Static and Dynamic Analyses for Reliable Concurrency

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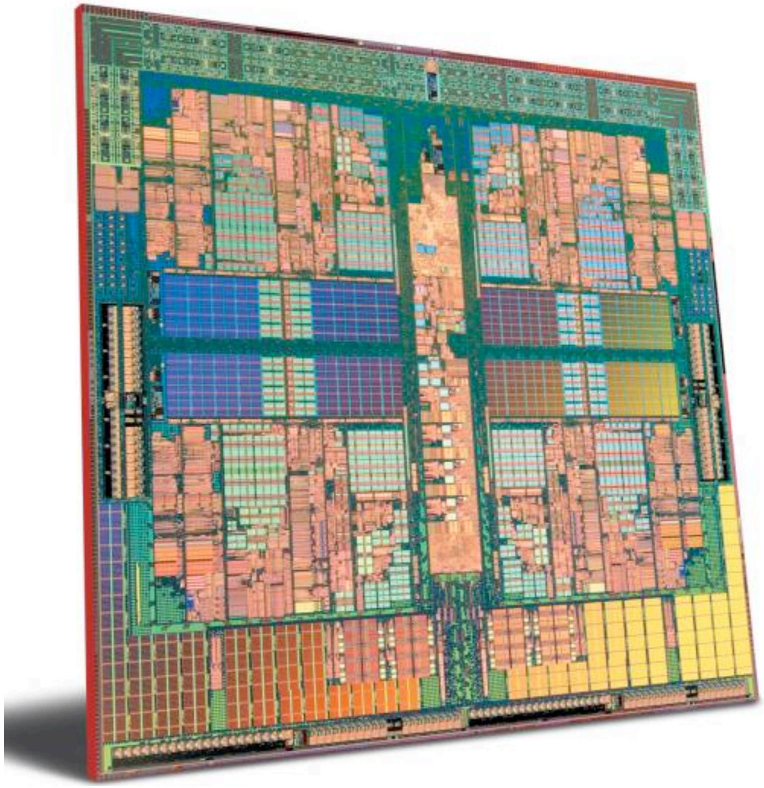
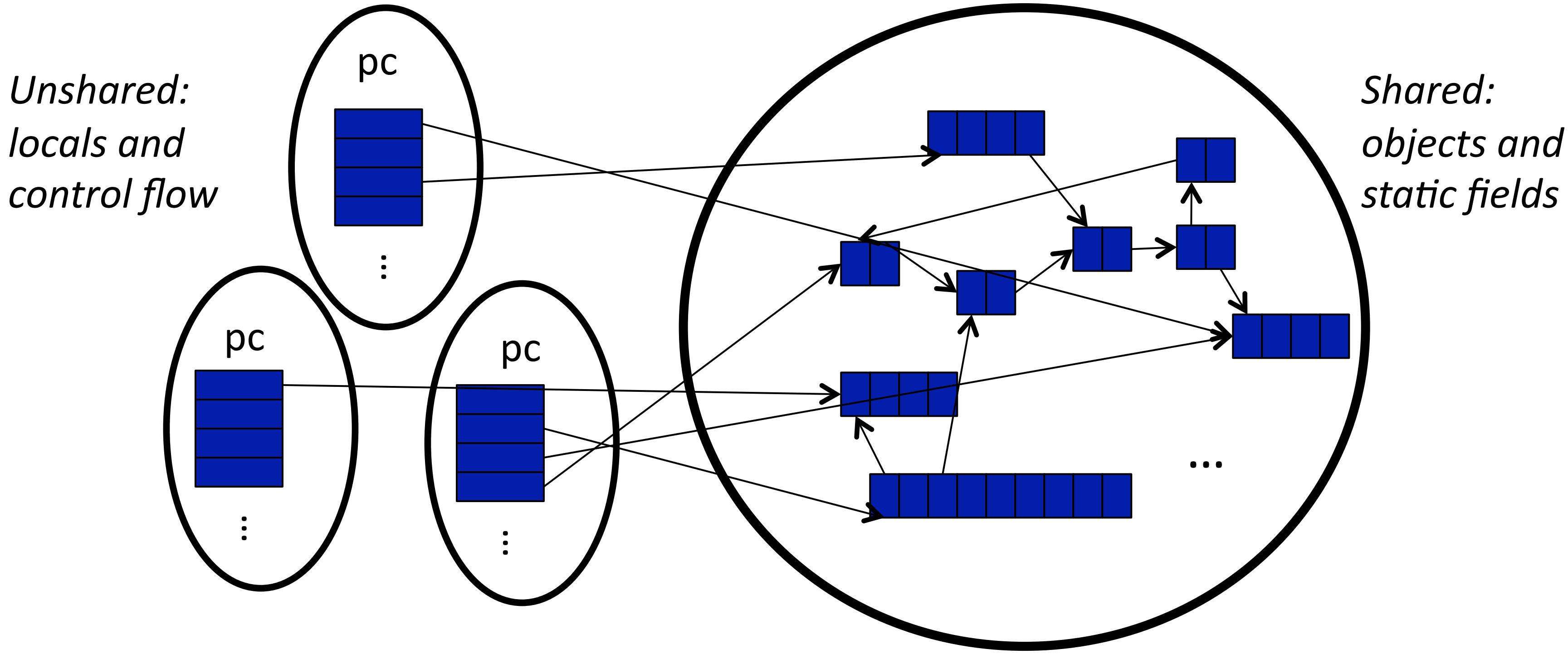
Multicore CPUs



Concurrent Programming Models

- Multiple threads, shared memory, sync



- Multithreaded programming is difficult.
  - *schedule-dependent* behavior
  - race conditions, deadlocks, atomicity violations, ...
  - difficult to detect, reproduce, or eliminate

Multiple Threads

x++

is a non-atomic read-modify-write

```
x = 0;
thread interference?
while (x < len) {
    thread interference?
    tmp = a[x];
    thread interference?
    b[x] = tmp;
    thread interference?
    x++;
    thread interference?
}
```

Single Thread

x++

```
x = 0;

while (x < len) {

    tmp = a[x];

    b[x] = tmp;

    x++;

}
```

Controlling Thread Interference: #1 Manually

```
 x = 0;
thread interference?
 while (x < len) {
thread interference?
     tmp = a[x];
thread interference?
     b[x] = tmp;
thread interference?
     x++;
thread interference?
 }
```

1 Inspect code

2 Identify where interference does not occur

```
 x = 0;

 while (x < len) {
thread interference?
     tmp = a[x];
thread interference?
     b[x] = tmp;

     x++;

 }
```

Controlling Thread Interference: #1 Manually w/ Productivity Heuristic

```
 x = 0;
thread interference?
 while (x < len) {
thread interference?
     tmp = a[x];
thread interference?
     b[x] = tmp;
thread interference?
     x++;
thread interference?
 }
```

1 Assume no interference

2 Use sequential reasoning

```
x = 0;

while (x < len) {

    tmp = a[x];

    b[x] = tmp;

    x++;

}
```

- Works some of the time, but subtle bugs…

Controlling Thread Interference: #2 Enforce Race Freedom

- Race Conditions

  two concurrent unsynchronized accesses, at least one write

```
Thread A
  ...
  t1 = bal;
  bal = t1 + 10;
  ...
```

```
Thread B
  ...
  t2 = bal;
  bal = t2 - 10;
  ...
```

Thread A	Thread B
t1 = bal	
bal = t1 + 10	
	t2 = bal
	bal = t2 - 10

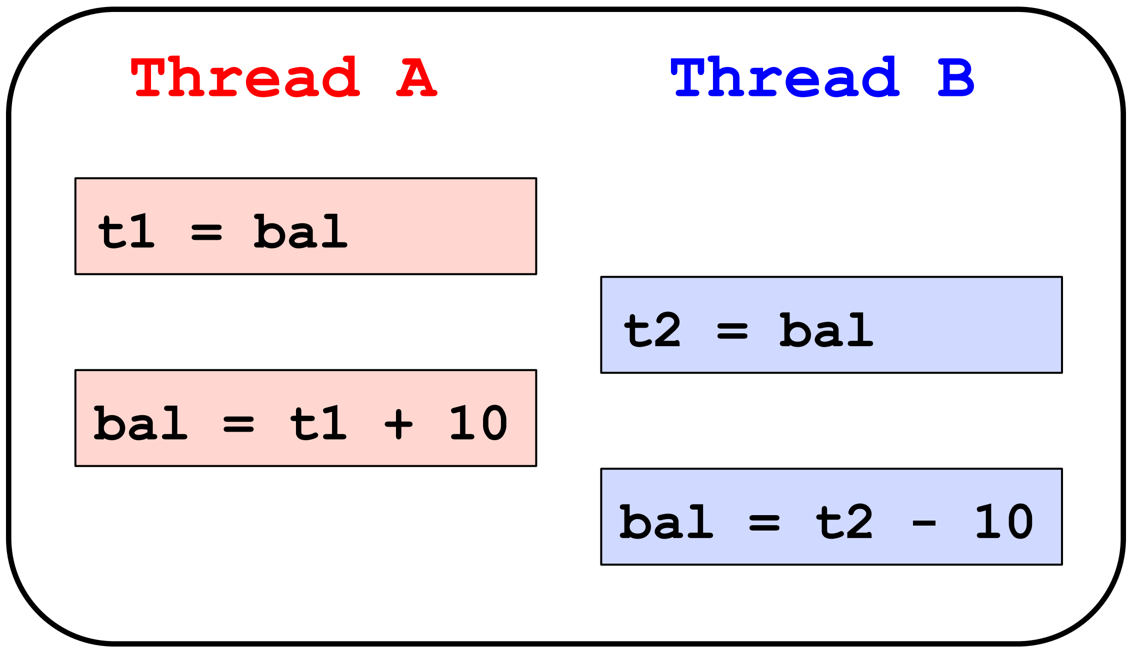
Controlling Thread Interference: #2 Enforce Race Freedom

- Race Conditions

  two concurrent unsynchronized accesses, at least one write

```
Thread A
  ...
  t1 = bal;
  bal = t1 + 10;
  ...
```

```
Thread B
  ...
  t2 = bal;
  bal = t2 - 10;
  ...
```



Controlling Thread Interference: #2 Enforce Race Freedom

- Race Conditions

  two concurrent unsynchronized accesses, at least one write

- Races are correlated to defects
- Race-freedom ensures sequentially-consistent behavior, even on relaxed memory models
- Static and dynamic analysis tools to detect races

- But...

Controlling Thread Interference:
#2 Enforce Race Freedom

```
Thread A
  ...
  acq(m);
  t1 = bal;
  rel(m);

  acq(m);
  bal = t1 + 10;
  rel(m);
```

```
Thread B
  ...
  acq(m);
  bal = bal - 10;
  rel(m);
```

Thread A	Thread B
acq(m)	
t1 = bal	
rel(m)	
	acq(m)
	bal = bal-10
	rel(m)
acq(m)	
bal = t1 + 10	
rel(m)	

Controlling Thread Interference: #3 Enforce Atomicity

Atomic method must behave as if it executed serially, without interleaved operations of other thread

```
void copy() {
  x = 0;
  thread interference?
  while (x < len) {
    thread interference?
    tmp = a[x];
    thread interference?
    b[x] = tmp;
    thread interference?
    x++;
    thread interference?
  }
}
```

