Determinism Is Not Enough: Making Parallel Programs Reliable with Stable Multithreading

Junfeng Yang
http://www.cs.columbia.edu/~junfeng
Joint work w/ my brilliant students
Heming Cui, Jingyue Wu, Yang Tang, Gang Hu
Columbia University

One-slide overview

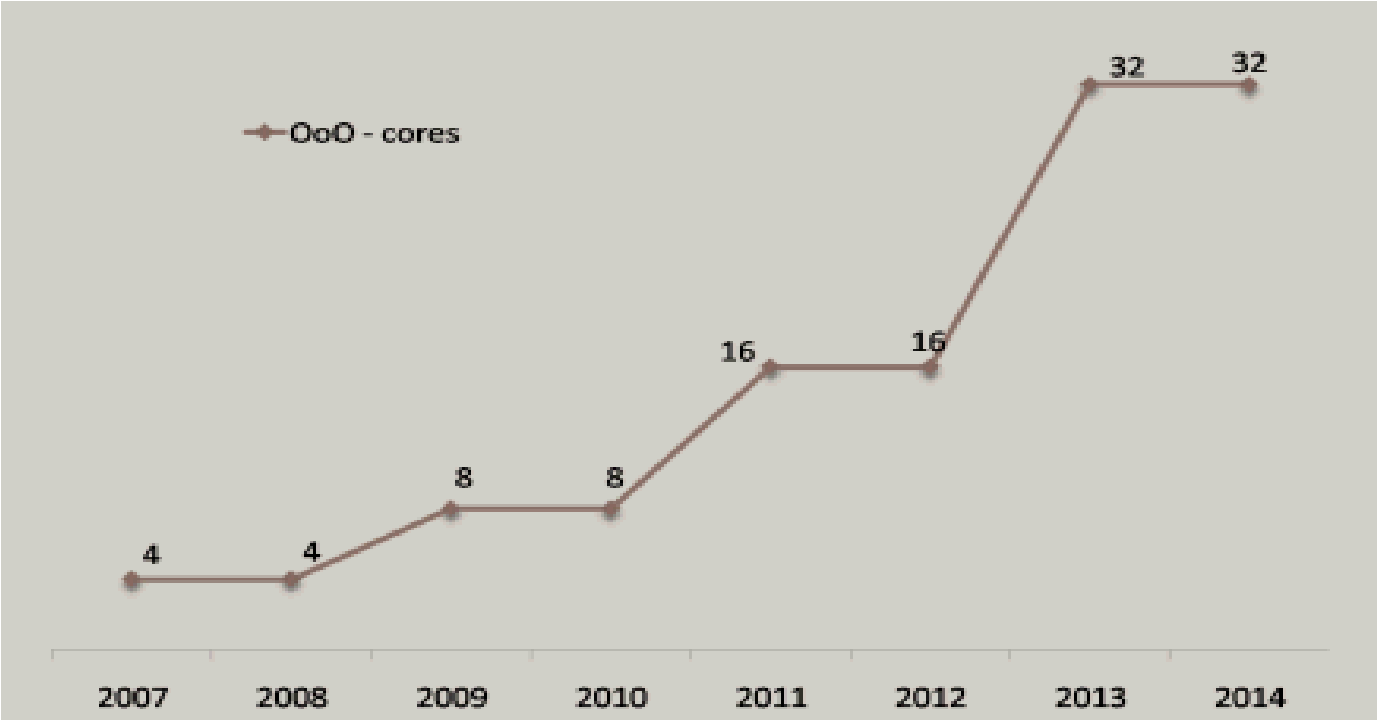
- Despite major advances in tools, multithreading remains hard to get right

- Why? ~~Nondeterminism~~ too many thread interleavings, or *schedules*

- *Stable Multithreading (StableMT)*: a radical approach to reducing the set of schedules for reliability with low overhead [Tern OSDI 10] [Peregrine SOSP 11] [Specialization PLDI 12] [Parrot SOSP 13] [HotPar 13] [CACM 14]

Background and motivation

Multithreaded programs: pervasive and critical



http://www.drdobbs.com/parallel/design-for-manycore-systems/219200099

Multithreaded programs: pervasive and critical

But, extremely hard to get right

Getty

But, extremely hard to get right

- Plagued with concurrency bugs [Lu ASPLOS 09]
  - Data races, atomicity violations, order violations, deadlocks, etc

But, extremely hard to get right

- Plagued with concurrency bugs [Lu ASPLOS 09]
  - Data races, atomicity violations, order violations, deadlocks, etc
- Concurrency bugs: bad
  - Have taken lives in the Therac 25 incidents and caused the 2003 Northeast blackout
  - May be exploited by attackers to violate confidentiality, integrity, and availability of critical systems [Hotpar 12]

Concurrency bug example

```
    Thread 0               Thread 1
mutex_lock(M)
*obj = …
mutex_unlock(M)
                    mutex_lock(M)
                    free(obj)
                    mutex_unlock(M)
```

Apache Bug #21287 (simplified)

Concurrency bug example

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    Thread 0              Thread 1
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- *Input*: everything a program reads from environment
  - E.g., main() arguments, data read from file or socket

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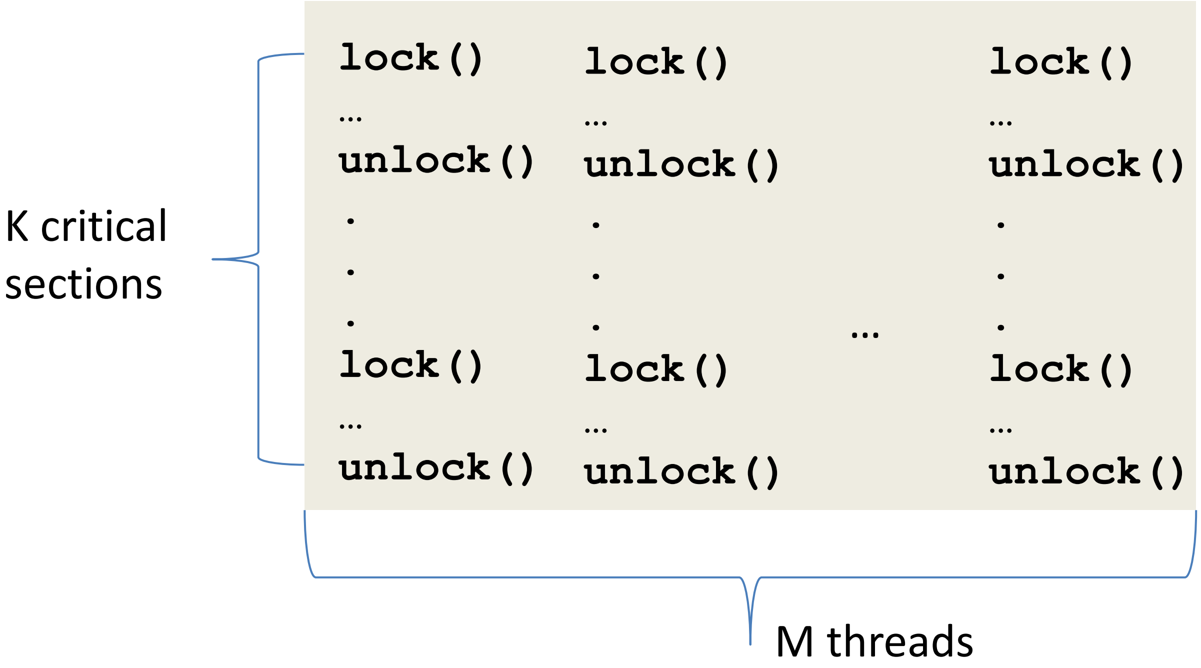
- *Schedule*: sequence of communication operations
  - E.g., total order of synchronizations such as lock()/unlock()
- *Buggy schedule*: schedule triggering concurrency bug

Advances in tools

- The pursuit of results: systems research focus shifted from speed to reliability around 2000
- More effective static analysis, model checking, symbolic execution, verification
  - E.g., vulgar version of model checking that enumerates through real executions for bugs [Verisoft POPL 97] [CMC OSDI 02] [FiSC OSDI 04] [eXplode OSDI 06] [MaceMC NSDI 07] [Chess ODSI 08] [MoDIST NSDI 09] [Inspect SPIN 09] [dBug SPIN 11]
- Unfortunately, concurrency/multithreading remains the bane of these tools

