A Proposed Semantics for Multithreaded Java

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Basic Framework

- Operational semantics
- Actions occur in a global order
  - consistent with original order in each thread
    - except for prescient writes
- If program not correctly synchronized
  - reads non-deterministically choose which value to return from set of candidate writes

Terms

- Variable
  - a field or array element
- Value
  - a primitive type or reference to an object
- Local
  - a value stored in a local or on the stack

Write Sets

- Sets of writes
  - a write is a variable/value pair
- allWrites: all writes performed
- Threads/monitors/volatiles have/know:
  - overwritten: a set of writes known to be overwritten
  - previous: a set of writes known to be in the past

Multimap basics

- These are all monotonic multimaps
  - they only grow
- Standard set operations apply
- Applying a multimap to a variable:
  - $M(v) = \{ w \mid \langle v, w\rangle \text{ in } M \}$
- Writes have hidden GUID
  - two writes of 42 are distinct
- Subscripts used to indicate thread, monitor or volatile that "owns / knows" a multimap

Read/Write Semantics (in thread *t*)

- ReadNormal(Variable *v*)

```
    $w$ = choose( allWrites($v$) - $\text{overwritten}_t(v)$ )
    return $w$
```

- WriteNormal(Variable *v*, Value *w*)

```
    $\text{overwritten}_t(v) \cup= \text{previous}_t(v)$
    $\text{previous}_t(v)$ += $w$
    allWrites($v$) += $w$
```

Invariants

- $\text{overwritten}_t \subset \text{previous}_t \subseteq \text{allWrites}$

- For correctly synchronized code, at point where you access variable *v*:
  - $\text{previous}_t(v) = \text{allWrites}(v)$
  - $|\ \text{allWrites}(v) - \text{overwritten}_t(v)\ | = 1$

Initial write of default value

- When a variable v is created, all threads t know the initial write w of the default value to that variable is previous
  - – $\text{allWrites}(v) = \{ w \}$
  - – $\text{previous}_t(v) = \{ w \}$
  - – $\text{overwritten}_t(v) = \{ \}$