Controlling Thread Interference: #3 Enforce Atomicity

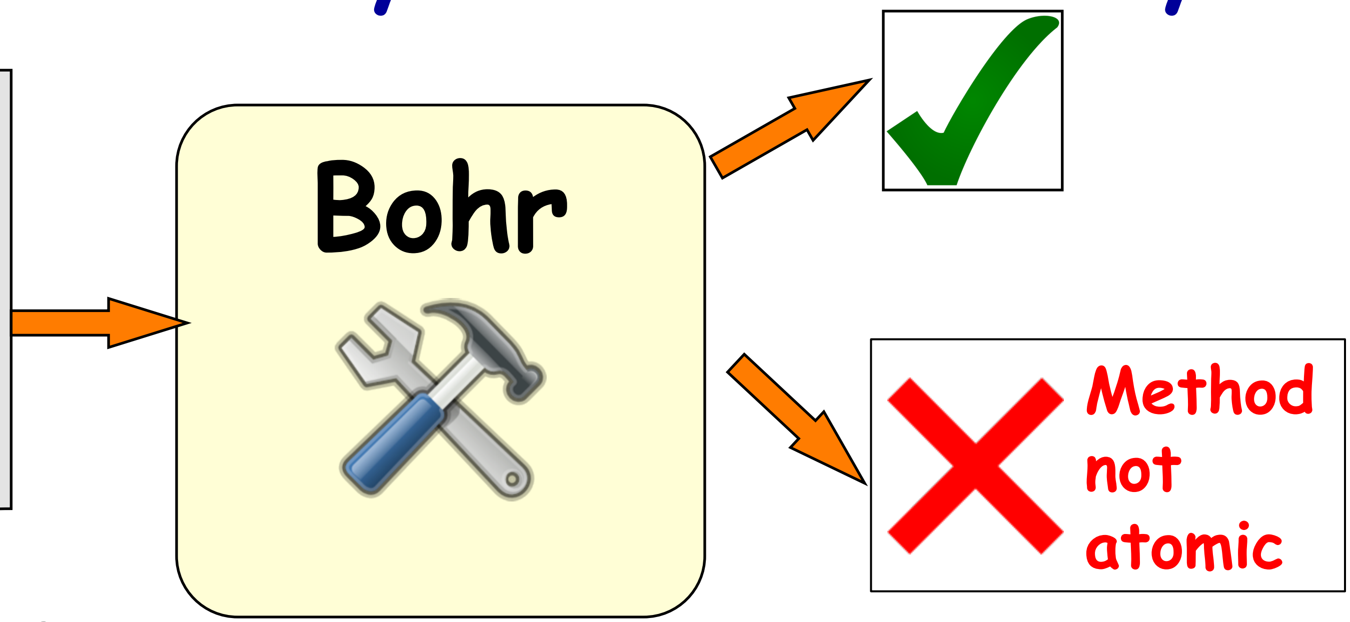
Atomic method must behave as if it executed serially, without interleaved operations of other thread

```
atomic void copy() {
  x = 0;

  while (x < len) {

   tmp = a[x];

   b[x] = tmp;

   x++;

  }
}
```

- Can use sequential reasoning in atomic methods
- 90% of methods are atomic

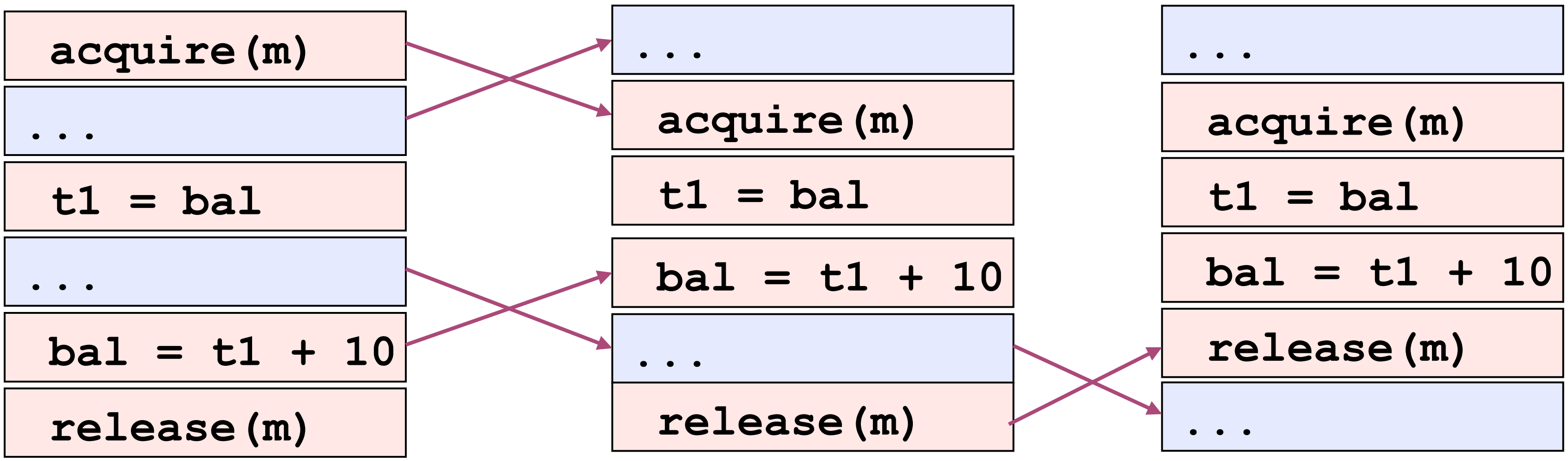
Bohr: Static Analysis for Atomicity

```
class A {
 int x
  guarded_by this;

 atomic void m(){
  synchronized …
  …
 }
}
```



- Extension of Java's type system [TOPLAS'08]
- Input: Java code with
  - traditional synchronization
  - atomicity annotations
  - annotations describing protecting lock for fields
- Theorem: In any well-typed program, all paths through atomic methods are serializable

Theory of Reduction [Lipton 76]



R	Right-mover	Acquire
L	Left-mover	Release
M	Both-mover	Race-Free Access
N	Non-mover	Racy Access

Serializable blocks have the pattern: R* [N] L*

Examples

```
void deposit(int n) {
  synchronized(m) {
     t1 = bal;
     bal = t1 + n;
  }
}
```

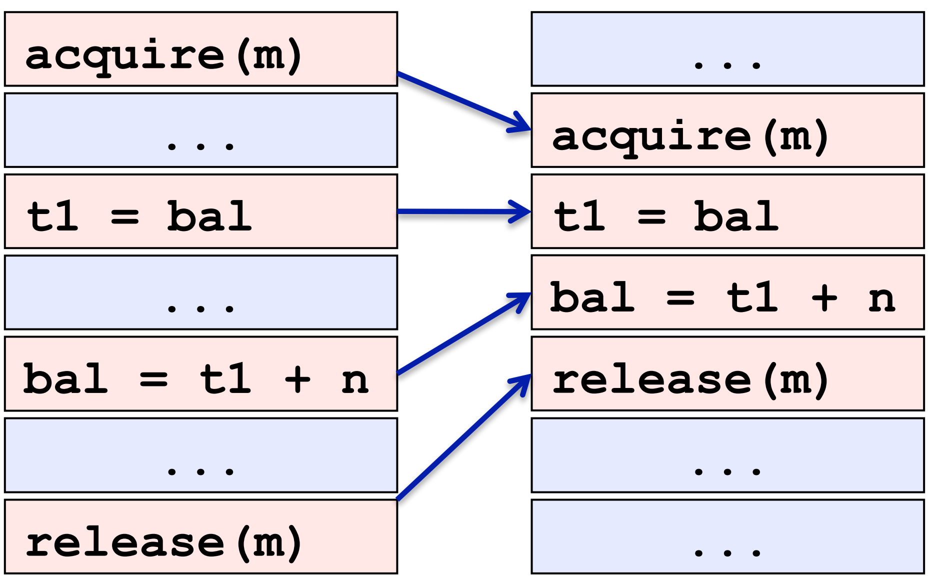
R

M

M

L

✓



(R* [N] L*)

Examples

```
void deposit(int n) {
   synchronized(m) {
      t1 = bal;
      bal = t1 + n;
   }
}
```

acquire(m)	...
...	acquire(m)
t1 = bal	t1 = bal
...	bal = t1 + n
bal = t1 + n	release(m)
...	...
release(m)	...

✓

```
void deposit(int n) {
   synchronized(m) {
      t1 = bal;
   }
   synchronized(m) {
      bal = t1 + n;
   }
}
```

R
M
L
R
M
L

acquire(m)	R
t1 = bal	M
release(m)	L
...	
acquire(m)	R
bal = t1 + n	M
release(m)	L

✗

(R* [N] L*)

Dynamic Analysis for Atomicity

- Atomizer [POPL'04]
  - based on reduction, abstracts ops as R/L/M/N
  - leads to false alarms

- Other techniques: [Wang-Stoller 06], [Xu-Bodik-Hill 06], [Hatcliff et al. 04], [Park-Lu-Zhou 09]

- Velodrome [PLDI 08]
  - reason about serializability via happens-before relation
  - precise for observed trace, no false alarms

```
int x = 0;
volatile int b = 1;
```

Thread i accesses x
only when b == i

Thread 1

```
while (true) {
  loop until b == 1;
  atomic {
    x = x + 100;
    b = 2;
  }
}
```

Thread 2

```
while (true) {
  loop until b == 2;
  atomic {
    x = x - 100;
    b = 1;
  }
}
```

Execution Trace

Thread 1

```
while (true) {
   loop until b == 1;
   atomic {
     x = x + 100;
     b = 2;
   }
}
```

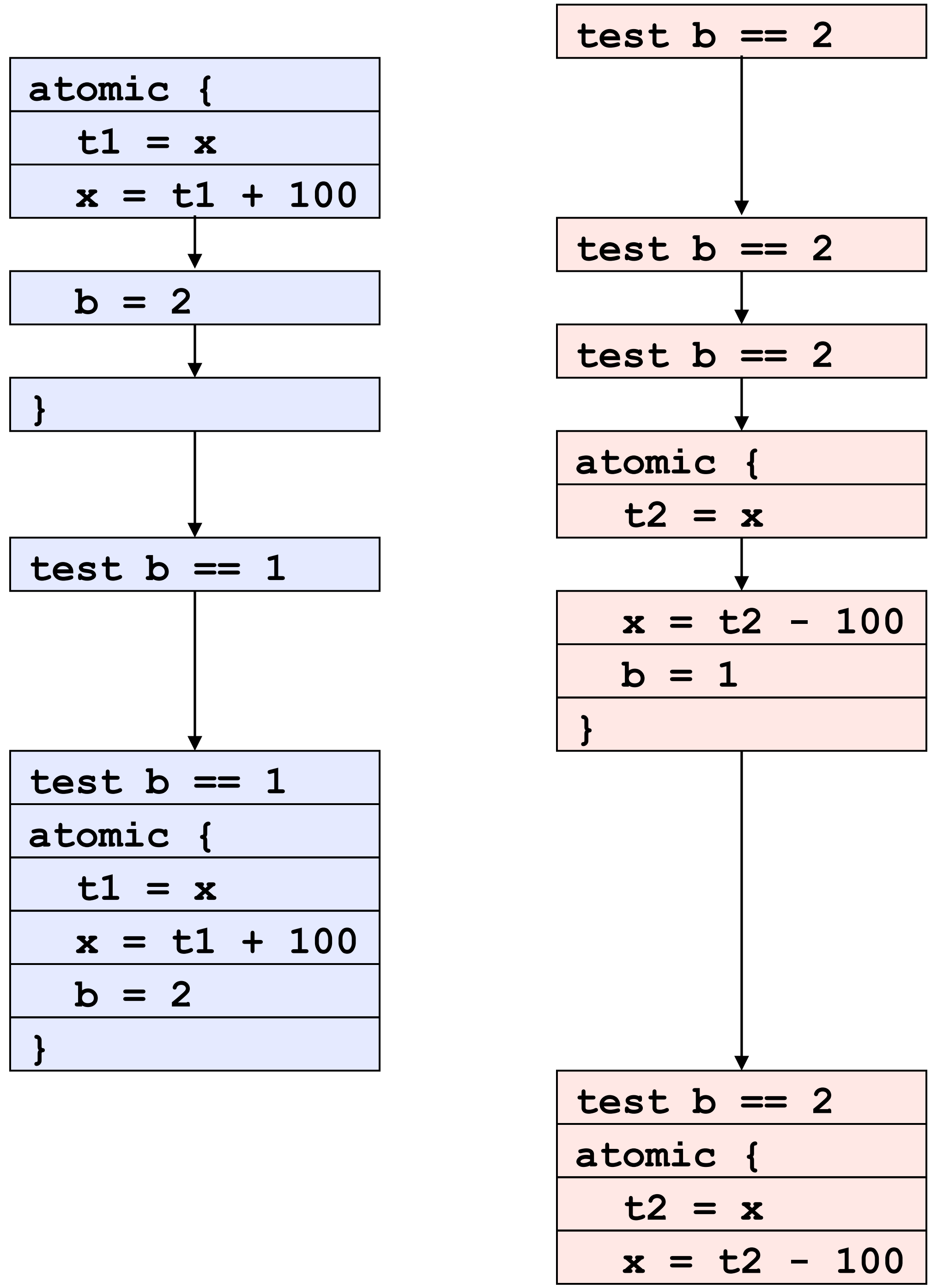
Thread 2

```
while (true) {
   loop until b == 2;
   atomic {
     x = x - 100;
     b = 1;
   }
}
```