Why hard?



```
lock()      lock()                lock()
…           …                     …
unlock()    unlock()              unlock()
.           .                     .
.           .                     .
.           .             …       .
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```

K critical sections

M threads

- Number of schedules: exponential in K, M
- Even more schedules aggregated over all inputs

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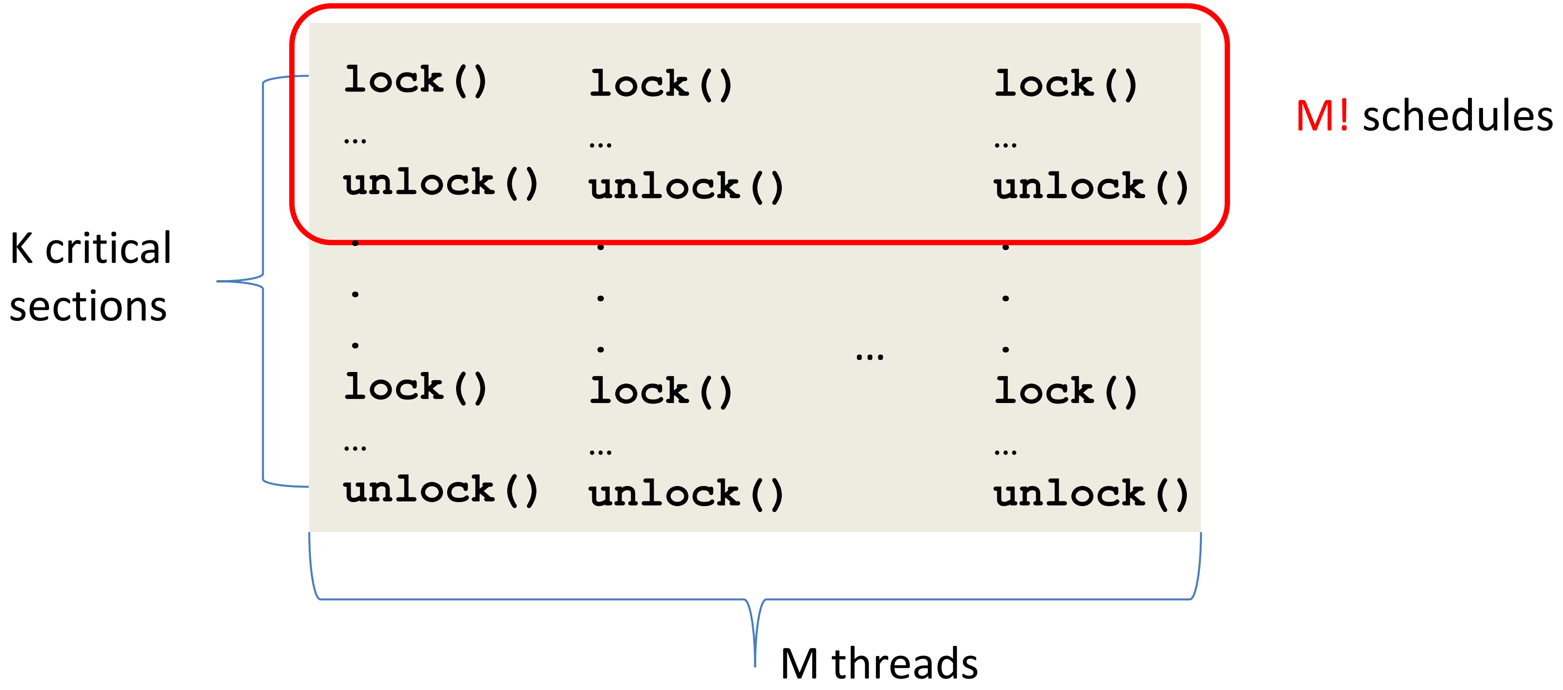

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M! schedules

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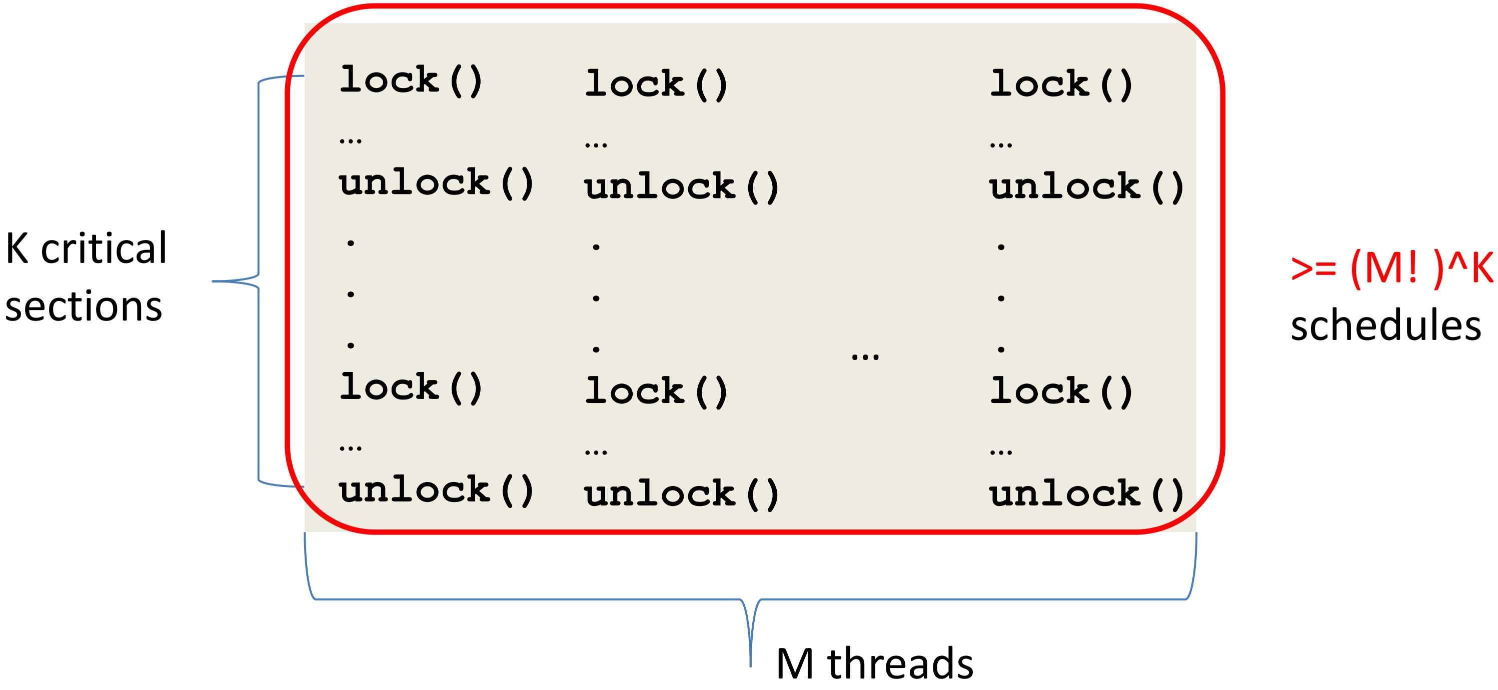

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K critical sections

>= (M!)^K schedules

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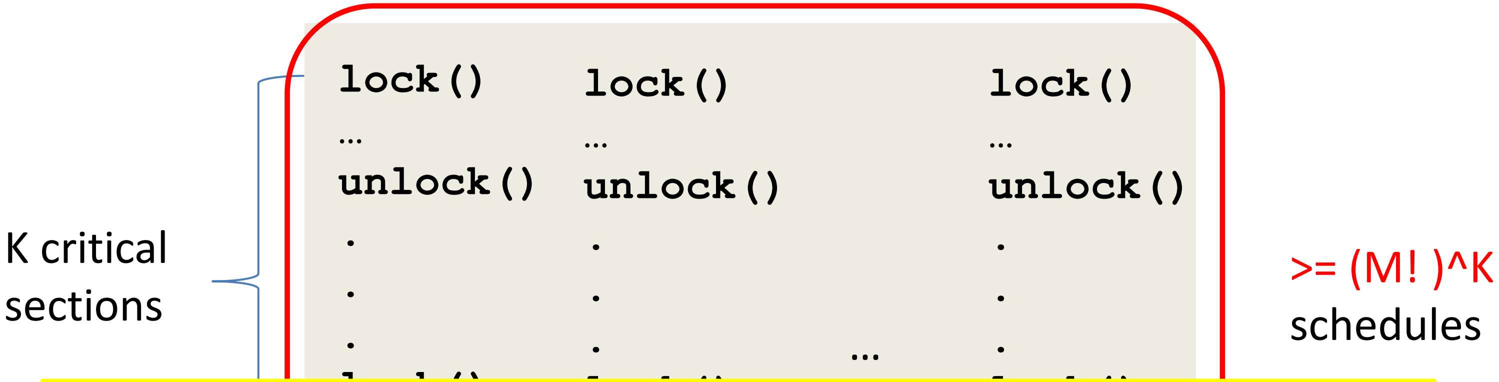

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…           …                    …
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.           .                    .
.           .                    .
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```

Finding concurrency bugs

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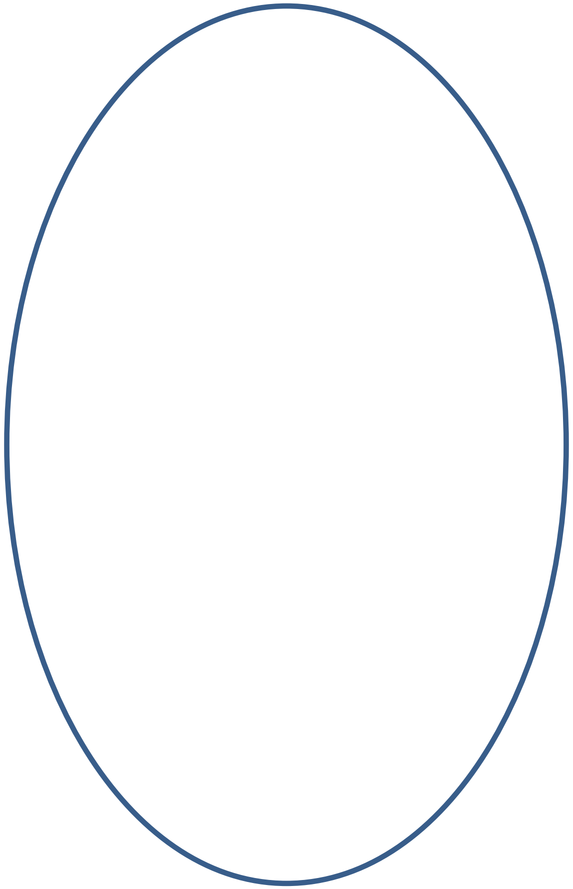
finding needles in a haystack

- N
- Even more schedules aggregated over all inputs

How to improve checking coverage?

All possible runtime schedules



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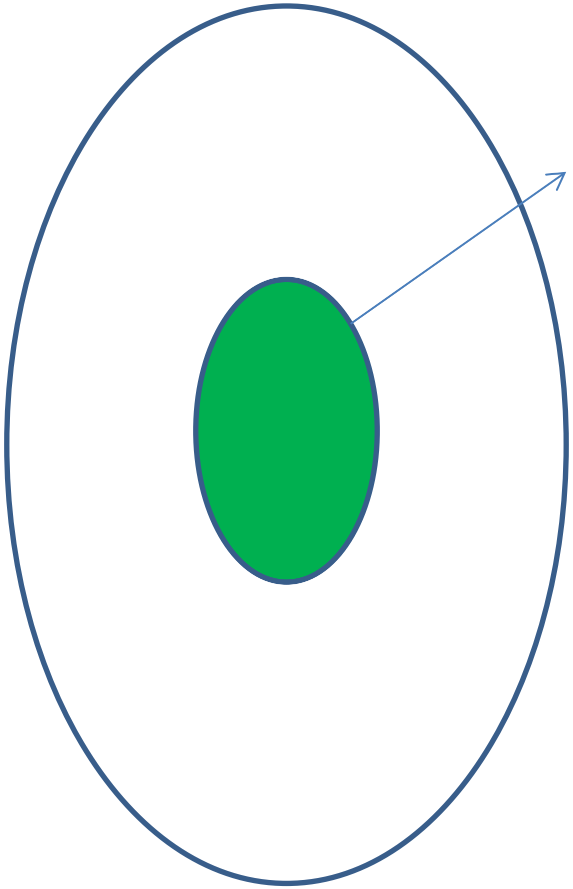

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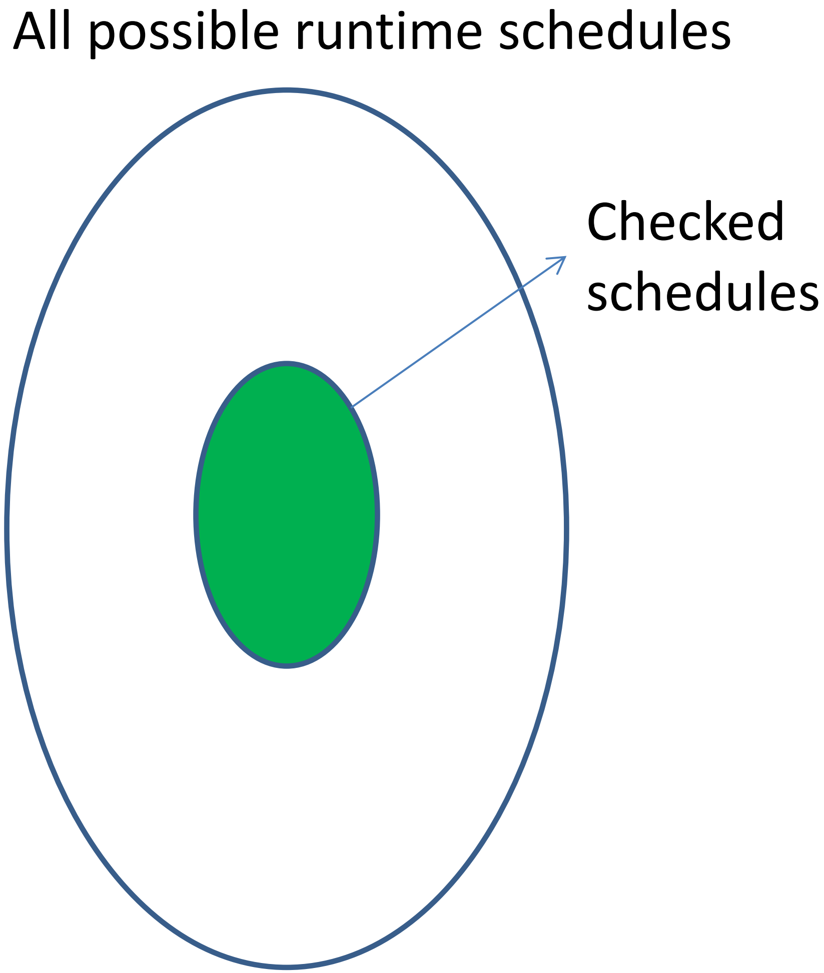

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- Coverage = Checked/All

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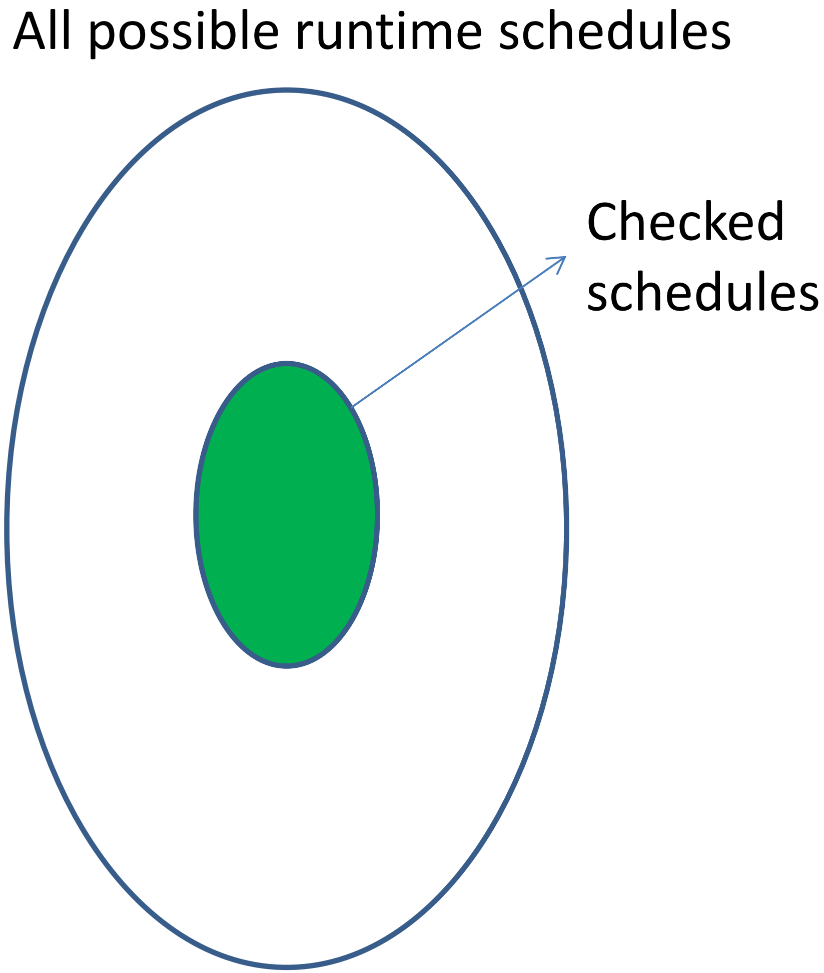

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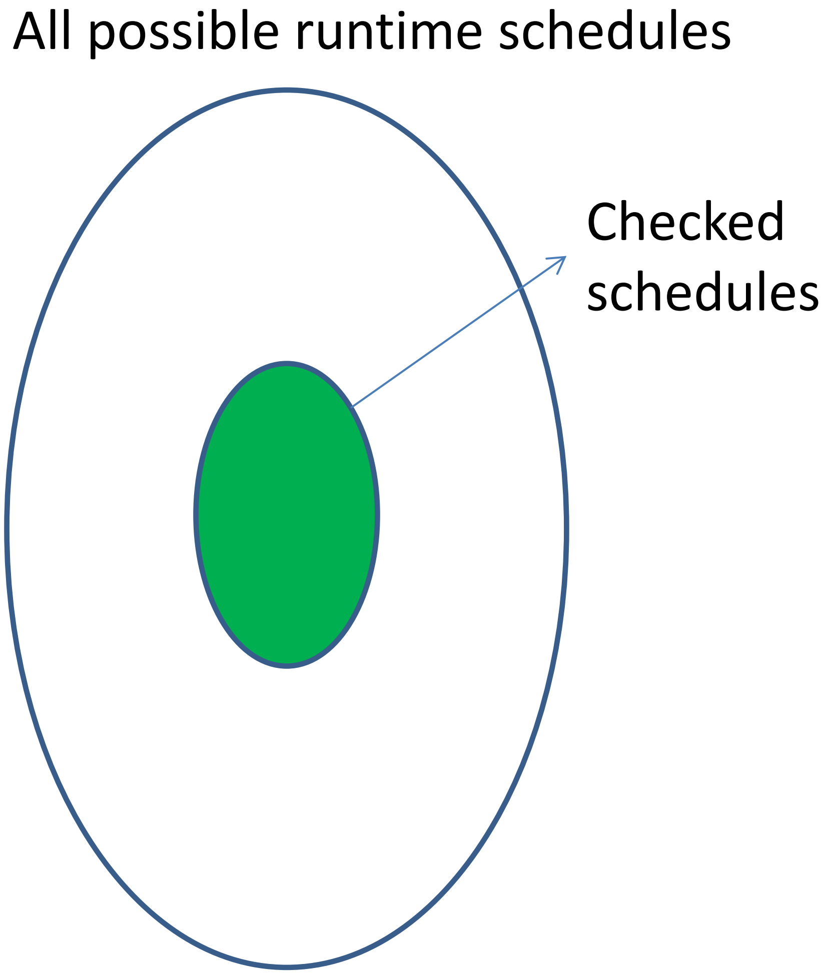

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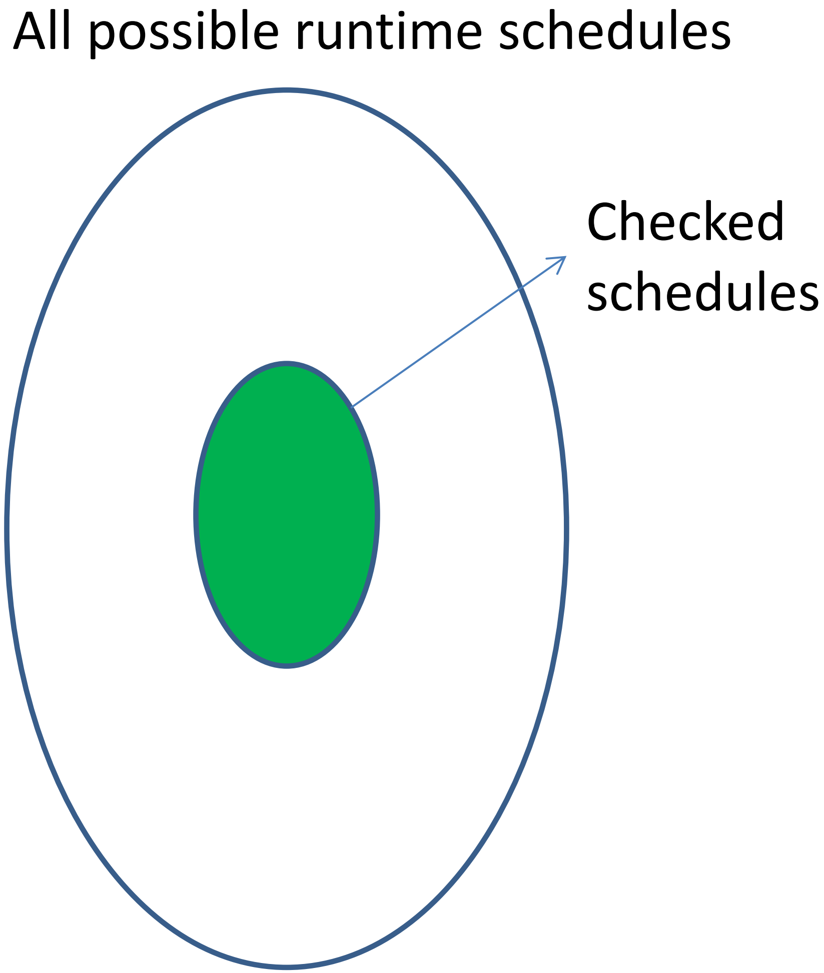

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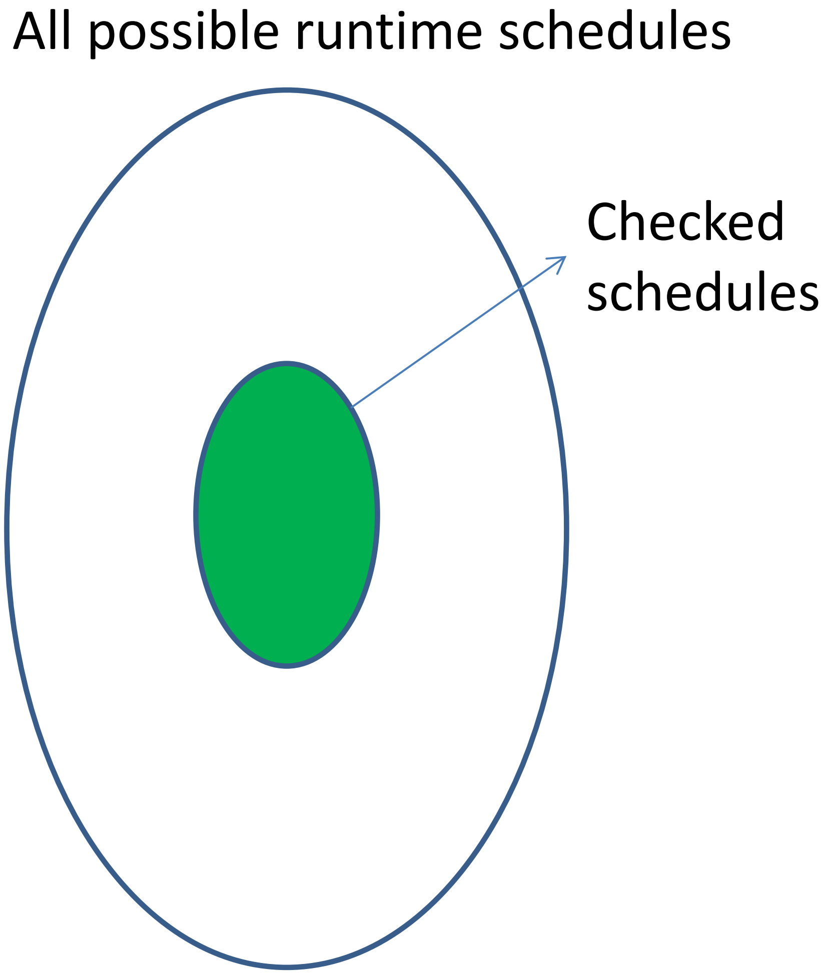

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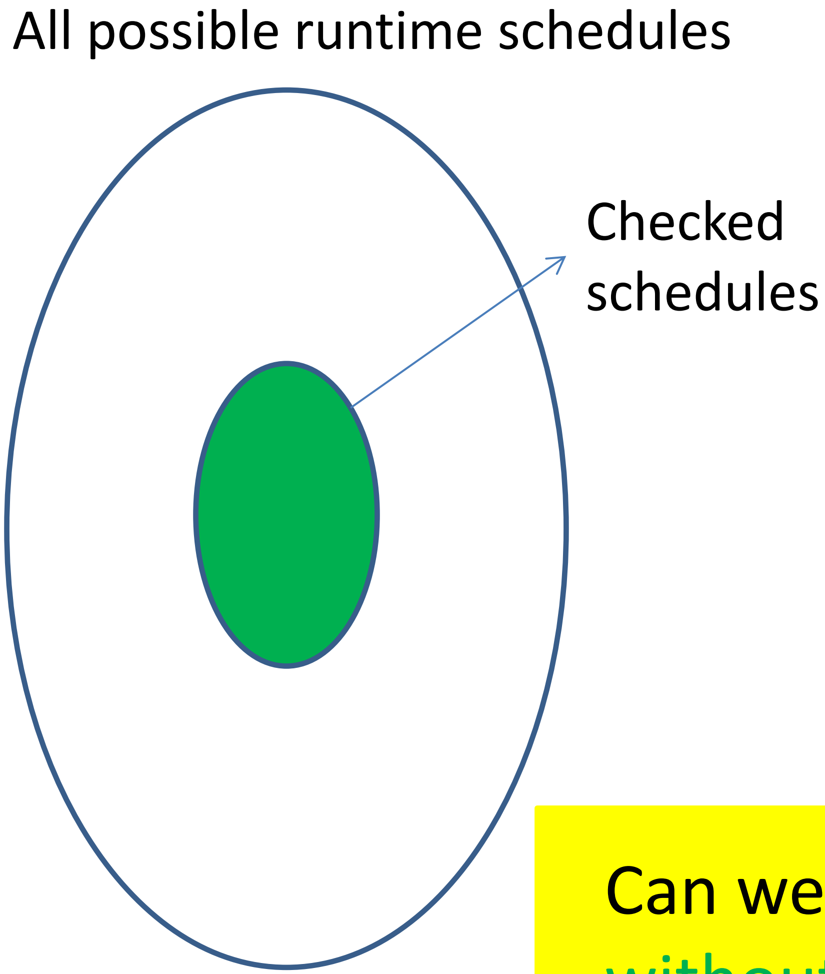

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Can we increase coverage without enlarging Checked?

How to improve checking coverage?

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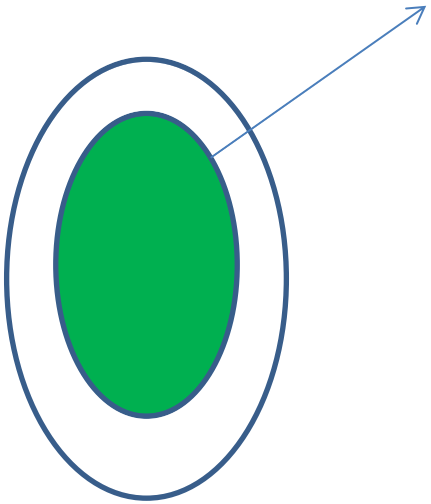

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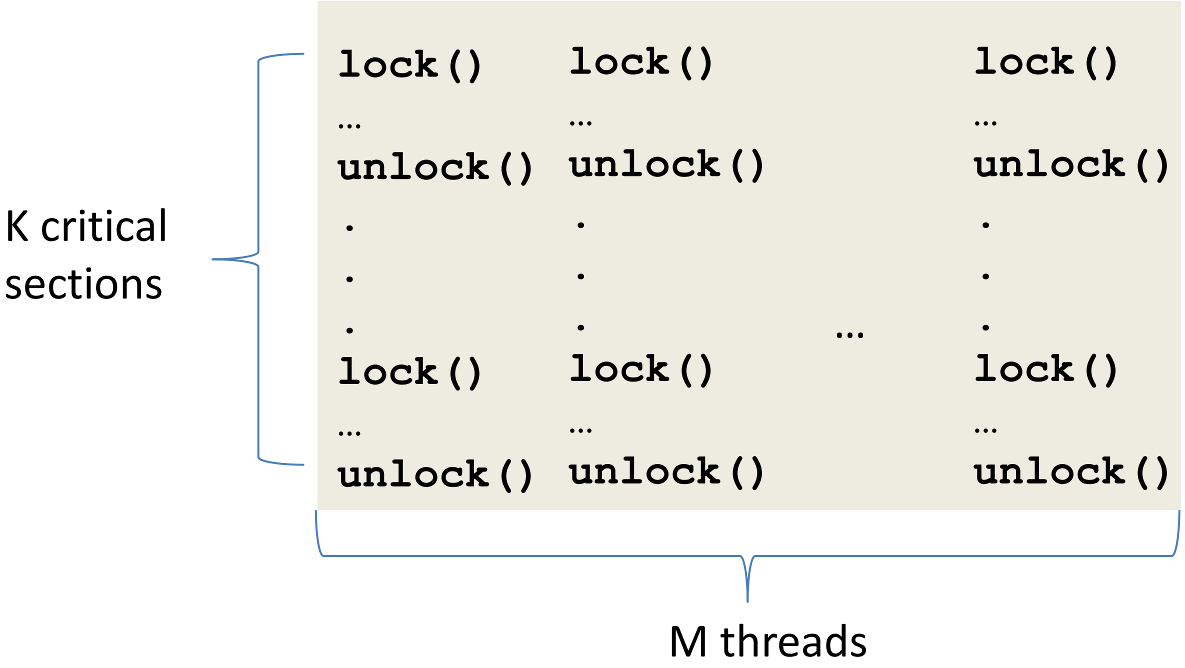
Can we increase coverage without enlarging Checked?

High coverage with StableMT



K critical sections

