Detecting Data Races in Parallel Programs

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Papers for the Day

- **Happens-before**
  - —On-the-fly detection of data races for programs with nested fork-join parallelism, John Mellor-Crummey, Supercomputing 1991: Proceedings of the 1991 ACM/IEEE conference on Supercomputing, 1991, Albuquerque, New Mexico, New York, NY, 24-33.
  - —Efficient detection of determinacy races in Cilk programs, Mingdong Feng and Charles E. Leiserson, SPAA '97: Proceedings of the 9th Annual ACM Symposium on Parallel Algorithms and Architectures, June 23-25, 1997, Newport, Rhode Island, New York, NY, USA, 1-11.
- **Lock covers**
  - —Eraser: a dynamic data race detector for multithreaded programs, Stefan Savage, Michael Burrows, Greg Nelson, Patrick Sobalvarro, and Tom Anderson. In Proceedings of the 16th ACM symposium on Operating systems principles. Saint Malo, France, 27-37, 1997.

Outline

- Defining the problem
- Detecting data races with happened-before
- Detecting data races with lock covers: Eraser
- Discussion

Data Races

- Logically concurrent accesses to the same variable
  - —no happens-before ordering
- At least one is a write
- No mechanism used to prevent simultaneous accesses
  - —e.g., lock, atomic variable

- Notes
  - —data race causes non-determinism, but is not synonymous
  - —here data race = atomicity violation

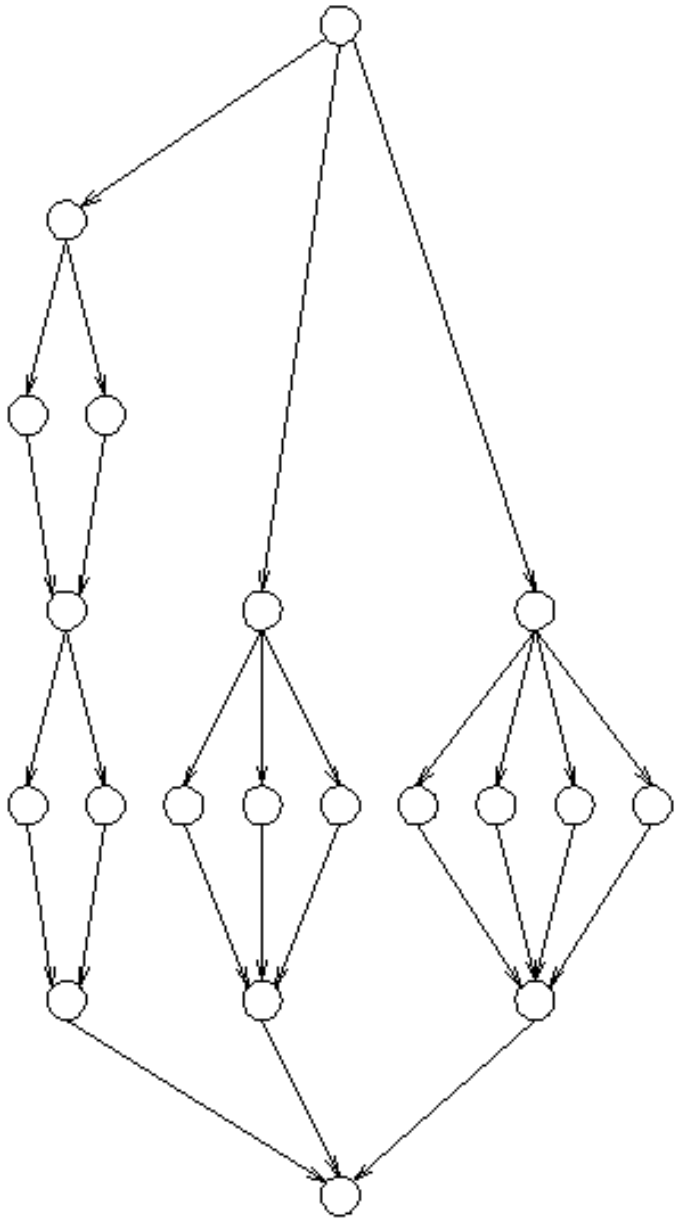
The Problem

- Domain
  - —shared-memory programs with nested fork-join parallelism
    - e.g. Cilk programs, nested parallel loops in OpenMP
- The challenge
  - —schedule-dependent bugs: unpredictable erroneous behavior on some executions with a particular input data set
- Principal cause
  - —unsafe communication through shared variables
    - "data races," "access anomalies," "determinacy races"

Fork-Join Parallelism

Nested parallel loops

```
...
DOALL I=2,4
  ...
  IF (I.EQ.2) THEN
    DOALL J = 1,2
      ...
    ENDDO
  ENDIF
  DOALL J=1,I
    ...
  ENDDO
  ...
ENDDO
...
```



Data Race Example

```
DOALL I=1,2
  PRIVATE T
  T=SUM
  SUM=T+I
ENDDO
PRINT SUM
```

Difficulty of Isolating Data Races

- Different executions may exhibit different behavior
  - —behavior depends upon access interleaving order
- Adding tracepoints or breakpoints may cause erroneous behavior to disappear
  - —alters probable interleavings

Approaches for Detecting Data Races

- **Static analysis**
  - —examine program text only
  - —conservative approximations (parallelizing compilers)
    - e.g. data dependences carried on loops
  - —drawback: false positives
- **Post-mortem analysis**
  - —examine execution traces
  - —report only actual races (Intel thread checker)
  - —drawback: large trace logs
- **On-the-fly analysis**
  - —during execution
  - —report only actual races without trace logs
  - —drawback: potentially high run-time overhead

On-the-fly Method: Access Summaries

Making Asynchronous Parallelism Safe for the World
Guy Steele POPL 1989

- **Detect the presence of races**
- **Protocol sketch**
  - **— cell's marked with state of nest of threads that accessed them**
    - **<(p1, e1), (p2, e2) … (pm, em) >**
    - **either pi or ei may be a *: more than one thread or operation type**
  - **— access e on a "cell" by nested thread p1, p2, …, pk**
    - **"augment" cell marks with access <(p1, e), (p2, e) … (pk, e) >**
  - **— idea: use bitvector encoding [p1][e1][p2][e2]…[pj][ej]**
    - **assign a distinct "k of m" bit-pattern to parallel siblings**
    - **update access history with bitwise-OR**
  - **— maintain accessed cells in thread "responsibility set"**
  - **— turn over "responsibility set" to parent when thread finishes**
    - **prune cell access state to bitvector reflecting current nesting depth**
    - **detect races at history pruning time**

      check access history for violations by finding illegal bit pattern

      both pj and ej have more than k bits set
- **Drawback: unable to pinpoint endpoints**

On-the-fly Method: Access Histories

Pinpoint races present

- **State**
  - —maintain information about thread concurrency
  - —maintain an access history for each shared variable
    - contains (thread, access type) pairs
- **When performing an access**
  - —use a protocol to augment an "access history" for the shared variable as necessary
  - —determine if any of the accesses are conflicting
    - two or more accesses by concurrent threads
    - at least one is a write

Access History Protocol

to check access of type x to V by thread t_j:

```
for each pair (t_i, y) in V's access history
  if Concurrentp(t_i, t_j) and
      (Writep(y) or Writep(x)) then
    report a data race
  endif
  update V's access history as necessary
endfor
```