Thread 1	Thread 2
	test b == 2
atomic {	
t1 = x	
x = t1 + 100	
	test b == 2
b = 2	
	test b == 2
}	
	atomic {
	t2 = x
test b == 1	
	x = t2 - 100
	b = 1
	}
test b == 1	
atomic {	
t1 = x	
x = t1 + 100	
b = 2	
}	
	test b == 2
	atomic {
	t2 = x
	x = t2 - 100

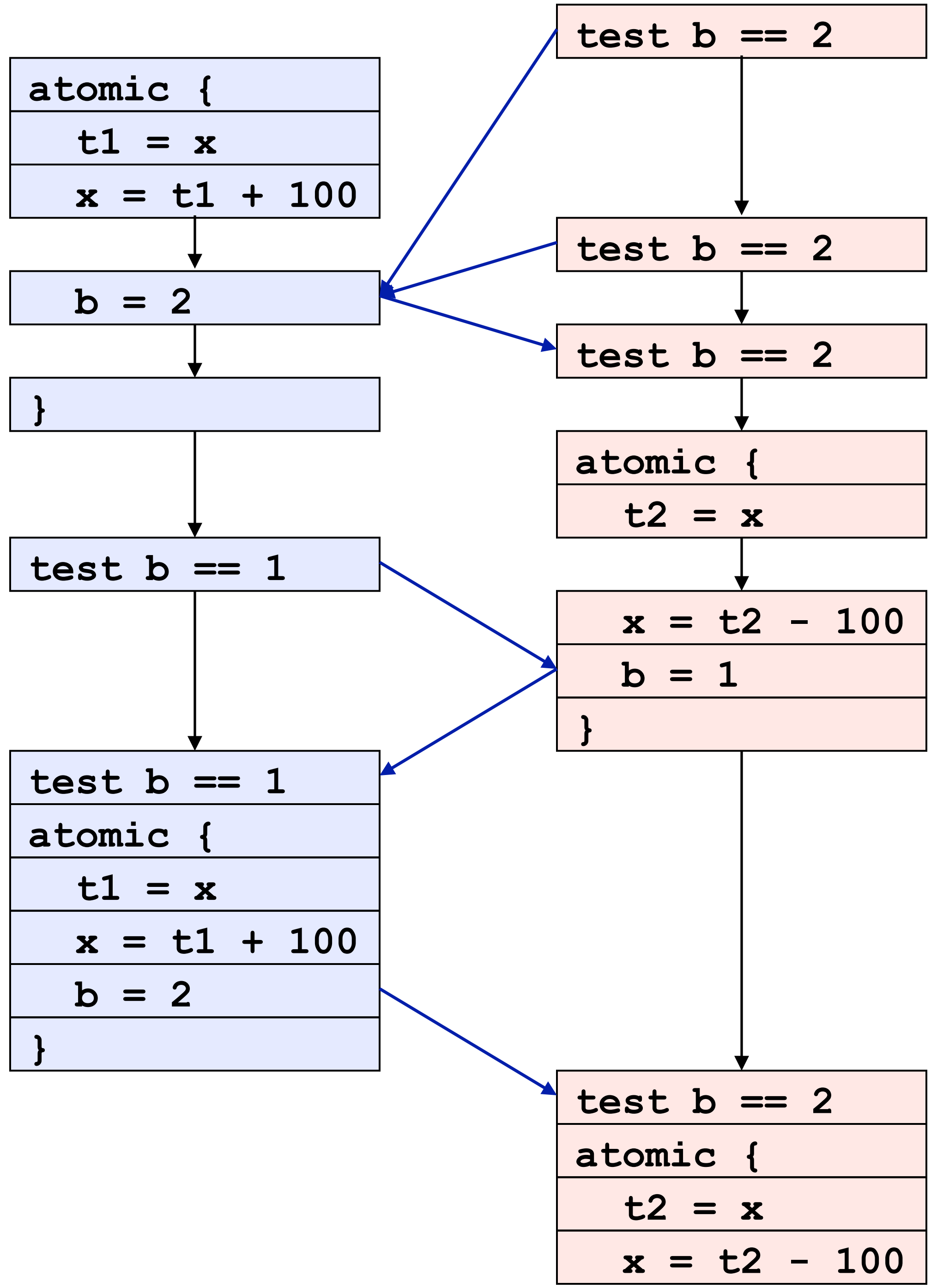
Happens-Before Ordering on Operations

- program order



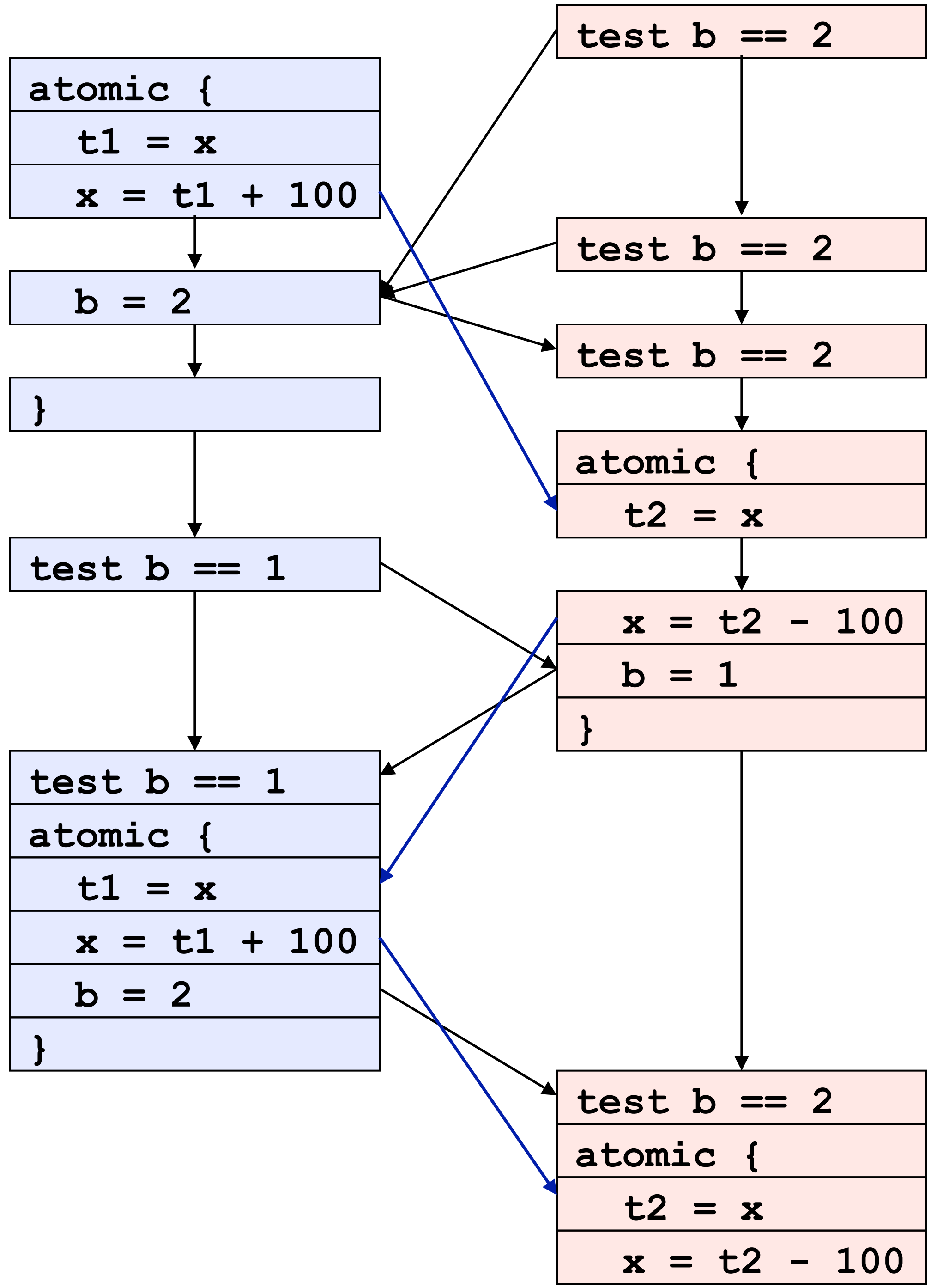
Happens-Before Ordering on Operations

- program order
- synchronization order

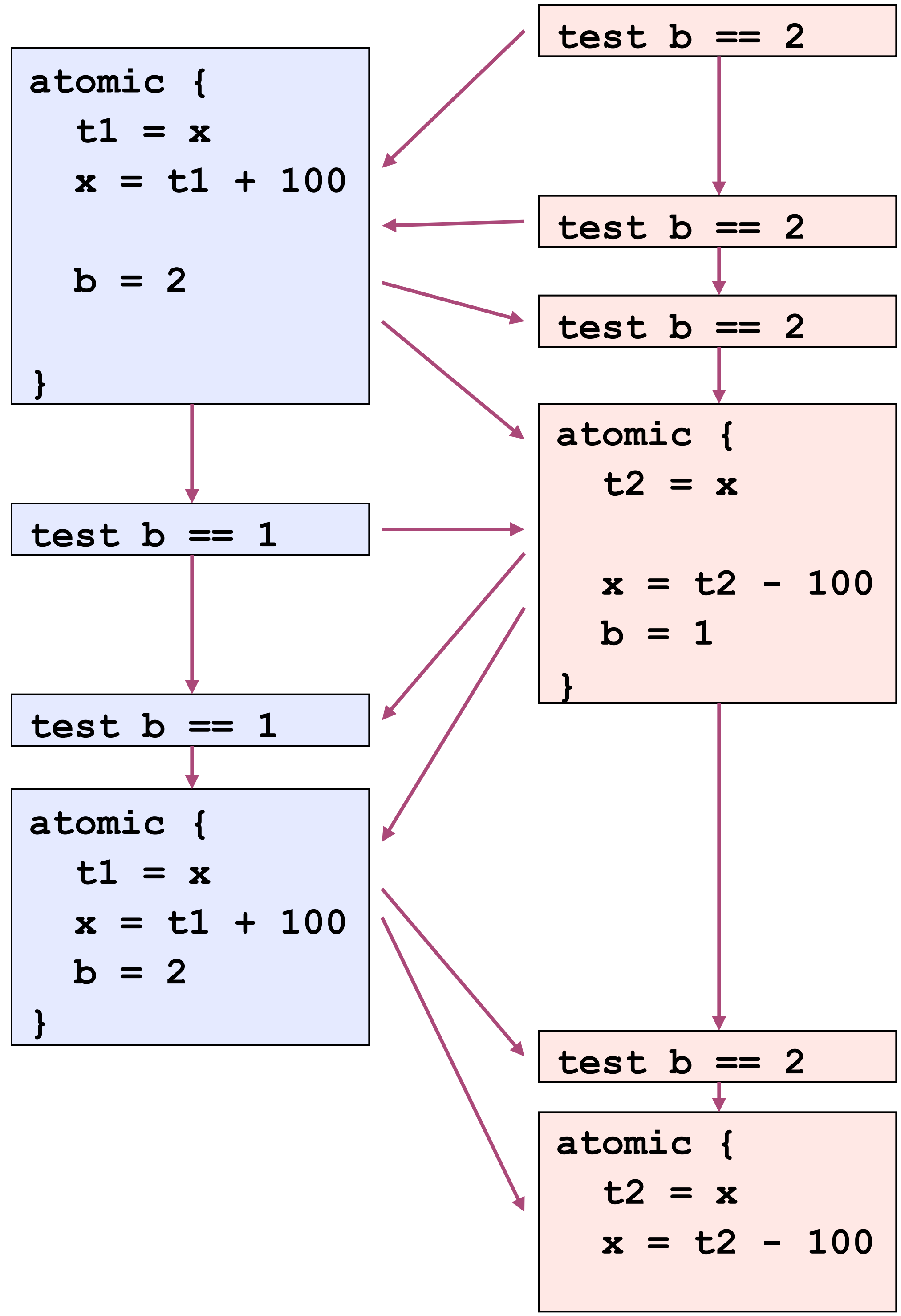


Happens-Before Ordering on Operations

- program order
- synchronization order
- communication order



Transactional Happens-Before Ordering



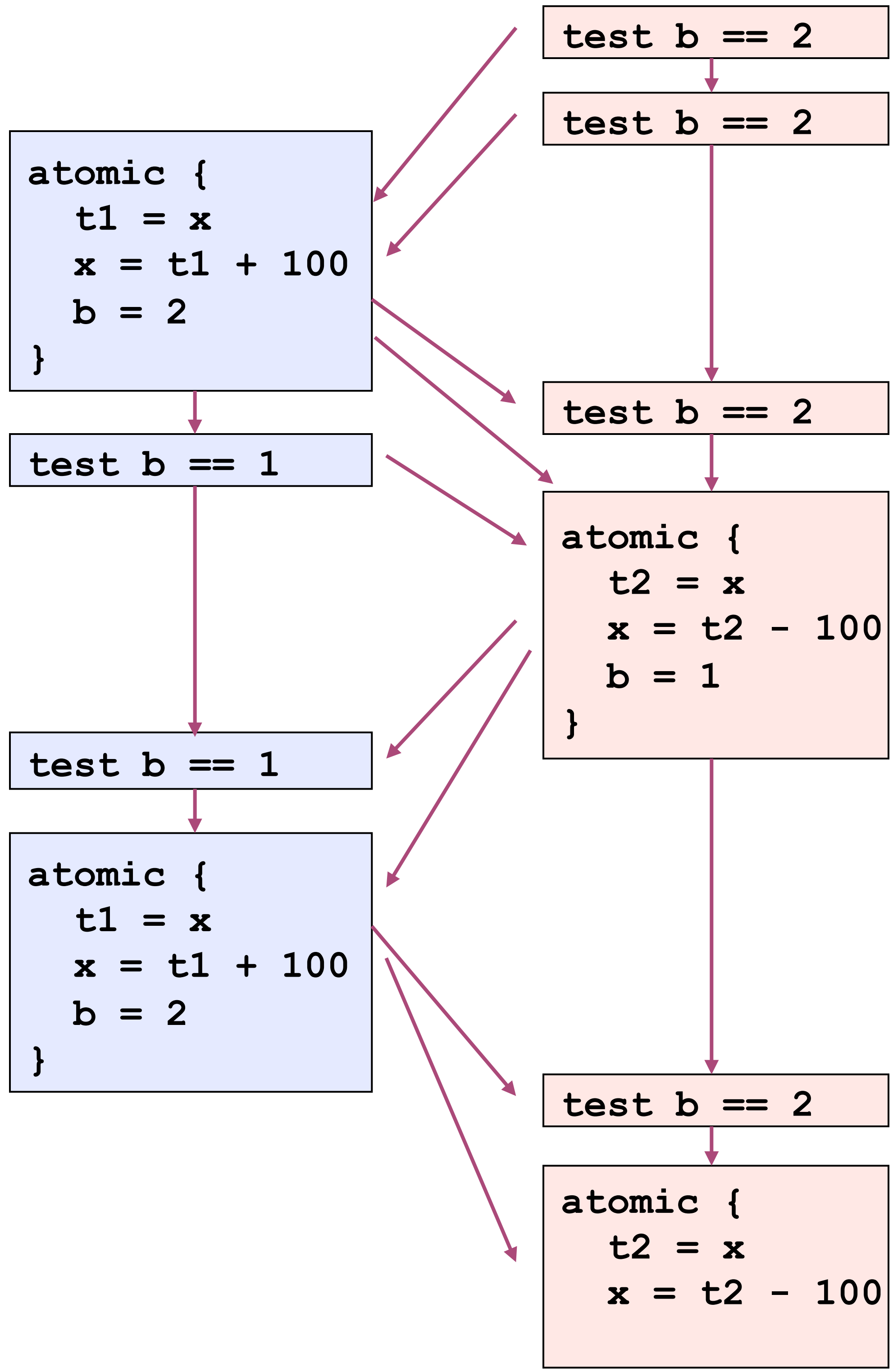
__**Theorem**__

Transactional HB order has no cycles

if and only if

Trace is serializable

Equivalent Serial Trace



Equivalent Serial Trace

```
test b == 2
```

```
test b == 2
```

```
atomic {
  t1 = x
  x = t1 + 100
  b = 2
}
```

```
test b == 2
```

```
test b == 1
```

```
atomic {
  t2 = x
  x = t2 - 100
  b = 1
}
```

```
test b == 1
```

```
atomic {
  t1 = x
  x = t1 + 100
  b = 2
}
```

```
test b == 2
```

```
atomic {
  t2 = x
  x = t2 - 100
```

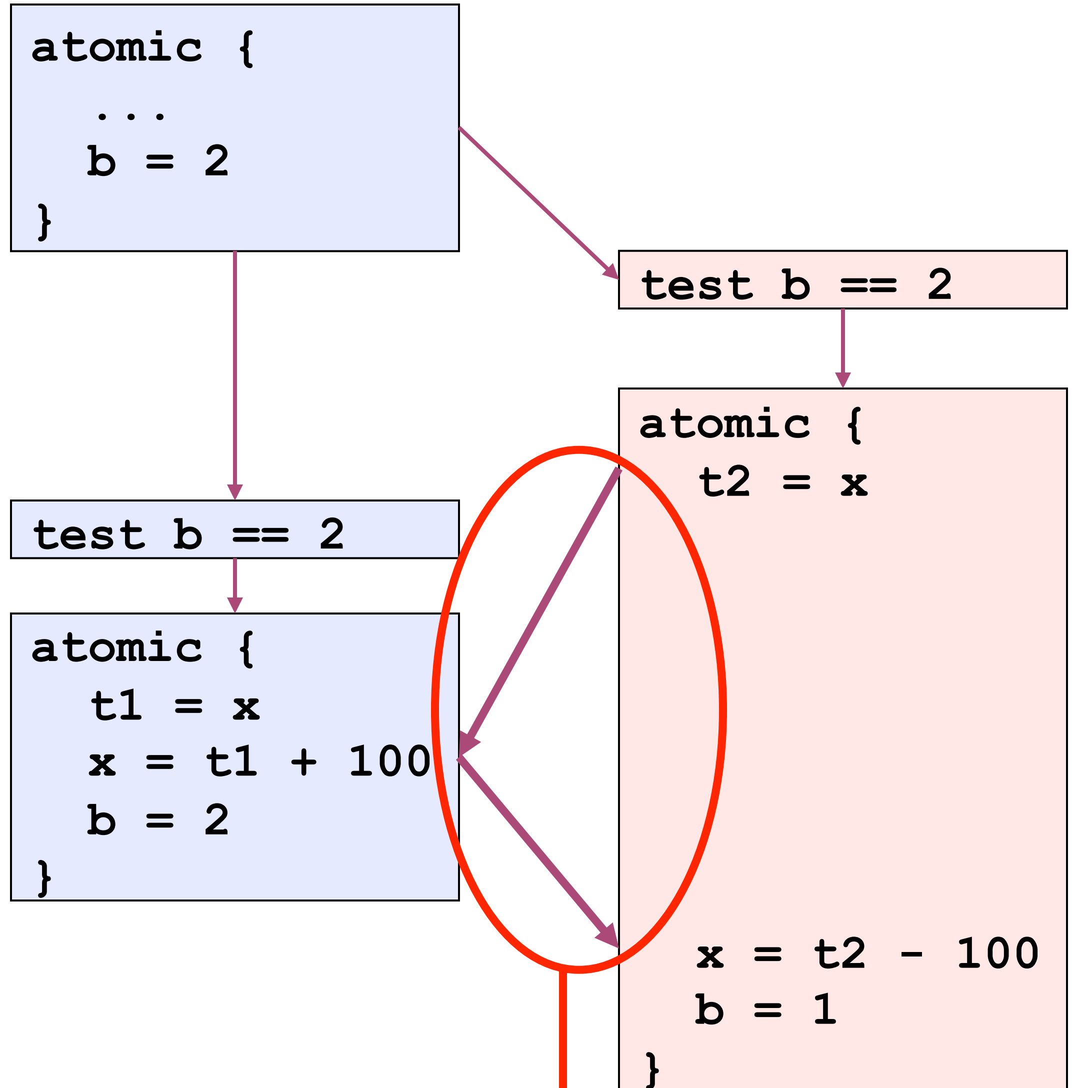
Atomicity Violation

Thread 1

```
while (true) {
   loop until b == 2;
   atomic {
      x = x + 100;
      b = 2;
   }
}
```

Thread 2

```
while (true) {
   loop until b == 2;
   atomic {
      x = x - 100;
      b = 1;
   }
}
```