```
lock()     lock()              lock()
…          …                   …
unlock()   unlock()            unlock()
.          .                   .
.          .                   .
.          .             …     .
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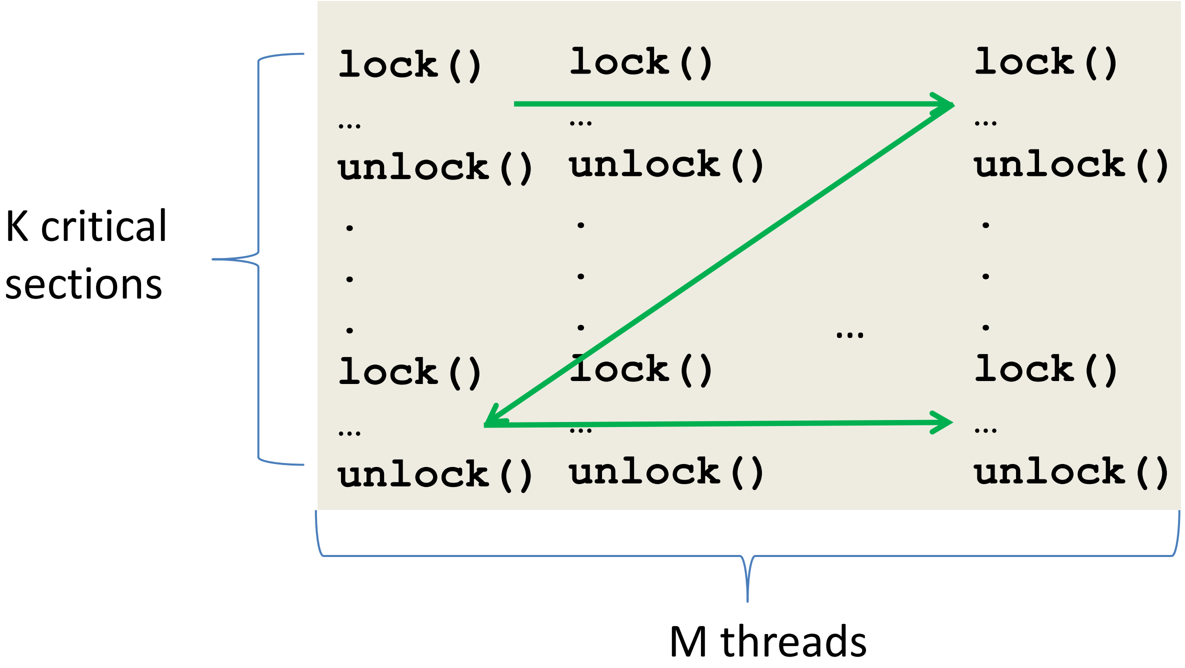
```

M threads

- Enforce round-robin synchronization order

High coverage with StableMT



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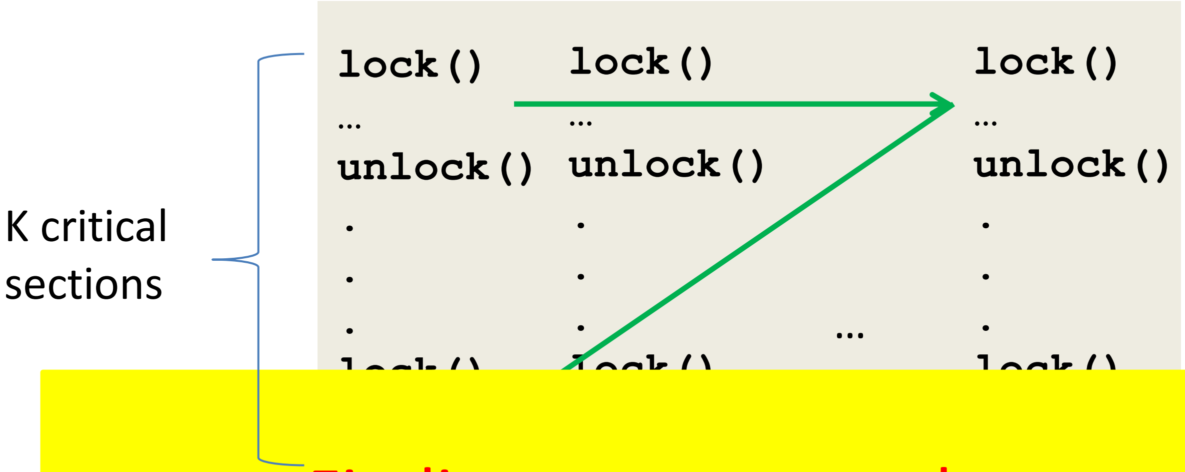

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Finding concurrency bugs

==

checking one schedule

- er

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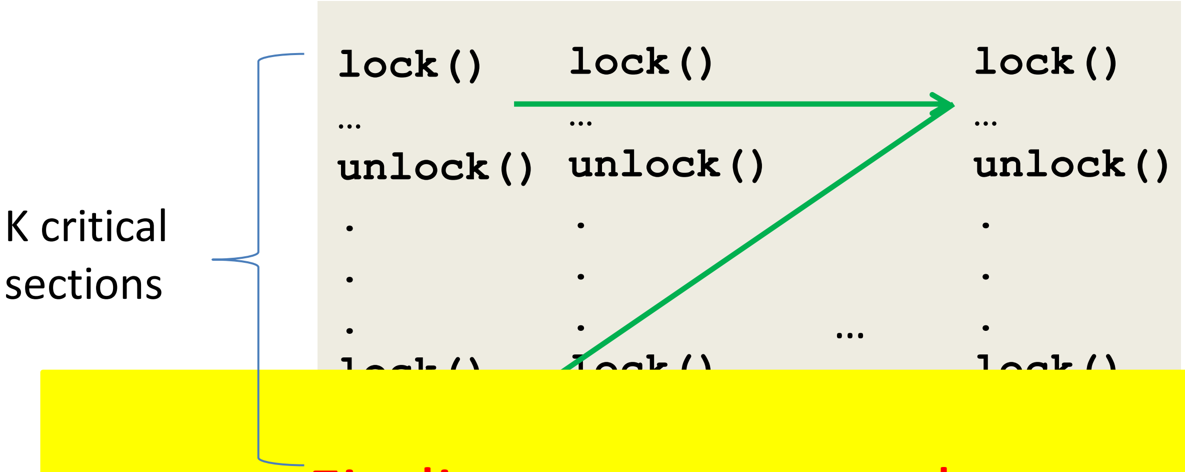

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.           .                         .
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```

Finding concurrency bugs

==

checking one schedule

Simple enough that it feels like cheating ☺

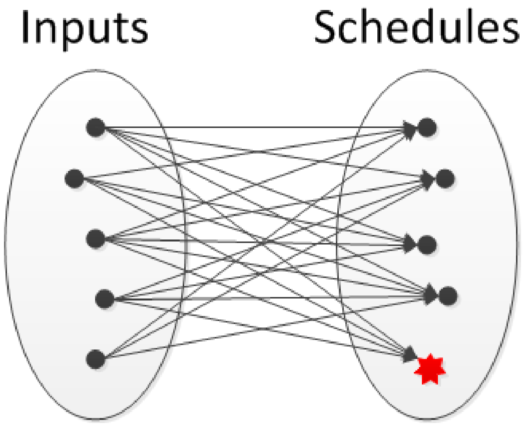
- er

Are all of the exponentially many schedules necessary?

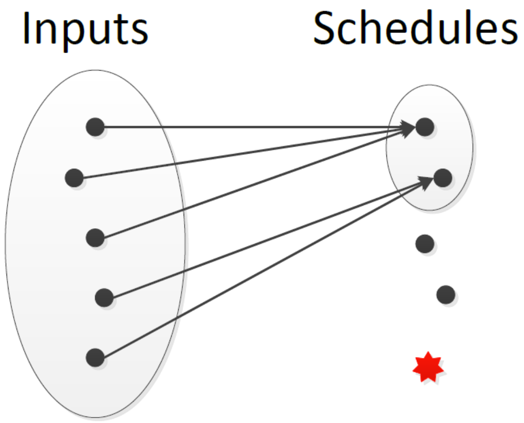
- Insight 1: for many programs, a wide range of inputs shares the same set of schedules [Tern OSDI 10] [Peregrine SOSP 11]

- Insight 2: the overhead of enforcing a schedule on different inputs is low (e.g., 15%) [Tern OSDI 10] [Peregrine SOSP 11]

Stable Multithreading



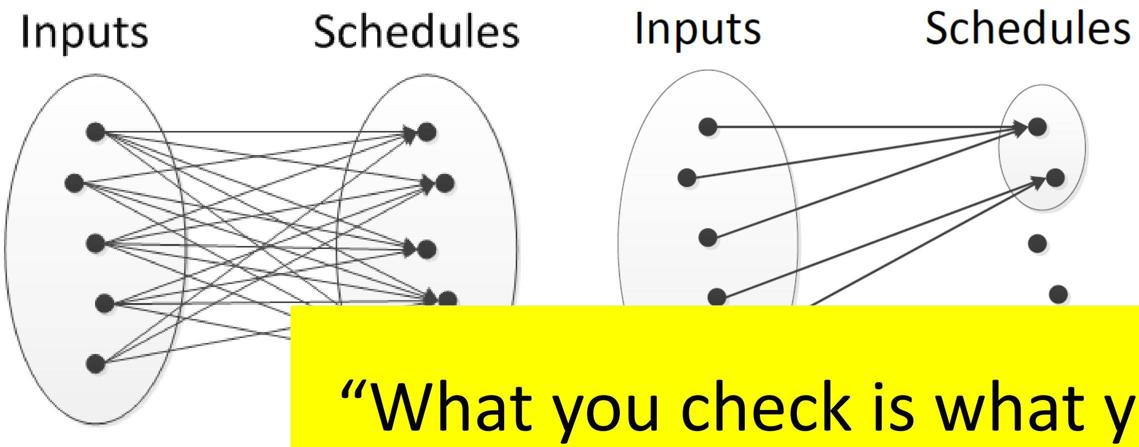
Traditional multithreading



Stable multithreading

- All inputs → a greatly reduced set of schedules
- Key benefits
  - Vastly shrink the haystack → needles much easier to find
  - Provide anticipated *stability* (robustness against input or program perturbations)

Stable Multithreading



Traditio
multith

“What you check is what you run”

“What you can’t check is not run”

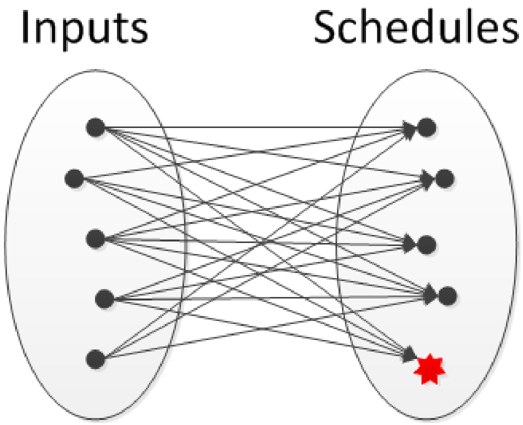
Tool + runtime co-design

- All inpu
- Key be
  - Vastly shrink the haystack ➔ needles much easier to find
  - Provide anticipated *stability* (robustness against input or program perturbations)

Stability and determinism are two separate, complementary properties.

Stability is more useful for reliability.

Deterministic multithreading (DMT): one input → one schedule



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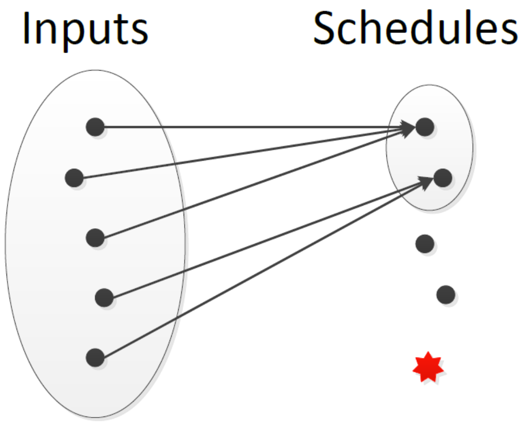

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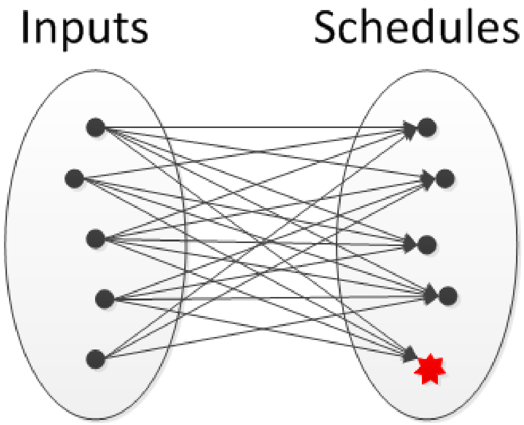

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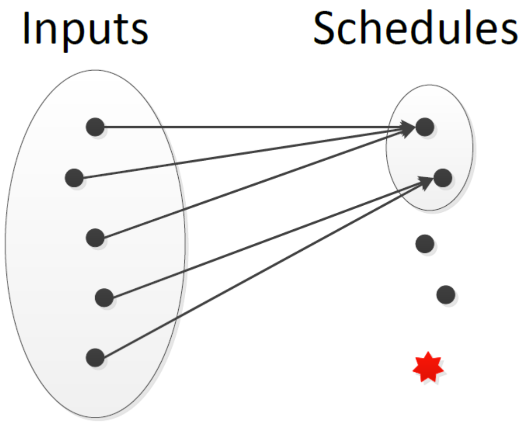

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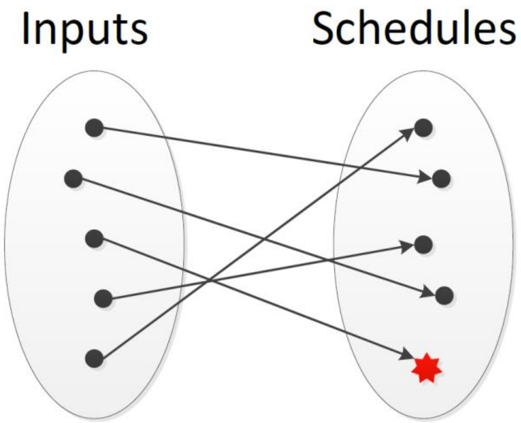

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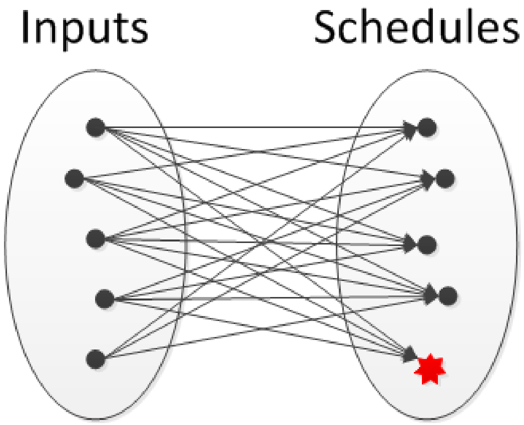

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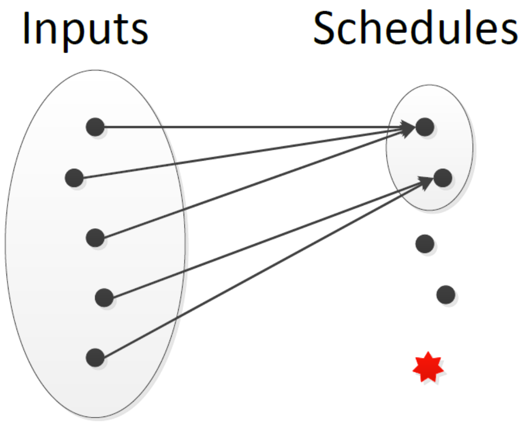

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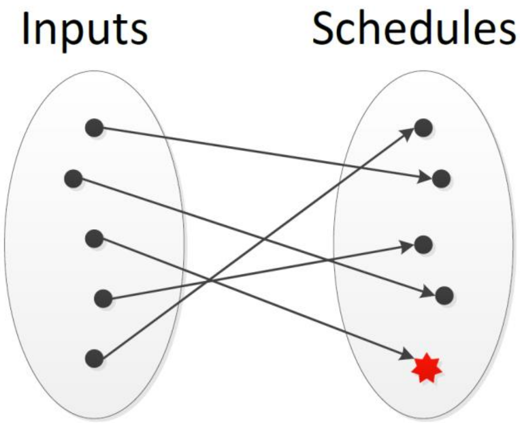
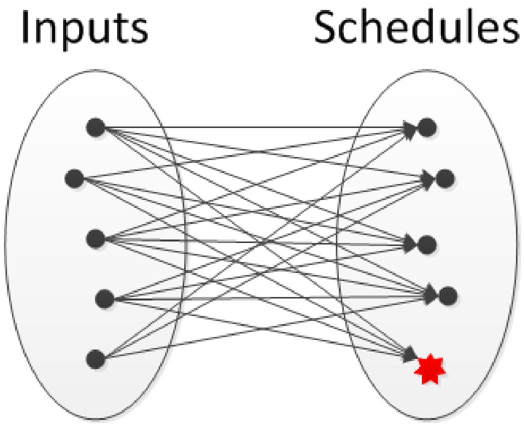


Deterministic multithreading

- One testing execution validates all future executions on the same input
- Reproducing a concurrency bug requires only the input

Deterministic multithreading (DMT): one input → one schedule



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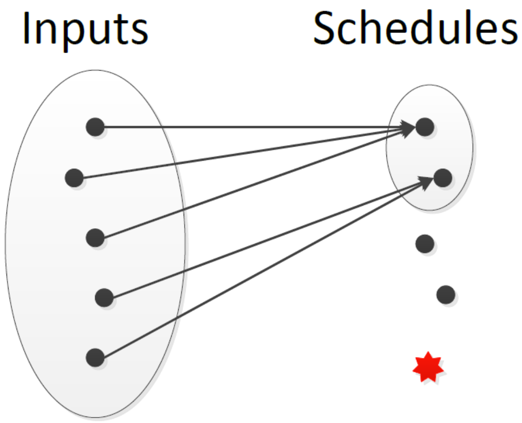
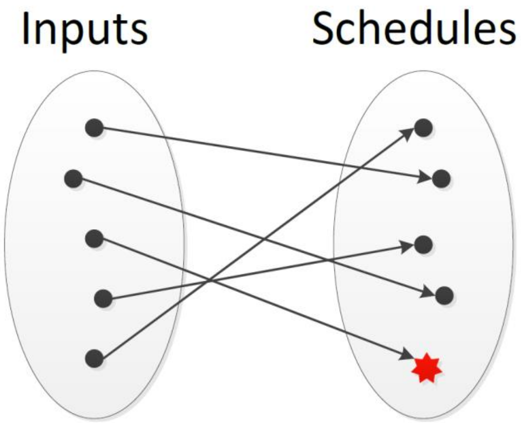


Stable, deterministic multithreading



Deterministic multithreading

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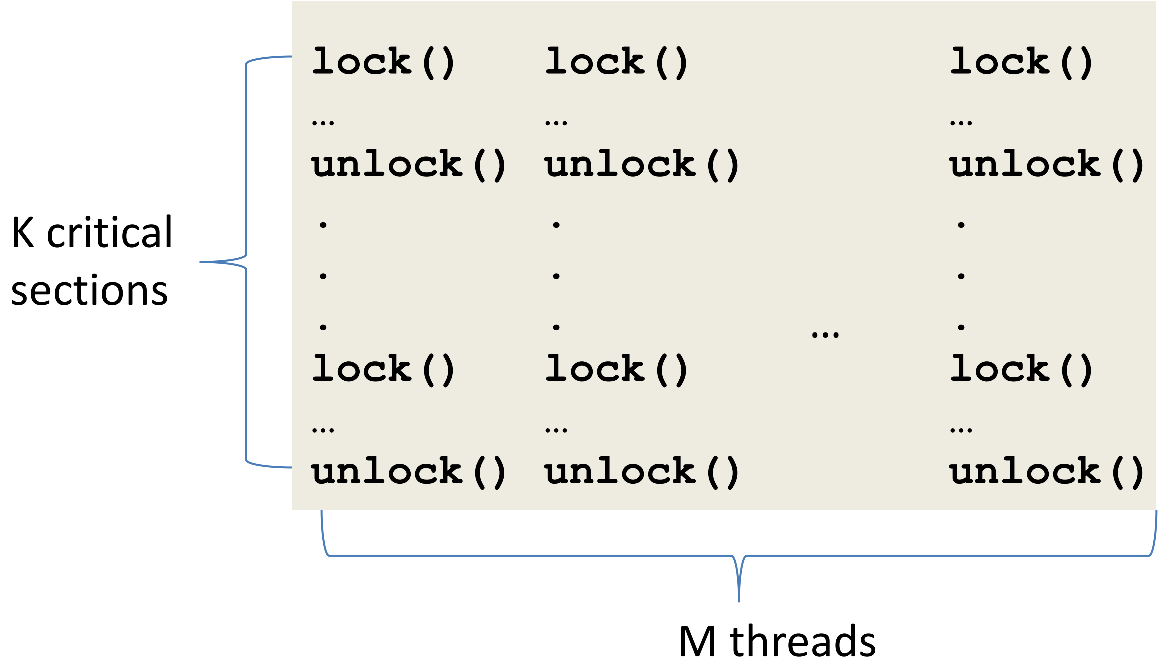
Input or program perturbation → different schedules

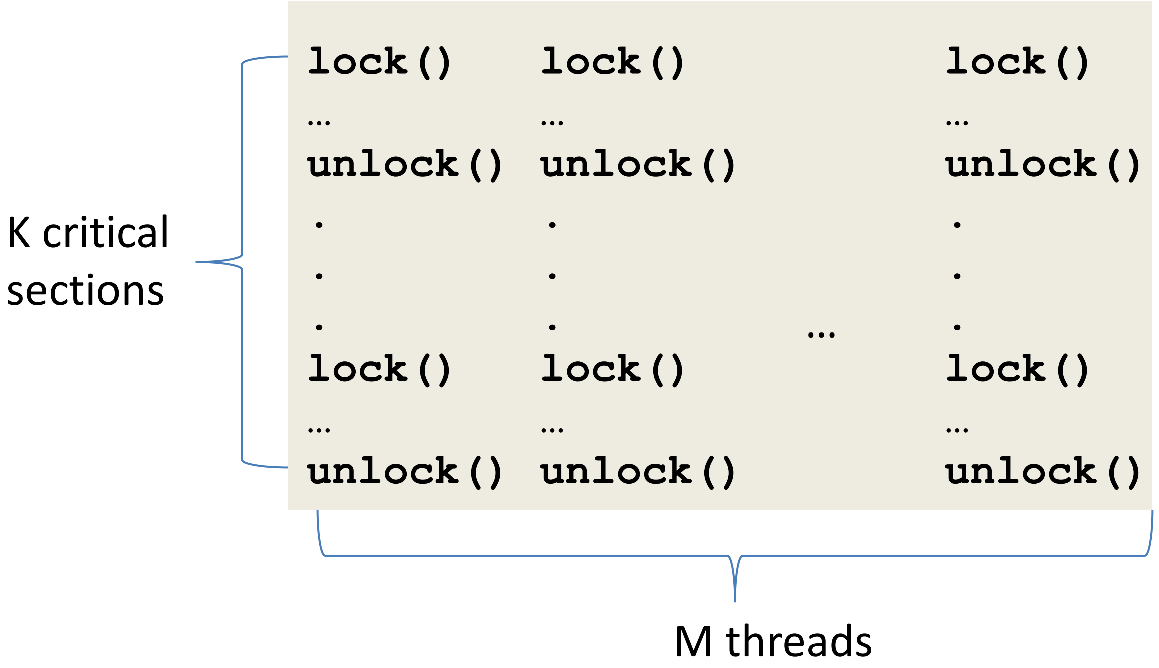


