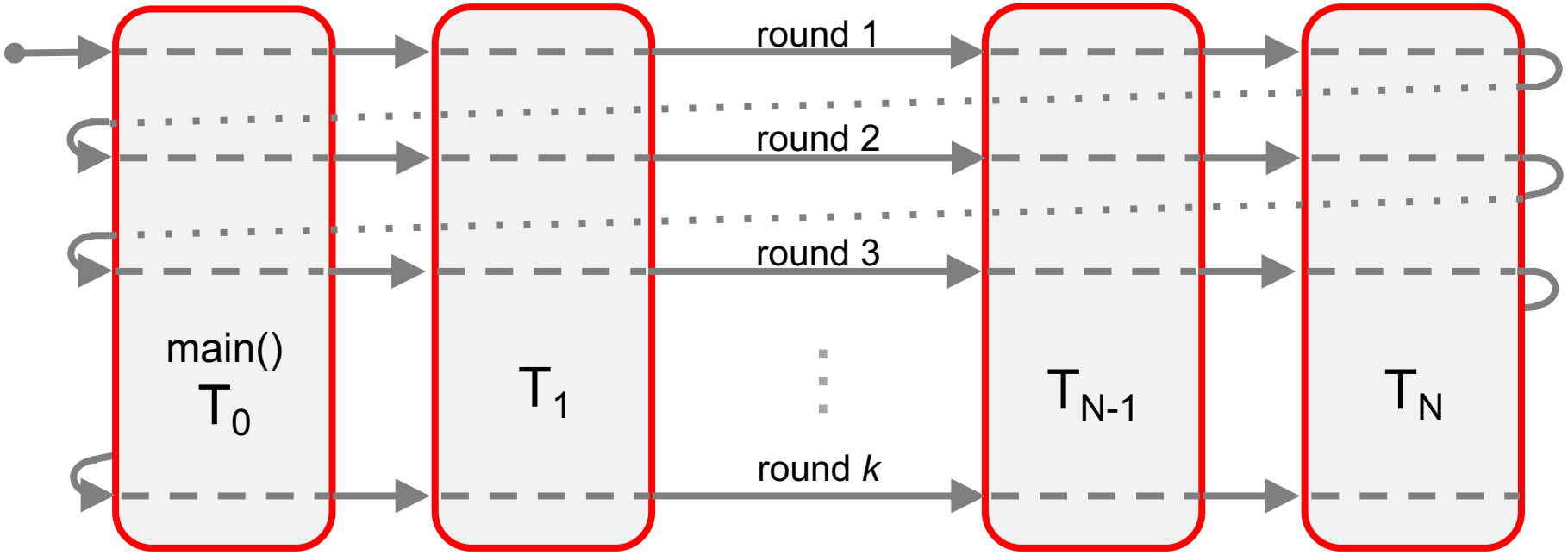
UNIVERSITY OF SUSSEX

Tiling Threads

Tiling threads

UNIVERSITY OF SUSSEX

Assumption: bounded concurrent programs

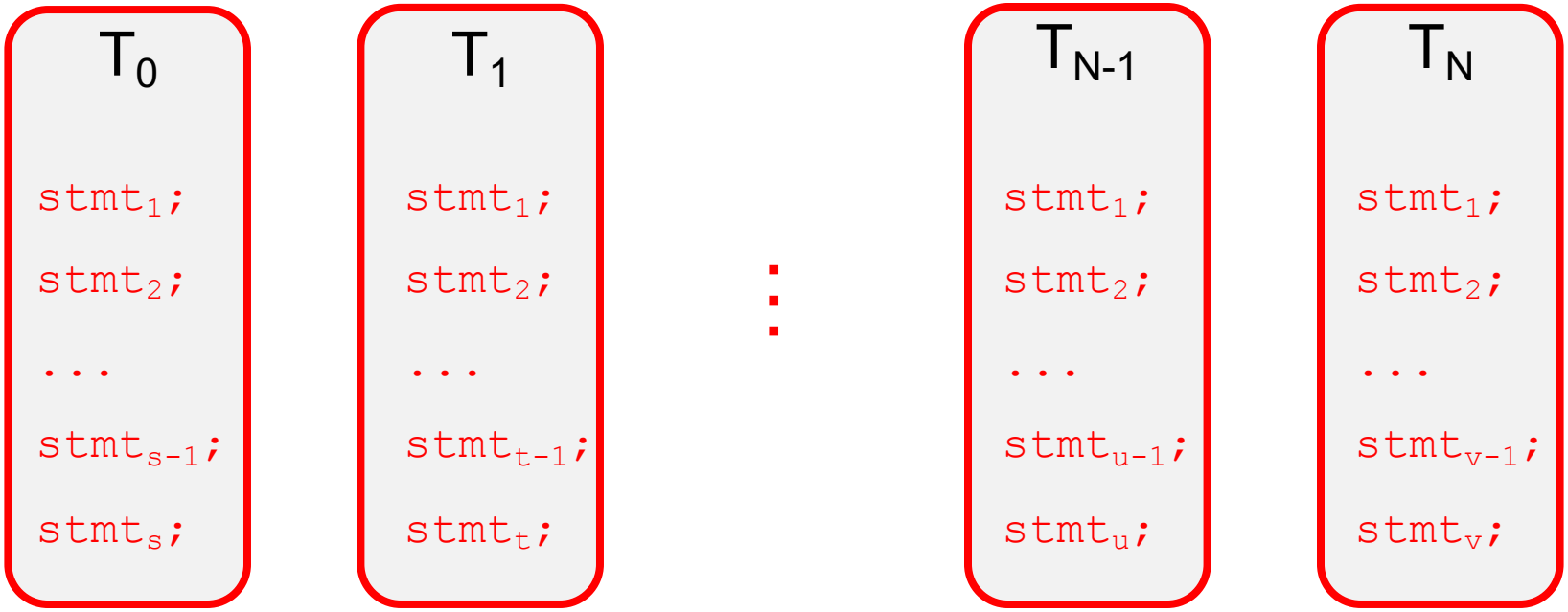


- finite #threads, fixed (but arbitrary) schedule
  - captures all bounded round-robin computations for given bound
