Run-Time Detection of Potential Deadlocks for Programs with Locks, Semaphores, and Condition Variables

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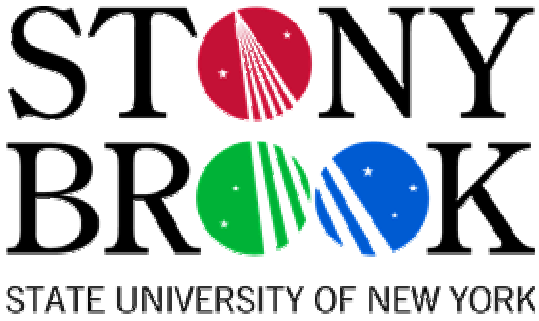
Joint work with Prof. Scott D. Stoller



Deadlock

- Concurrent programs are notorious for containing errors that are difficult to reproduce and diagnose.
- A common kind of concurrency error is a deadlock.
- Informally, a deadlock occurs when some threads are permanently blocked.

Synchronization Mechanisms

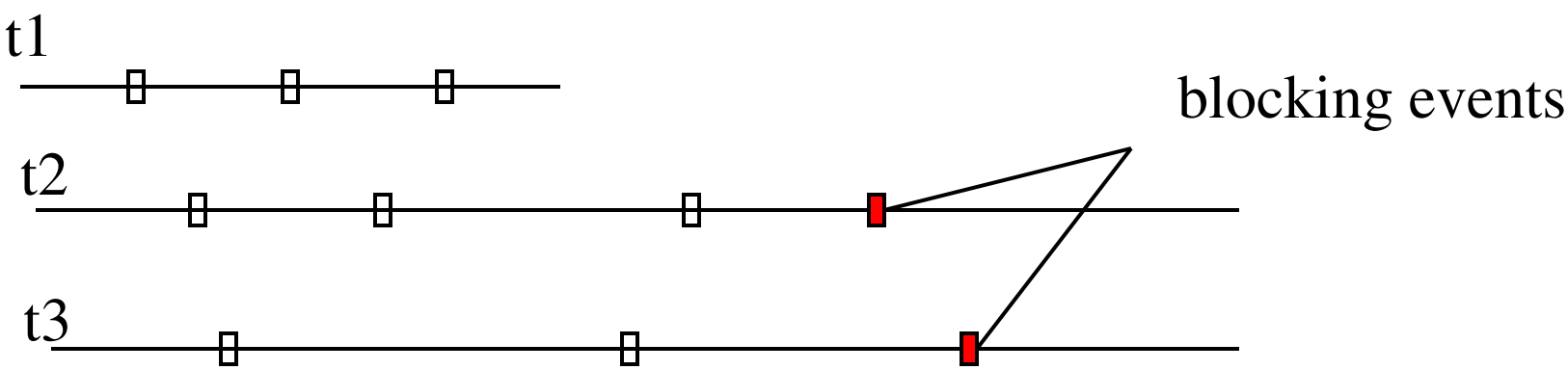
- Locks (block structured and non block structured)
  - Operations: acquire(), release()
- Semaphores
  - Operations: up(), down()
- Condition variables
  - A lock is associated with each condition variable.
  - Operations: wait(), notify(), notifyAll()
- Thread synchronization
  - Operations: start(), join()
- Available in Java 5 concurrency library and POSIX pthread library for C.

Blocking Event

- An event is one step in the execution of a program.
  - Consider synchronization events and access to shared variables.
- A trace is a sequence of events in an execution.
- An event *e* in a trace *tr* is called a blocking event if one of the following holds:
  - *e* is an acquire of a lock *l* by thread *t*, and *l* is currently held by another thread.
  - *e* is a wait on a condition variable.
  - *e* is down on a semaphore whose value is 0.

Deadlock

- A trace *tr* deadlocks if a set T of threads in *tr* exists, such that the last event for each thread in T is a blocking event, and all threads in *tr* not in T have terminated.