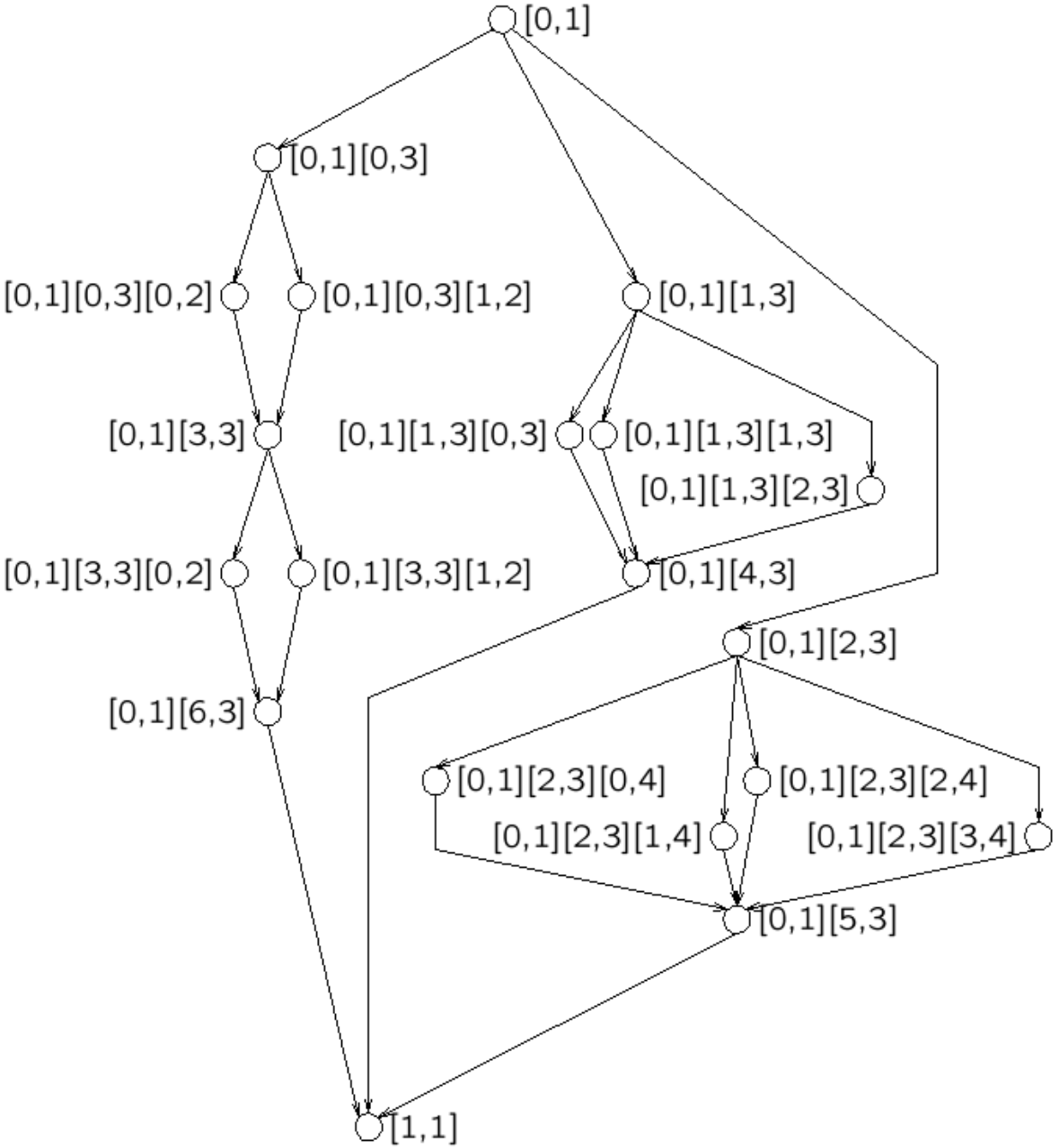
- **Difficulty: how many accesses must one store in a history?**
  - **— can one store a list asymptotically shorter than O(T) for each variable and not miss any races?**

  (T = maximum amount of logical concurrency)

Offset-span Labeling

- A thread's offset span label requires space proportional to the nesting depth of the fork-join construct that spawned it
- Description
  - each thread is labeled with a sequence of [offset, span] pairs that reflects its position in the graph
- Labeling rules
  - initial thread gets [0,1]
  - a thread that is the i^{th} child spawned by an n-way fork of thread with label L gets label L [i,n]
  - a thread after a join that pairs with a fork of thread with label L[o,s] gets label L[o+s, s]

Offset Span Labeling Example



Offset-Span Labeling Protocol

- **Access history per shared variable**
  - **last writer (last)**
  - **lowest "leftmost" reader (ll)**
  - **lowest "rightmost" reader (lr)**
- **`checkread` protocol**
  - **if concurrent with last writer, report RACE**
  - **update reader(s) in history as necessary**
- **`checkwrite` protocol**
  - **if concurrent with last writer or either reader, report RACE**

Checkwrite Protocol

```
checkwrite(access_history, thread_label)
  if access_history^.W_last ↛*_G thread_label then
    report a WRITE-WRITE data race
  endif
  if access_history^.R_ll ↛*_G thread_label or
      access_history^.R_lr ↛*_G thread_label then
    report a READ-WRITE data race
  endif
  access_history^.W_last := thread_label
end checkwrite
```

Checkread Protocol

```
checkread(access_history, thread_label)
  if access_history^.W_last ⊀*_G thread_label then
    report a WRITE-READ data race
  endif
  if thread_label ≺_G access_history^.R_11 or
      access_history^.R_11 ⇝_G thread_label then
    access_history^.R_11 := thread_label
  endif
  if access_history^.R_1r ≺_G thread_label or
      access_history^.R_1r ⇝_G thread_label then
    access_history^.R_1r := thread_label
  endif
end checkread
```

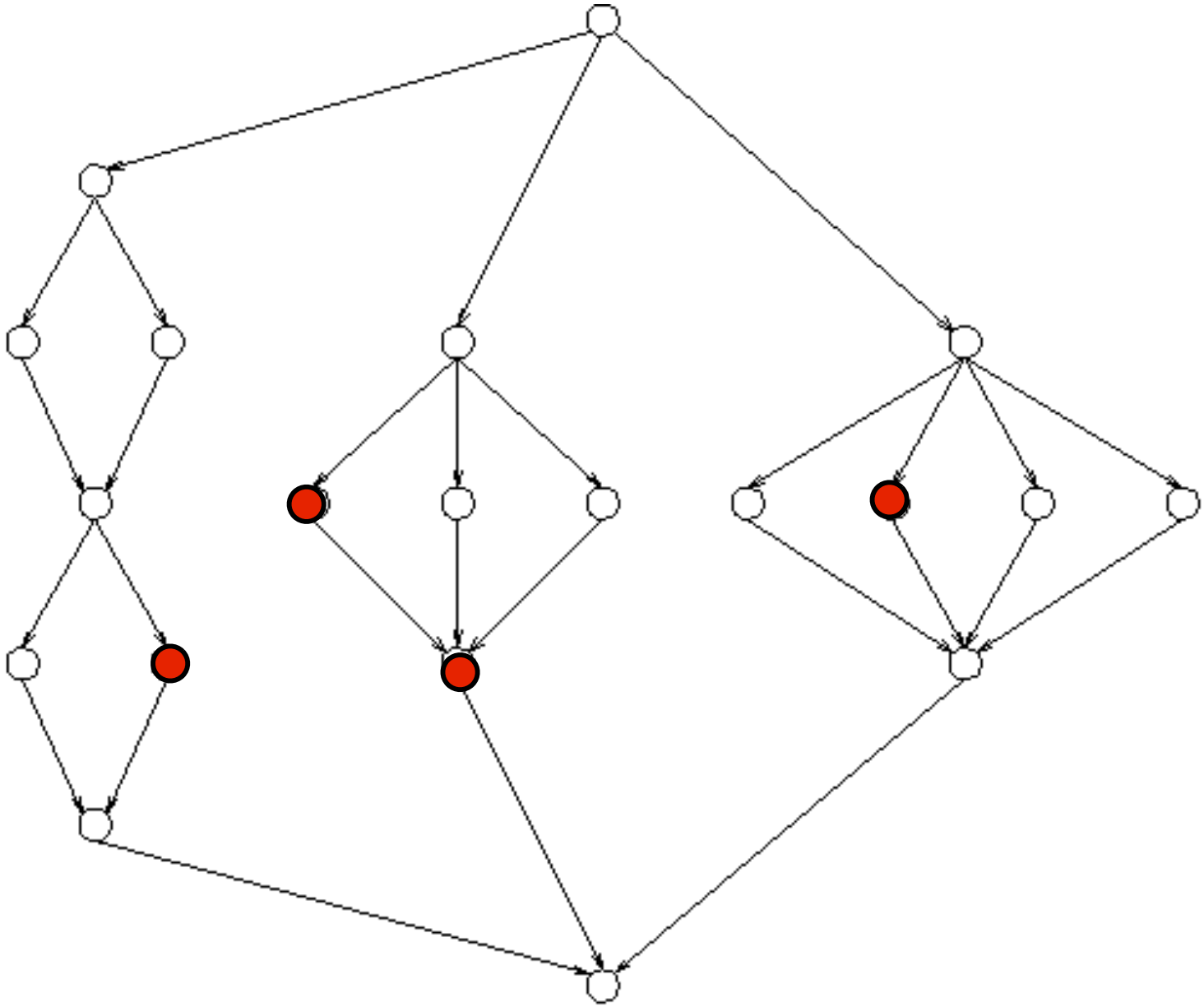
Principal Protocol Properties

- **Lemma WRITE-WRITE**
  - **if any two writes are concurrent, then `checkwrite` will report a data race**
- **Lemma READ-WRITE**
  - **`checkwrite` will report a data race for any write that is logically concurrent with a temporally earlier read**
- **Lemma WRITE-READ**
  - **`checkread` will report a data race for any read that is logically concurrent with a temporally earlier write**
- **Offset-span labeling theorem**
  - **if an execution of a program with nested fork-join parallelism contains one or more data races, at least one will be reported**