- bugs manifest within very few rounds [Musuvathi, Qadeer, PLDI'07]

Tiling threads

UNIVERSITY OF SUSSEX

Assumption: bounded concurrent programs

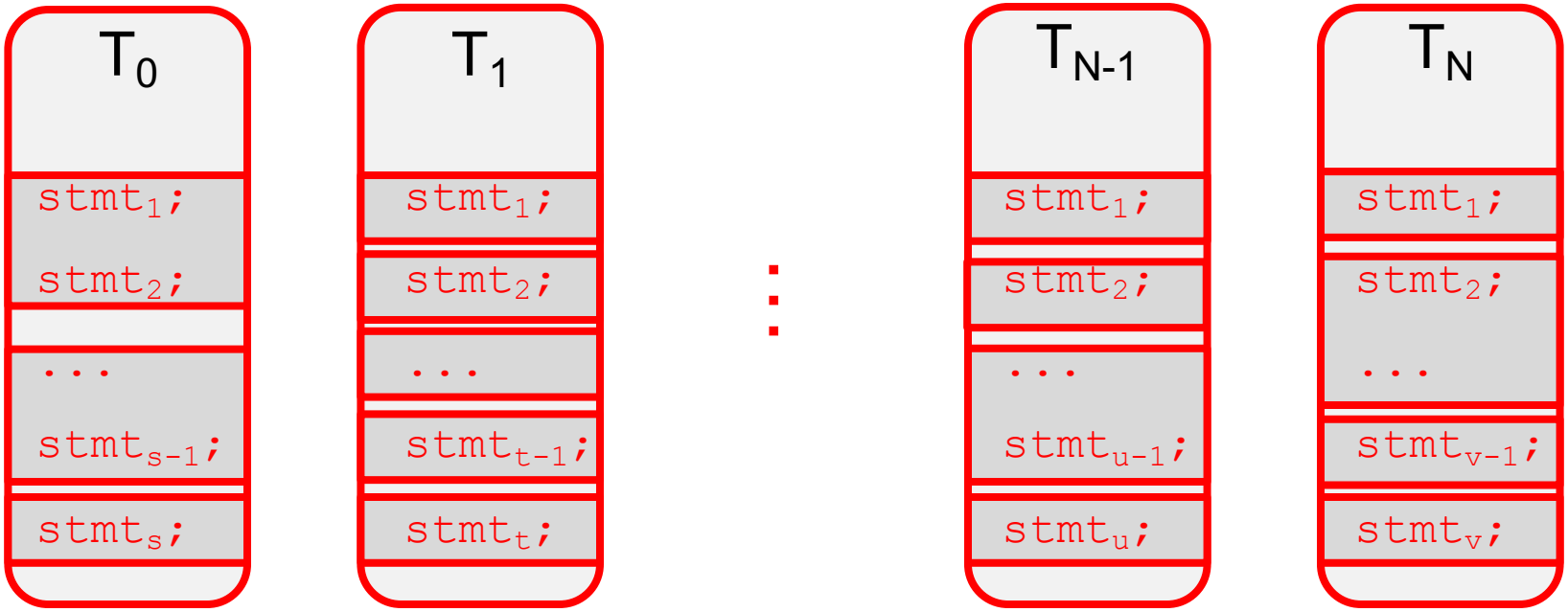


- finite #stmts
- control can only go forward
  - simplifies analysis and tiling

Tiling threads

UNIVERSITY OF SUSSEX

Tiles:

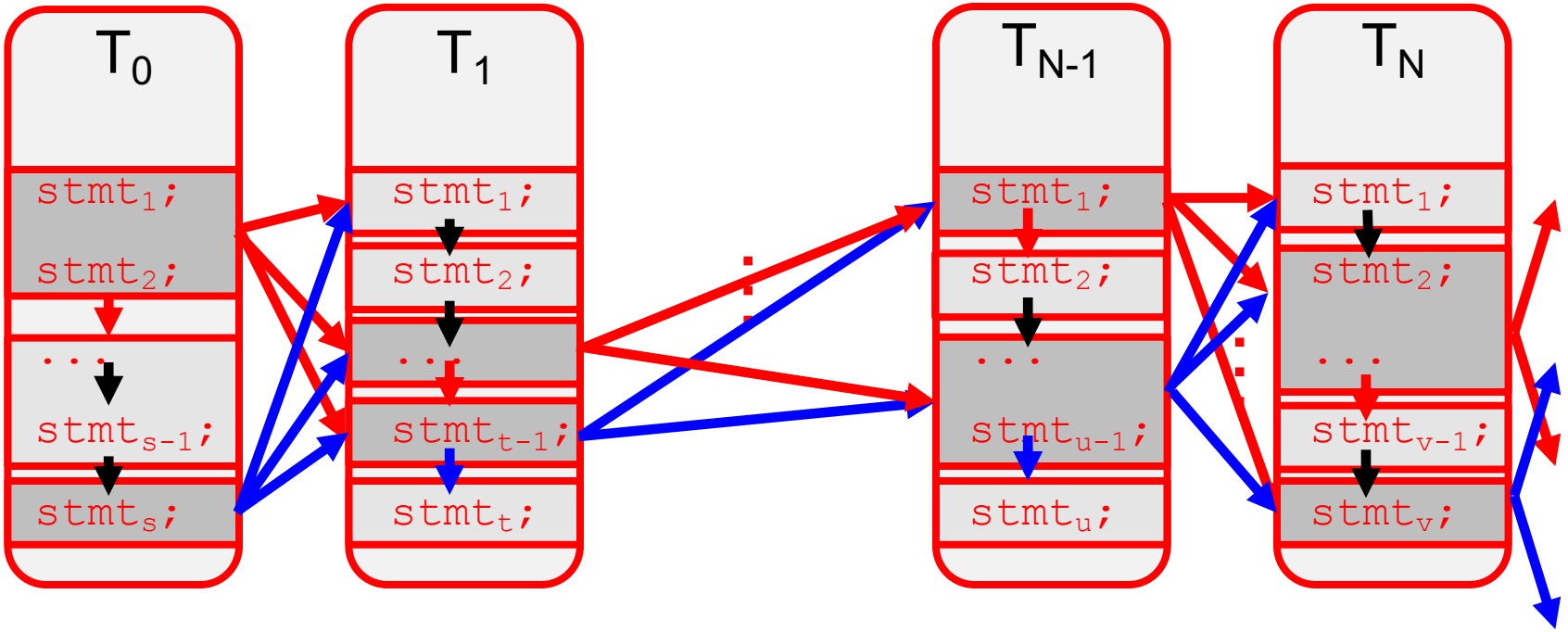


- **tile**: (contiguous) subset of visible statements
  - other tile types possible: random subsets, data-flow driven, …
- **tiling**: partition of program into tiles
- **uniform window tiling**: all tiles have same size
  - number of visible statements

Tiling threads

UNIVERSITY OF SUSSEX

Tile selection:

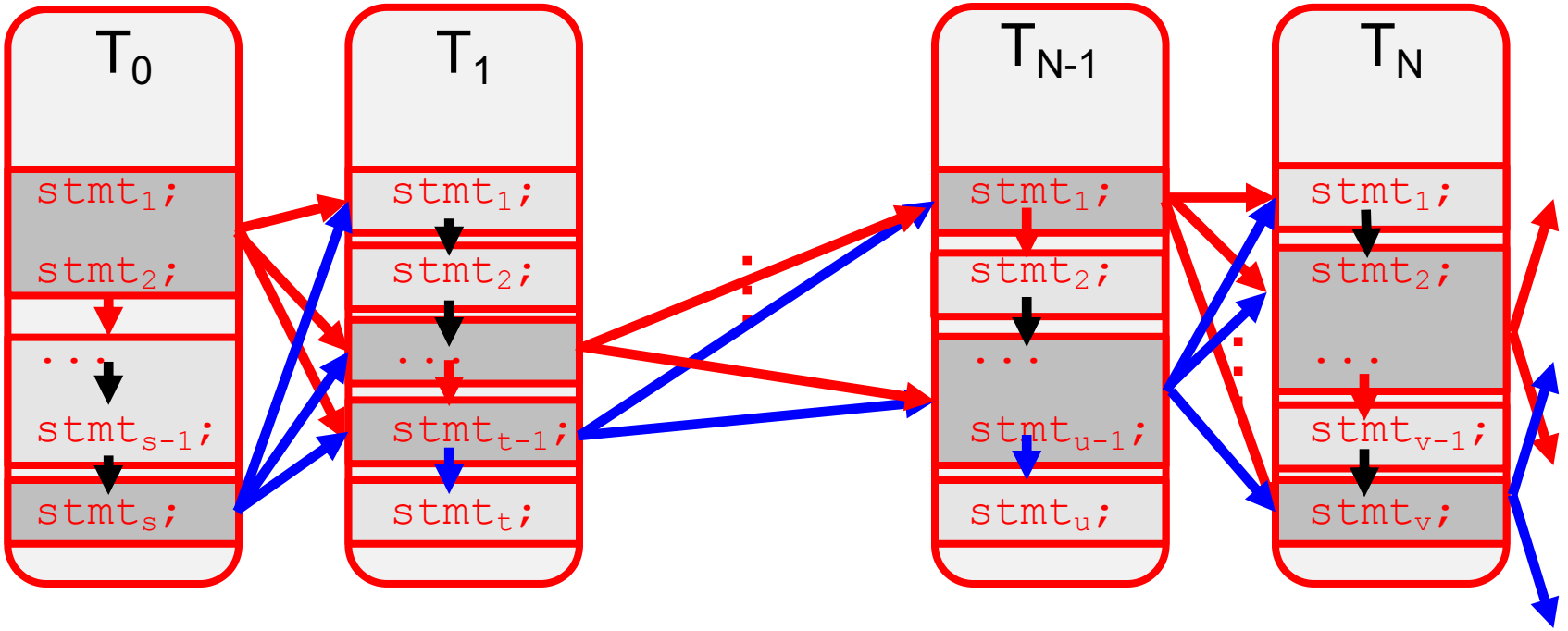


- **z-selection**: subset of z tiles for each thread
  - **context switches** are **only** allowed from **selected tiles**

  ⇒ context switches can only go into other selected tiles (or first thread statement)
- each z-selection specifies a **reduced interleaving instance**

Tiling threads

Completeness of selections:



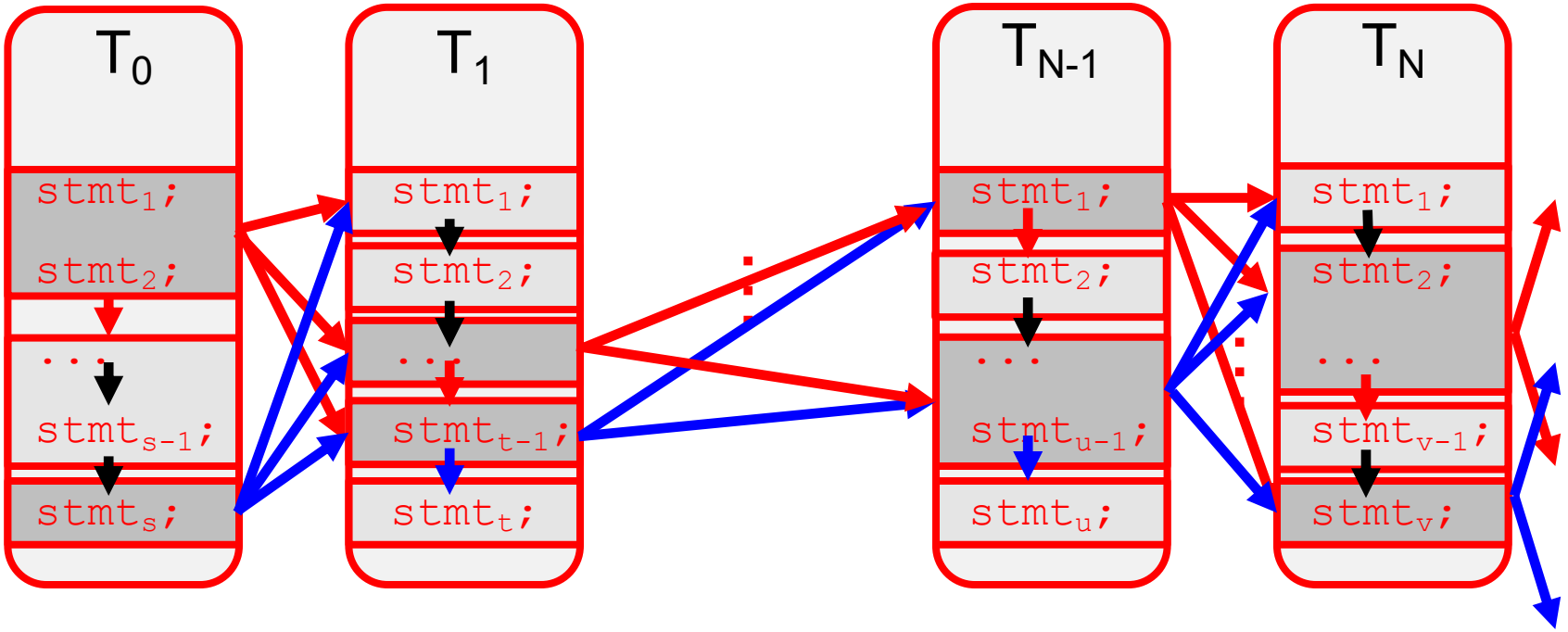
- each interleaving with *k* context switches can be covered by a [*k*/2]-selection $\vartheta \in \Theta_P$
  - each thread can only switch out at most [*k*/2] times