Cycle in transactional HB order
⇒ trace is not serializable
⇒ report atomicity violation

Controlling Thread Interference: #3 Enforce Atomicity

Atomic method must behave as if it executed serially, without interleaved operations of other thread

```
atomic void copy() {
  x = 0;

  while (x < len) {

   tmp = a[x];

   b[x] = tmp;

   x++;

  }
}
```

- Can use sequential reasoning in atomic methods
- 90% of methods are atomic
- Static and dynamic analyses

Controlling Thread Interference: #3 Enforce Atomicity

- 10% of methods not atomic
- Local atomic blocks awkward
- Atomicity provides no information about thread interference
-

```
void busy_wait() {
  acq(m);
  thread interference?
  while (!test()) {
    thread interference?
    rel(m);
    thread interference?
    acq(m);
    thread interference?
    x++;
    thread interference?
  }
}
```

Controlling Thread Interference: #3 Enforce Atomicity

```
atomic void copy() {
  x = 0;

  while (x < len) {

    tmp = a[x];

    b[x] = tmp;

    x++;

  }
}
```

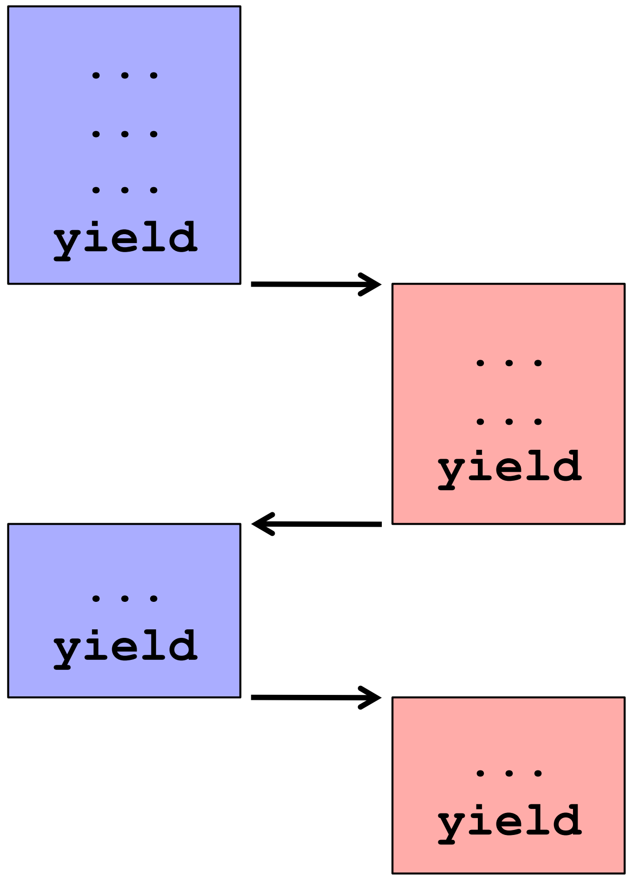
```
void busy_wait() {
  acq(m);
   thread interference?
  while (!test()) {
    thread interference?
    rel(m);
    thread interference?
    acq(m);
    thread interference?
    x++;
    thread interference?
  }
}
```

Bimodal Semantics

increment
vs.
non-atomic
read-modify-write

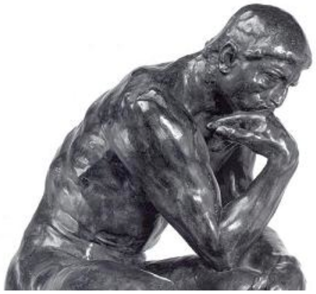
Controlling Thread Interference: #4 Cooperative Multitasking