Feasible Permutation of a Trace

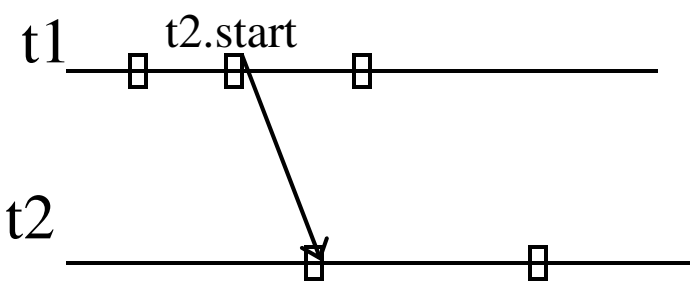
- A feasible permutation of a trace *t* is a permutation of *t* that preserves the original order of events from each thread and is consistent with constraints imposed by synchronization events.
  - Constraint imposed by locks is that no lock is held by multiple threads at same time.
  - Constraints due to other synchronization mechanisms are expressed as happens-before orderings.

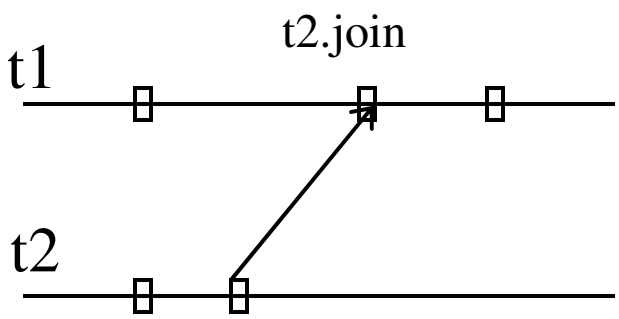
Happens-before

- Happens-before is a partial order on the events in an execution.
- If event e_1 happens before event e_2, then e_1 must precede e_2 in all feasible permutations of the trace.

Happens-before Ordering Due to Thread Synchronization

- When a thread t_1 calls t_2.`start()` to start another thread t_2, then the thread start event in t_1 happens before the first event of t_2.
- When thread t_1 calls t_2.`join()` to wait for another thread t_2 to terminate, last event of t_2 happens before join event in t_1.





Potential for Deadlock

- A trace has potential for deadlock if some feasible permutation of the trace deadlocks.
  - This definition considers all synchronization mechanisms together.

Potential for Deadlock Due to Locks

- A trace has potential for deadlock due to locks if some feasible permutation of trace restricted to operations on locks and operations on threads deadlocks.
- A simpler condition below can be checked efficiently.
  - Ignores gate locks and thread operations.
- A program has potential for deadlock due to locks ignoring gate locks (PDL-IGL) if there exist distinct threads $t_0,..,t_{m-1}$ and locks $l_0,..,l_{m-1}$ in a given trace s.t. for all $i= 0,..,m-1$, t_i holds lock l_i while acquiring lock $l_{i+1 \bmod m}$.

Lock Trees

- Root labeled by name of the thread.
- One child for each lock acquired by thread t.
- Each of those nodes is labeled with name *l* of one of those locks and has child labeled with a lock *l'* iff *t* acquired *l'* while holding *l*. Note: Height at most 2.

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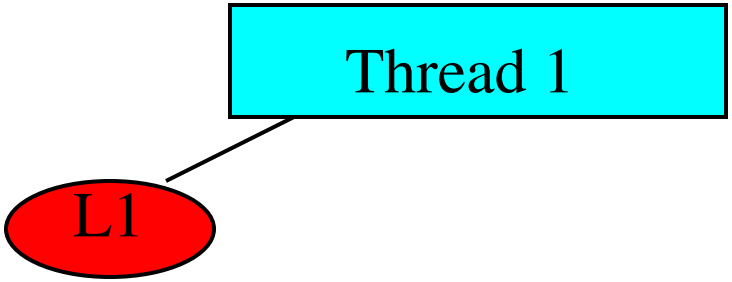
acquire(L1)