Lemma WRITE-WRITE

- If any two writes are logically concurrent, then `checkwrite` will report a data race
- Proof sketch:
  - access history contains last writer
  - `checkwrite` uses this to report a WRITE-WRITE race when two concurrent writes are temporally adjacent
    - if there are two concurrent writes to a shared variable, then there must be two temporally adjacent concurrent writes
      - proof by contradiction: if for all pairs of temporally adjacent writes, the first write of the pair sequentially precedes the second, then by transitivity none of the writes are concurrent

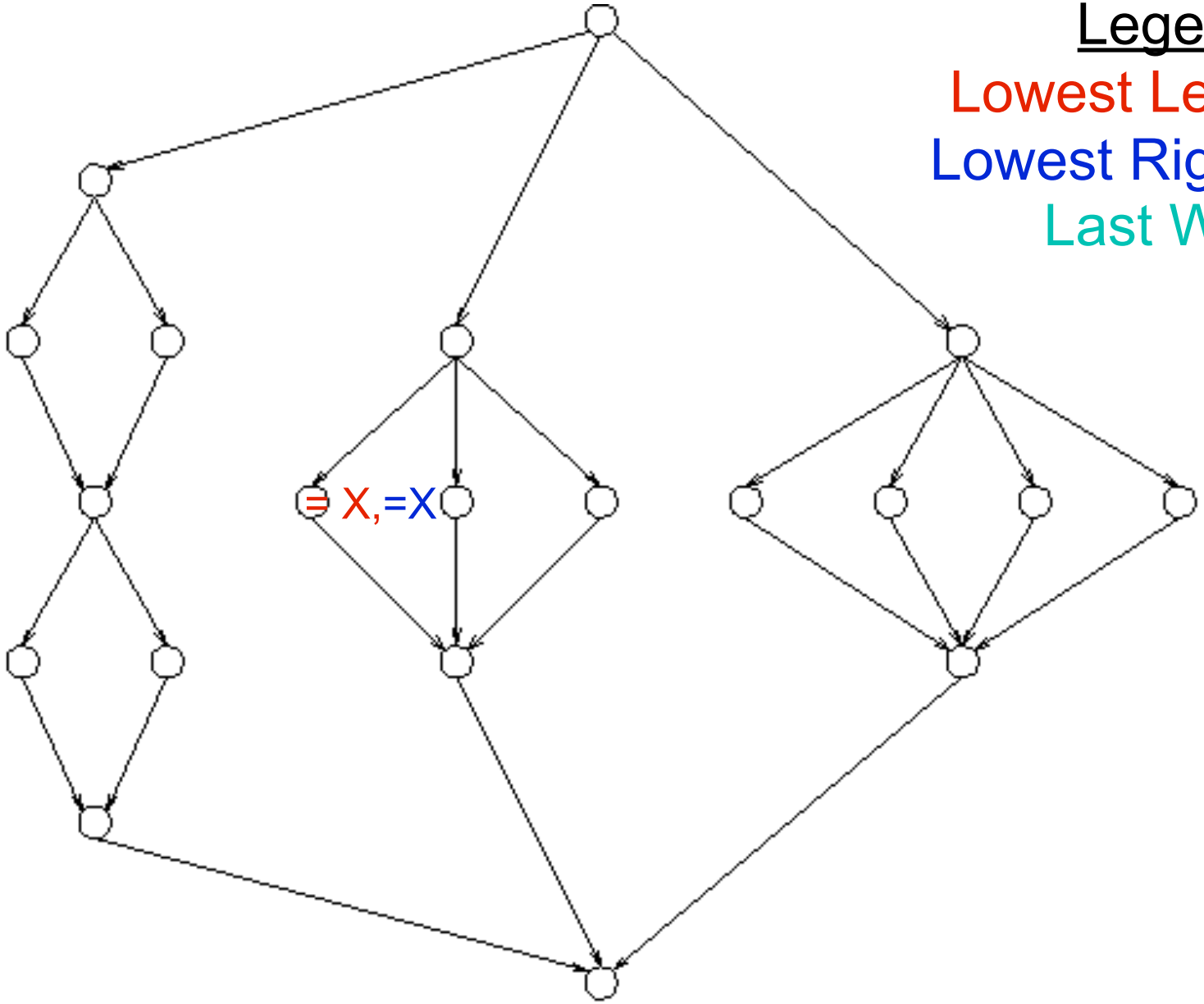
Data Race Detection Among Writers



Lemma READ-WRITE

- `checkwrite` will report a data race for any write that is logically concurrent with a temporally earlier read
  - Proof sketch
    - an access history contains
      - the lowest leftmost reader
      - the lowest rightmost reader
    - a read write race would be missed if the present write was not concurrent with either of these reads, but was concurrent with some temporally earlier read
    - with the lowest leftmost and lowest rightmost readers, the join point is as low as possible, thus a READ-WRITE race will always be reported if any are present