```
lock()     lock()                lock()
…          …                     …
unlock()   unlock()              unlock()
.          .                     .
.          .                     .
.          .               …     .
lock()     lock()                lock()
…          …                     …
unlock()   unlock()              unlock()
```

K critical sections

M threads

Input or program perturbation ➔ different schedules



```
lock()    lock()              lock()
…         …                   …
unlock()  unlock()            unlock()
.         .                   .
.         .                   .
.         .         …         .
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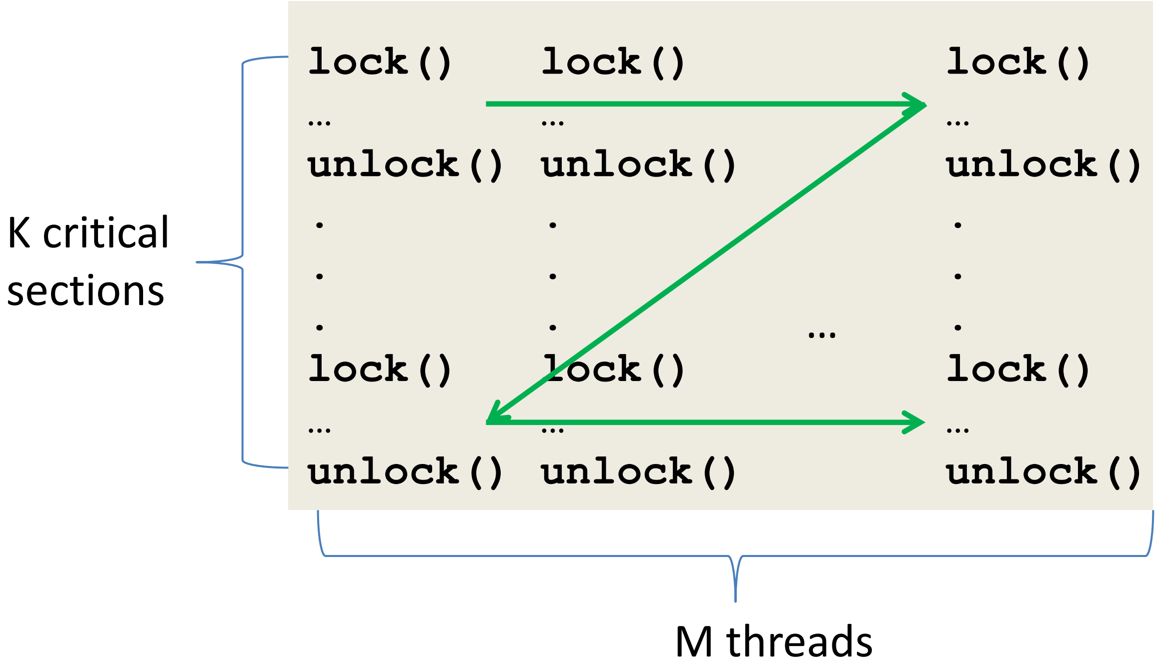
K critical sections

M threads

Input 1

Input or program perturbation ➔ different schedules



```
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…         …                   …
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.         .                   .
.         .                   .
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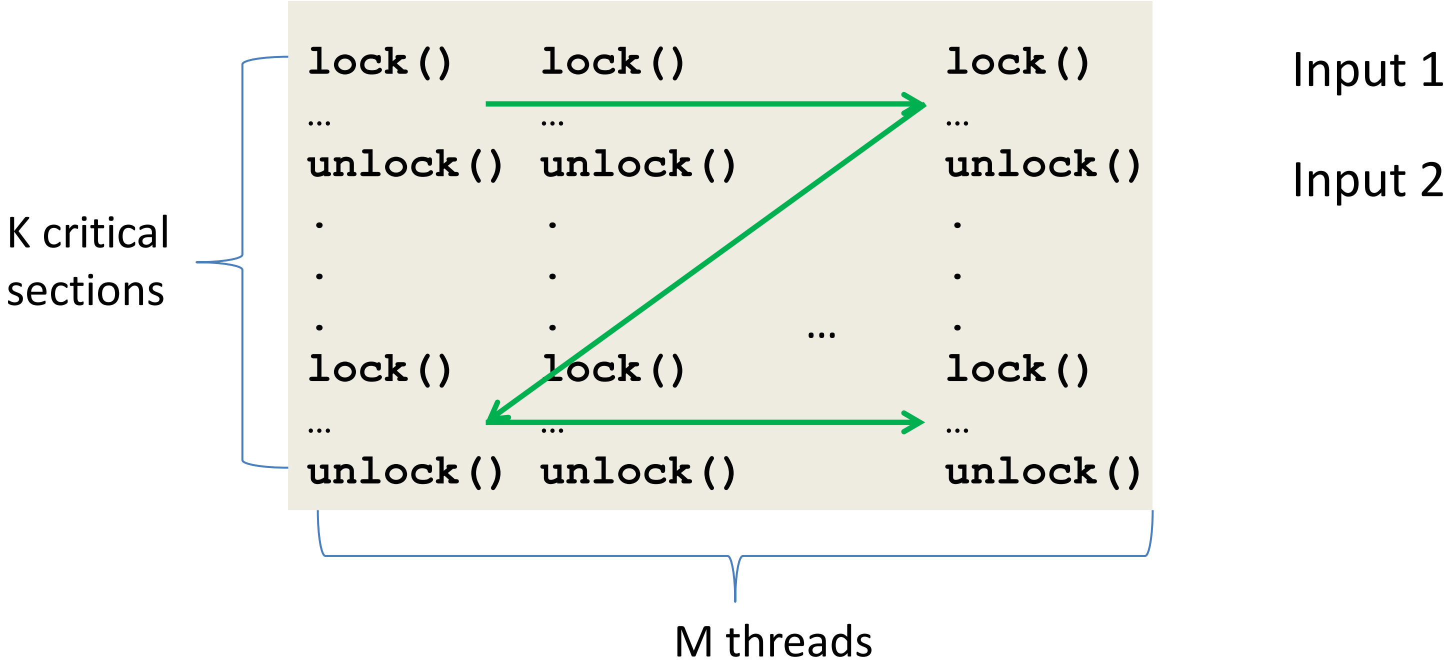
Input or program perturbation ➔ different schedules



```
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.         .                   .
.         .                   .
.         .          …        .
lock()    lock()              lock()
…         …                   …
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```

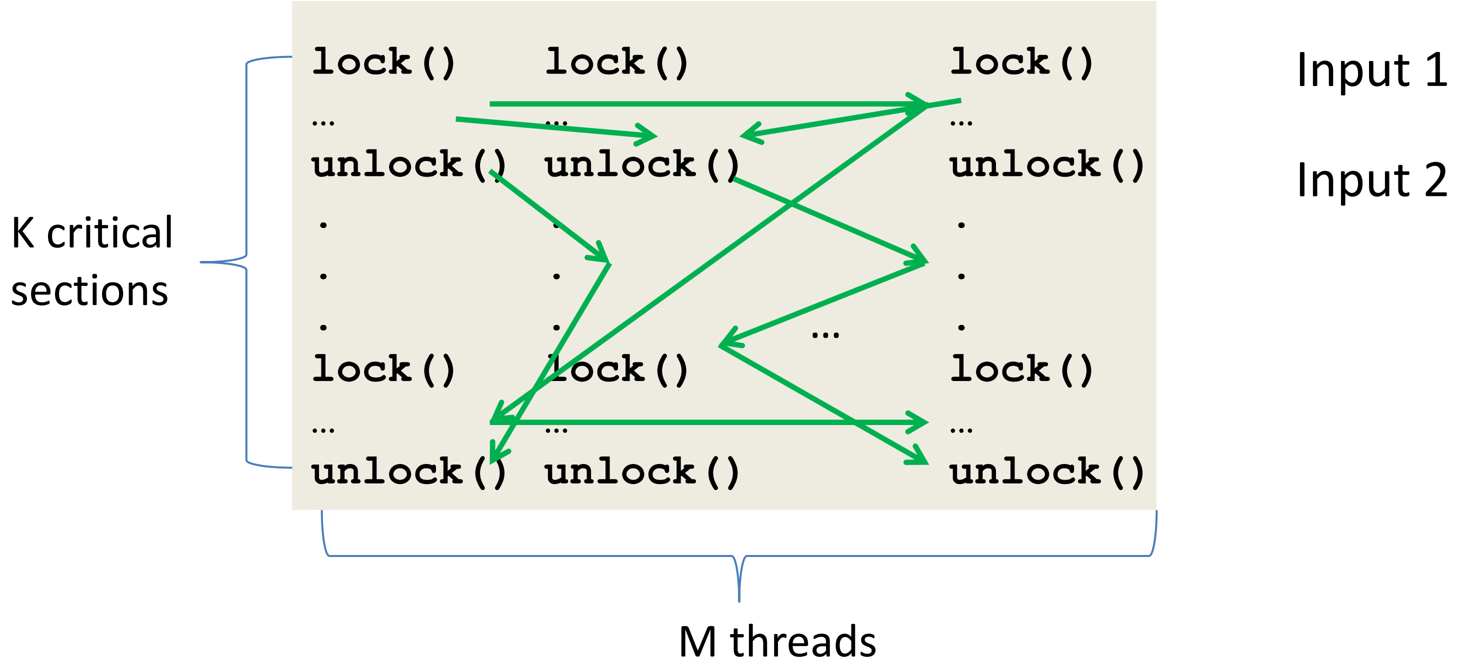
K critical sections

M threads

Input 1

Input 2

Input or program perturbation ➔ different schedules



```
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…          …                 …
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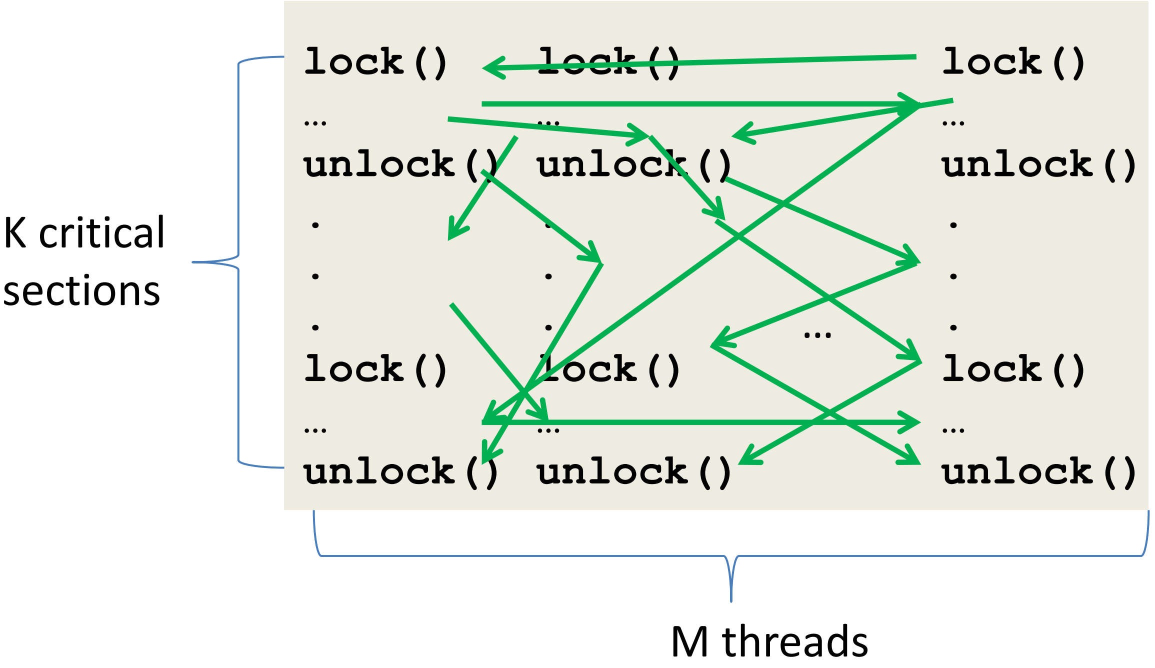

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Input 2

…

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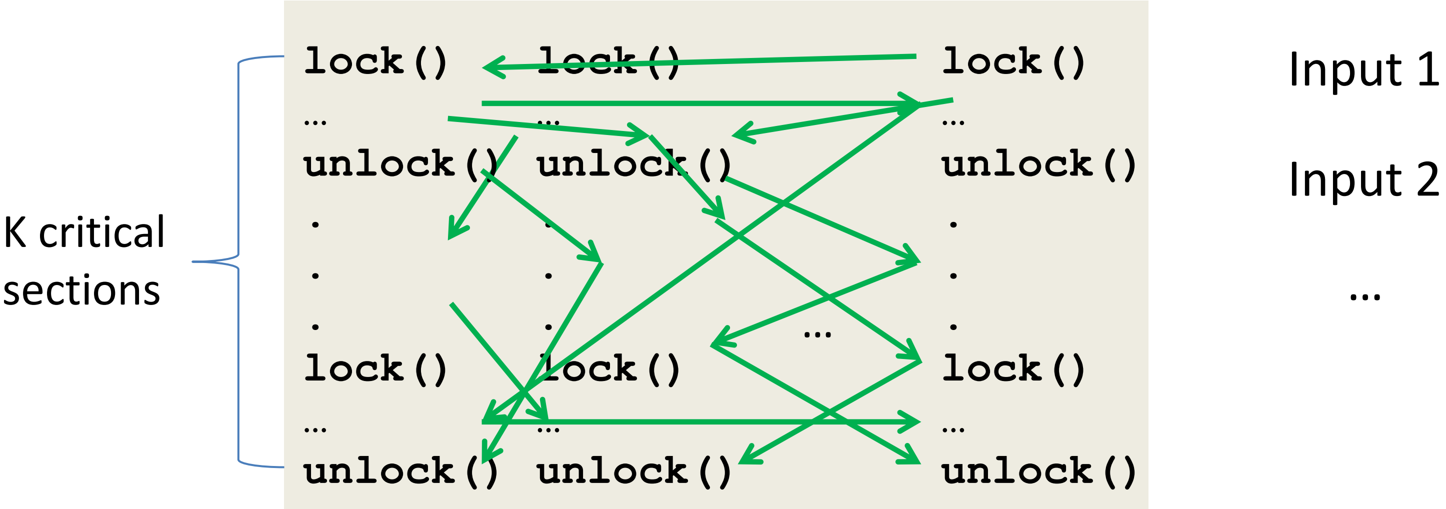

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.          .                 .
.          .                 .
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```

Input 1

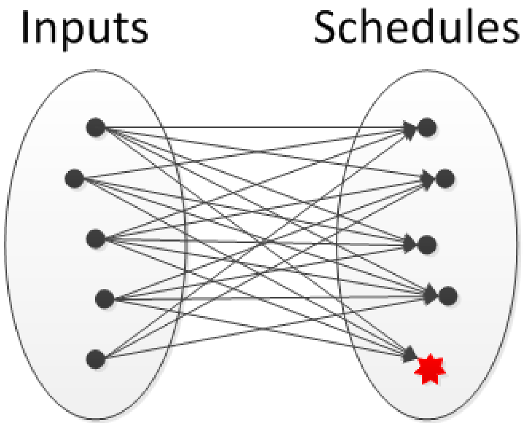
Input 2

…

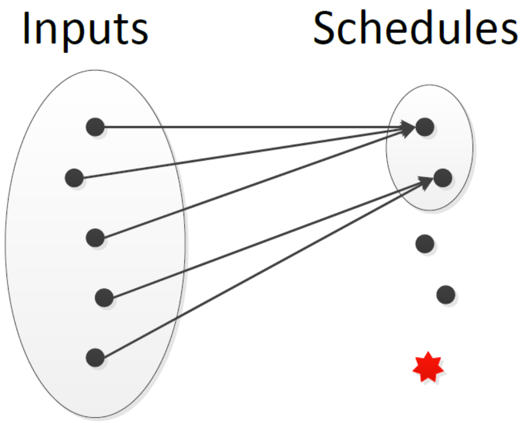
Still too many schedules

Unstable!

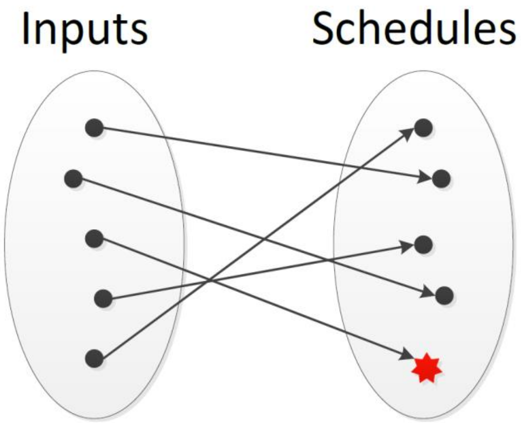
Deterministic but not stable



Traditional
multithreading



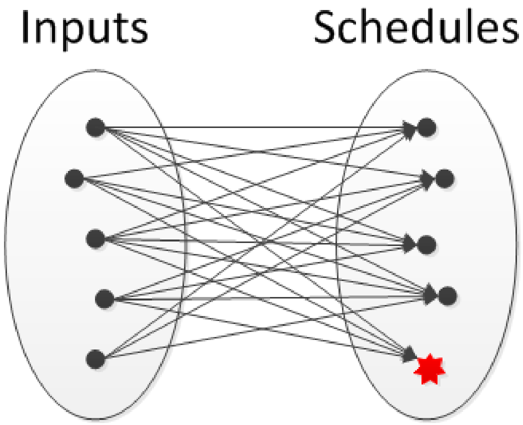
Stable, deterministic
multithreading



Deterministic, unstable
multithreading

- Determinism is a narrow property
  - Same input + same program ➔ same behavior
  - Input or program changes slightly? Can be unstable

Deterministic but not stable



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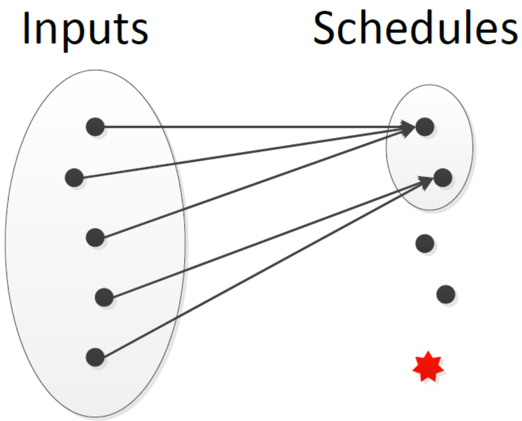

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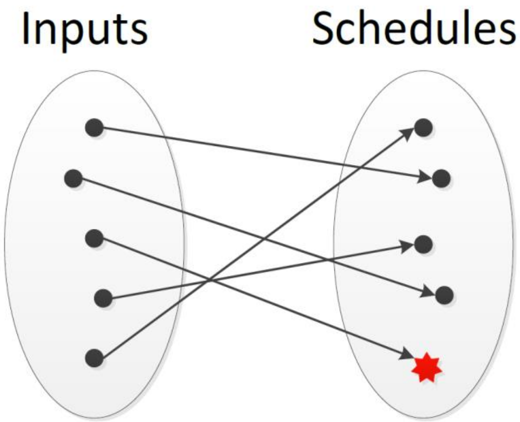

Deterministic, unstable multithreading

- Determ
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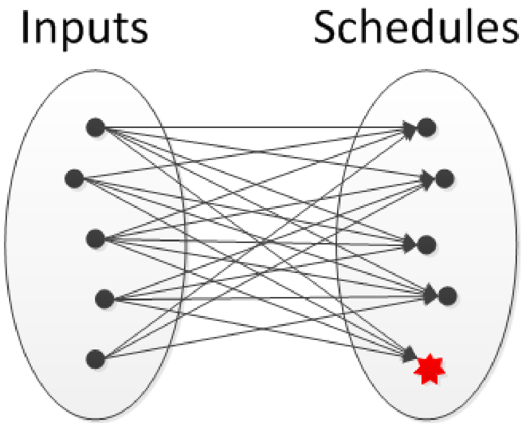
Determinism and stability are often mistakenly conflated

Stable but not deterministic



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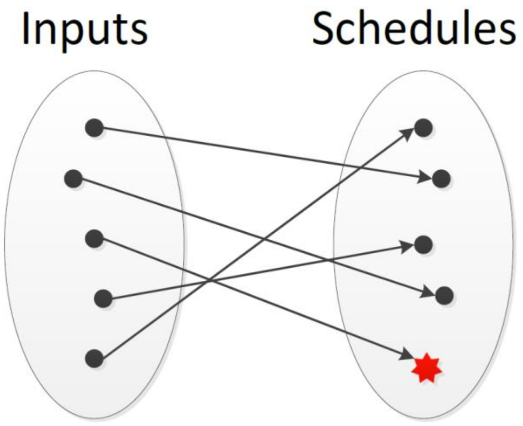
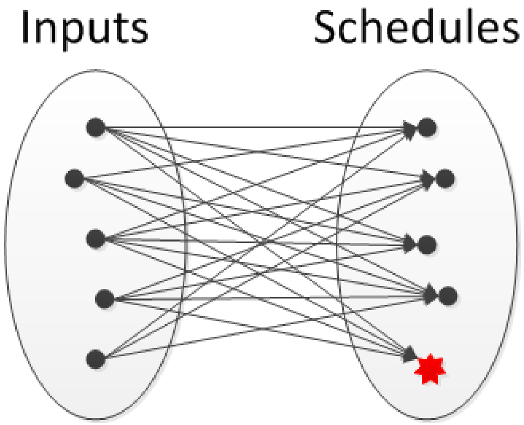


Deterministic multithreading

- Determinism is a binary property
  - Nondeterministic if one input → n > 1 schedules

Stable but not deterministic



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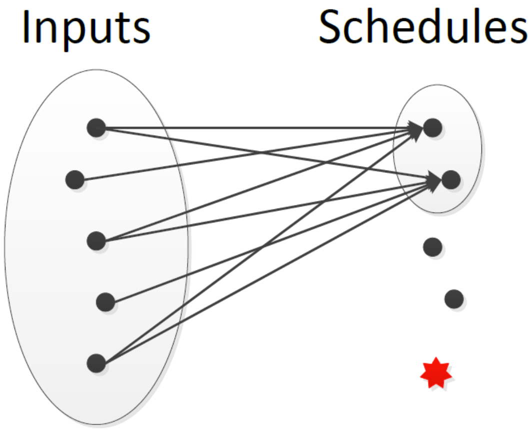

Stable, nondeterministic
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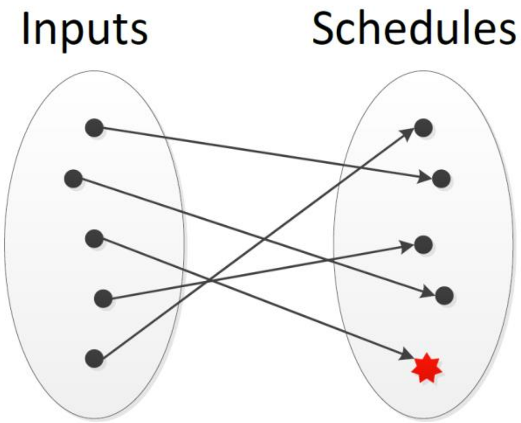

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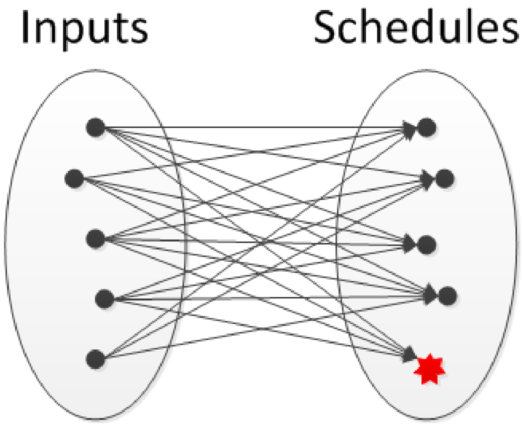

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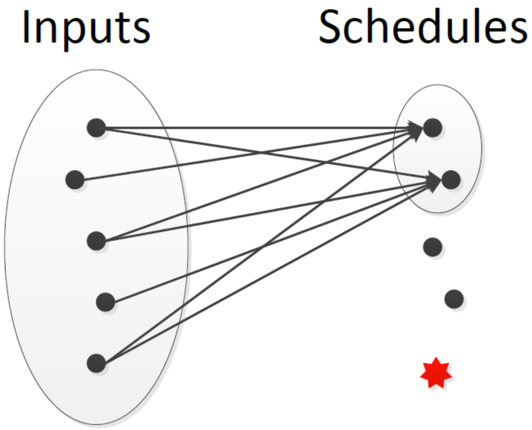

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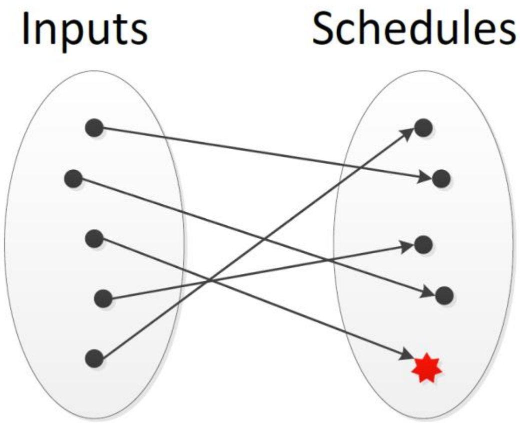

Deterministic multithreading

- Det
  - N

  es

Nondeterministic but stable → easy to be made reliable through checking

How to build StableMT systems

Key challenge: how to compute the schedules to map inputs to

- Requirements on the schedules
  - Stability: process many inputs
  - Performance: reasonably fast

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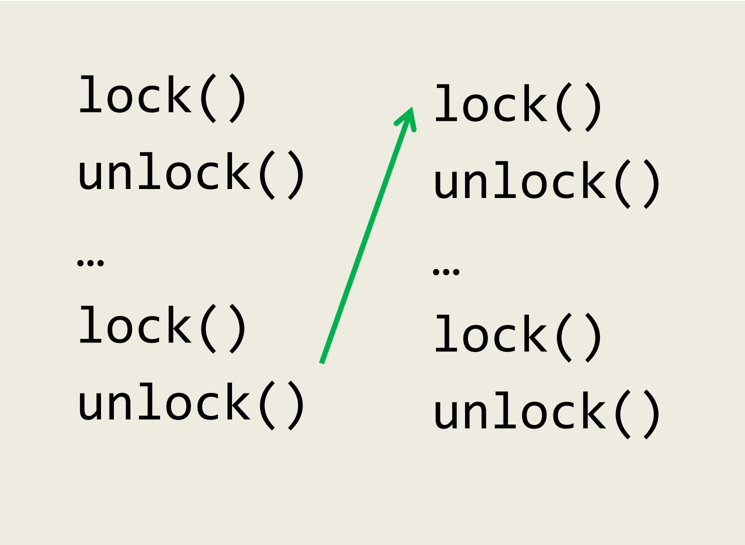