Lock / Unlock Semantics

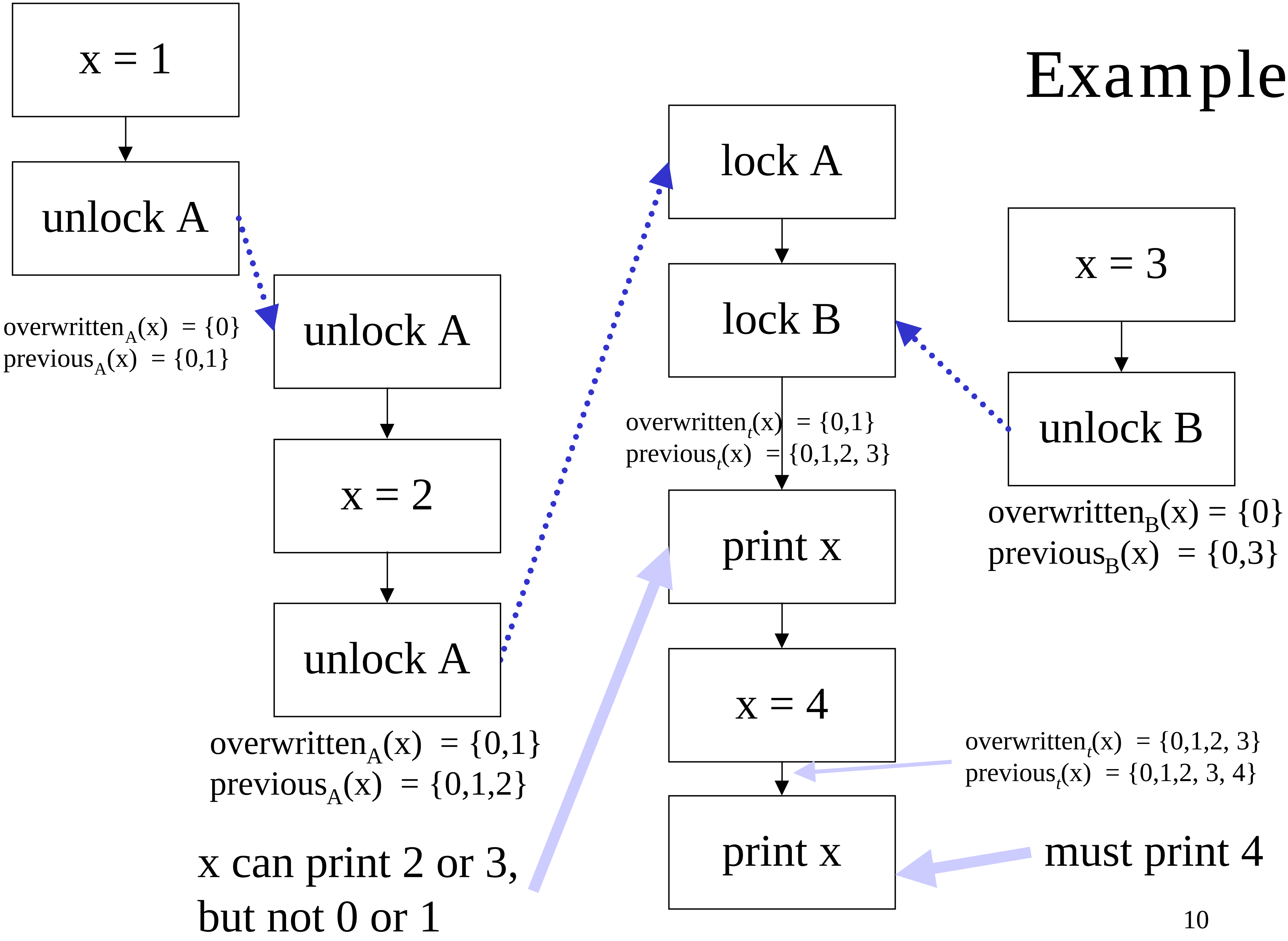
- Lock(Monitor *m*)

```
    wait until lock on $m$ has been acquired
    $\text{overwritten}_t \cup= \text{overwritten}_m$
    $\text{previous}_t \cup= \text{previous}_m$
```

- Unlock(Monitor *m*)

```
    $\text{overwritten}_m \cup= \text{overwritten}_t$
    $\text{previous}_m \cup= \text{previous}_t$
    release lock
```

Example



x = 1

unlock A

$\text{overwritten}_A(x) = \{0\}$
$\text{previous}_A(x) = \{0,1\}$

unlock A

x = 2

unlock A

$\text{overwritten}_A(x) = \{0,1\}$
$\text{previous}_A(x) = \{0,1,2\}$

lock A

lock B

$\text{overwritten}_t(x) = \{0,1\}$
$\text{previous}_t(x) = \{0,1,2, 3\}$

print x

x = 4

$\text{overwritten}_t(x) = \{0,1,2, 3\}$
$\text{previous}_t(x) = \{0,1,2, 3, 4\}$