$\Rightarrow$ set of all [*k*/2]-selections together covers all interleavings with *k* context switches: $\mathcal{I}_k(P) = \bigcup_\vartheta \mathcal{I}_k(P_\vartheta)$

Tiling threads

UNIVERSITY OF SUSSEX

Completeness of selections:



- number of selections grows exponentially

$\Rightarrow$ sampling

UNIVERSITY OF SUSSEX

VERISMART

(Verification Smart)

http://users.ecs.soton.ac.uk/gp4/cseq/

VERISMART implements swarm verification by task competition for multi-threaded C

UNIVERSITY OF SUSSEX

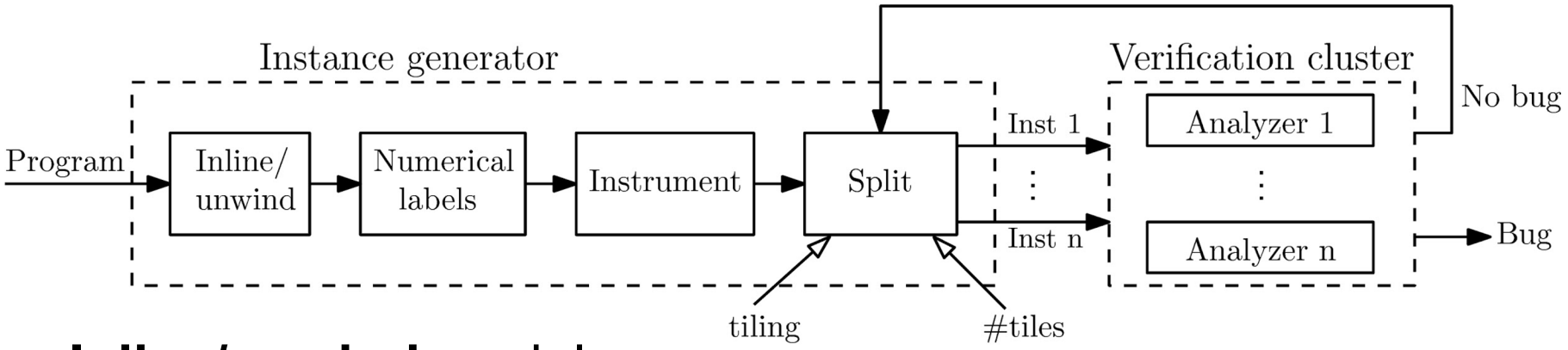
Target:

- C programs with "**rare**" concurrency bugs, i.e.,
  - "**large**" number of interleavings
  - "**few**" interleavings lead to a bug
- **automatic bug-finding** (bounded analysis, not complete)
- **reachability**
  - assertion failure
  - out-of-bound array, division-by-zero, …

Approach:

- source-to-source translation to generate instances (for tiling)
  - instances are bounded concurrent programs
- use cluster to run Lazy-CSeq over instances [Inverso et al., CAV'14]

VERISMART architecture



- **Inline/unwind** module:
  - concurrent program ⟶ bounded concurrent program
- **Numerical labels** module:
  - inject numerical labels at each visible statement
- **Instrument** module:
  - instrument the code with guarded commands (`yield`) that can enable/disable context switch points at numerical labels
- **Split** module:
  - generate variants with configuration from tiling and #tiles
  - randomize number of generated variants when #variants is large

Why does this work?

UNIVERSITY OF SUSSEX

Remember:

Each P_ϑ allows only a (small) subset of P's interleavings

We assume bugs are rare,

- so for most ϑ, P_ϑ does not exhibit the bug…
- … and the analysis will run out of time
- but if P_ϑ does exhibit the bug…
- … the analysis will find it quick(er)

Hence,

- overall CPU time consumption goes (way) up…
- … but with enough cores CPU time is free and…
- mean wall clock time to find failure goes down