Data Race Detection Example



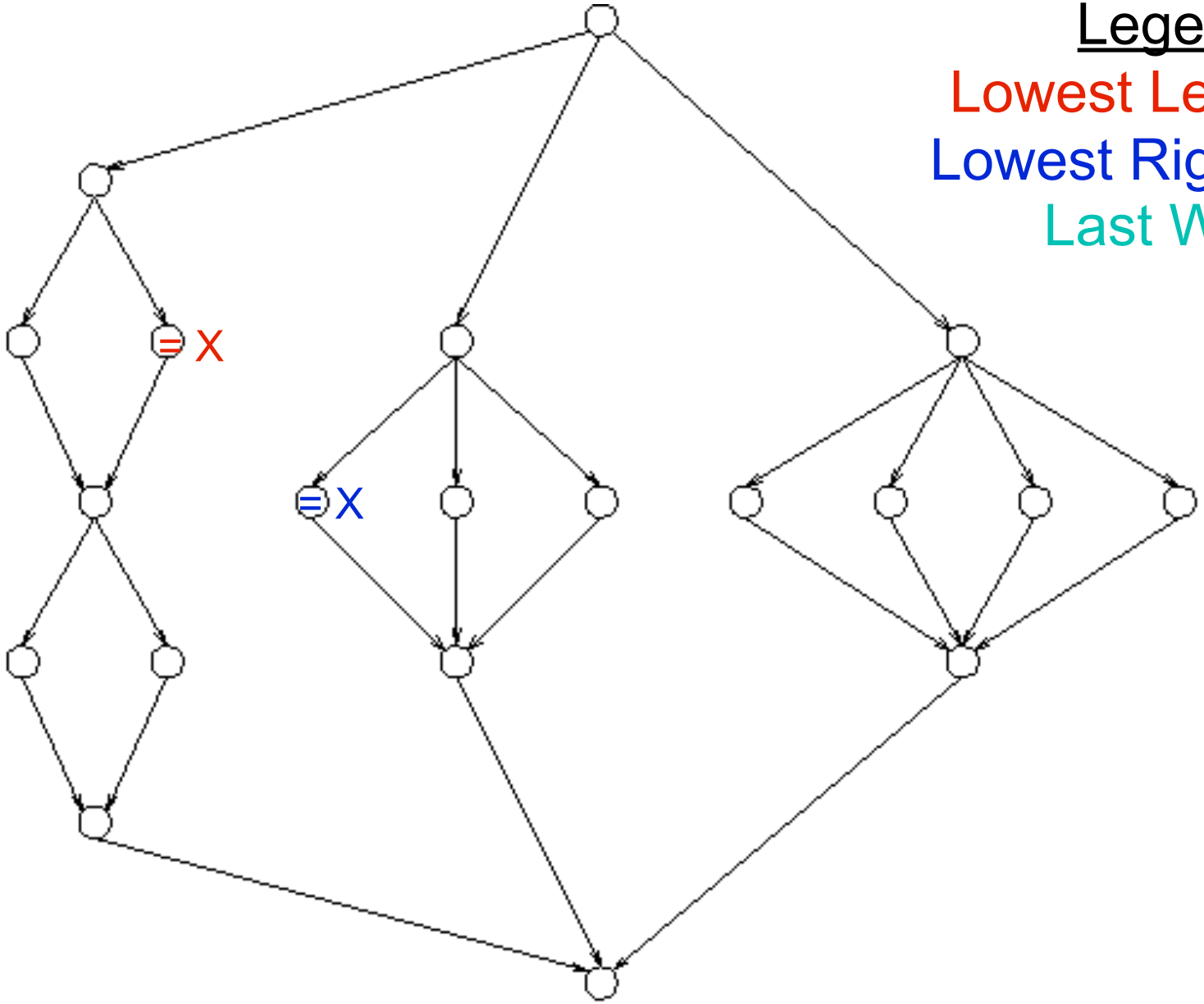
Legend

Lowest Left Read

Lowest Right Read

Last Write

Data Race Detection Example



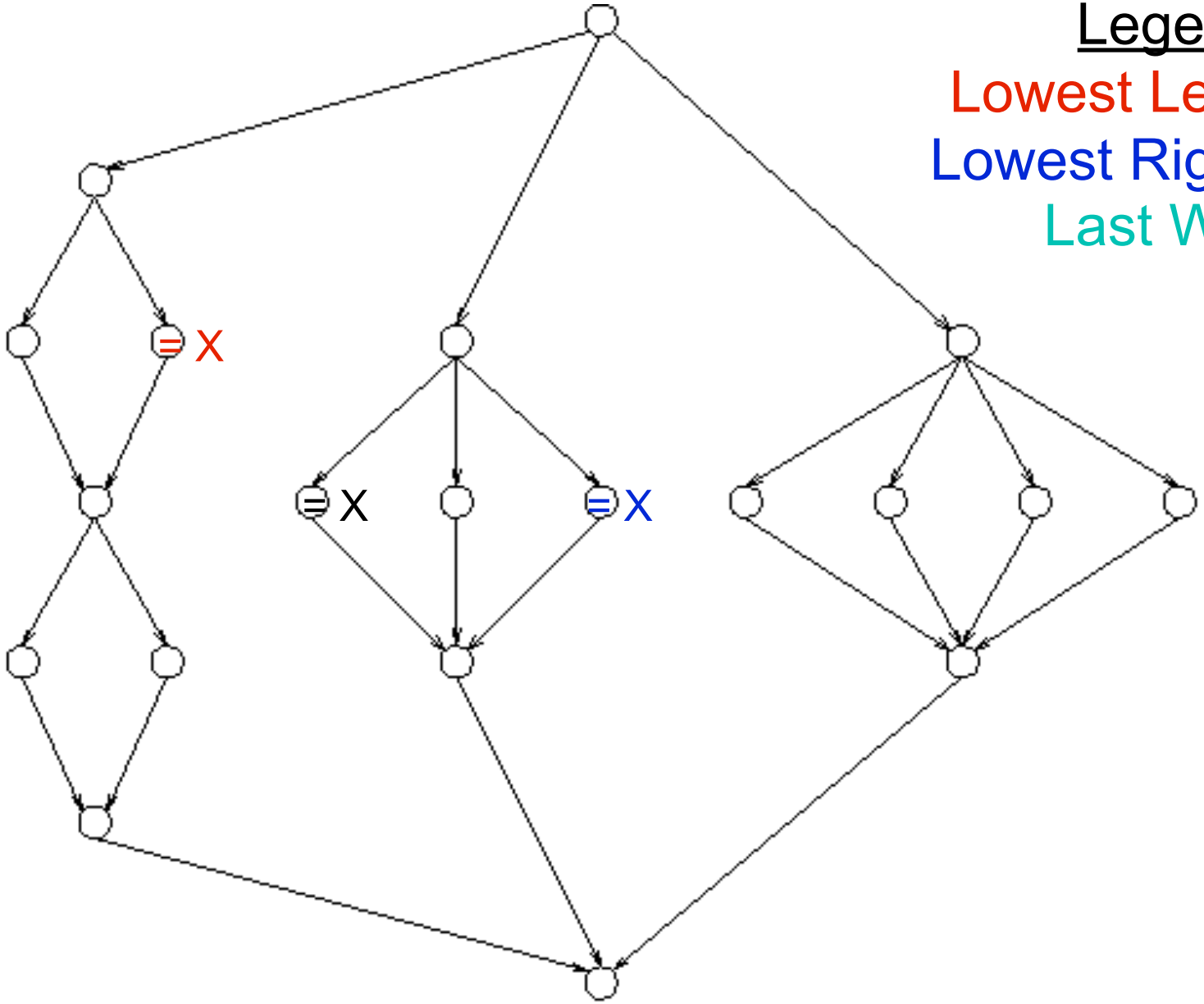
Legend

Lowest Left Read

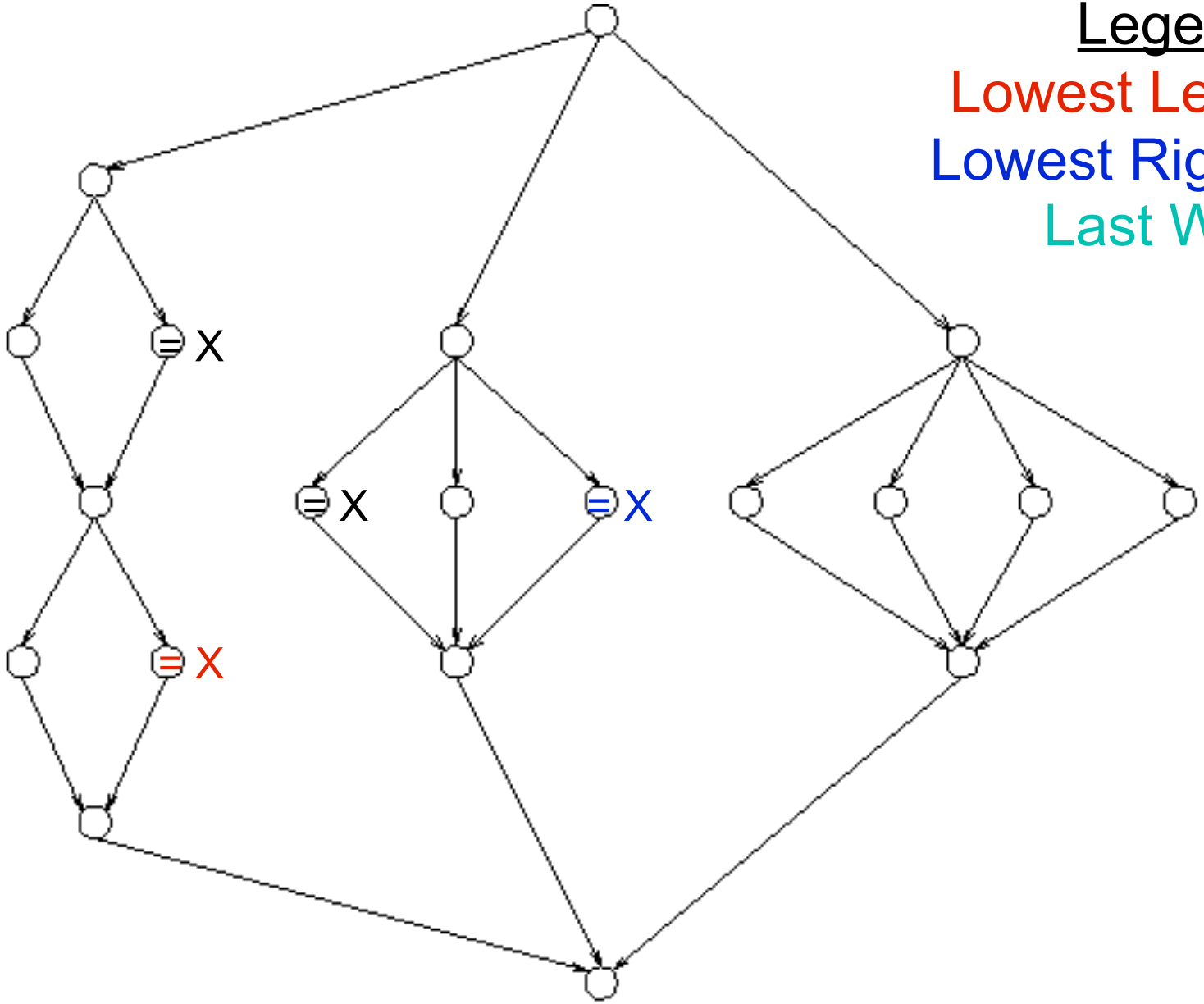
Lowest Right Read

Last Write

Data Race Detection Example

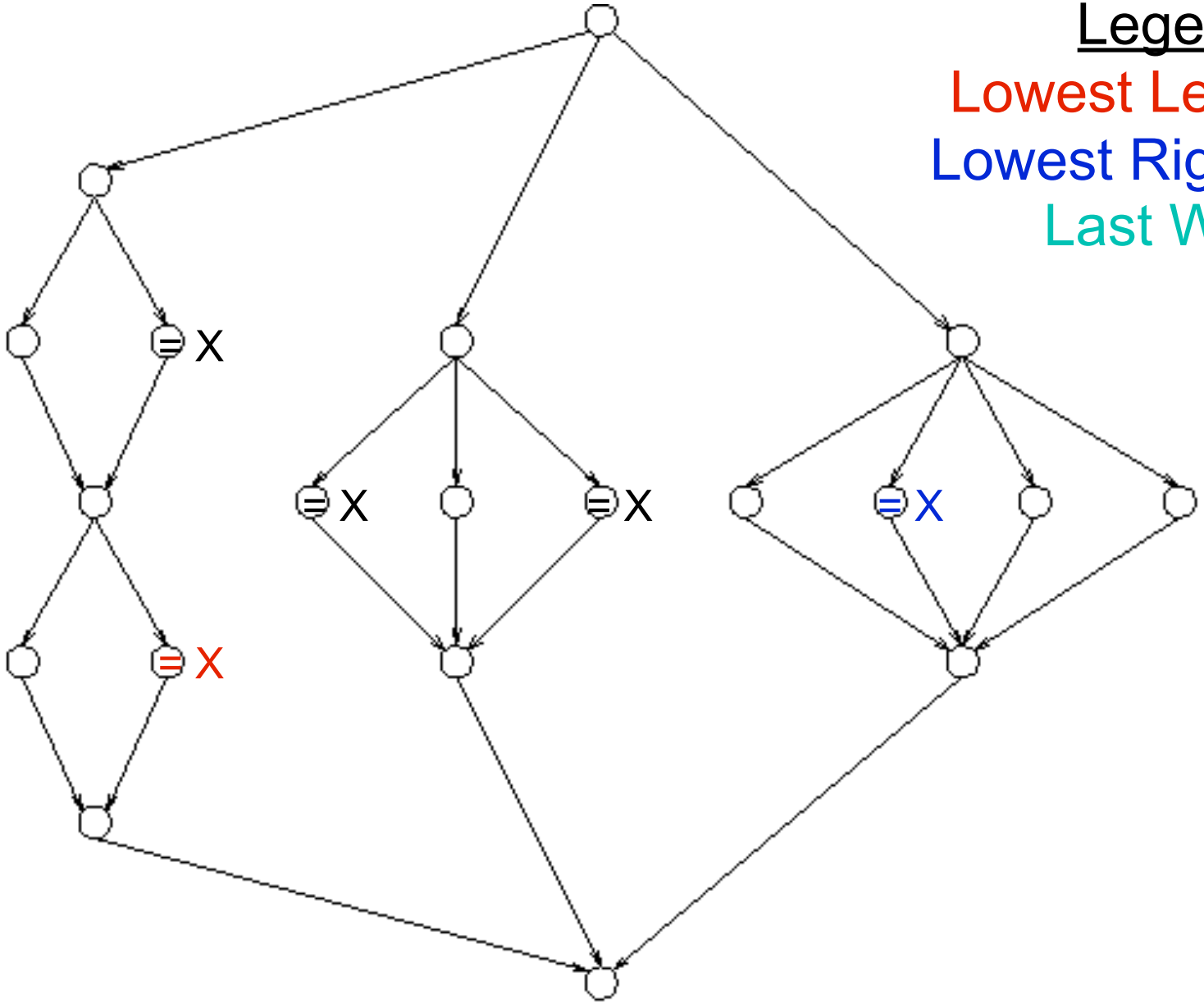


Data Race Detection Example

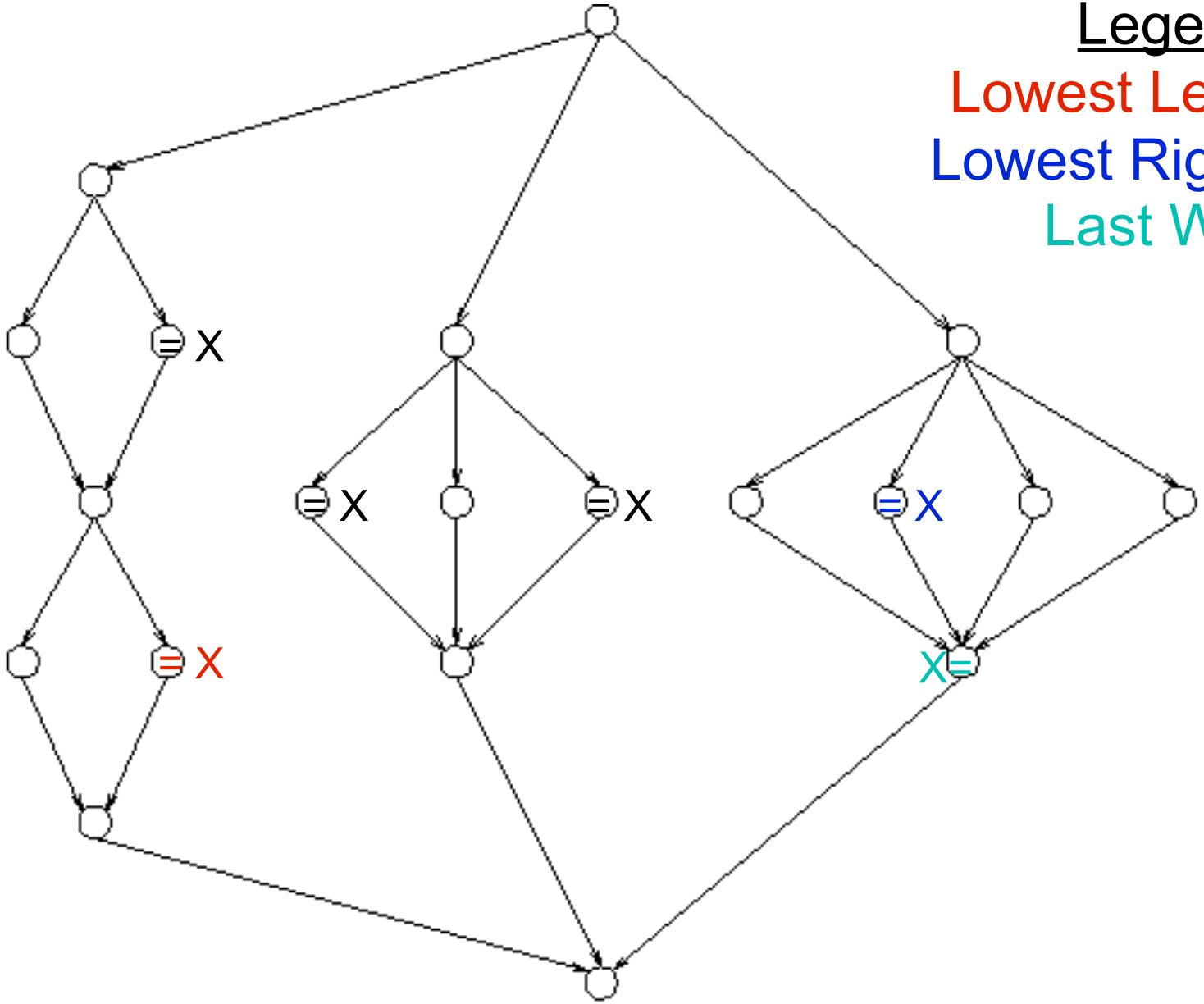


Legend
Lowest Left Read
Lowest Right Read
Last Write

Data Race Detection Example



Data Race Detection Example



Lemma WRITE-READ

- A data race will be reported if a read is logically-concurrent with some temporally earlier write
- Proof sketch
  - if the read is concurrent with the last write, `checkread` reports a WRITE-READ data race
  - if the read is concurrent with some earlier write, but not the last one, then there exists a pair of concurrent writes and Lemma WRITE-WRITE guarantees that a data race is reported

Thought Question

If we apply offset-span labeling in a single-threaded execution of a parallel loop, do we need all components of the access history?