print x

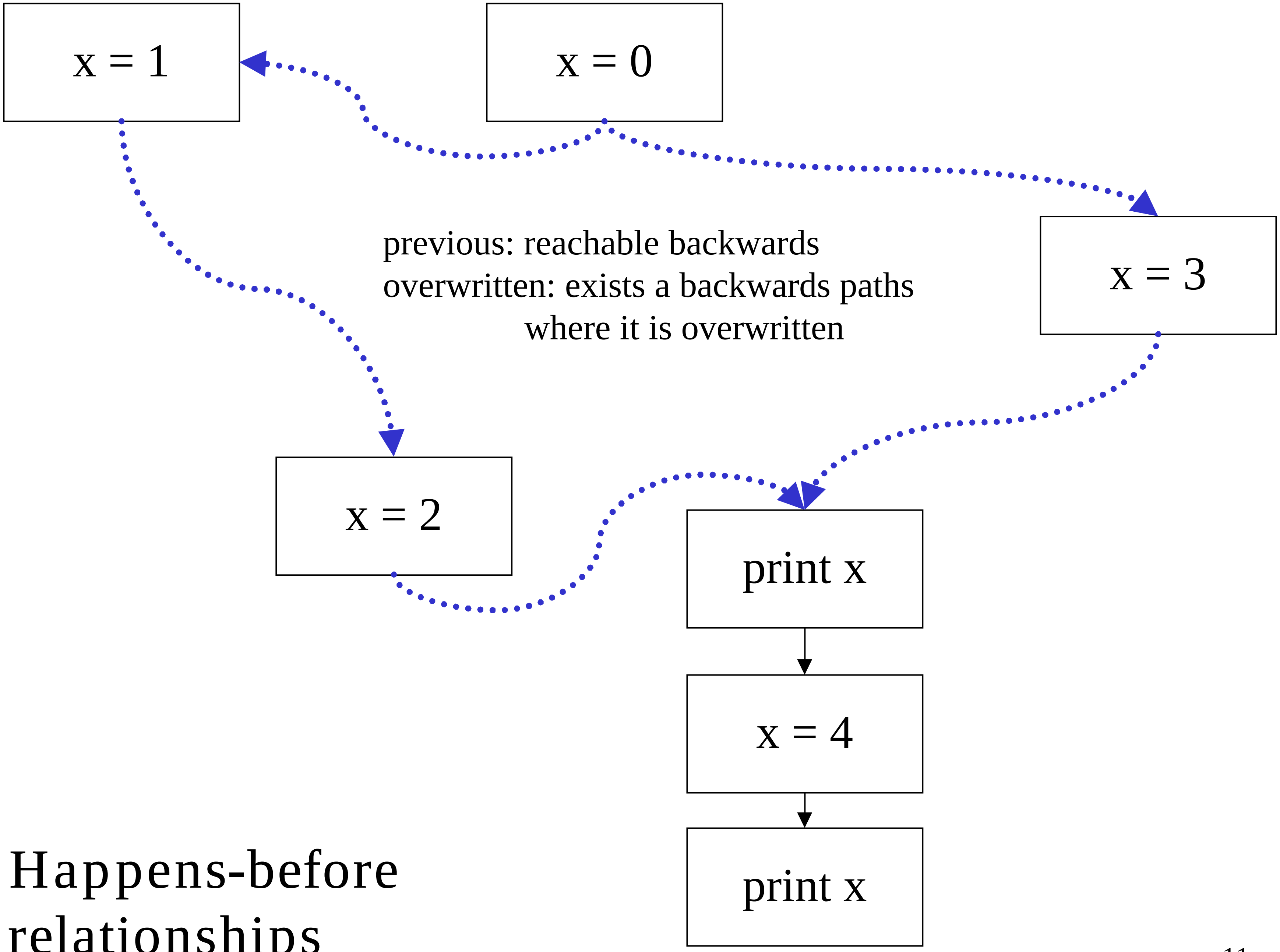
x = 3

unlock B

$\text{overwritten}_B(x) = \{0\}$
$\text{previous}_B(x) = \{0,3\}$

x can print 2 or 3,
but not 0 or 1

must print 4



previous: reachable backwards
overwritten: exists a backwards paths
where it is overwritten

Happens-before relationships

Volatile Semantics

- Very similar to monitors

- ReadVolatile(Variable *v*)

```
    $\text{overwritten}_t \cup= \text{overwritten}_v$
    $\text{previous}_t \cup= \text{previous}_v$
    return $\text{volatileValue}_v$
```