```
lock()          lock()
unlock()        unlock()
…               …
lock()          lock()
unlock()        unlock()
```

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- Requirements on the schedules
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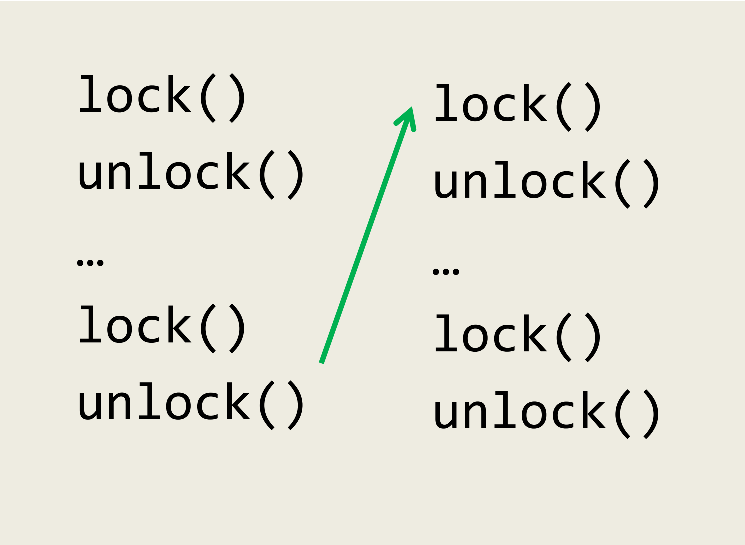

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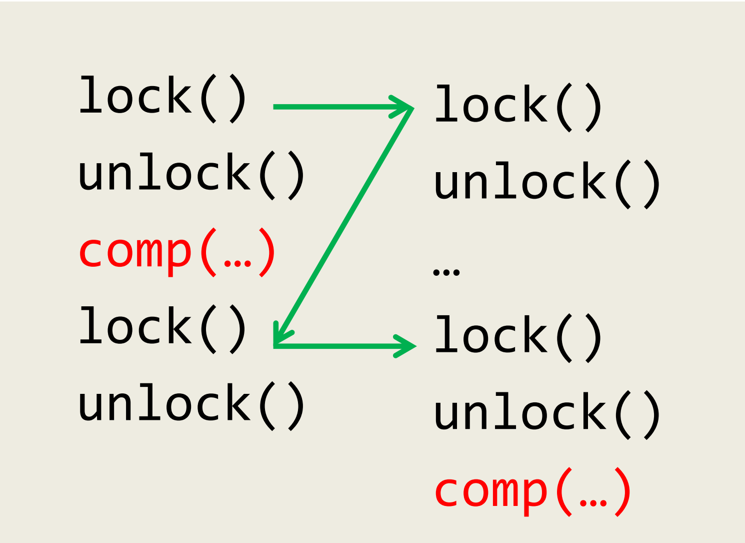

```
lock()          lock()
unlock()        unlock()
comp(…)         …
lock()          lock()
unlock()        unlock()
                comp(…)
```

Our 1st attempt: record and reuse synchronization schedules

- On new input, run program as is to record reasonably fast synchronization schedule
- Compute relaxed, quickly checkable precondition of the schedule to capture dependencies on input
- Reuse schedule on inputs satisfying precondition

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Precondition should constrain x, but not y

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```
i
}
  ...; // no synch
```

Solution: symbolic execution to track constraints and precondition slicing to remove unnecessary constraints

Precondition should constrain x, but not y

The problem of data races

- May cause execution to deviate from schedule

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```
x = 1;
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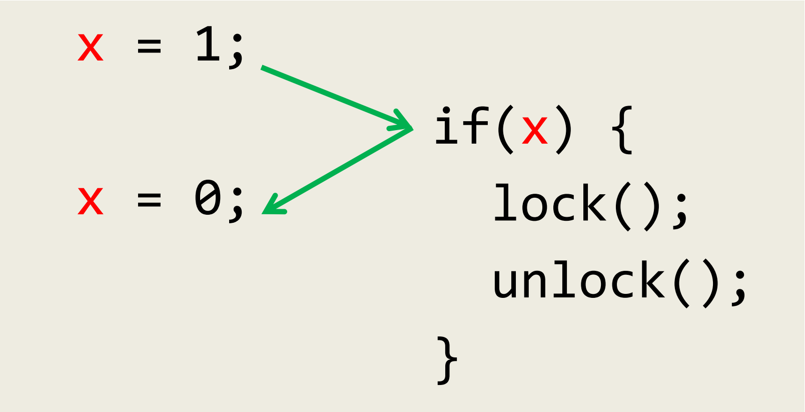

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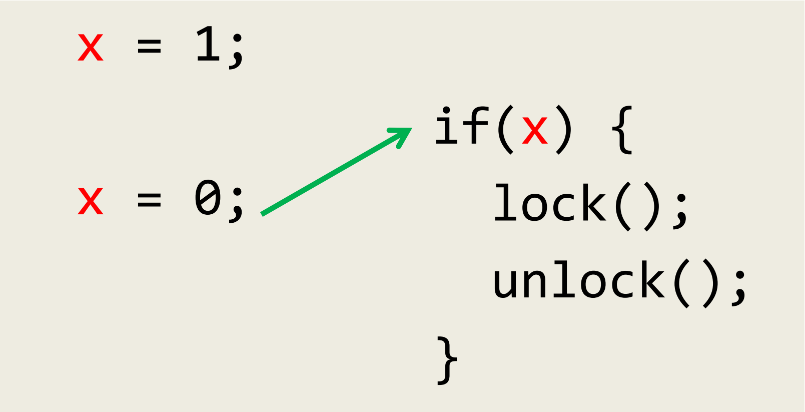

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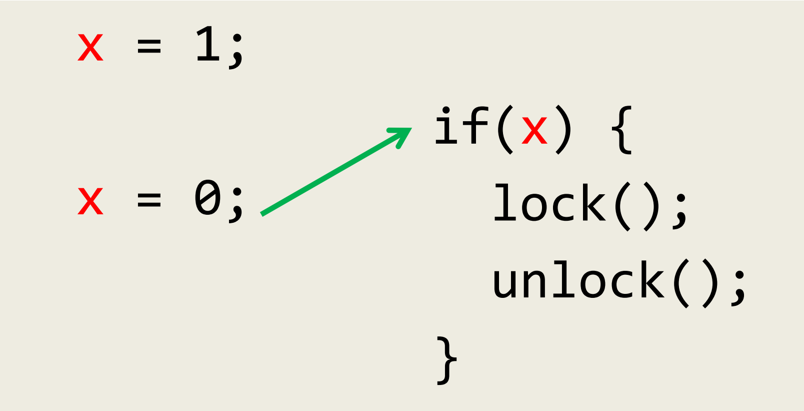

```
x = 1;
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x = 0;         lock();
               unlock();
             }
```

```
a[x] = 1;
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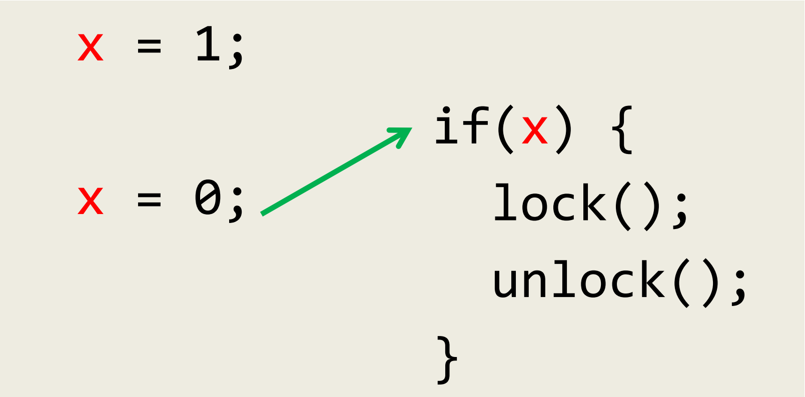

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Solution: custom race detector to detect such races, then custom instrumentor to deterministically resolve races at runtime

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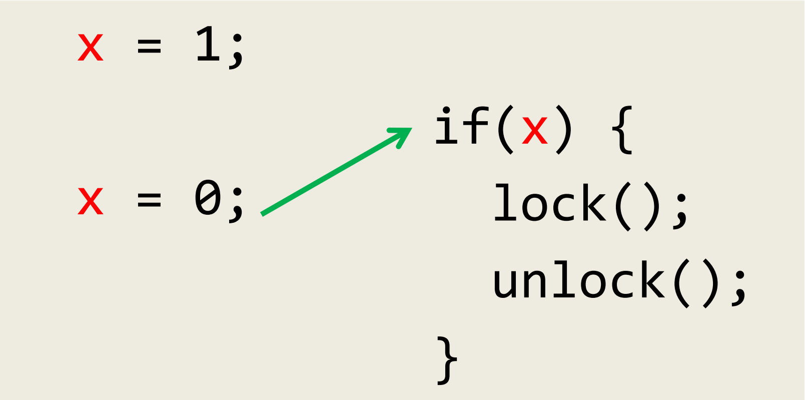

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Solution: custom race detector to detect such races, then custom instrumentor to deterministically resolve races at runtime

Our 1st attempt: sophisticated enough that it needed [Tern OSDI 10] [Loom OSDI 10] [Peregrine SOSP 11] to explain

Attempts by others

- Ignore thread load imbalance [Dthreads SOSP 11] ➔ sometimes pathological slowdown (e.g., 100x) because parallel computations are serialized
- Fine-grained load balancing with instruction counts [DMP ASPLOS 09] [Kendo ASPLOS 09] [CoreDet ASPLOS 10] ➔ unstable

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Seems a very hard challenge,
but there's a simple solution!

Insight

- Empirical study of 100+ programs
- Most threads spend majority of time in a small # of core computations
  - Obvious in retrospect: another example of 80-20 rule
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Coarse-grained load balancing
is good enough!

Performance hints in Parrot

[Parrot SOSP 13]

- By default, the Parrot thread runtime runs synchronizations round-robin
- When necessary, developers add performance hints to their code for speed
  - Soft barrier: “coschedule these computations”
  - Performance critical section: “get through this code section fast”
- Evaluation on 100+ programs shows that hints are easy to add and make executions fast
- https://github.com/columbia/smt-mc/

Example based on PBZip2

```
main thread:
  create 2 consumer threads;
  for each file block {
    char *block = read_block();
    Enqueue;
  }

consumer thread:
  while(1) {
    Wait or Dequeue;
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pthread_mutex_lock(&mu);
enqueue(q, block);
pthread_cond_signal(&cv);
pthread_mutex_unlock(&mu);
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// termination logic elided
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char *block = dequeue(q);
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```
$ LD_PRELOAD=parrot.so ./a.out file_with_two_blocks
```

Schedule ignoring load imbalance

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main   consumer 1   consumer 2

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```
main      consumer 1    consumer 2
          (waiting)     (waiting)
```

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main	consumer 1 (waiting)	consumer 2 (waiting)
read_block Enqueue		

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Enqueue	(woken up)	

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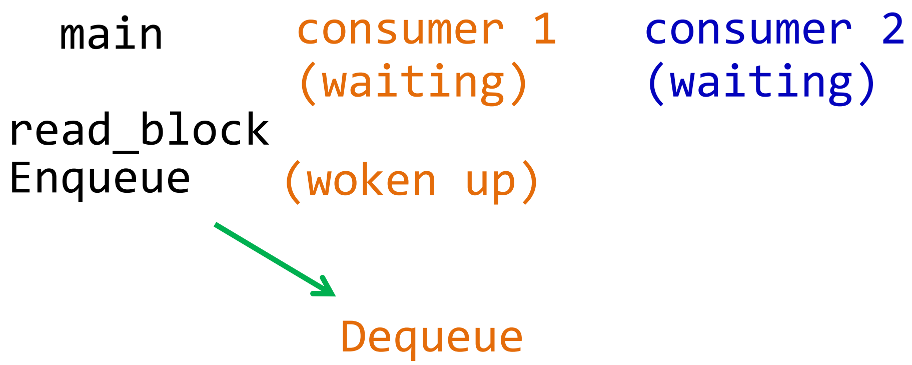

main

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(waiting)

consumer 2
(waiting)

read_block
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(woken up)

Dequeue

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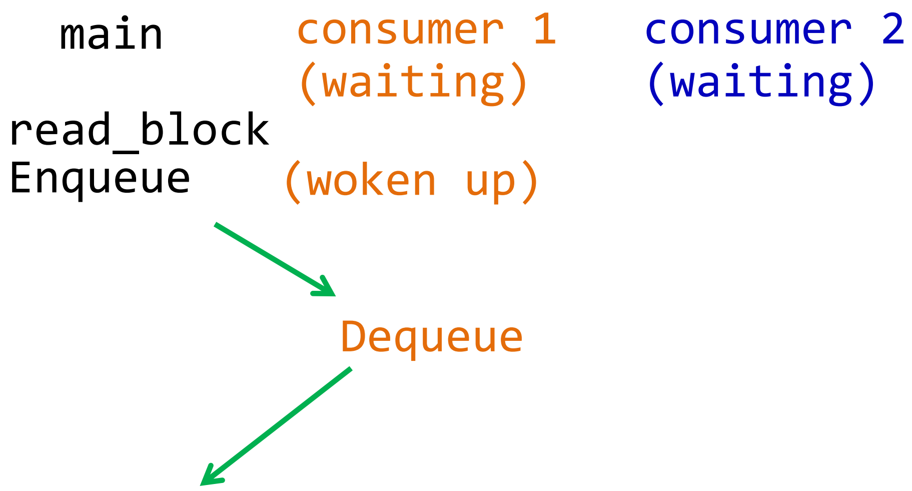