- Cooperative scheduler performs context switches only at yield statements
- Clean semantics
  - Sequential reasoning valid by default ...
  - ... except where yields highlight thread interference



- Limitation: Uses only a single processor

Yield-oriented Programming



Cooperative Scheduler
- Sequential Reasoning
- Except at yields

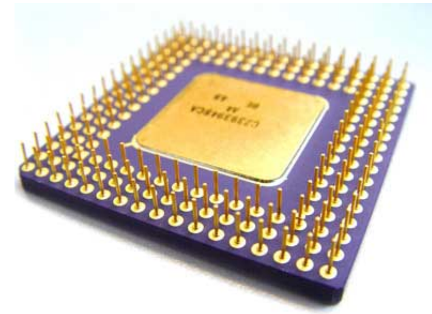
```
acq(m)
x = 0
rel(m)
yield
```

```
...
barrier
yield
```

```
...
yield
```

```
acq(m)
x = 2
rel(m)
yield
```

```
acq(m)
x = 0
rel(m)
yield
```



Preemptive Scheduler
- Full performance
- No overhead

```
acq(m)
x = 0
rel(m)
yield
```

```
...
barrier
yield
```

```
...
yield
```

```
acq(m)
x = 2
rel(m)
yield
```

Cooperative Correctness $\wedge$

Yield Correctness: yields mark all thread interference

$\rightarrow$ Preemptive Correctness

Yield vs. Atomic

- Atomic methods are those with no yields

```
atomic void copy() {
  x = 0;

  while (x < len) {

   tmp = a[x];

   b[x] = tmp;

   x++;

  }
}
```

```
void busy_wait() {
  acq(m);
 thread interference?
  while (!test()) {
   thread interference?
   rel(m);
   thread interference?
   acq(m);
   thread interference?
   x++;
   thread interference?
  }
}
```

Yield vs. Atomic

- Atomic methods are those with no yields

```
atomic void copy() {
  x = 0;

  while (x < len) {

   tmp = a[x];

   b[x] = tmp;

   x++;

  }
}
```

```
void busy_wait() {
  acq(m);

  while (!test()) {

   rel(m);
   yield;
   acq(m);

   x++;

  }
}
```

- `atomic` is a method-level spec.
- `yield` is a code-level spec.

Non-Interference Design Space

Non-Interference Specification

Policy Enforcement

	`atomic`	`yield`
traditional sync + analysis	atomicity, serializability	**Yield-oriented programming**
new run-time systems	transactional memory	automatic mutual exclusion

Transactional Memory, Larus & Rajwar, 2007
Automatic mutual exclusion, Isard & Birrell, HOTOS '07

Multiple Threads

x++

is a non-atomic read-modify-write

```
x = 0;

while (x < len) {
    thread interference?
    tmp = a[x];
    thread interference?
    b[x] = tmp;
    thread interference?
    x++;
    thread interference?
}
```

Single Thread

x++

```
x = 0;

while (x < len) {

    tmp = a[x];

    b[x] = tmp;

    x++;

}
```

Yield-Oriented Programming

```
x++   vs.   { int t=x;
              yield;
              x=t+1; }
```

```
x = 0;
while (x < len) {
   yield;
   tmp = a[x];
   yield;
   b[x] = tmp;

   x++;

}
```

Single Thread

```
x++
```

```
x = 0;

while (x < len) {

   tmp = a[x];

   b[x] = tmp;

   x++;

}
```

Yield-Oriented Programming Examples

```
class StringBuffer {

  synchronized StringBuffer append(StringBuffer sb){
    ...
    int len = sb.length();
    yield;
    ... // allocate space for len chars
    sb.getChars(0, len, value, index);
    return this;
  }

  synchronized void getChars(int, int, char[], int) {...}

  synchronized void expandCapacity(int) {...}

  synchronized int length() {...}
```

Version 1

```
volatile int x;

void update_x() {

  x = slow_f(x);

}
```

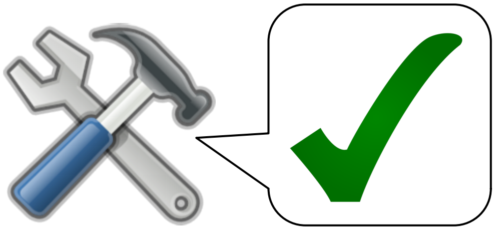
No yield between accesses to x

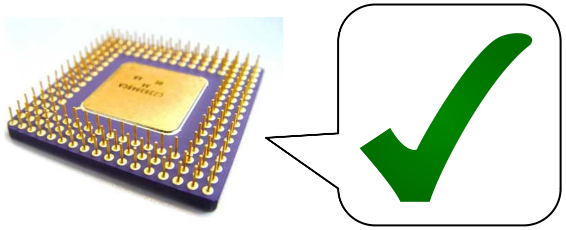
Cooperative Correctness ∧ Yield Correctness → Preemptive Correctness

Version 2

```
void update_x() {
  acquire(m);
  x = slow_f(x);
  release(m);
}
```

But...
Bad performance





Cooperative Correctness $\wedge$ Yield Correctness $\rightarrow$ Preemptive Correctness

Version 3

```
void update_x() {
  int fx = slow_f(x);

  acquire(m);
  x = fx;
  release(m);
}
```

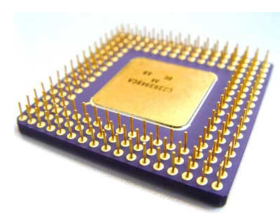
No yield between accesses to x

Cooperative Correctness $\wedge$ Yield Correctness $\rightarrow$ Preemptive Correctness

Version 4

```
void update_x() {
  int fx = slow_f(x);
  yield;
  acquire(m);
  x = fx;
  release(m);
}
```

Stale value after yield



Cooperative Correctness $\wedge$ Yield Correctness $\rightarrow$ Preemptive Correctness

Version 5
(test and retry)

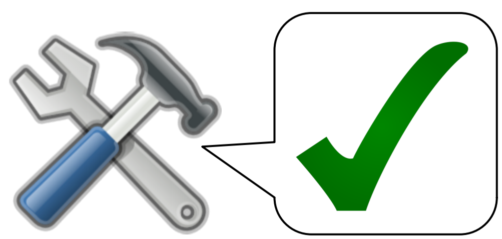
```
void update_x() {
  int y = x;
  for (;;) {
    yield;
    int fy = slow_f(y);

    if (x == y) {
      x = fy; return;
    }
    y = x;
  }
}
```

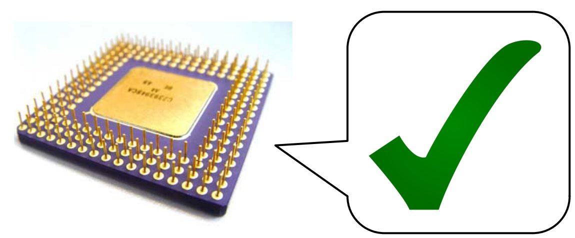
No yield between accesses to x

Cooperative Correctness $\wedge$ Yield Correctness $\rightarrow$ Preemptive Correctness

Version 6

```
void update_x() {
  int y = x;
  for (;;) {
    yield;
    int fy = slow_f(y);
    acquire(m);
    if (x == y) {
      x = fy; release(m); return;
    }
    y = x;
    release(m);
  }
}
```





Cooperative Correctness $\wedge$ Yield Correctness $\rightarrow$ Preemptive Correctness

Do Yields Help?

- Hypothesis: Yields help code comprehension and defect detection

- User study [Sadowski, Yi PLATEAU 2010]

- Methodology
  - Web-based survey, background check on threads
  - Two groups: shown code with or without yields
  - Three code samples, based on real-world bugs
  - Task: Identify all bugs

Do Yields Help?

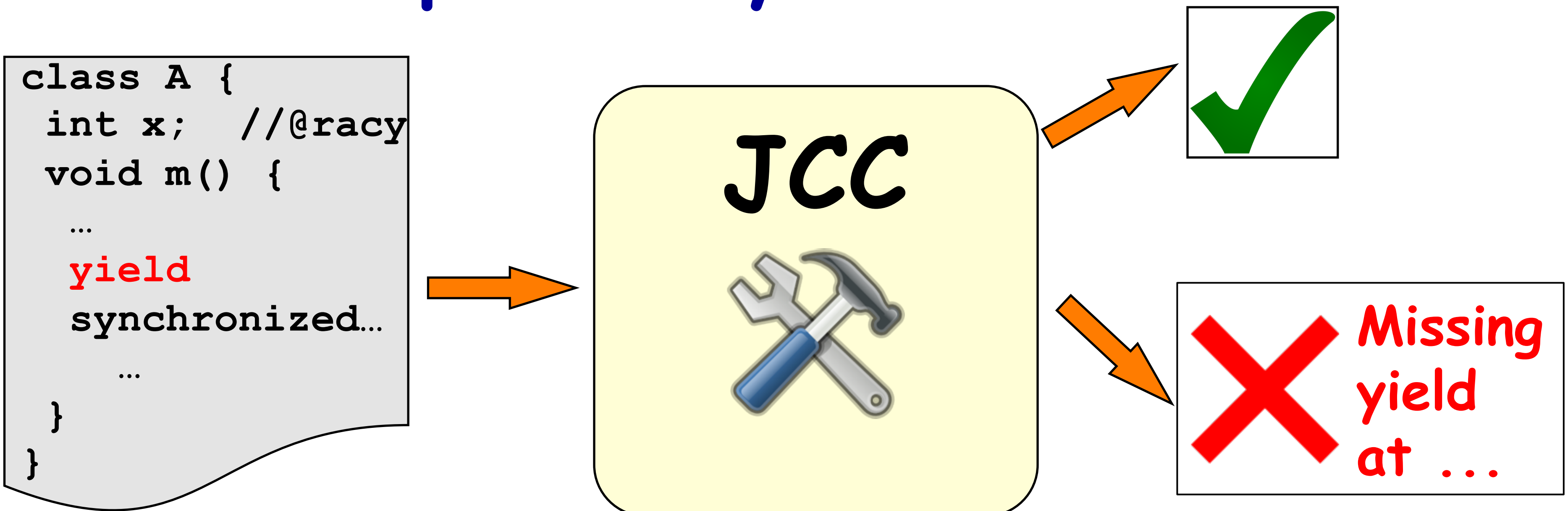
StringBuffer	Concurrency bug	Some other bug	Didn't find bug	Total
Yields	10	1	1	12
No Yields	1	5	9	15

All Samples	Concurrency bug	Some other bug	Didn't find bug	Total
Yields	30	3	3	36
No Yields	17	6	21	44

Difference is statistically significant

Static Program Analysis for Yield Correctness

JCC: Cooperability Checker for Java



- Extension of Java's type system
- Input: Java code with
  - traditional synchronization
  - yield annotations
  - annotations on racy variables (verified separately)
- Theorem: Well-typed programs are yield correct (cooperative-preemptive equivalent)

Identifying Serializable Code

- Compute an *effect* for each stmt to summarize how stmt interacts with other threads

R	Right-mover	Acquire
L	Left-mover	Release
M	Both-mover	Race-Free Access
N	Non-mover	Racy Access

- Serializable blocks have the pattern:

R* [N] L*

Identifying Yield-Correct Code

- Compute an *effect* for each stmt to summarize how stmt interacts with other threads