- WriteVolatile(Variable *v*, Value *w*)

```
    $\text{overwritten}_v \cup= \text{overwritten}_t$
    $\text{previous}_v \cup= \text{previous}_t$
    $\text{volatileValue}_v = w$
```

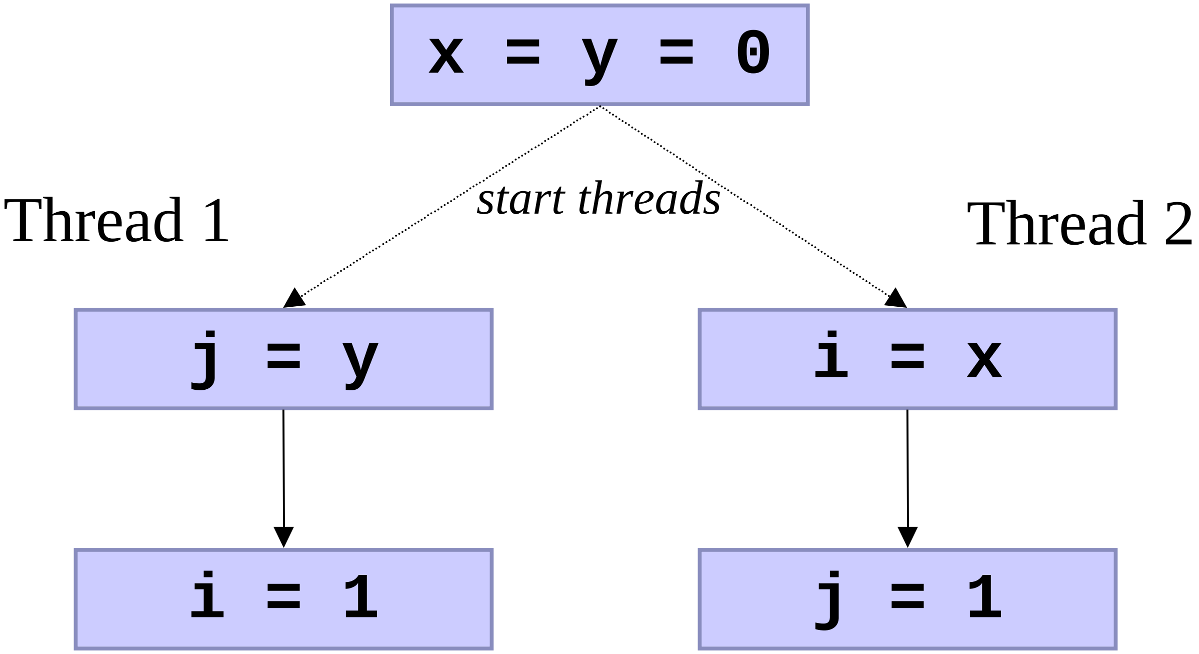
Synchronization optimizations

- Thread local monitors are no-ops
  - Information known by monitor must be subset of information known by thread
- Thread local volatile fields can be treated as non-volatile fields
- Recursive locks are no-ops
  - recursive lock can’t reveal any new information
  - recursive unlock won’t be read

Lock Coarsening

- If you guarantee that no other thread acquires a lock between a unlock and lock
  - information written by unlock in monitor will not be read by any other thread
  - lock will not acquire any new information
  - Unlock and locks have no effect

Problem



`x = y = 0`

start threads

Thread 1

`j = y`

`i = 1`

Thread 2

`i = x`

`j = 1`

Can this result in i = 1 and j = 1?