- lowest leftmost reader
- lowest rightmost reader
- last writer

Offset-span Labeling Results Summary

Applicable to nested fork-join parallel programs

- **No centralized bottleneck**
  - **labeling of each node can be determined locally from a single ancestor**
- **Constant length access history**
- **Time per access: O(N), where N is max fork-join nesting depth**
- **Space: O(V + min(VN, BN)), where B is total # threads**

Efficient Detection of Determinacy Races

(SP-bags algorithm)

Feng and Leiserson

Review: Cilk Model

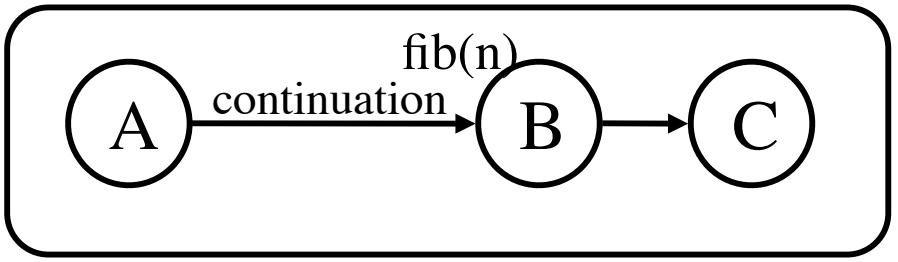
- **Parallel control = spawn, sync, return from spawned function**
- **Thread = maximal sequence of instructions not containing parallel control (task in earlier terminology)**

```
cilk int fib(n)  {
  if (n < 2) return n;
  else {
    int n1, n2;
    n1 = spawn fib(n-1);
    n2 = spawn fib(n-2);
    sync;
   return (n1 + n2);
  }
}
```

Thread A: if statement up to first spawn

Thread B: computation of n-2 before 2nd spawn

Thread C: n1+ n2 before the return



Principal Contributions

- **Shorter labels**
  - rather than having labels proportional in length to the maximum nesting depth, thread labels can have log V bits (a program constant)
- **Smaller space bound**
  - constant length labels
  - constant length access history per variable
  - O(V) space total
- **Lower time for checking concurrency**
  - check concurrency using Tarjan's union-find O(α(v,v)) time
    - α is Tarjan's functional inverse of Ackermann's function

Relative Contributions In a Nutshell

Compared to offset span labeling

- **Reduced O(VN) space to O(V)**
- **Reduced O(N) time per access to O(α(v,v))**
- **Drawback: their protocol is strongly sequential**
  - **— can only be used to check for races within a sequential execution**

SP-Bags Approach

- Fork-join parallelism as before
- Access history per variable
  - single-element reader
  - single-element writer

SP-Bags Protocol

Designed for the Cilk model

Each procedure F maintains two bags

- **S-bag: set of thread IDs of F's completed children that logically precede the current thread, as well as ID for F itself**
- **P-bag: set of thread IDs of descendants of F's completed children that operate logically "in parallel" with the currently executing thread**

SP-Bag Representation

Disjoint set union data structure

- Σ, a dynamic collection of disjoint sets
- Operations
  - Make_set(x): $\Sigma \leftarrow \Sigma \cup \{\{x\}\}$
  - Union(X, Y): $\Sigma \leftarrow \Sigma - \{ X, Y \} + \{ X \cup Y \}$
  - Find(x): returns the set $X \in \Sigma$, such that $x \in X$

Tarjan shows that any m of these operations on n sets take a total of $O(m\alpha(m,n))$ time.

SP-Bags Concurrency Bookkeeping

`spawn` procedure F:

$S_F \leftarrow$ MAKE-SET(F)

$P_F \leftarrow \emptyset$

`sync` in a procedure F:

$S_F \leftarrow$ UNION(S_F, P_F)

$P_F \leftarrow \emptyset$

`return` from procedure F' to F:

$P_F \leftarrow$ UNION($P_F, S_{F'}$)

SP-Bags Representation In Action

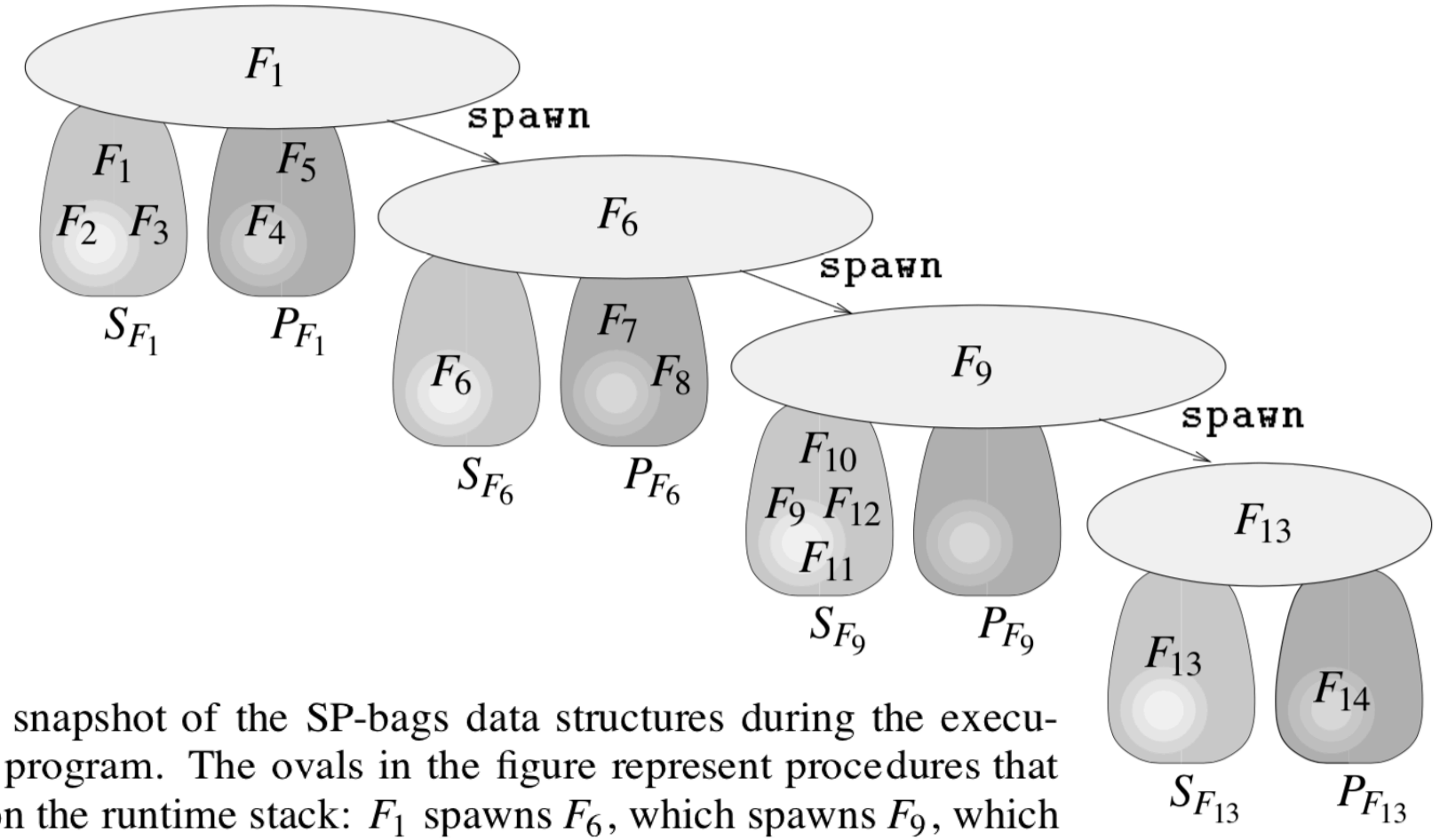


Figure 7: A snapshot of the SP-bags data structures during the execution of a Cilk program. The ovals in the figure represent procedures that are currently on the runtime stack: F_1 spawns F_6, which spawns F_9, which spawns F_{13}. Each procedure contains an S-bag and a P-bag. Each descendant of a completed child of a procedure F belongs either to F's S-bag or to F's P-bag. For example, F_2, F_3, F_4, and F_5 are descendants of F_1 that complete before F_1 spawns F_6, and so these procedures belong to either F_1's S-bag or its P-bag. In addition, every procedure F belongs to its own S-bag.