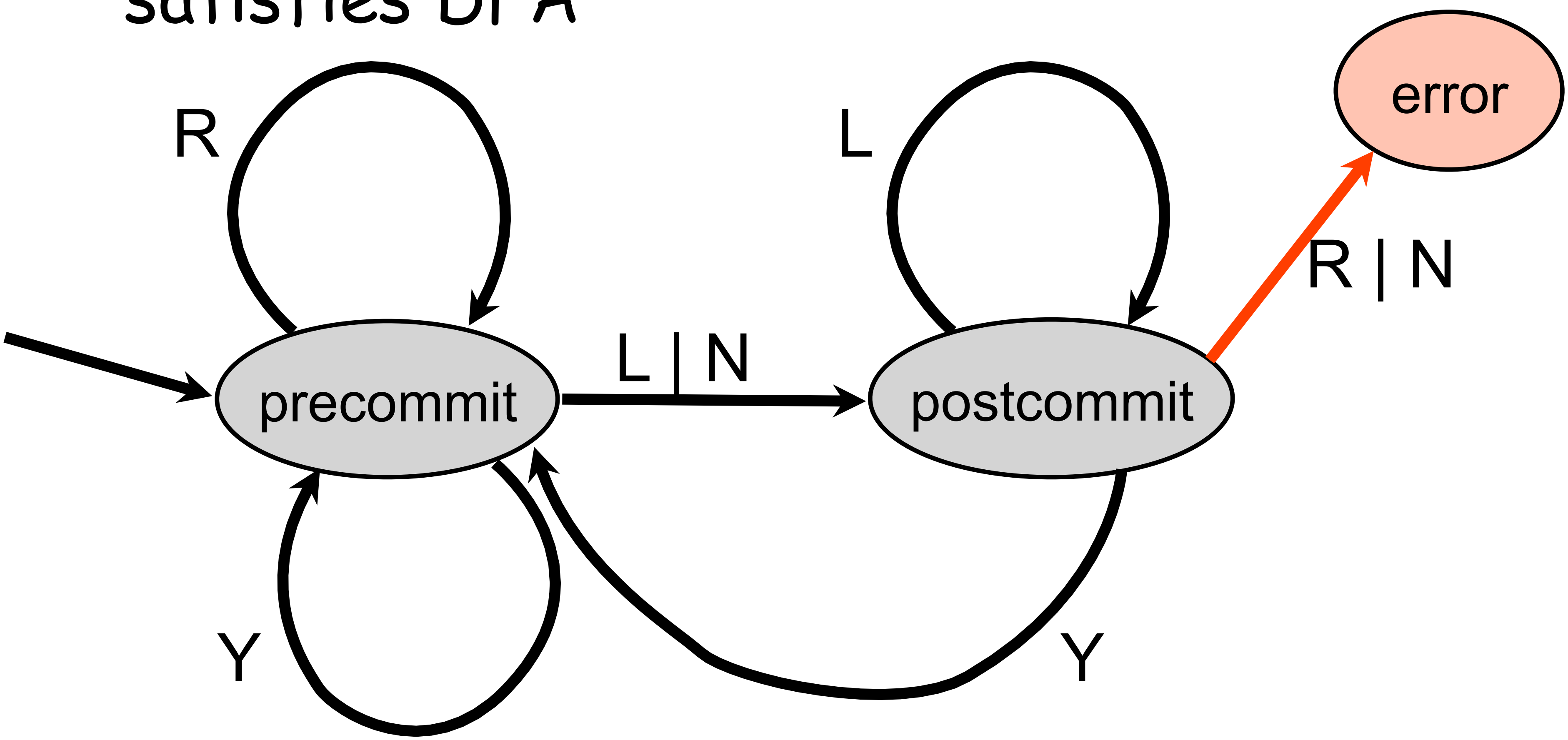
R	Right-mover	Acquire
L	Left-mover	Release
M	Both-mover	Race-Free Access
N	Non-mover	Racy Access
Y	Yielding	`yield`

- Yield-correct threads have the pattern:

((R* [N] L*) Y)* (R* [N] L*)

DFA for Yield-Correctness

- Trace is yield-correct if each thread satisfies DFA



Concurrency Control and Recover in Database Systems, Bernstein, Hadzilacos, Goodman, 1987

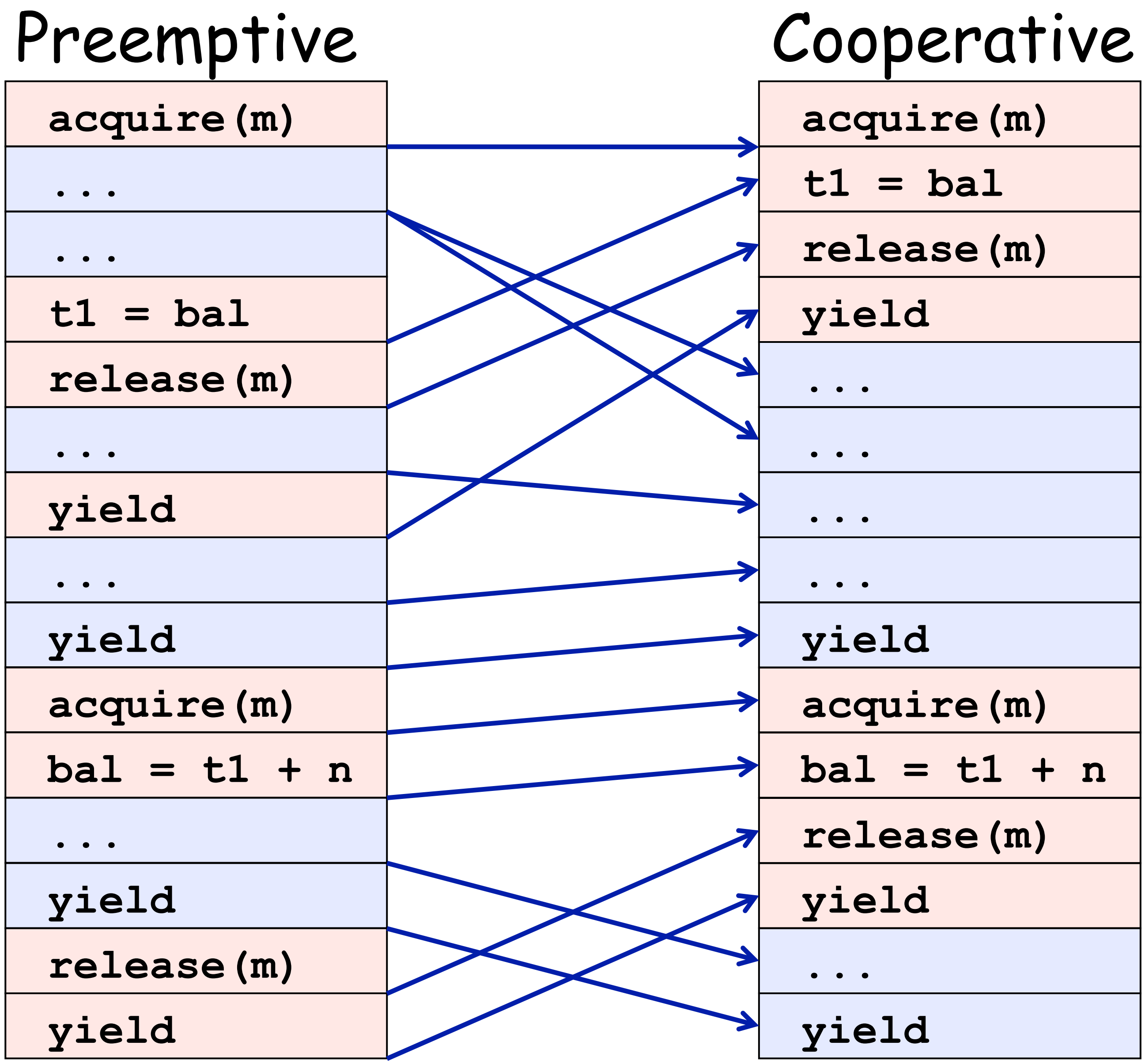
Examples

```
void deposit(int n) {
  synchronized(m) {
     t1 = bal;
  }
  yield;
  synchronized(m) {
     bal = t1 + n;
  }
}
```

R M L Y R M L

((R* [N] L*) Y)* (R* [N] L*)

Traces


Preemptive
acquire(m)
...
...
t1 = bal
release(m)
...
yield
...
yield
acquire(m)
bal = t1 + n
...
yield
release(m)
yield
Cooperative
acquire(m)
t1 = bal
release(m)
yield
...
...
...
...
yield
acquire(m)
bal = t1 + n
release(m)
yield
...
yield

```
class TSP {

  volatile int shortestPathLength;

  void searchFrom(Path path) {
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {


        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();

    } else {
      for (Path c : path.children()) {

        searchFrom(c);
      }
    }
  }
}
```

Racy Read

Racy Write

```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  void searchFrom(Path path) {
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {
      yield;
      synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

```
class TSP {
  Object lock;
  volatile int shortest

  void searchFrom(Path
    if (path.length() >

    if (path.isComplete()) {
      yield;
      synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

```
class Path {
  mover int length() ...
  mover boolean isComplete() ...
  ...
}
```

one transaction that commutes with other thread operations

```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  compound void searchFrom(Path path) {
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {
      yield;
      synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

series of transactions
that do not commute

```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  compound void searchFrom(Path path) {
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {
      yield;
      synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

M

N

((R* [N] L*) Y)* (R* [N] L*)

```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  compound void searchFrom(Path path) {
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {
      yield;
      synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

M; N

M

Y

R

M; M

M; N

L

((R* [N] L*) Y)* (R* [N] L*)

```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  compound void searchFrom(Path path) {
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {
      yield;
      synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

M; N

M

M

Y

N

(Y;N)*

((R* [N] L*) Y)* (R* [N] L*)

```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  compound void searchFrom(Path path) {
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {
      yield;

        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();

    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

M; N

M

Y

M; N

M; N

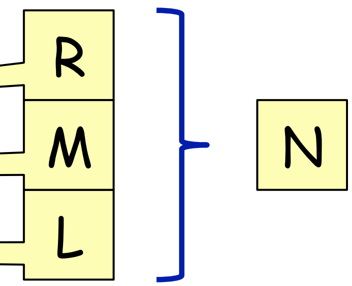
((R* [N] L*) Y)* (R* [N] L*)

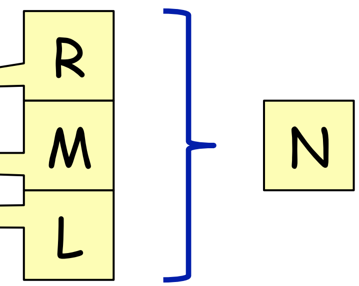
```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  compound void searchFrom(Path path) {
    yield;
    if (path.length() >= shortestPathLength) return;

    if (path.isComplete()) {
      yield;
      synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {
        yield;
        searchFrom(c);
      }
    }
  }
}
```

```
class TSP {
  Object lock;
  volatile int shortestPathLength; // lock held on writes

  compound void searchFrom(Path path) {

    if (path.length() >= ..shortestPathLength) return;

    if (path.isComplete()) {

      ..synchronized(lock) {
        if (path.length() < shortestPathLength)
          shortestPathLength = path.length();
      }
    } else {
      for (Path c : path.children()) {

        ..searchFrom#(c);
      }
    }
  }
}
```

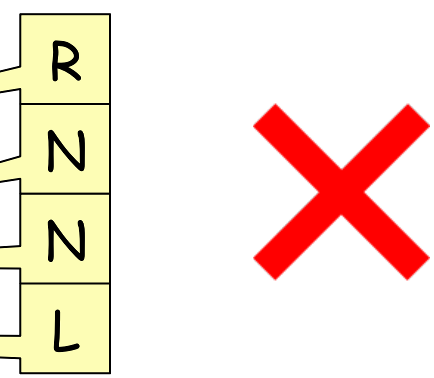
Conditional Effects