Lock Trees

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- One child for each lock acquired by thread t.
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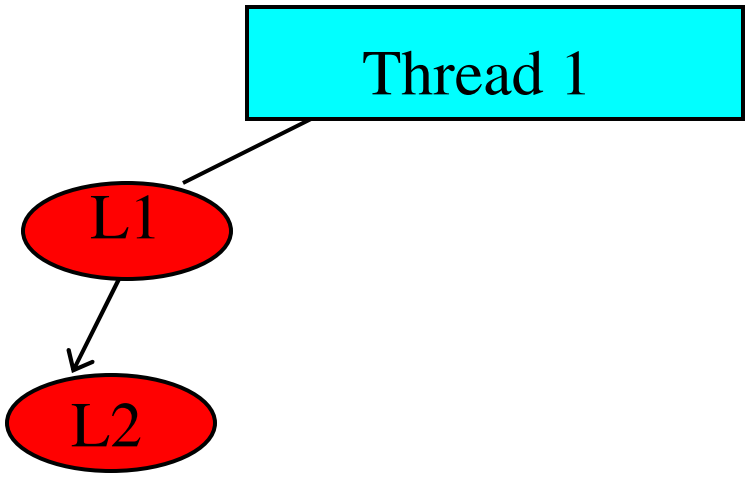
acquire(L1)

acquire(L2)



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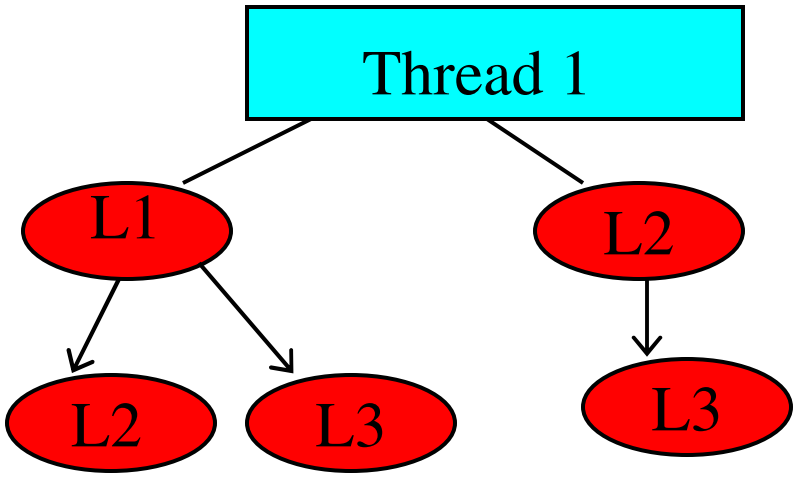

acquire(L1)

acquire(L2)

acquire(L3)

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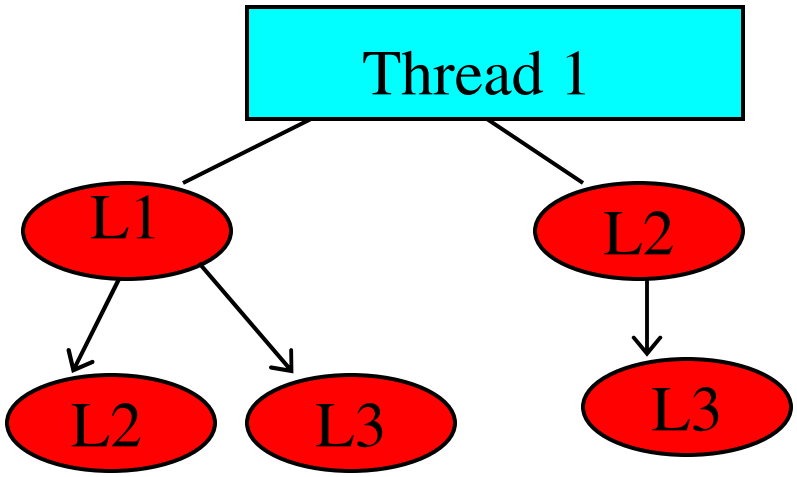

acquire(L1)

acquire(L2)

acquire(L3)

release(L2)