SP-Bags Access Protocol

`write` a shared location l by procedure F:

if FIND-SET($reader(l)$) is a P-bag
or FIND-SET($writer(l)$) is a P-bag
then a determinacy race exists
$writer(l) \leftarrow F$

`read` a shared location l by procedure F:

if FIND-SET($writer(l)$) is a P-bag
then a determinacy race exists
if FIND-SET($reader(l)$) is an S-bag
then $reader(l) \leftarrow F$

How about the Slick Bounds?

- Let n be the number of spawned procedures
- Total number of make_set, union, find operations is at most T, serial running time
- O(T α(v,v)) running time, where T is the serial running time
- O(V + n) space
  - shadow space takes O(V)
  - disjoint set data structure takes O(n)
- Use garbage collection to reduce time and space bounds
  - run algorithm for V time steps
  - garbage collect
    - max of V thread ids can be in use
    - remove unused IDs from disjoint-set data structure

      O(v α(v,v)) time
    - algorithm needs only O(V) space with garbage collection

Eraser

Stefan Savage, Michael Burrows, Greg Nelson, Patrick Sobalvarro, and Tom Anderson

Preventing Races with Monitors

- Approach
  - —single anonymous lock
  - —shared data accessed only through methods
  - —methods must obtain lock
- Benefits
  - —serialized access to monitor data
  - —static, compile-time guarantee that no races exist
- Drawbacks
  - —all shared variables must be static globals
    - – no dynamic allocation
  - —no fine-grain parallelism
    - – e.g. over array elements

Happens-before Relation

- Partial order on all events of all threads
- Benefits
  - —less restrictive than monitors
  - —tools test for happens-before between threads
    - observe every data reference and sync operation
    - if not ordered by happens before, data race could occur
  - —supports fine-grain parallelism
- Drawbacks
  - —efficient implementation is difficult
  - —“effectiveness depends on interleaving”

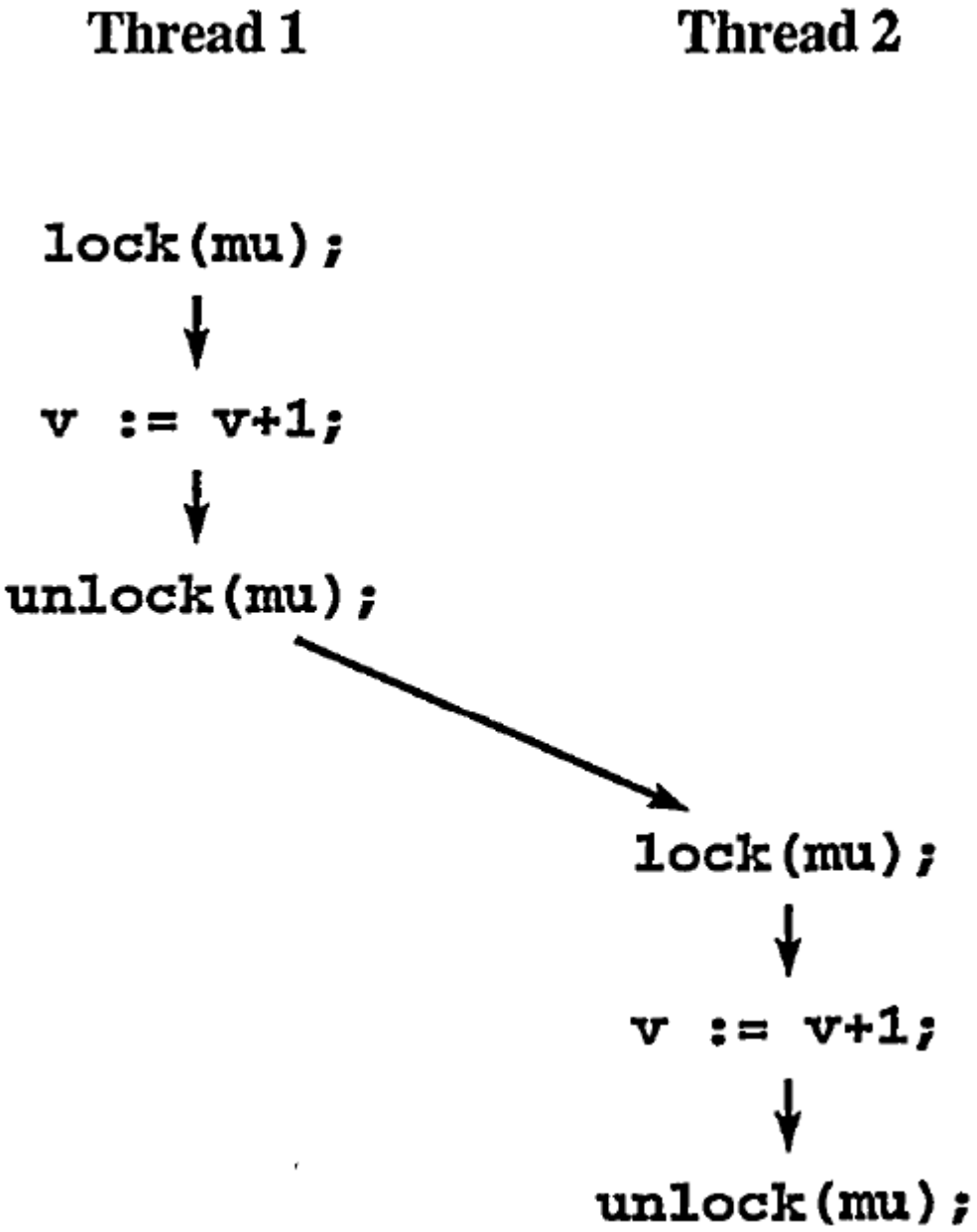
Eraser Paper Claims

- Race detection based on “happens before”
  - “requires per thread info about accesses per shared variable”
    - not quite right

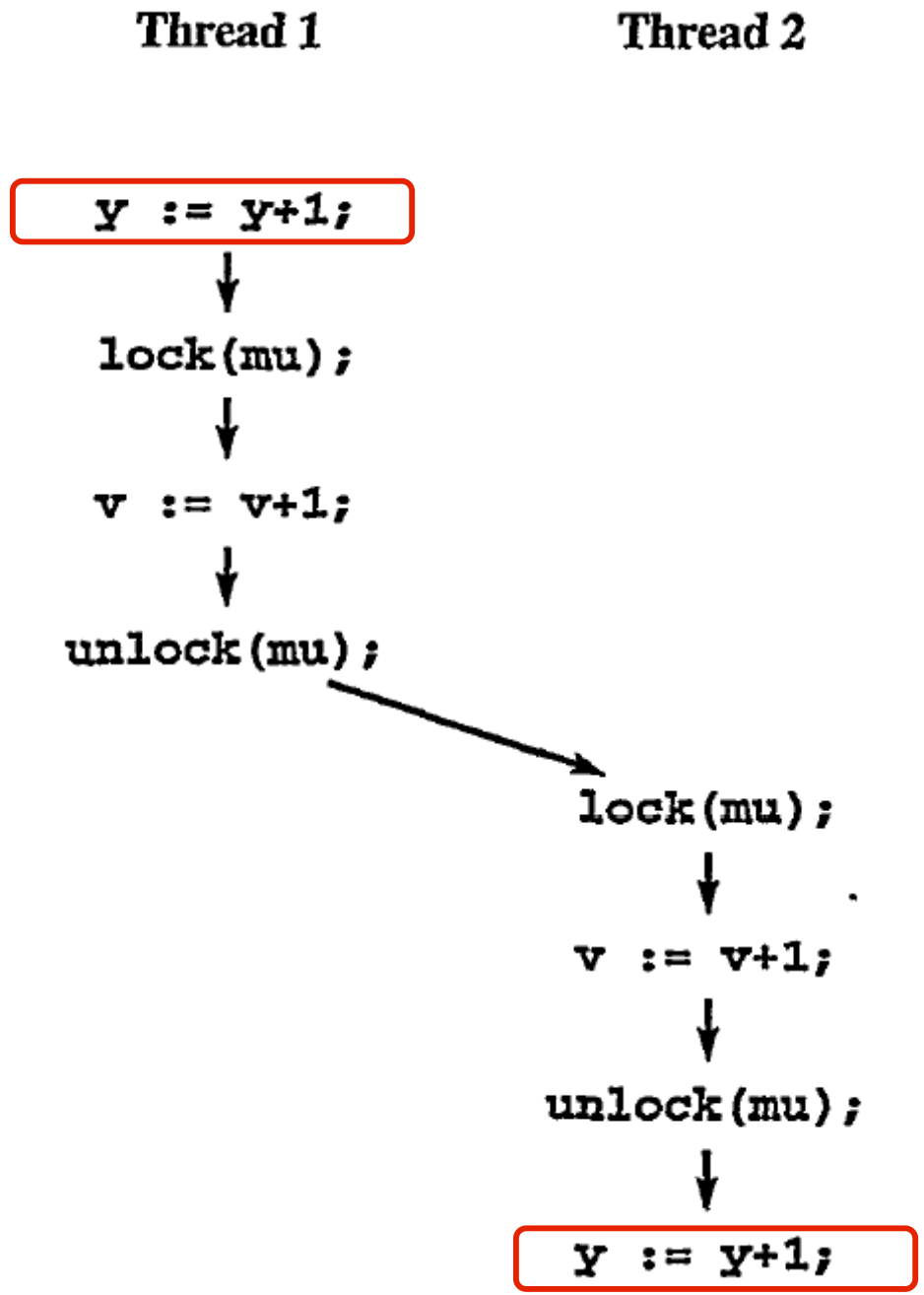
      requires per variable information about accesses by threads