```
class StringBuffer {
  int count;

  non-mover
  synchronized int length() {
    return count;
  }

  non-mover
  synchronized void add(String s) {
    ...
  }
}
```






```
StringBuffer sb;
synchronized (sb) {
  if (sb.length() < 10)
    sb.add("moo");
}
```



Conditional Effects

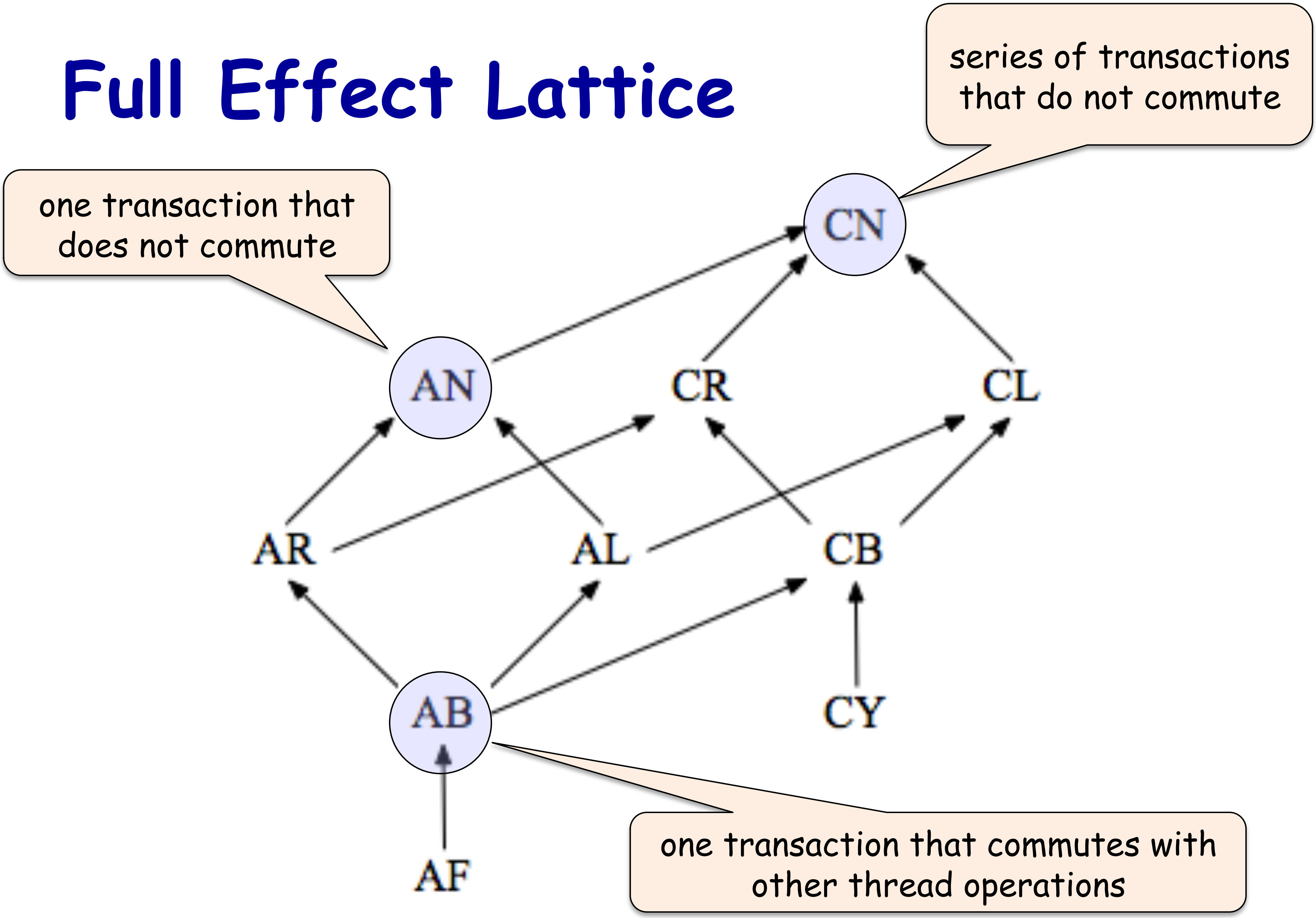
```
class StringBuffer {
  int count;

  this ? mover : non-mover
  synchronized int length() {
    return count;
  }

  this ? mover : non-mover
  synchronized void add(String s) {
    ...
  }
}
```

	this not held	this held
`synchronized int length() {`	R	M
`return count;`	M	M
`}`	L	M
`synchronized void add(String s) {`	R	M
`...`	M	M
`}`	L	M

```
StringBuffer sb;
synchronized (sb) {
  if (sb.length() < 10)
    sb.add("moo");
}
```

`synchronized (sb) {`	R
`if (sb.length() < 10)`	M
`sb.add("moo");`	M
`}`	L

Full Effect Lattice



Program	Size (LOC)	Annotation Time (min.)	Anotation Count
java.util.zip.Inflater	317	9	4
java.util.zip.Deflater	381	7	8
java.lang.StringBuffer	1,276	20	10
java.lang.String	2,307	15	5
java.io.PrintWriter	534	40	109
java.util.Vector	1,019	25	43
java.util.zip.ZipFile	490	30	62
sparse	868	15	19
tsp	706	10	45
elevator	1,447	30	64
raytracer-fixed	1,915	10	50
sor-fixed	958	10	32
moldyn-fixed	1,352	10	39
Total	13,570	231	490
Total per KLOC		17	36

Program	Number of Interference Points					Unintended Yields
	No Spec	Race	Atomic	Atomic Race	Yield	
java.util.zip.Inflater	36	[illegible]	[illegible]	[illegible]	0	0
java[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
jav[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1
jav[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
jav[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9
jav[illegible]	[illegible]	106	44	24	4	1
jav[illegible]	[illegible]	105	85	53	30	0
spar[illegible]	[illegible]	98	48	14	6	0
tsp	445	115	437	80	19	0
elevator	454	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
raytracer-fixed	565	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
sor-fixed	249	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
moldyn-fixed	983	130	[illegible]	37	30	0
Total	3,928	1,291	1,890	432	180	13
Total per KLOC	289	95	139	32	13	1

Interference at:

- field accesses
- all lock acquires
- atomic method calls

in non-atomic methods

...rence at:

...nts

...rence at:

- field accesses
- all lock acquires

Fewer Interference Points: Easier to Reason about Code!

Dynamic Program Analysis for Yield Correctness

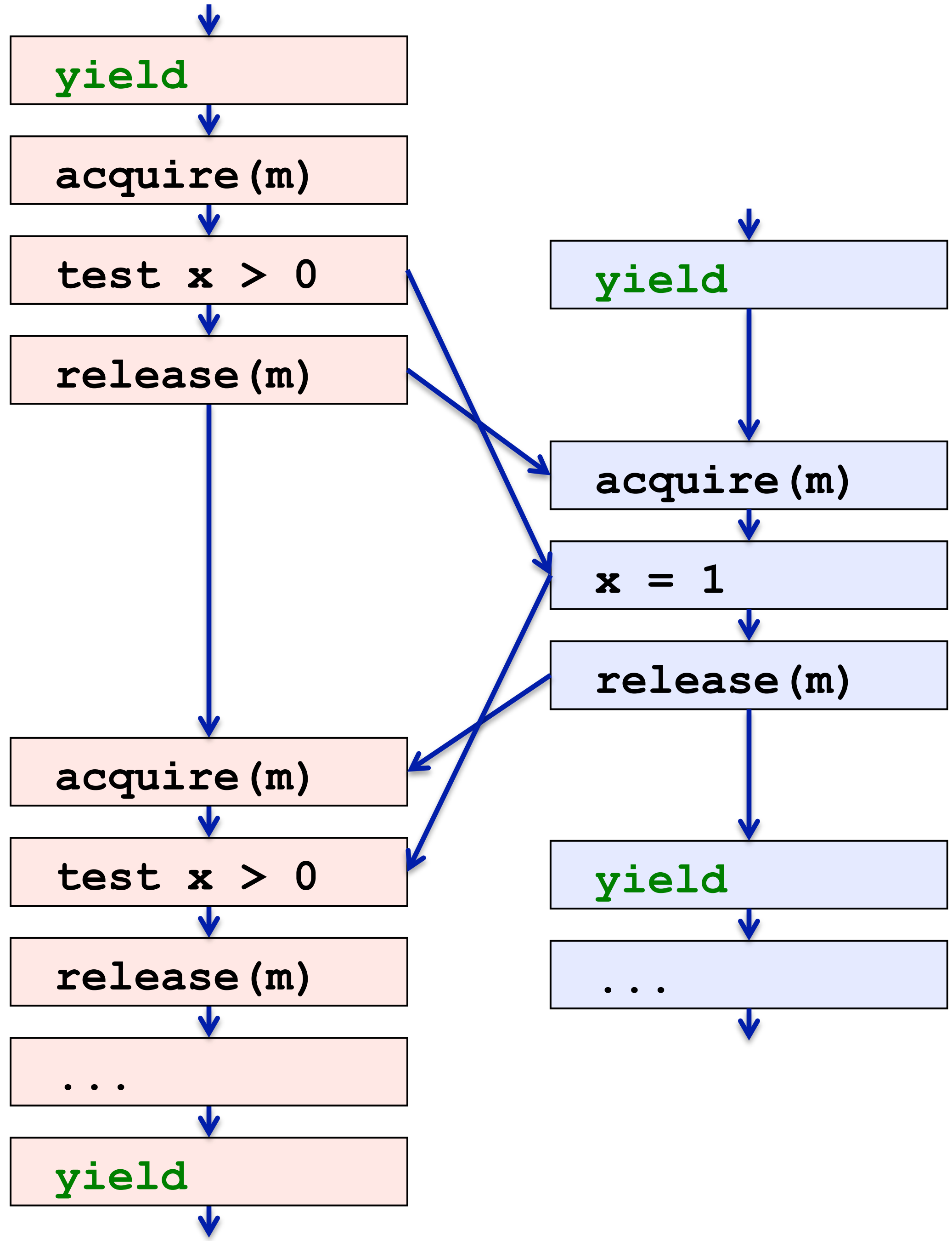
Copper [PPOPP 11]

```
yield;
acquire(m);
while(x>0) {
  release(m);