UNIVERSITY OF SUSSEX

Experimental Evaluation

on lock-free data structures

eliminationstack

UNIVERSITY OF SUSSEX

- C implementation of Hendler et al.'s EliminationStack (lock-free data structure)
  [Hendler, Shavit, Yerushalmi, SPAA'04]
- analyzed under SC
- annotated with several assertions to check linearizability
  [Bouajjani, Emmi, Enea, Hamza, POPL'15]
- ABA problem: requires 7 threads for exposure
- Lazy-CSeq can find bug in **~13h** and **4GB**
  - #unwind=1, #rounds=2, #threads=8, size=52 visible stmts
- all other tools fail (afaik)

safestack

UNIVERSITY OF SUSSEX

- small implementation of lock-free stack (<100 loc)
- bug requires context bound of 5

safestack

UNIVERSITY OF SUSSEX

- small implementation of lock-free stack (<100 loc)
- bug requires context bound of 5
- analyzed for SC, PSO, TSO
- Lazy-CSeq can find bug in **~7h** and **6.5GB**
  - #unwind=3, #rounds=4, #threads=4, size=152 visible stmts
- all other tools fail (afaik)

eliminationstack: Results

UNIVERSITY OF SUSSEX

- Lazy-CSeq: 46764 sec, 4.2 GB
- CBMC (sequential): 80.8 sec, 0.7 GB
  - average over 3000 interleavings, bug not found

fastest instances very fast – 1000x

reduced memory consumption – 4x

ERISMART: 2 til								
#1: tile si			#2: tile size 14, t			size 18, t_max 3hrs		
Verification	Time	Memory	Verification	Time	Memory	Verification	Time	Memory
Min	34.9	945.2	Min	39.7	979.84	Min	37.1	999.8
Max	4753.6	1199.1	Max	7195.2	1281.3	Max	10762.0	1785.5
Average	1116.3	1017.8	Average	2169.5	1096.3	Average	3162.41	1156.91
instances with bug: 38.33%			instances with bug: 61.38%			instances with bug: 69.01%		