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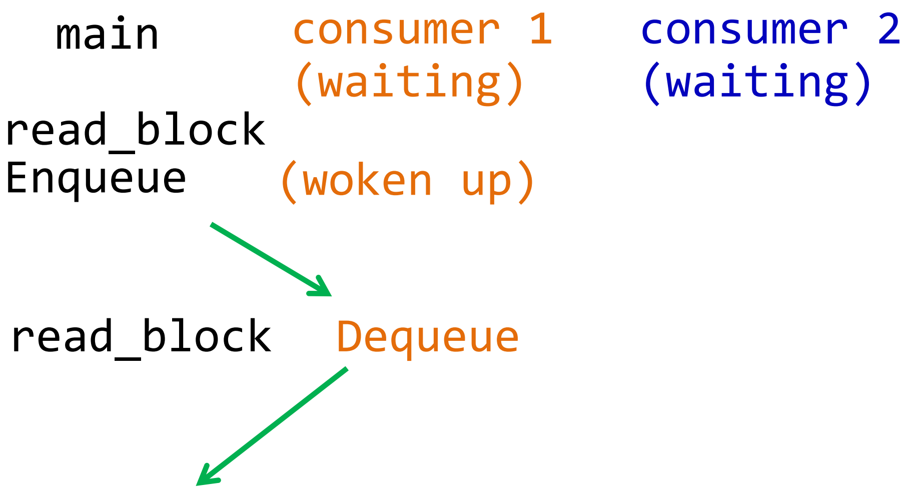

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(woken up)

read_block

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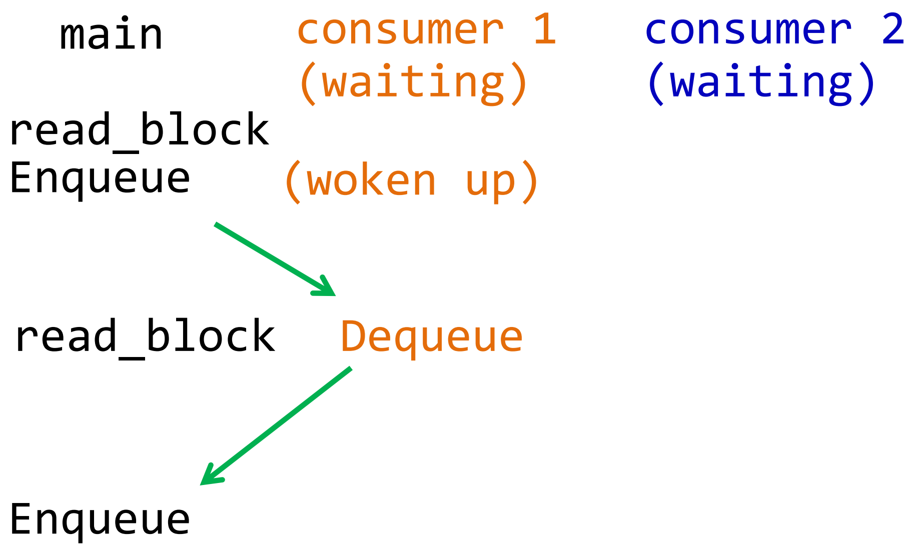

main

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(waiting)

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read_block
Enqueue

(woken up)

read_block

Dequeue

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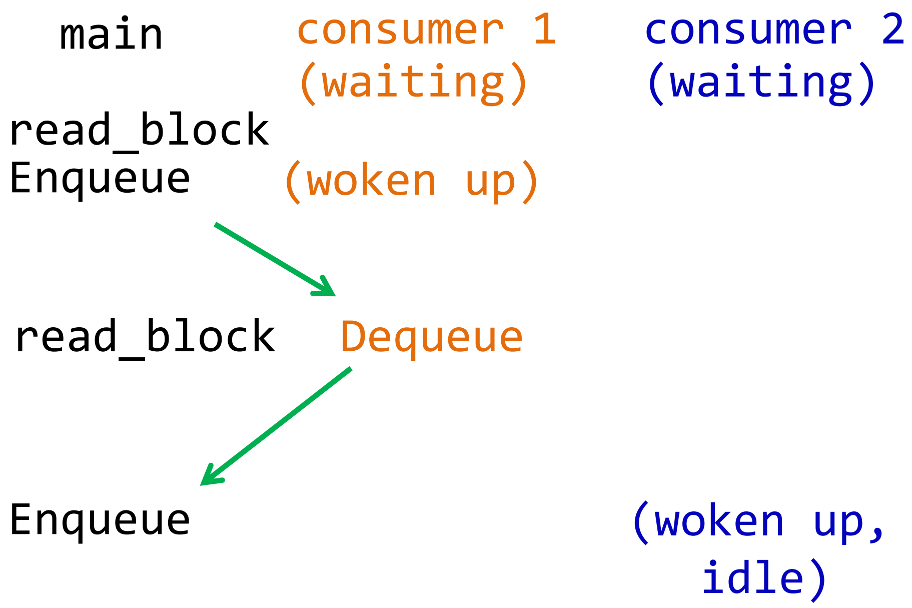

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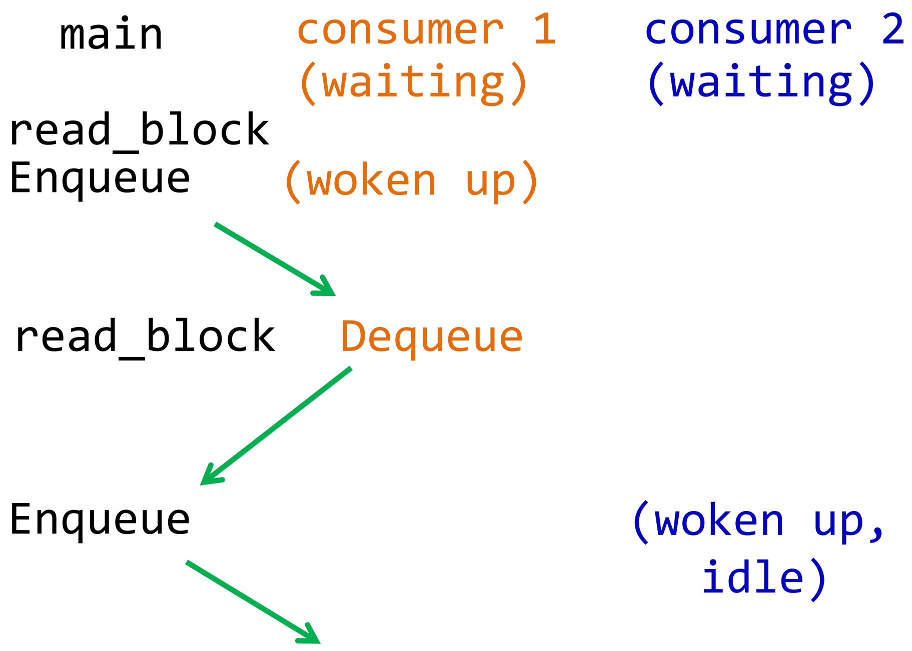

main

consumer 1
(waiting)

consumer 2
(waiting)

read_block
Enqueue

(woken up)

read_block

Dequeue

Enqueue

(woken up,
idle)

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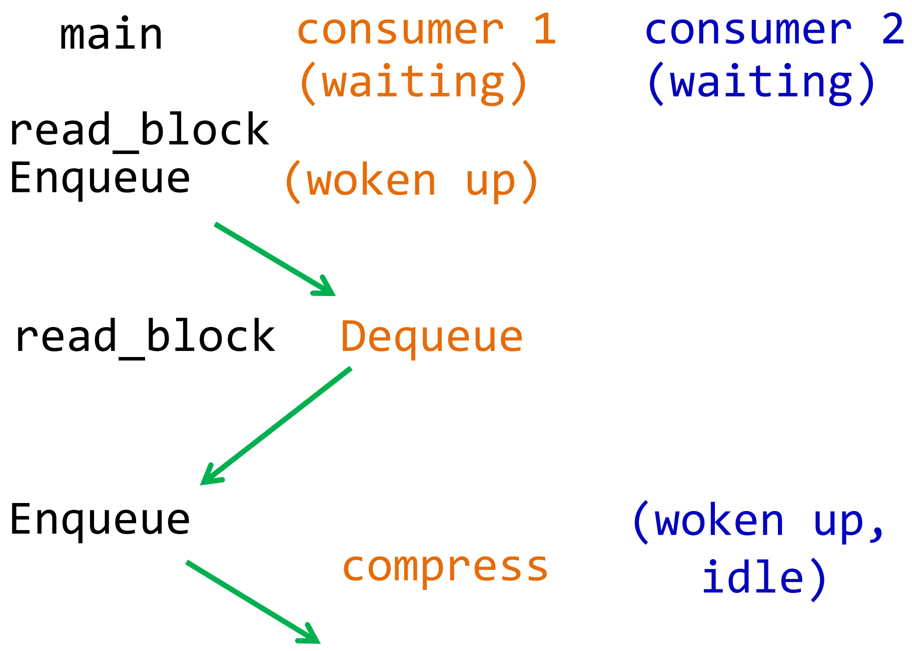

main

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consumer 2
(waiting)

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Enqueue

(woken up)

read_block

Dequeue

Enqueue

compress

(woken up,
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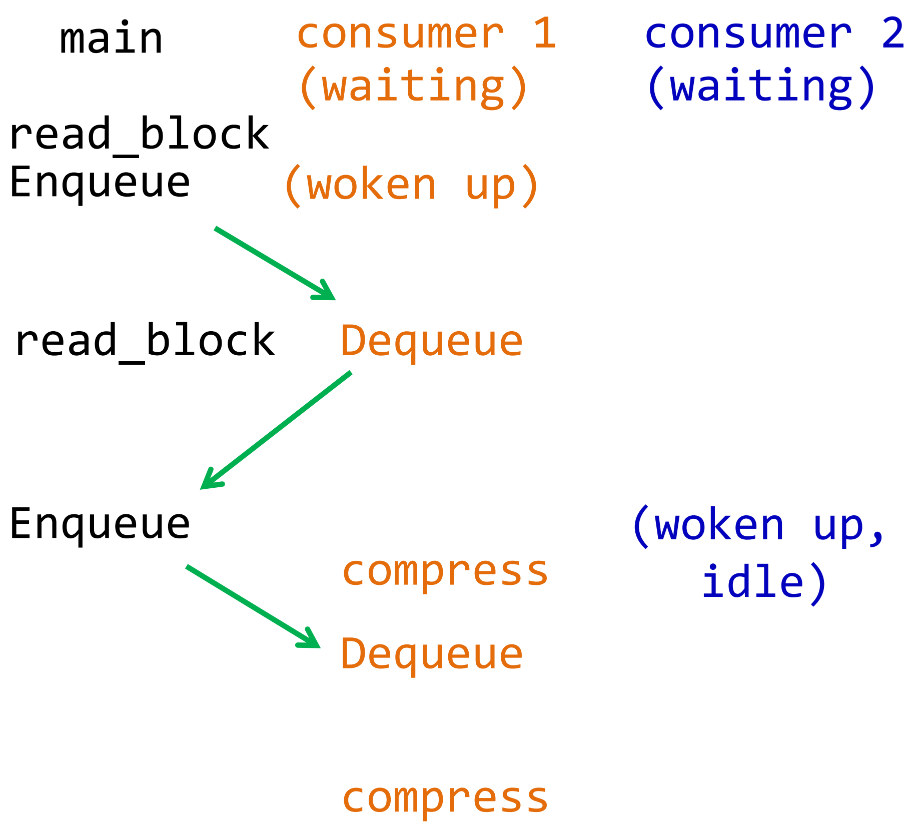
    compress(block);
  }
```



main	consumer 1 (waiting)	consumer 2 (waiting)
read_block Enqueue	(woken up)	
read_block	Dequeue	
Enqueue		(woken up, idle)
	compress	
	Dequeue	
	compress	

Schedule ignoring load imbalance

```
main thread:
  create 2 consumer threads;
  for each file block {
    char *block = read_block();
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consumer thread:
  while(1) {
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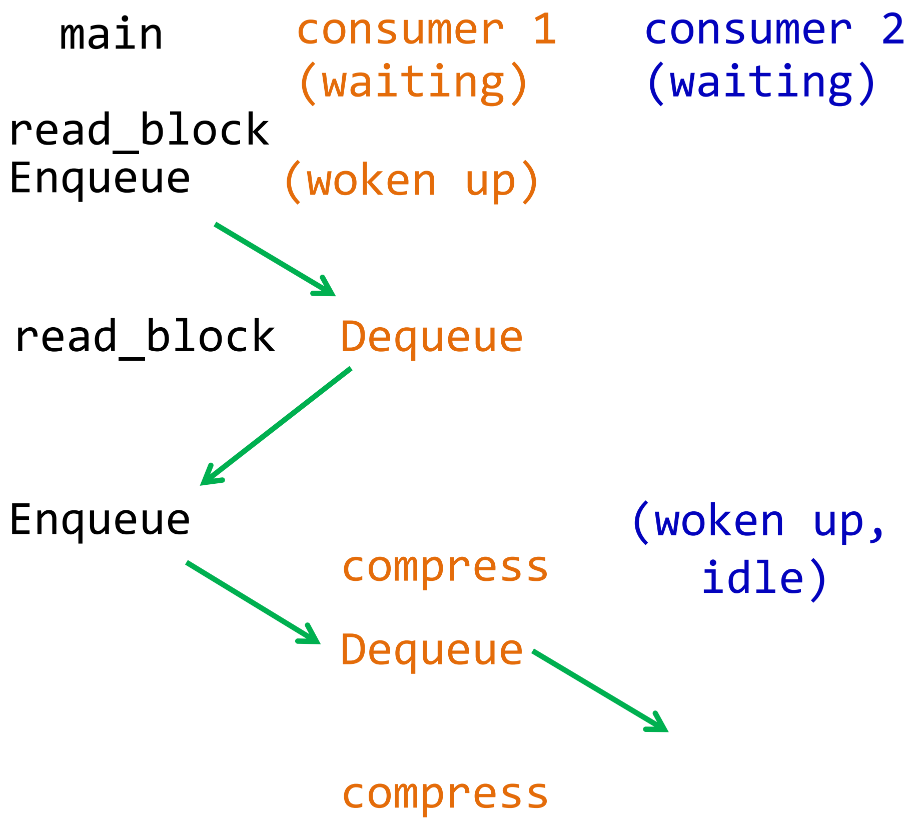

main

consumer 1 (waiting)

consumer 2 (waiting)

read_block

Enqueue

(woken up)

read_block

Dequeue

Enqueue

compress

(woken up, idle)

Dequeue

compress

Schedule ignoring load imbalance

```
main thread:
  create 2 consumer threads;
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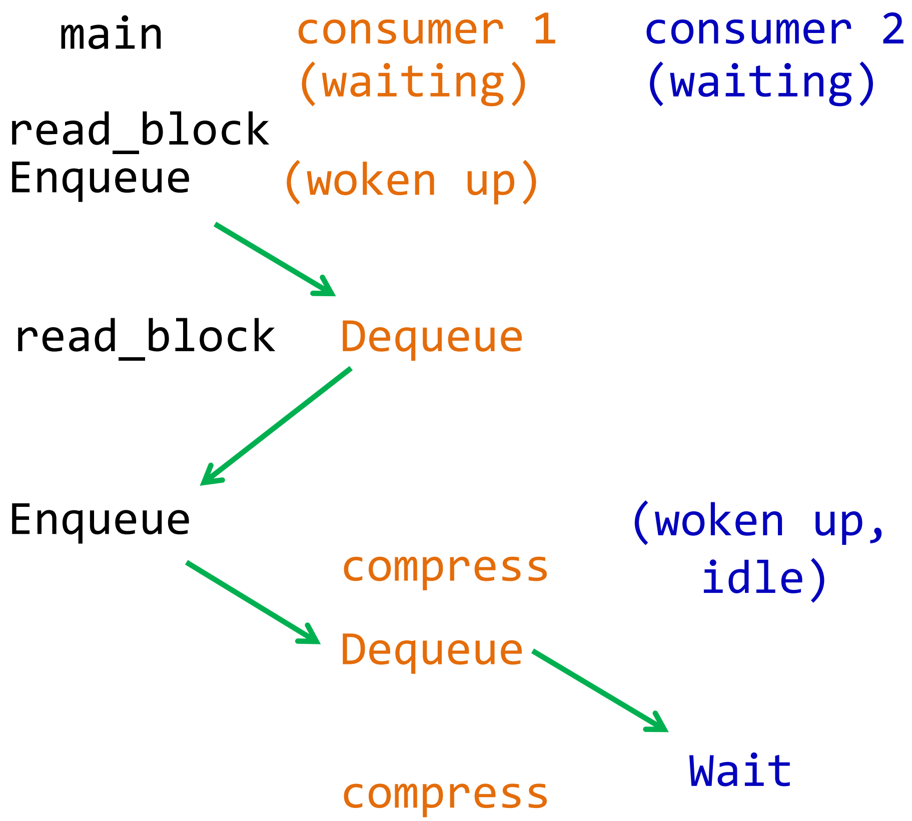

main

consumer 1
(waiting)

consumer 2
(waiting)

read_block
Enqueue

(woken up)

read_block

Dequeue

Enqueue

(woken up,
idle)

compress

Dequeue

Wait

compress

Schedule ignoring load imbalance

```
main thread:
  create 2 consumer threads;
  for each file block {
    char *block = read_block();
    Enqueue;
  }

consumer thread:
  while(1) {
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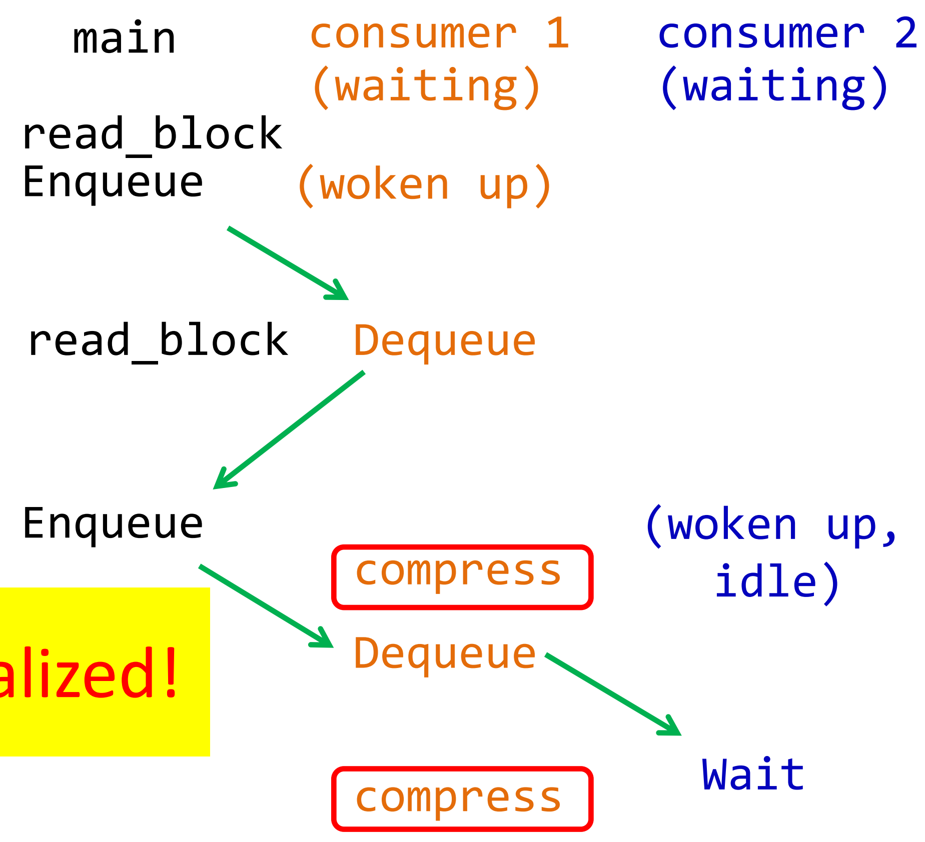

main

consumer 1 (waiting)

consumer 2 (waiting)

read_block

Enqueue

(woken up)

read_block

Dequeue

Enqueue

compress

(woken up, idle)

Dequeue

Wait

compress

Serialized!