Need Prescient Writes

- A thread may perform a write early only if the following conditions hold
  - The write is guaranteed to happen
  - The variable written to and the value written are fixed
    - including across non-deterministic values returned by reads
  - it is not moved past another access to that variable

Prescient writes (continued)

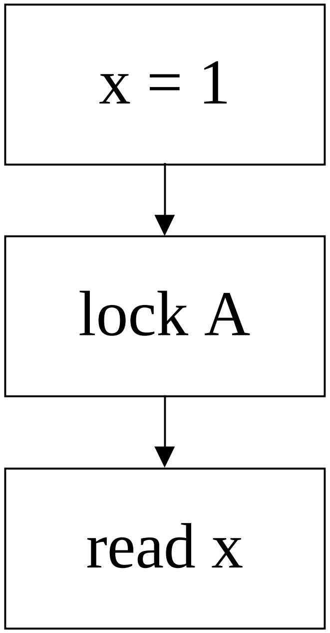
- A Prescient write may not be reordered with a preceding lock action unless the previous unlock on that monitor (if any) is guaranteed to have been done by the same thread
  - circularity problem?

Prescient Reads?

- Prescient Reads are not needed
- Reads can be done early
  - so long as value read is guaranteed to not be in overwritten set at original point of read

Very Prescient Reads

- Can even do forward substitution across lock
  - At point of lock (and of read), no other thread knows x=1 to be previous
  - cannot learn that x=1 is overwritten at lock

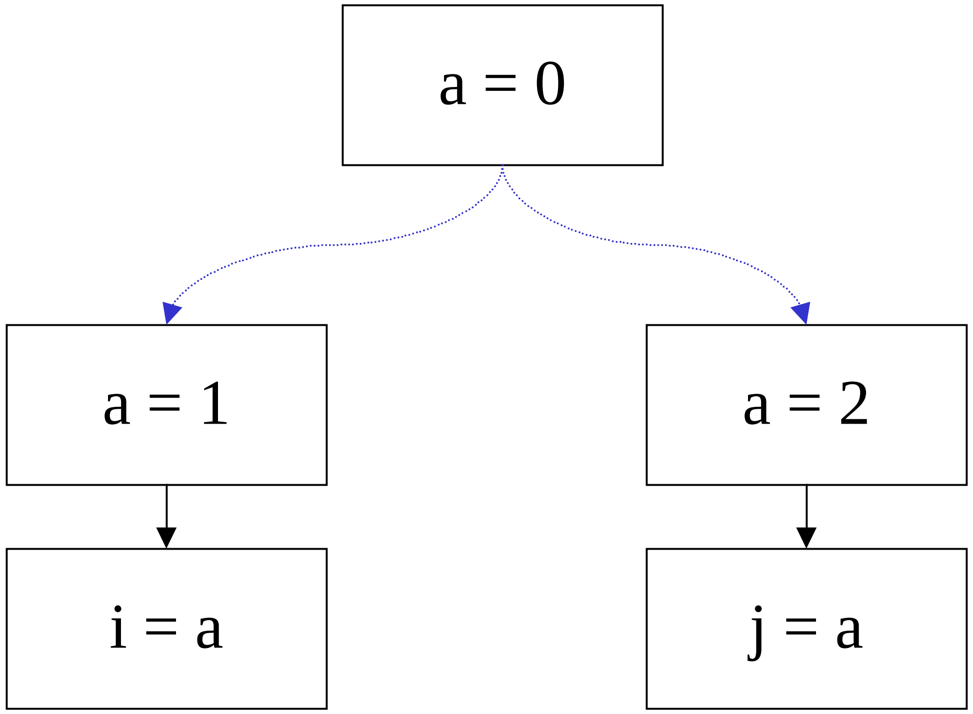


x = 1

lock A

read x

Requires G-CRF



a = 0

a = 1

a = 2

i = a

j = a

Can this result in i = 2 and j = 1?