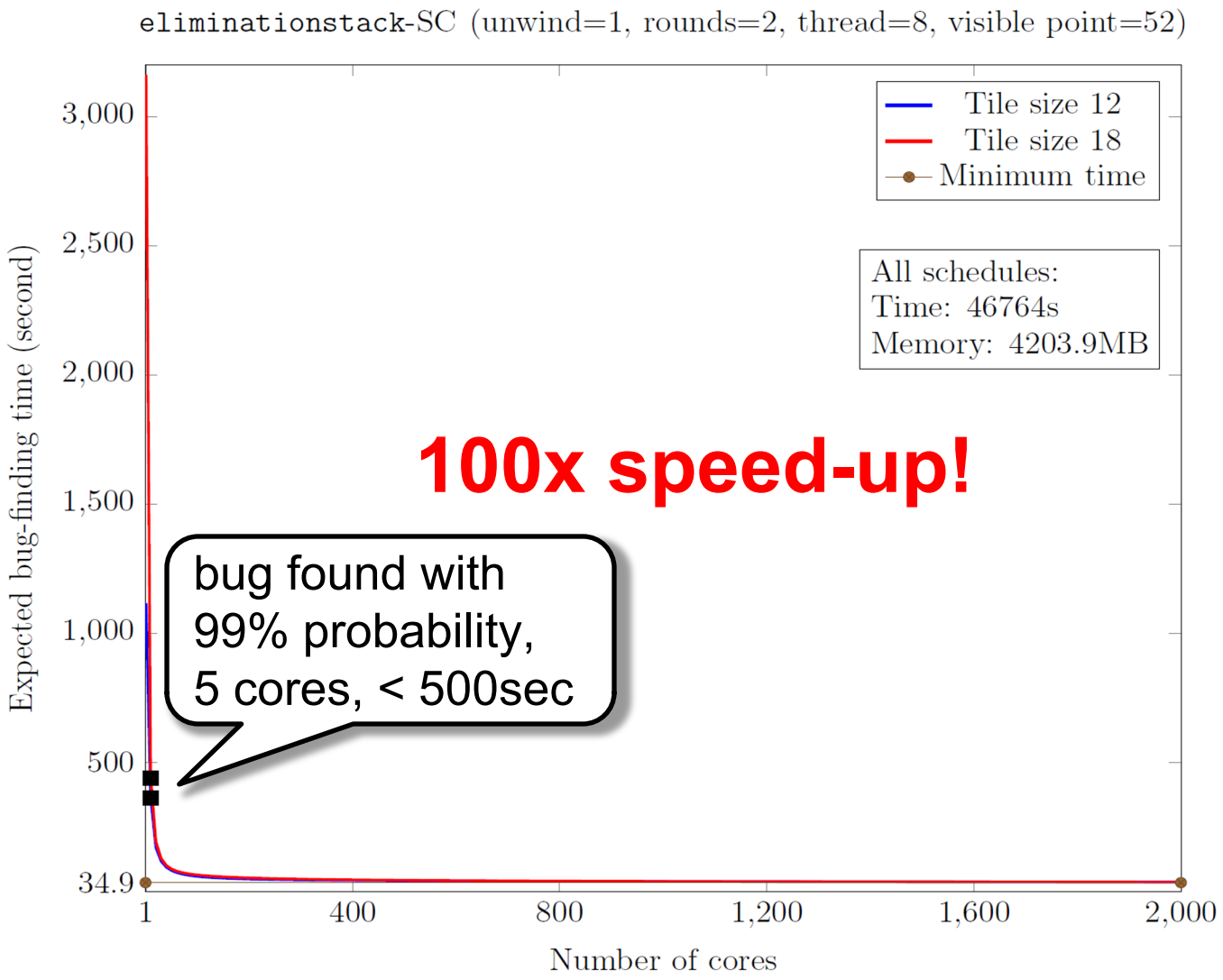
average still very fast – 40x

high fraction of bug-exposing instances

some slowdown for larger tile sizes – 10x

eliminationstack: Expected bug finding time

UNIVERSITY OF SUSSEX



safestack (SC): Results

UNIVERSITY OF SUSSEX

- Lazy-CSeq: 24139 sec, 6.6 GB
- CBMC (sequential): 55.4 sec, 0.7 GB
  - average over 3000 interleavings, bug not found

VeriSMART: 4 tiles per thread								
#1: tile size 11, t_max 1hr			#2: tile size 14, t_max 1hr			#3: tile size 20, t_max 4hrs		
Verification	Time	Memory	Verification	Time	Memory	Verification	Time	Memory
Min	195.6	774.5	Min	574.8	846.6	Min	313.0	850.3
Max	2662.6	1265.7	Max	3521.8	1450.4	Max	10315.8	3830.8
Average	1172.2	928.8	Average	1851.1	1147.3	Average	2167.5	1230.1
instances with bug: 1.26%			instances with bug: 2.14%			instances with bug: 10.20%		

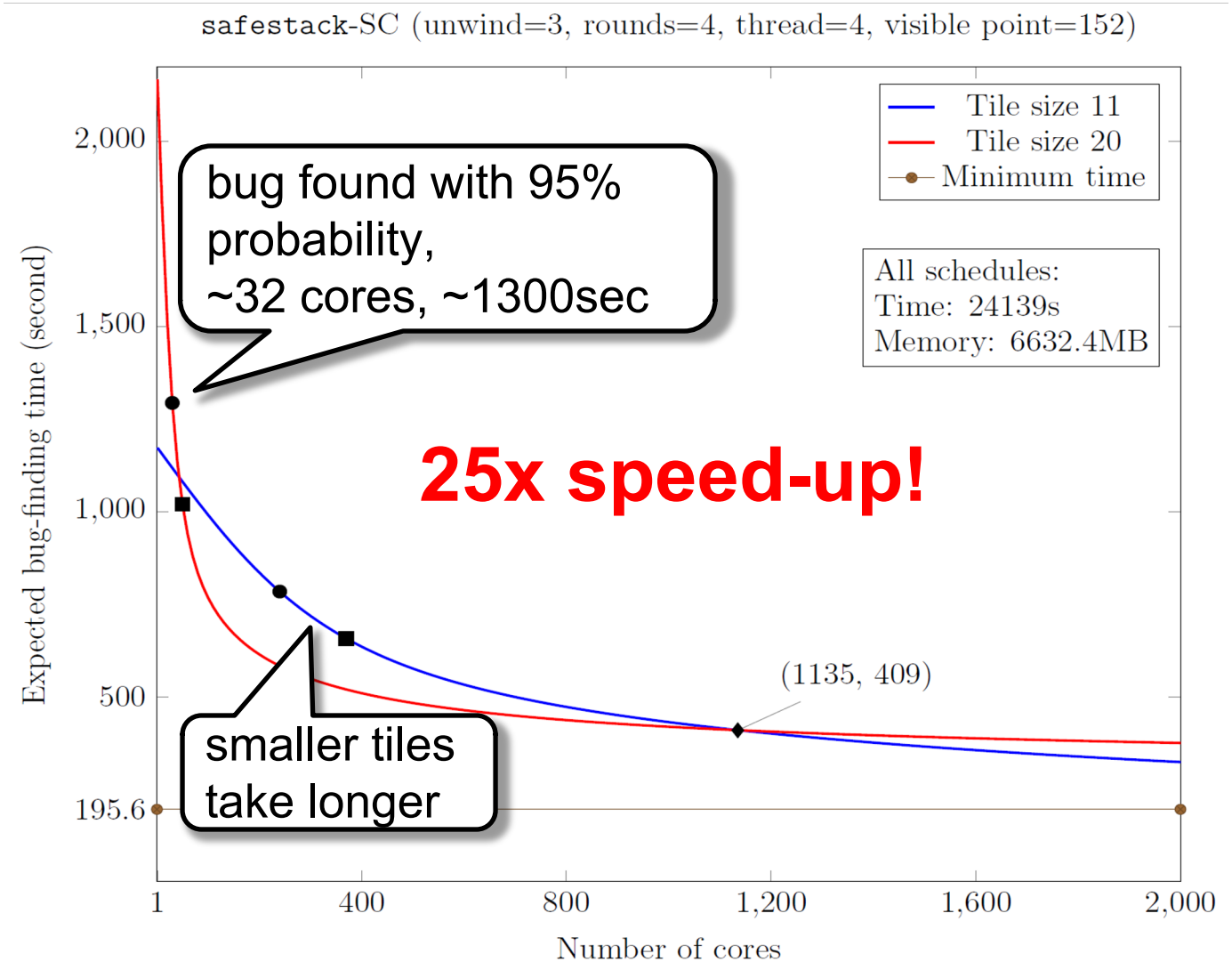
lower fraction of bug-exposing instances than eliminationstack