      requires information about thread ordering
  - “highly depends on interleaving”
    - not quite right either

Happened-before Relation and Locks



Eraser Motivating Example



Lockset Algorithm

- Every shared variable access must be protected by a lock
  - differs from race detection for scientific computation
- Eraser checks whether program respects this discipline
  - monitor the reads and writes to variables
  - monitor the locks held
  - infer relation between locks and variables from execution history
    - maintain set of candidate locks C(v) for each shared variable v

Let $locks\_held(t)$ be the set of locks held by thread t.

For each v, initialize $C(v)$ to the set of all locks.

On each access to v by thread t,
set $C(v) := C(v) \cap locks\_held(t)$;
if $C(v) = \{\}$, then issue a warning.

Locksets in Action

Discovering a potential race with the lockset algorithm

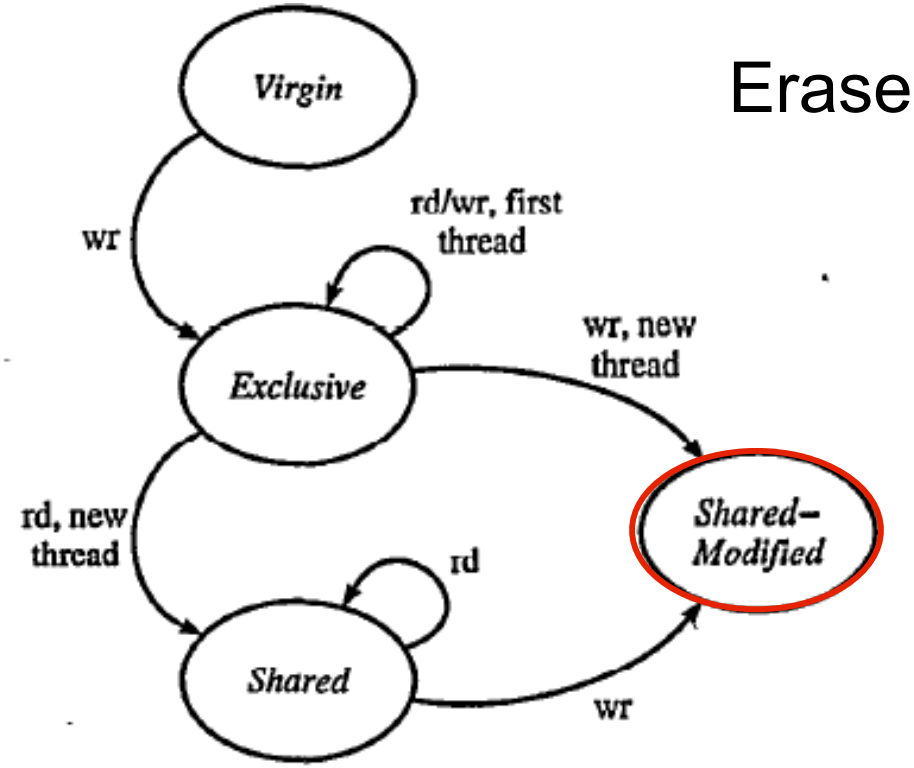
Program	*locks_held*	*C(v)*
	{}	{mu1,mu2}
lock(mu1);		
	{mu1}	
v := v+1;		
		{mu1}
unlock(mu1);		
	{}	
lock(mu2);		
	{mu2}	
v := v+1;		
		{}
unlock(mu2);		
	{}	

Issues with Simple Lockset Algorithm

- Initialization
  - shared variables frequently initialized without holding a lock
- Read-shared data
  - data written only during initialization and read-shared thereafter can be read without locks
- Read-write locks
  - multiple readers
  - single writer

Handling Read Sharing

- **Delay refinement of candidate set until after initialization**
- **Reads and writes by first thread before end of initialization**
  - **no effect on candidate set**
- **When does initialization end? Upon access by second thread**



Eraser's Memory States

report races here

Handling Read-write Locks

Adjust locking discipline

- Some lock m must be held in *write* mode for writes of v
- Lock m is held in *some* mode (read or write) for reads of v

For each v, initialize $C(v)$ to the set of all locks.

On each read of v by thread t,
set $C(v) := C(v) \cap locks\_held(t)$;
if $C(v) = \{\}$, then issue a warning.

On each write of v by thread t,
set $C(v) := C(v) \cap write\_locks\_held(t)$;
if $C(v) = \{\}$, then issue a warning.

Eraser Implementation

- Use binary rewriter (ATOM) to augment program
  - instrument calls to acquire or release a lock
    - enables maintain lock_held(t) for each thread t
  - instrument each call to storage allocator
    - enables initialization of C(v) for dynamically allocated data
  - instrument loads and stores to global locations and heap
    - don't instrument stack accesses (indexed off SP)
    - maintain information per 32-bit word (smallest memory coherence unit)
- Eraser reports
  - file and line number at which race discovered
  - backtrace listing of all active stack frames
  - (thread id, memory address, access type, PC, SP)
- Can log all accesses to a variable if origin of race is unclear

Representing Candidate Lock Sets

- Not a list of locks per memory location!
- Observation:
  - never more than 10K distinct sets of locks observed in a program
- Approach
  - lock set = { sorted list of lock addresses }
  - table of lock sets
    - entries in table are immutable
    - index table with hashing
  - shadow word per variable
    - 30 bit lock set id; 2-bit variable state (eraser state machine state)
    - find shadow word for V by adding fixed displacement to &V

Performance

- **Execution slows by a factor of 10-30**
  - **could improve by inlining checking rather than procedure call**
    - **e.g. Pin could do this**
  - **static analysis could eliminate need to check everything**

False Alarms with Eraser

- Sources of false alarms
  - memory reuse without resetting shadow memory
    - occurs with program-managed free lists, private allocators
      - no way for eraser to know item is protected by new locks
  - private locks
    - implementations of reader-writer locks outside pthreads
      - unknown to Eraser
    - interrupt masking (assign pseudo-lock per interrupt level)
  - benign races
    - don't affect correctness of program
      - some intentional
      - some accidental
  - post-wait synchronization
- Suppress false alarms with manual annotation
  - EraserIgnoreOn()
  - EraserIgnoreOff()

Eraser in Practice

- Found races
  - 3 of 4 server programs
  - undergraduate programs
- False alarms
  - able to suppress using annotations

Eraser Weakness

- Doesn't understand happens-before
  - leads to special case for variable initialization
    - turn on race detection when second thread starts accessing data