Example Execution

- T1: a = 1

  aW = {0, 1}; o_1 = {0}; p_1 = {0,1}
- T2: a = 2

  aW = {0, 1, 2}; o_2 = {0}; p_2 = {0,1}
- T1: i = a

  choose 2 from {0, 1, 2} – {0}
- T2: j = a

  choose 1 from {0, 1, 2} – {1}

Final fields

- Have to track data dependence
- Attach overwritten information to final fields and to local values
  - don’t need previous; sync arising from final should not be used for writes
- A local value consists of a

  <value, overwritten>

  tuple

Changes

- Changes semantics for reads / writes of normal fields and final fields
  - Operations now take an address (a local value) and a field
    - arrays treated as records
- Constructor termination freezes the appropriate final fields
  - details with constructor chaining

Read / Write Semantics

- ReadNormal(Value <*a*, *oF*>, Field `f`)

  ```
  Let $v$ be variable referenced by $a$.f
  $w$ = choose( allWrites($v$) – overwritten$_t$($v$) – $oF$)
  return <$w$, $oF$>
  ```

- WriteNormal(Value <*a*, —>, Field `f`, Value <*w*, —>)

  ```
  Let $v$ be variable referenced by $a$.f
  overwritten$_t$($v$) $\cup$= previous$_t$($v$)
  previous$_t$($v$) += $w$
  allWrites($v$) += $w$
  ```

Final Semantics

```
• ReadFinal(Value <$a$, $oF$>, Field f)
      Let $v$ be final variable referenced by $a$.f
      $oF'$ = $\text{overwritten}_v$
      return <$\text{finalValue}_v$, $oF \cup oF'$>

• WriteFinal(Value <$a$, —>, Field f, Value <$w$, —>)
      Let $v$ be variable referenced by $a$.f
      $\text{finalValue}_v = w$

• FreezeFinal(Value <$a$, —>, Field f)
      Let $v$ be variable referenced by $a$.f
      $\text{overwritten}_v = \text{overwritten}_t$
```

Pseudo-Final fields

- If you store a reference to an object *b* into the heap before the B constructor for *b* terminates
- Another threads loads that reference
- And synchronization doesn't guarantee that the load occurs after the B constructor terminates
  - all final fields of B in *b* become pseudo-final

Pseudo-Final fields

- Each read of a pseudo-final variable *v* non-deterministically returns either the default value or finalValue_v
  - overwritten_v is ignored

On pseudo-final fields

- In reality, having one improperly synchronized reference to an object
- shouldn’t affect reads of final fields through properly synchronized references

- But I couldn’t make the semantics work

Comparison with other models

- Post-hoc models
  - only tell you if a particular execution is legal
    - circularity issues
- Other operational models
  - impose weird little constraints not needed to enforce SC for correctly synchronized programs (or for safety reasons)
  - only arise in contrived cases

Simple memory models

- Some models have a simple global/cache memory model
  - one global memory
  - one cache per thread
- Actions get committed to global memory in some total order
- Updates applied to local cache in some total order

Models based on reordering

- A model based on reordering depends on rules for reordering
  - can you reorder read of t3.x?

```
t2 = t1.x;
t3 = A.p;
t4 = t3.x;
```

  - For example, to

```
t2 = t1.x;
t3 = A.p;
if (t3 == t1) t4 = t2
else t4 = t3.x
```

Behavior prohibited if dependent reads can't be reordered

- Initially

```
p.next = null
```

- Thread 1:

```
p.next = p
```

- Thread 2:

```
List tmp = p.next;
if (tmp == p && tmp.next == null) {
        // Can't happen under CRF
        }
```

Do we care about behaviors no one cares about?

- What if memory model prohibits a weird behavior
  - don’t know of any compiler optimizations that would perform it
  - don’t know of any architectures that would perform it
- is this a problem?

Why we should care

- If behavior is prohibited, need to prove:
  - architecture doesn’t allow it
  - compiler optimizations don’t allow it

- Even if a compiler doesn’t allow it, proving that is a burden

Challenge

- I don’t know of any examples of behaviors prohibited by my approach
  - except for those we must prohibit
  - and edge cases of final fields of objects escaping their constructors

- but I need outside eyes