…but boosted with larger tile sizes

⇒ similar picture, but less advantage for VeriSmart

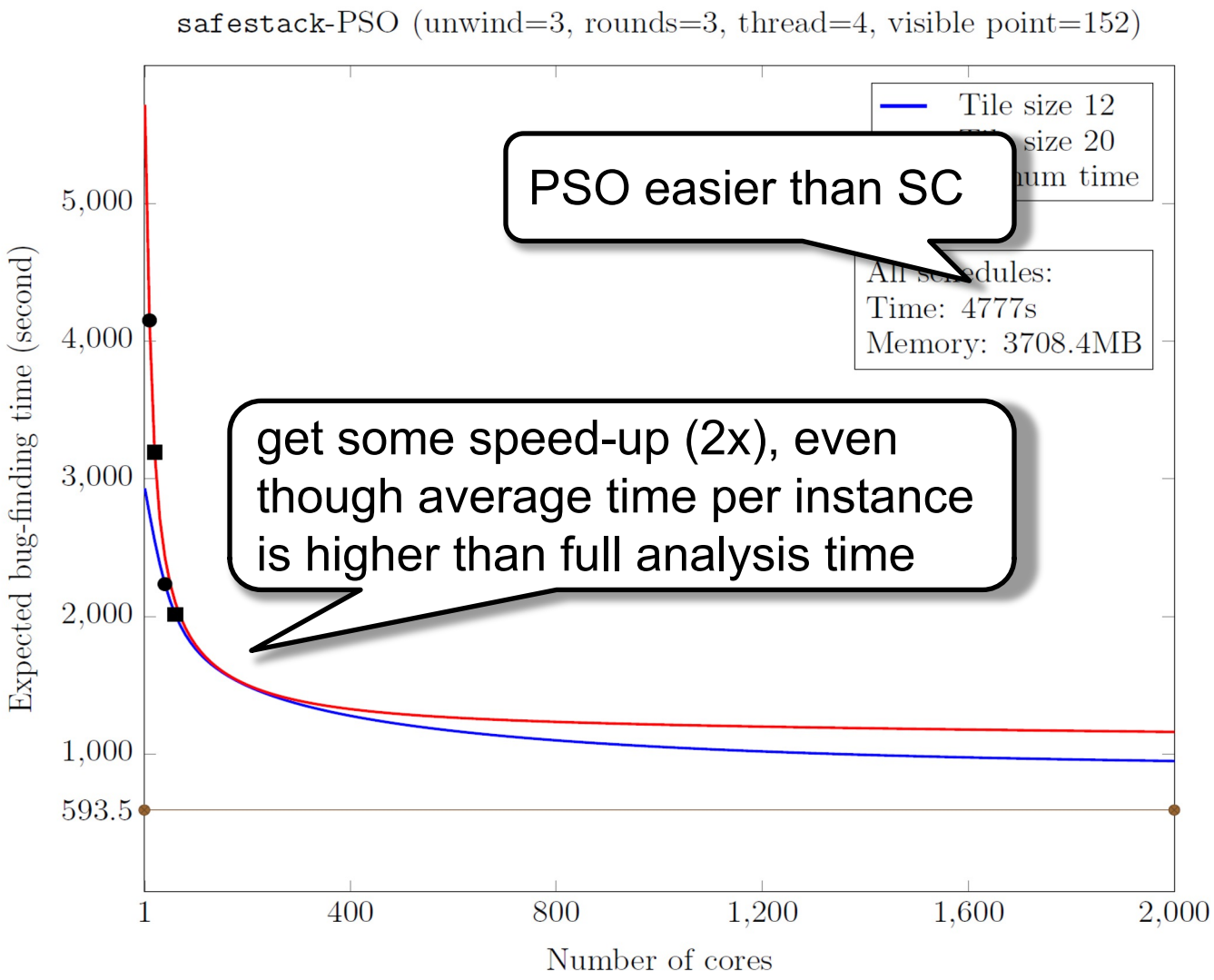
safestack (SC): Expected bug finding time

UNIVERSITY OF SUSSEX



safestack (PSO): Expected bug finding time

UNIVERSITY OF SUSSEX



Conclusions

UNIVERSITY OF SUSSEX

- first task-competitive swarm verification approach
- exploits availability of many cores to reduce mean wall clock time to find failure
  - allows us to handle very hard problems
  - high speed-ups already for 5-50 cores
- reduced interleaving instances boost bug-finding capabilities

Future Work

- other backends (testing)
- other tiling styles
- fast over-approximations to filter out safe instances