Schedule ignoring load imbalance

```
main thread:
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  }

consumer thread:
  while(1) {
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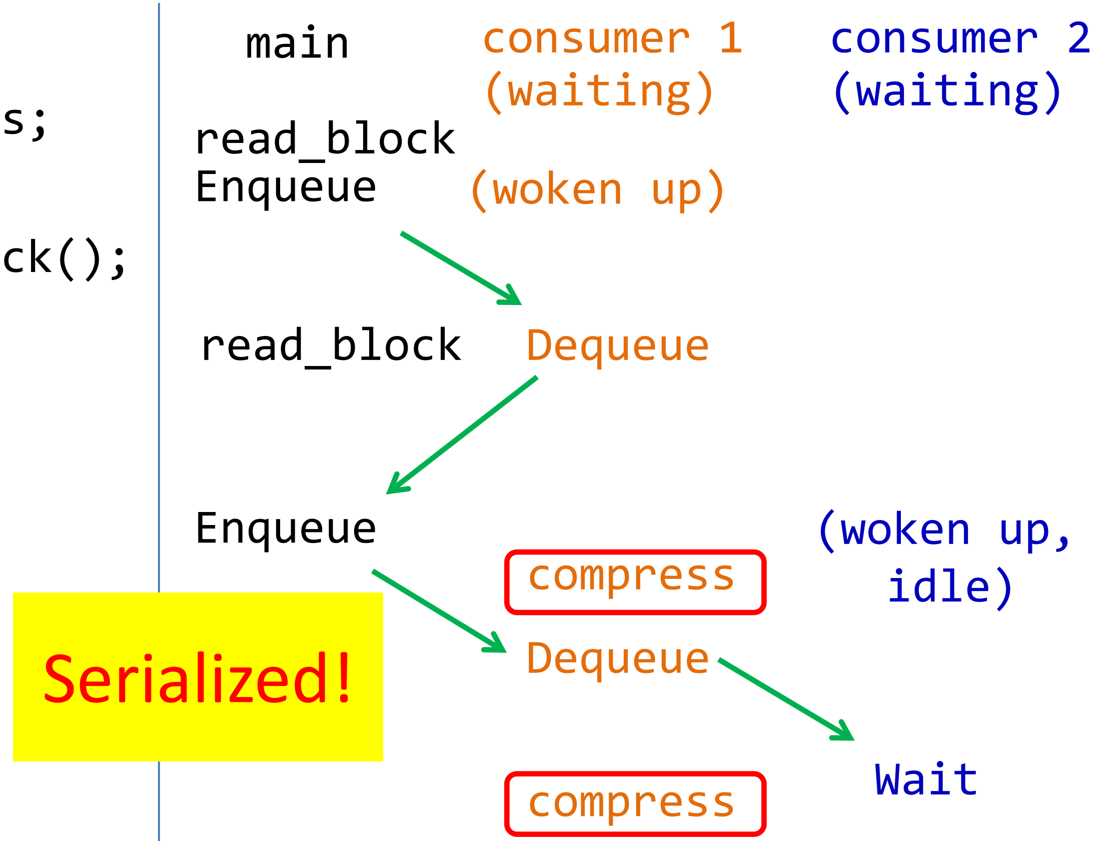

- Observed 770% overhead on 16 cores in prior system Dthreads [Dthreads SOSP 11]

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
    char *block = read_block();
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consumer thread:
  while(1) {
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Parrot schedule with hints

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Parrot schedule with hints

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consumer thread:
  while(1) {
    Wait or Dequeue
    soba_wait();
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```

main   consumer 1   consumer 2

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
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consumer thread:
  while(1) {
    Wait or Dequeue
    soba_wait();
    compress(block);
  }
```

main	consumer 1 (waiting)	consumer 2 (waiting)

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
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consumer thread:
  while(1) {
    Wait or Dequeue
    soba_wait();
    compress(block);
  }
```

main	consumer 1	consumer 2
	(waiting)	(waiting)
read_block		
Enqueue	(woken up)	

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
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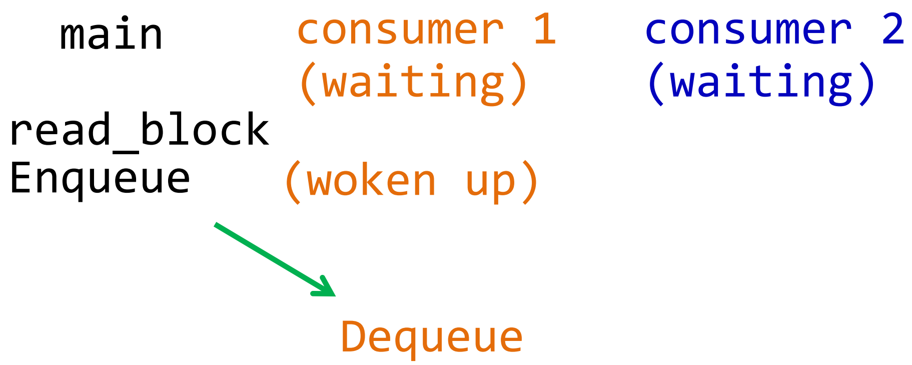

main

consumer 1
(waiting)

consumer 2
(waiting)

read_block
Enqueue

(woken up)

Dequeue

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
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    Enqueue;
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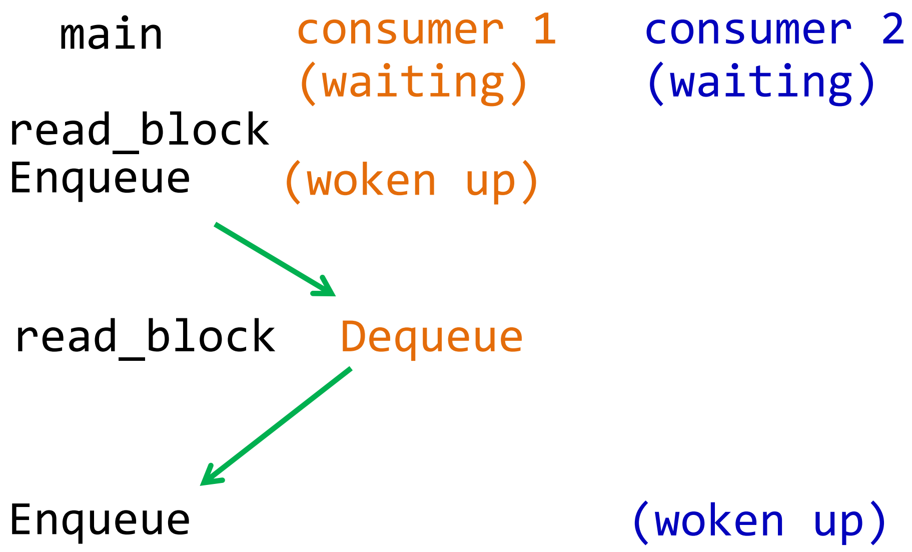

main

consumer 1
(waiting)

consumer 2
(waiting)

read_block
Enqueue

(woken up)

read_block

Dequeue

Enqueue

(woken up)

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
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    Enqueue;
  }

consumer thread:
  while(1) {
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    compress(block);
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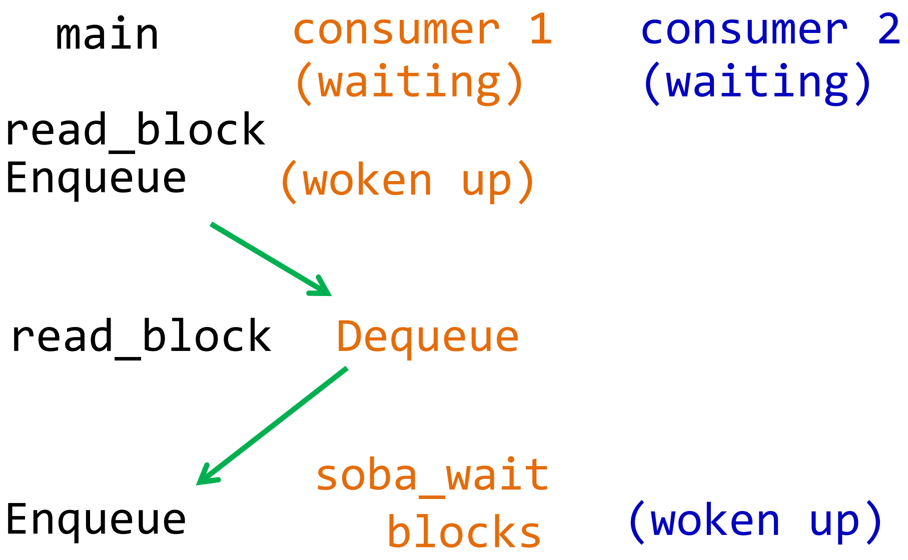
```



main	consumer 1	consumer 2
	(waiting)	(waiting)
read_block Enqueue	(woken up)
read_block	Dequeue
Enqueue	soba_wait blocks	(woken up)

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
    char *block = read_block();
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  }

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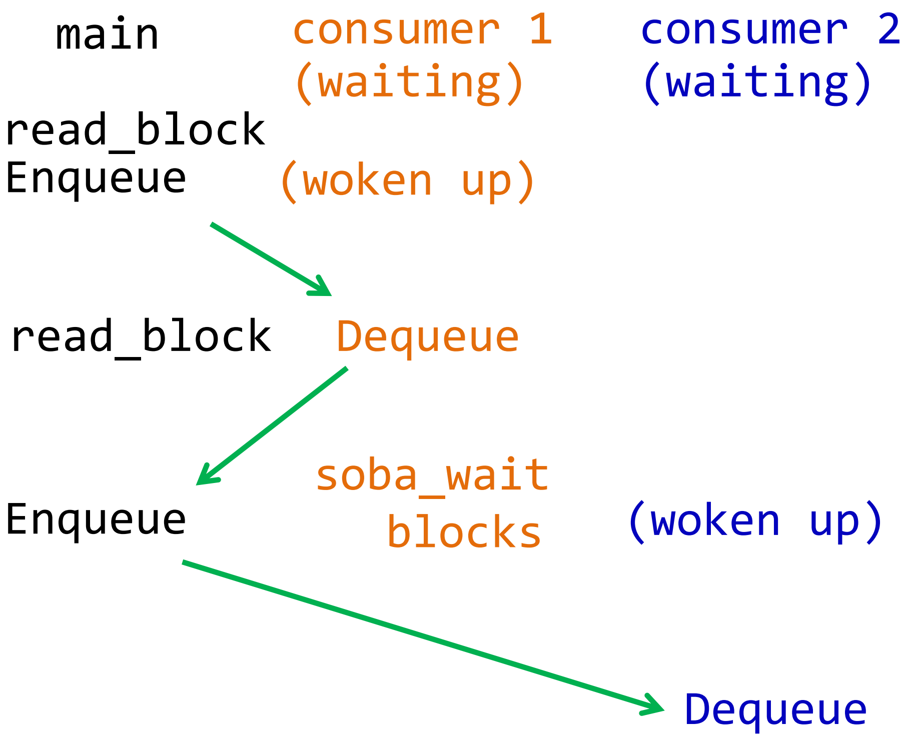

main

consumer 1 (waiting)

consumer 2 (waiting)

read_block

Enqueue

(woken up)

read_block

Dequeue

Enqueue

soba_wait blocks

(woken up)

Dequeue

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
    char *block = read_block();
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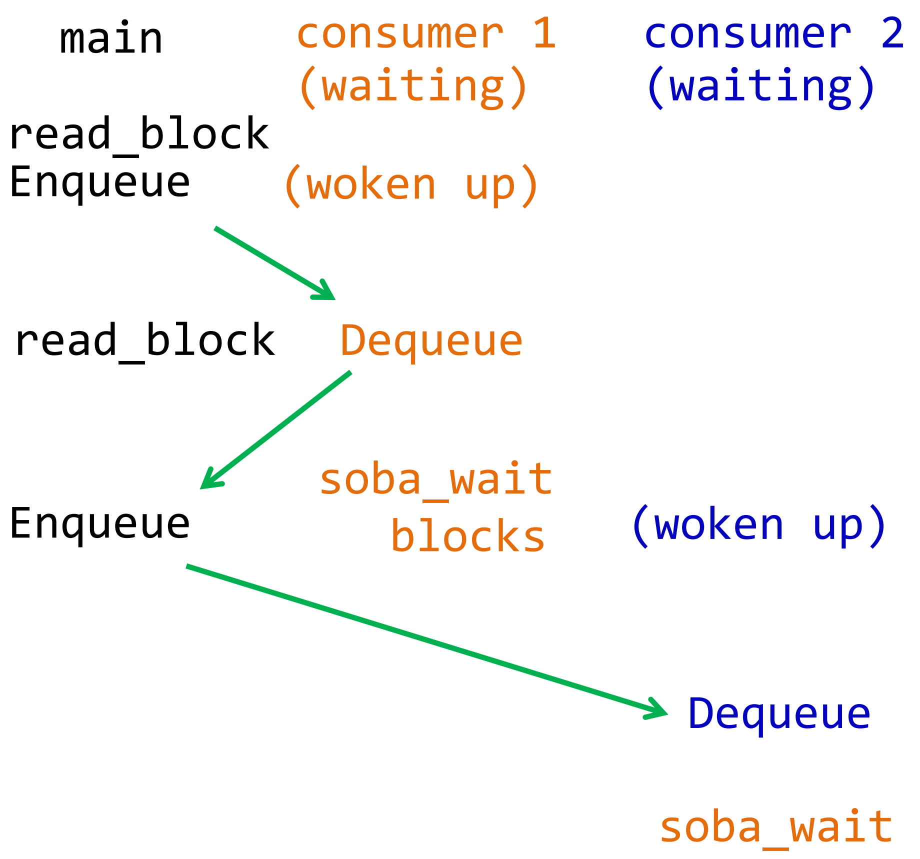

main

consumer 1 (waiting)

consumer 2 (waiting)

read_block

Enqueue

(woken up)

read_block

Dequeue

Enqueue

soba_wait blocks

(woken up)

Dequeue

soba_wait

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
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  }

consumer thread:
  while(1) {
    Wait or Dequeue
    soba_wait();
    compress(block);
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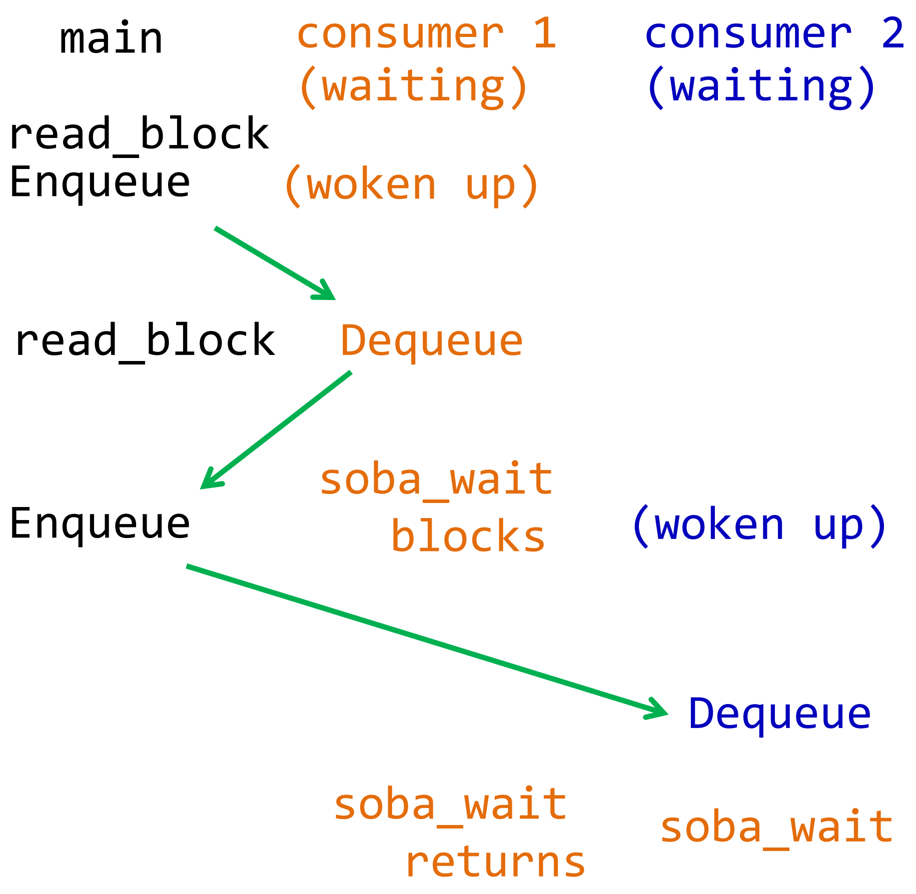

main | consumer 1 (waiting) | consumer 2 (waiting)

read_block

Enqueue | (woken up)

read_block | Dequeue

Enqueue | soba_wait blocks | (woken up)

Dequeue

soba_wait returns | soba_wait

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
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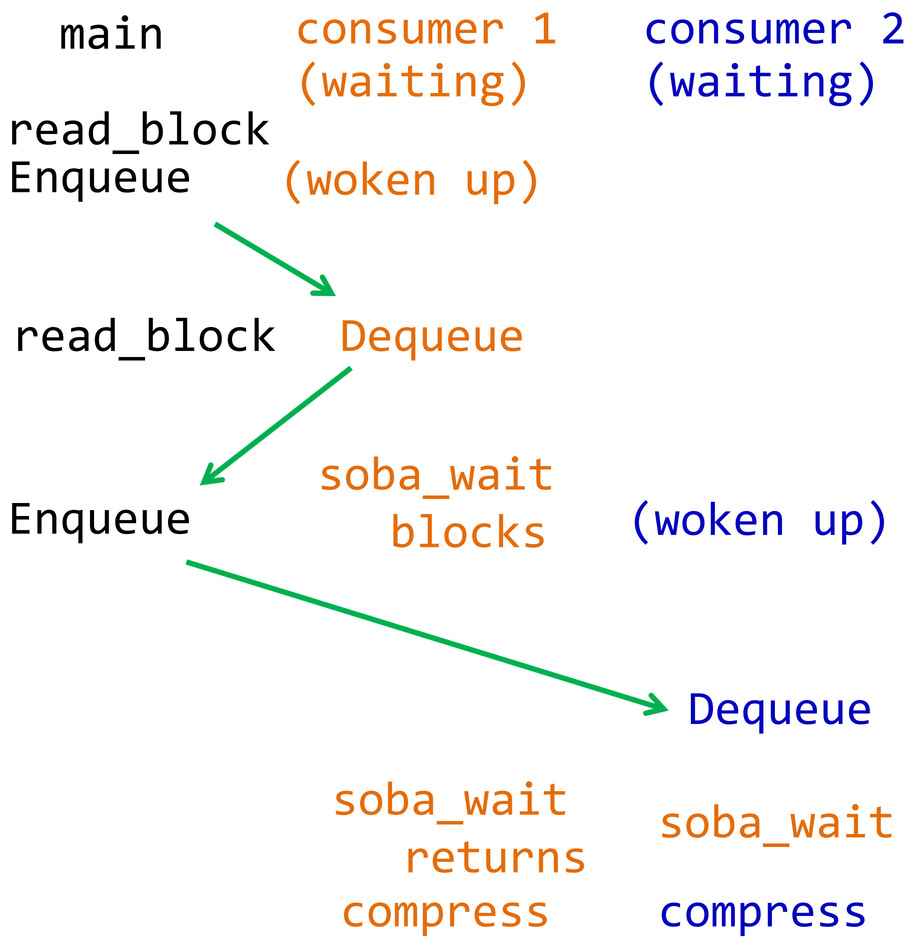

main
consumer 1 (waiting)
consumer 2 (waiting)

read_block
Enqueue
(woken up)

read_block
Dequeue

Enqueue
soba_wait blocks
(woken up)

Dequeue

soba_wait returns
compress

soba_wait
compress

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
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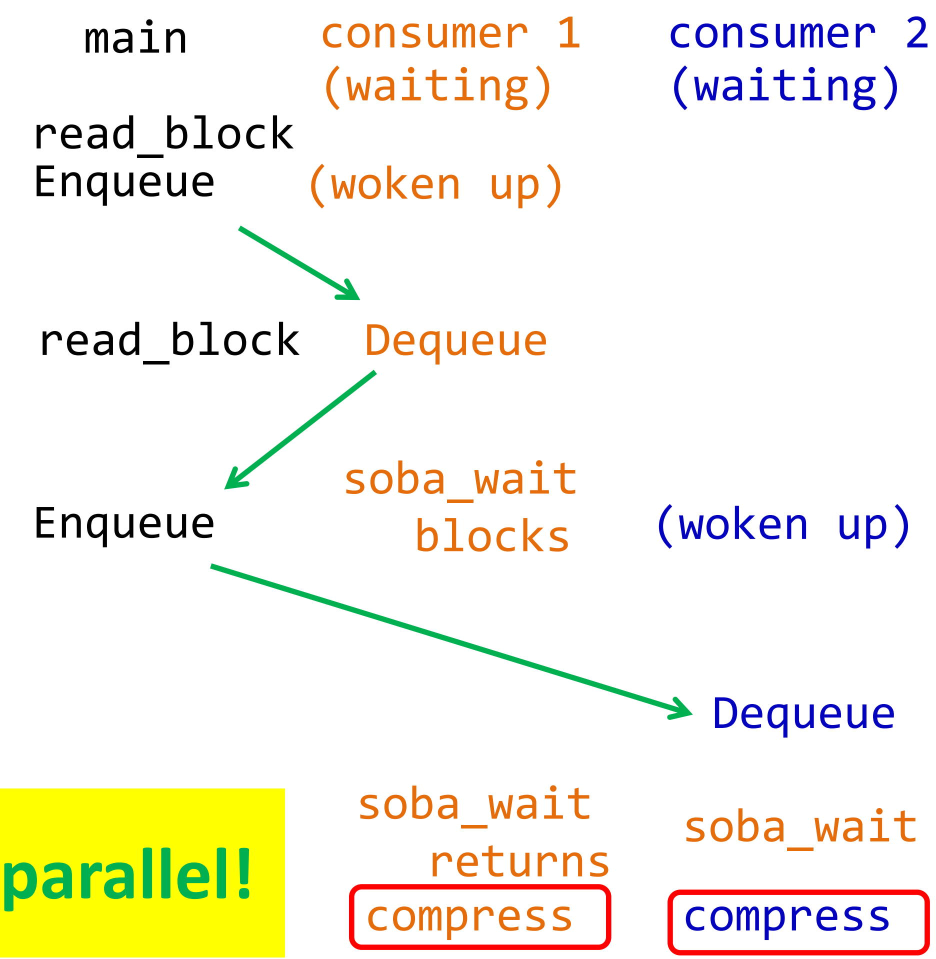

main

consumer 1 (waiting)

consumer 2 (waiting)

read_block

Enqueue

(woken up)

read_block

Dequeue

Enqueue

soba_wait blocks

(woken up)

Dequeue

soba_wait returns

compress

soba_wait

compress

Run in parallel!