  acquire(m);
}
assert x==0;
release(m);
yield;
```

yield	
acquire(m)	
test x > 0	yield
release(m)	
	acquire(m)
	x = 1
	release(m)
acquire(m)	
test x > 0	yield
release(m)	...
...	
yield	

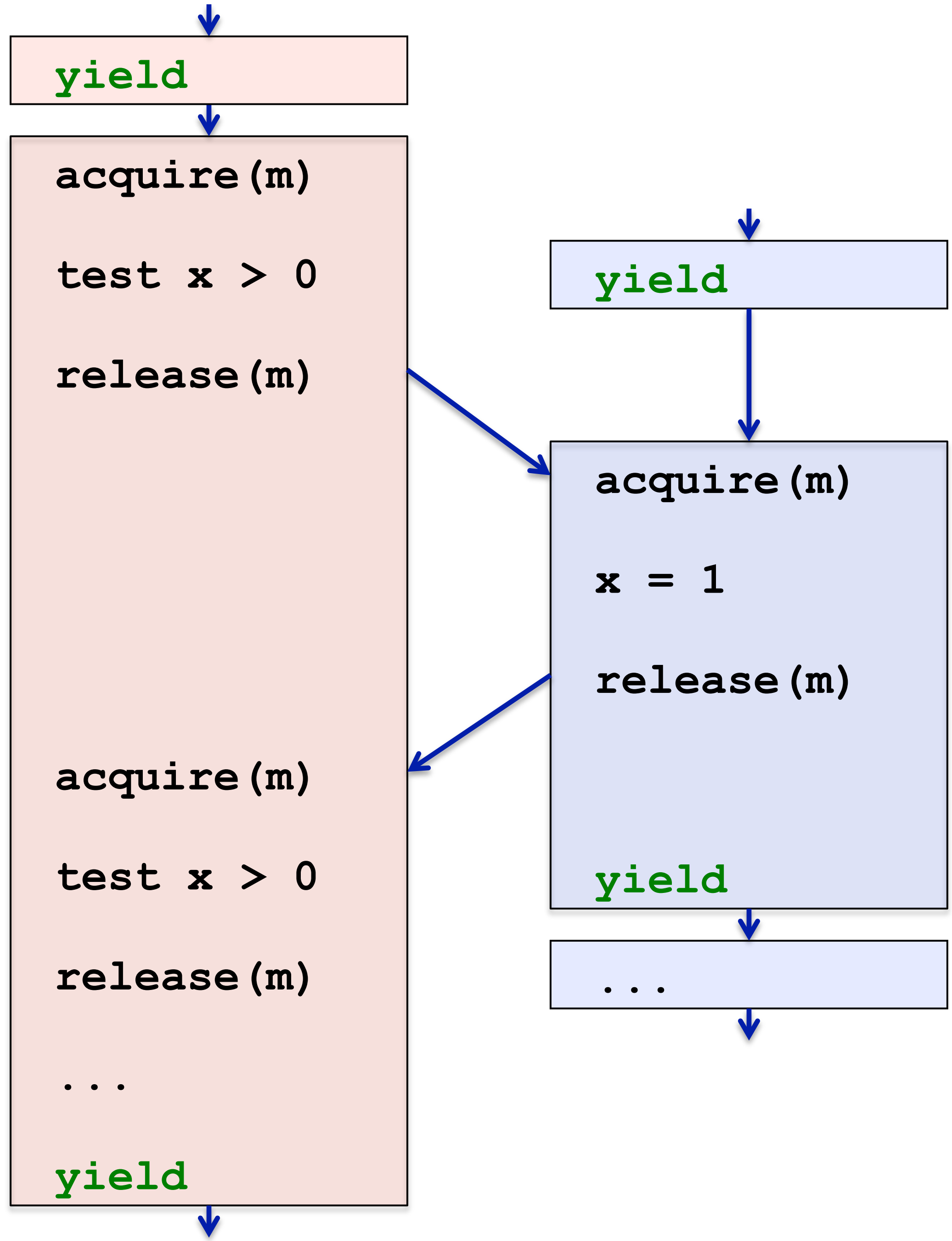
Copper

- Build Transactional Happens-Before
  - program order
  - sync. order
  - comm. order



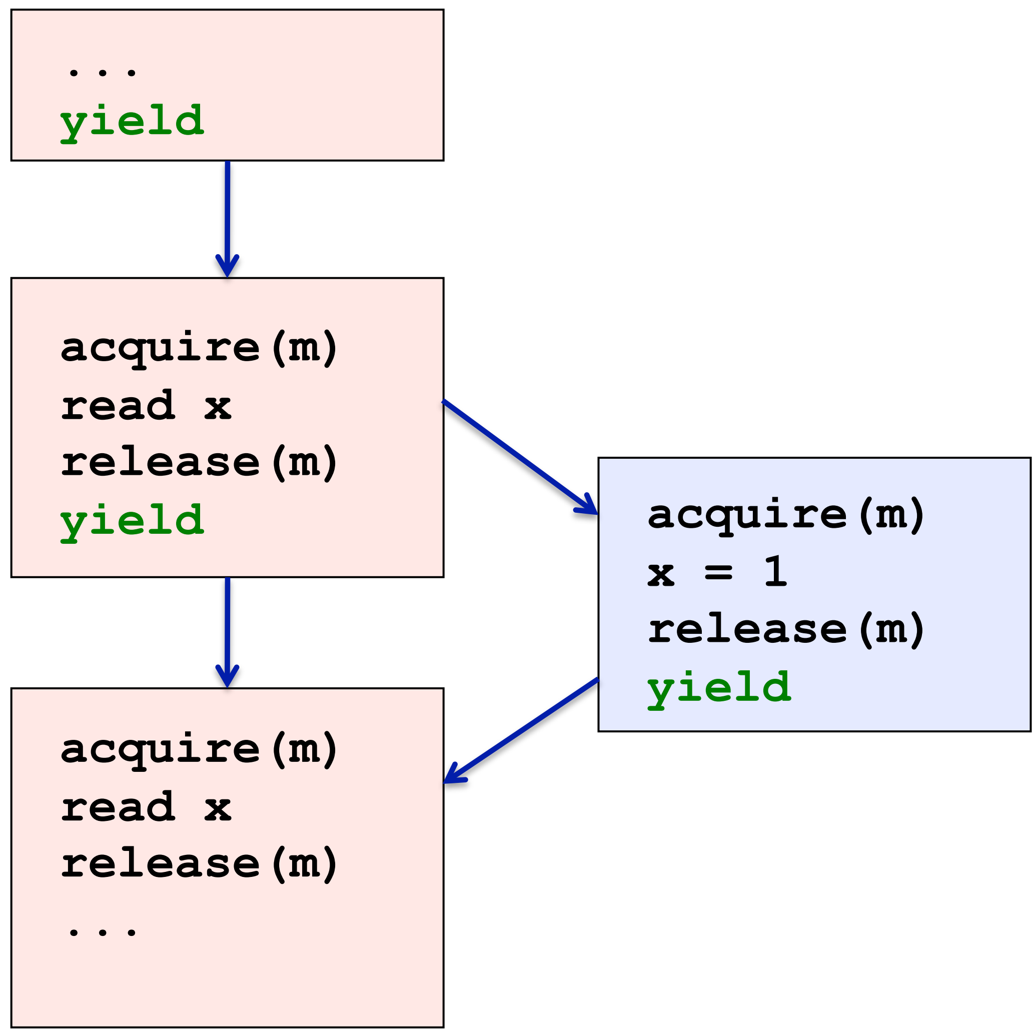
Copper

- Build Transactional Happens-Before
- Yields mark transaction ends
- Cycles indicate missing yields

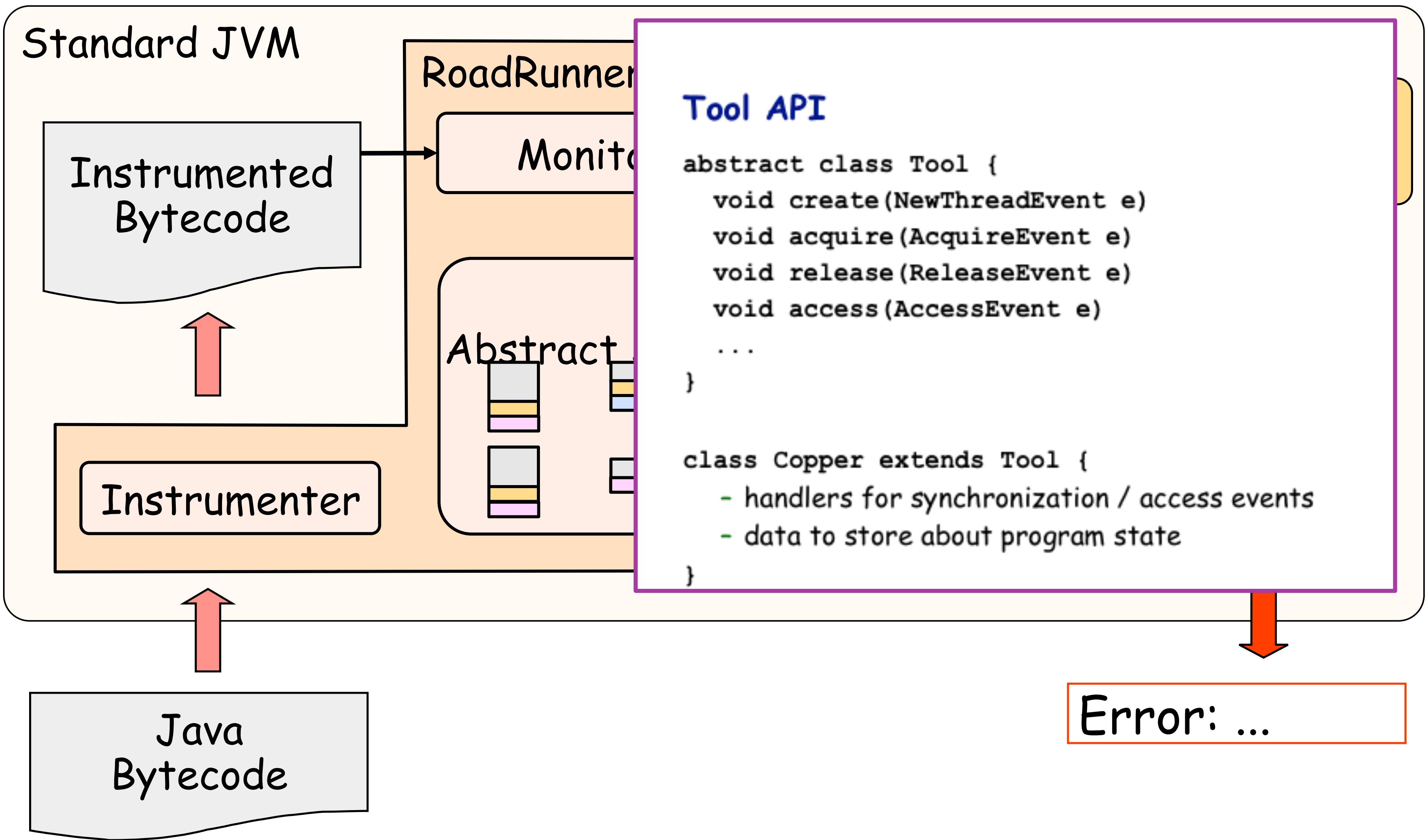


Copper

```
yield;
acquire(m);
while(x>0) {
  release(m);
  yield;
  acquire(m);
}
assert x==0;
release(m);
yield;
```



RoadRunner Framework for Dyanamic Concurrency Analyses [PASTE '10, github]



Tool API

```
abstract class Tool {
  void create(NewThreadEvent e)
  void acquire(AcquireEvent e)
  void release(ReleaseEvent e)
  void access(AccessEvent e)
  ...
}

class Copper extends Tool {
   - handlers for synchronization / access events
   - data to store about program state
}
```

Others: Sofya [KDR 07], CalFuzzer [JNPS 09]

Copper Results

program	LLOC	No Analysis	Atomic Methods	Yields
sparse	712			0
sor				
seri				
cry				
mo			64	
ele			54	3
lufa			57	3
raytr			65	3
montecarlo	3557	377	41	1
hedc	6409	305		
mtrt	6460	695		
raja	6863	396	45	0
colt	25644	601	113	13
jigsaw	48674	3415	550	47

Interference at:

- field accesses
- all lock acquires
- atomic method calls

in non-atomic methods

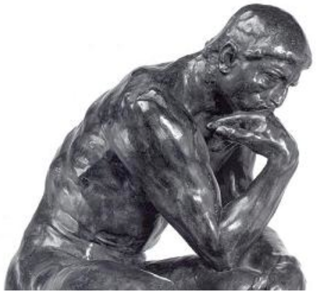
Interference at:

- *yield points*

ence at:

d accesses
- all lock acquires

Fewer interference points:
less to reason about!



Cooperative Scheduler

- Sequential Reasoning
- Except at yields

```
acq(m)
x = 0
rel(m)
yield
        ...
        barrier
        yield
...
yield
        acq(m)
        x = 2
        rel(m)
        yield
```

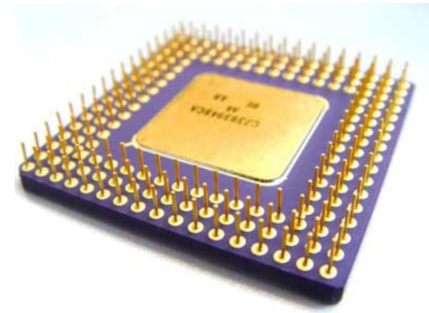
Cooperative Correctness

Yield-oriented Programming

```
acq(m)
x = 0
rel(m)
yield
```

Yield Correctness: yields mark all thread interference

∧ … ➔



Preemptive Scheduler

- Full performance
- No overhead

```
acq(m)
x = 0
rel(m)
yield
        ...
        barrier
        yield
...
yield
        acq(m)
        x = 2
        rel(m)
        yield
```

Preemptive Correctness

Summary

- Race freedom
  - code behaves **as if** on sequentially consistent machine
- Atomicity
  - code behaves **as if** atomic methods executed serially
- Yield-oriented programming
  - code behaves **as if** run on cooperative scheduler
  - sequential reasoning ok, except at yields (1-10/KLOC)
  - http://users.soe.ucsc.edu/~cormac/coop.html

- Other analyses for yield correctness
- Other non-interference properties: determinism, …
- Deterministic schedulers, record-and-replay
- Other programming models/hardware platforms

Summary

- Race freedom
  - code behaves **as if** on sequentially consistent memory model
- Atomicity
  - code behaves **as if** atomic methods executed serially
- Yield-oriented programming
  - use traditional synchronization & multicore hardware
  - document all interference with yields
  - static analyses check interference only at yields
  - code behaves **as if** run on cooperative scheduler
  - sequential reasoning ok, except at yields (1-10/KLOC)
  - http://users.soe.ucsc.edu/~cormac/coop.html

Summary

- Race freedom
  - code behaves **as if** on sequentially consistent memory model
- Atomicity
  - code behaves **as if** atomic methods executed serially
- Yield-oriented programming
  - code behaves **as if** run on cooperative scheduler
  - sequential reasoning ok, except where yields document thread interference (1-10/KLOC)
  - http://users.soe.ucsc.edu/~cormac/coop.html

Future Directions

- Other analyses for yield correctness
- Other non-interference properties
  - determinism, …
- Deterministic schedulers
- Record-and-replay
- Other programming models
  - domain-specific
  - multicore and distributed programming