Parrot schedule with hints

```
main thread:
  create 2 consumer threads;
  soba_init(2);
  for each file block {
    char *block = read_block();
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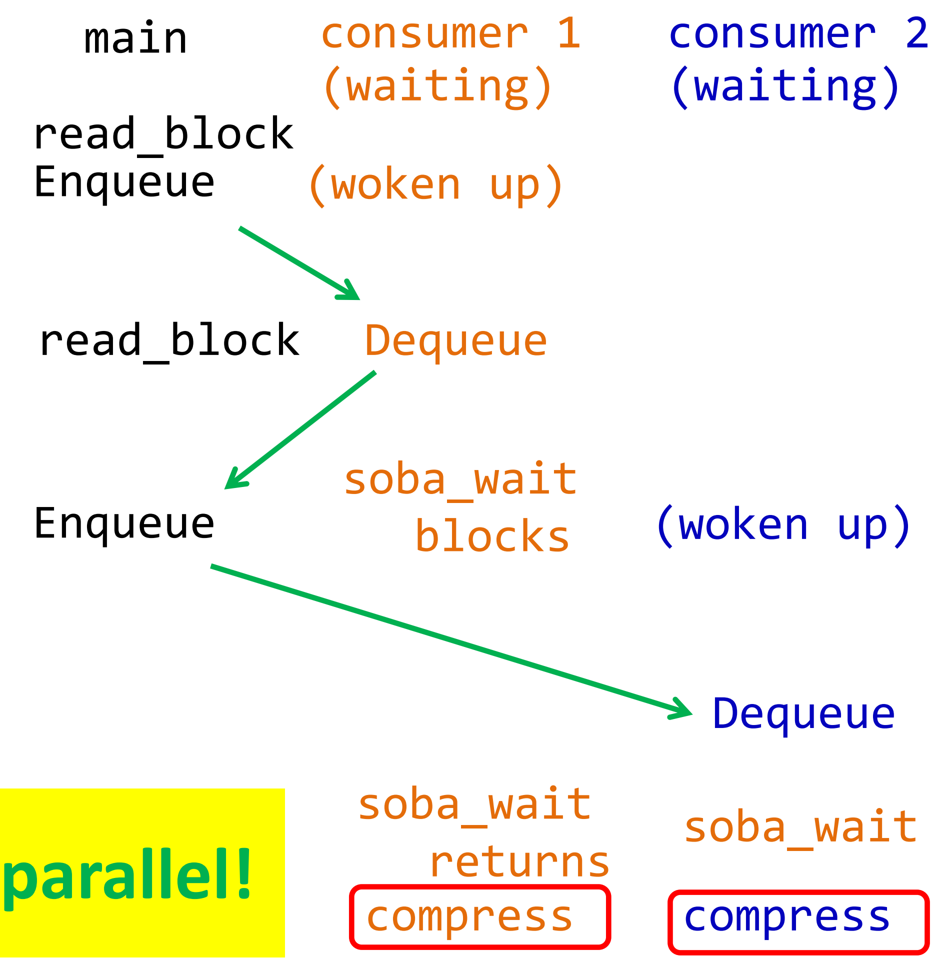
  }

consumer thread:
  while(1) {
    Wait or Dequeue
    soba_wait();
    compress(block);
  }
```

Run in parallel!



main	consumer 1	consumer 2
	(waiting)	(waiting)
read_block Enqueue	(woken up)	
read_block	Dequeue	
Enqueue	soba_wait blocks	(woken up)
		Dequeue
	soba_wait returns compress	soba_wait compress

- 0.8% overhead

Performance hint API

```
// soft barrier; doesn’t increase # of schedules
void soba_init(int count, void *chan = NULL, int
  deterministic_timeout = 20);
void soba_wait(void *chan = NULL);

// performance critical section; increase # of
// schedules, but can check!
void pcs_enter();
void pcs_exit();
```

Evaluation questions

- How fast is Parrot?
- How easy is it to add hints?
- How much can Parrot improve reliability?

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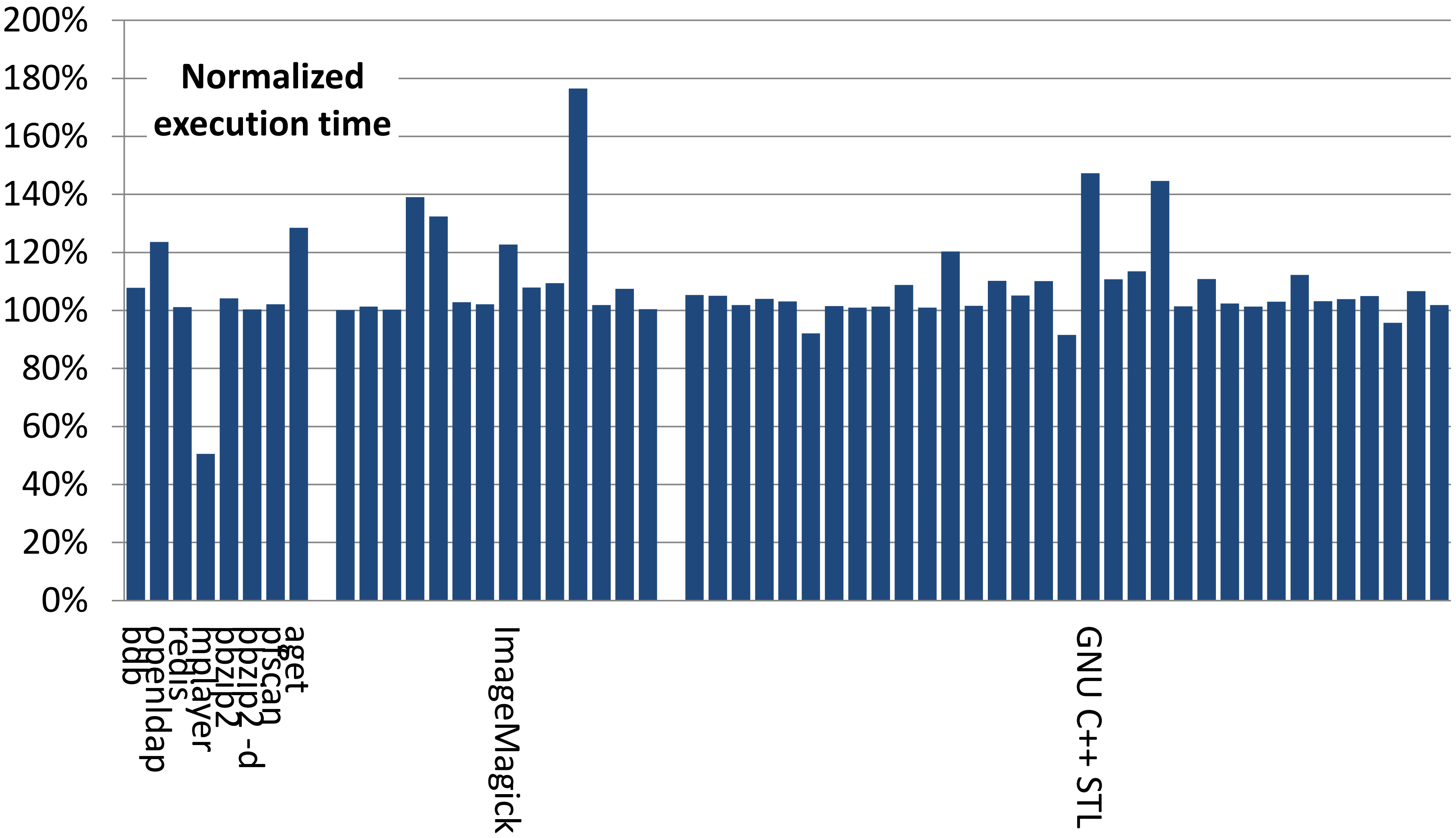
Evaluation Setup

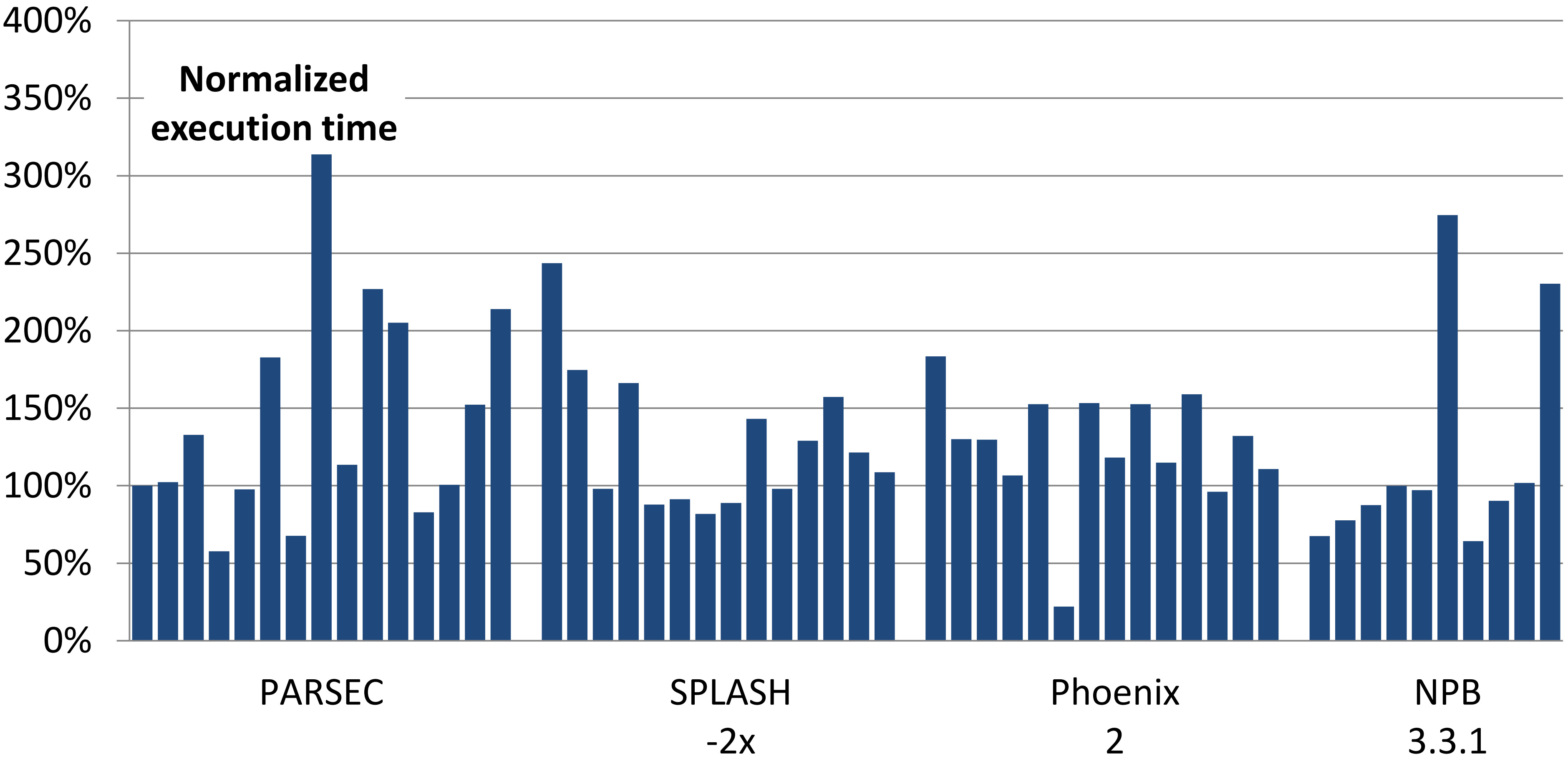
- A diverse set of of 108 programs
  - 55 Real-world programs: BerkeleyDB, OpenLDAP, Redis, MPlayer, ImageMagick, STL, PBZip2, pfscan, aget
  - 53 programs from 4 complete synthetic benchmark suites: PARSEC, SPLASH2X, PHOENIX, NPB.
  - Diverse: Pthreads, OpenMP, data partition, fork-join, pipeline, map-reduce, and workpile.
- Maximum allowed cores (24-core Xeon)
- Largest allowed or representative workloads

Overhead (real-world programs): small



- Mean overhead: 6.9% for real-world, 19.0% for synthetic, and 12.7% for all

Overhead (synthetic benchmarks): small



- Mean overhead: 6.9% for real-world, 19.0% for synthetic, and 12.7% for all

Evaluation questions

- How fast is Parrot?
- How easy is it to add hints?
- How much can Parrot improve reliability?

Hints: easy to add, effective

	# programs requiring hints	# lines of hints	Overhead w/o hints	Overhead w/ hints
Soft barrier	81	87	484%	9.0%
Performance critical section	9	22	830%	42.1%
Total	90	109	510%	11.9%

- Average to 1.2 lines per program
- A few hints in common libs benefit many programs
- 0.5--2 hours per program added by mostly MS students who didn't write the programs

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Evaluation questions

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- How much can Parrot improve reliability?

Model checking: higher coverage

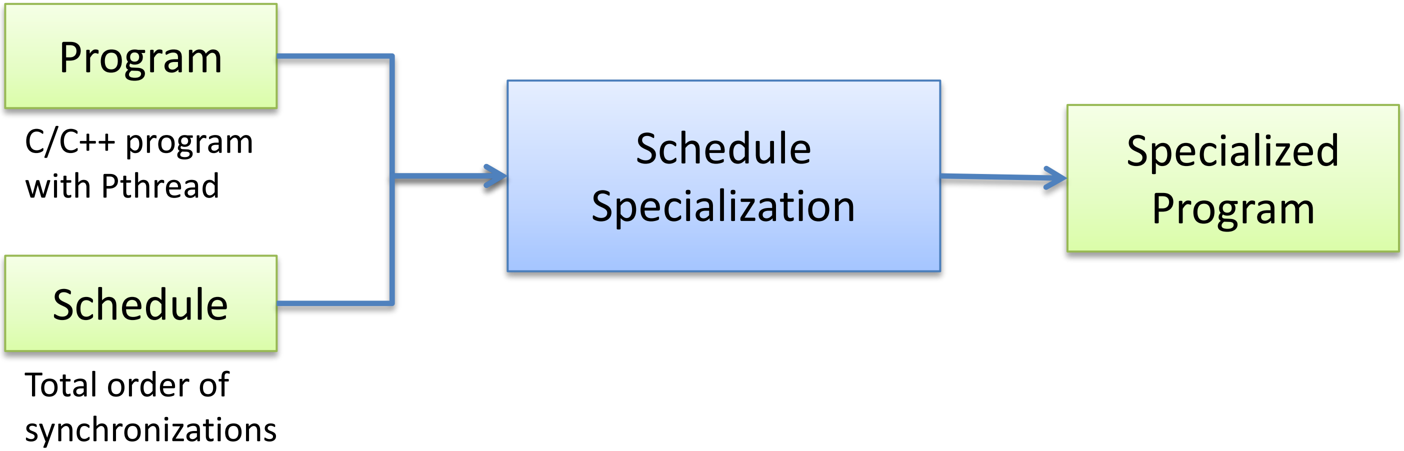
- Integrated Parrot with dBug [dBug SPIN 11] because it's open-source, runs on Linux, implements dynamic partial order reduction [DPOR POPL 05], can estimate number of possible schedules [Knuth]

- Parrot increases coverage by 10^{6}---10^{19734} (not a typo ;) for 53 programs
- Parrot increases number of verified programs from 43 to 99

Static analysis: more precise

[Specialization PLDI 12]

- Specialize a program according to a schedule
- Resultant program contains schedule info, improving precision of stock analysis



Static Race Detector

# of False Positives

Program	w/o StableMT	w/ StableMT
aget	72	0
PBZip2	125	0
fft	96	0
blackscholes	3	0
swaptions	165	0
streamcluster	4	0
canneal	21	0
bodytrack	4	0
ferret	6	0
raytrace	215	0
cholesky	31	7
radix	53	14
water-spatial	2447	1799
lu-contig	18	18
barnes	370	369
water-nsquared	354	333
ocean	331	292

Static Race Detector

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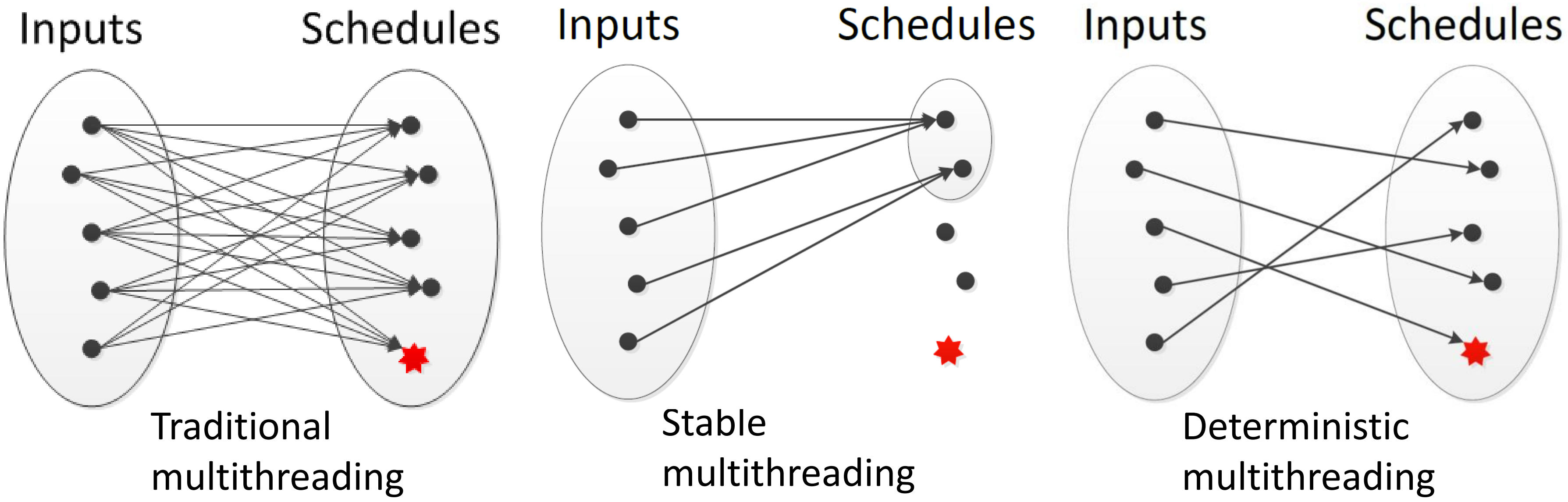
Previously Unknown Harmful Races Detected

- 4 in aget
- 2 in radix
- 1 in fft

Conclusion



- Root cause of the multithreading difficulties: ~~nondeterminism~~ too many schedules
- *Stable Multithreading (StableMT)*: a radical approach to vastly reducing schedules for reliability with low overhead [Tern OSDI 10] [Peregrine SOSP 11] [Specialization PLDI 12] [Parrot SOSP 13] [HotPar 13] [CACM 14]