Lock Trees

- Root labeled by name of the thread.
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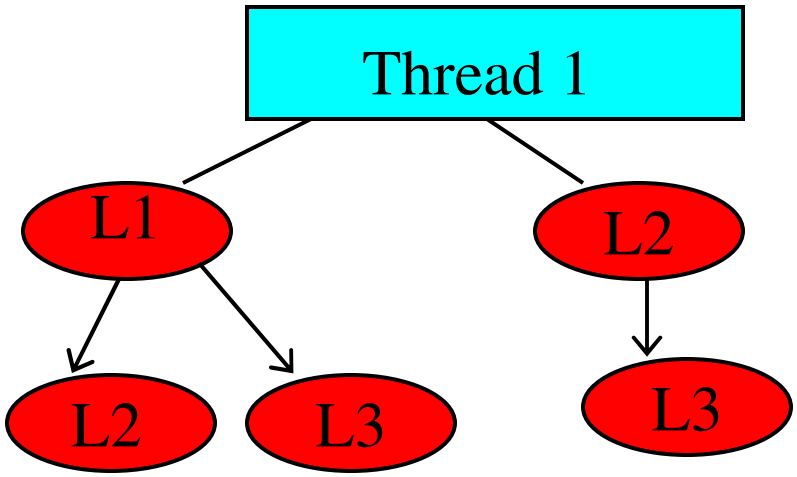


acquire(L1)

acquire(L2)

acquire(L3)

release(L2)

release(L3)

release(L1)

Detecting Potential for Deadlock Due to Locks Ignoring Gate Locks (PDL-IGL)

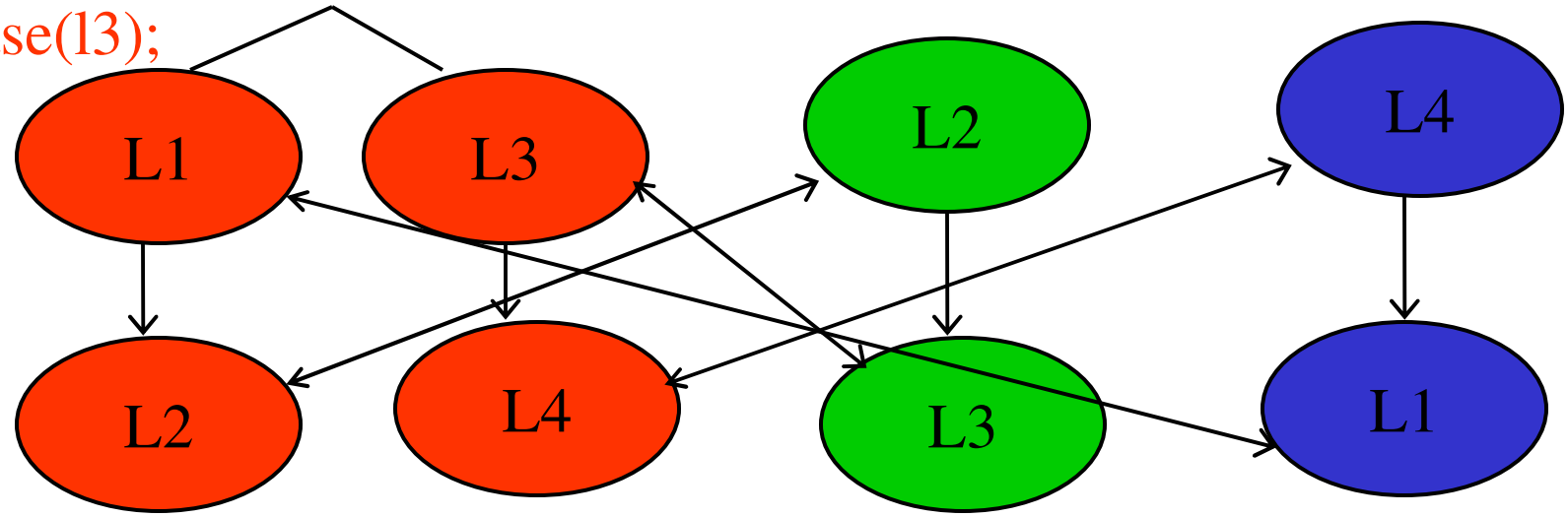
- Construct a run-time lock graph which contains
  - ***tree edges:*** the directed (from parent to child) edges in each of the run-time lock trees, and
  - ***inter edges:*** bidirectional edges between nodes that are labeled with the same lock and that are in different run-time lock trees.
- PDL-IGL holds iff the graph contains a *valid cycle*.
- Valid cycle is a cycle that
  - does not contain consecutive inter edges, and
  - nodes from each thread appear as at most one consecutive subsequence in the cycle.
- Related Work: GoodLock Algorithm [Havelund, 2000]

Example

acquire(l1);
acquire(l2);
release(l1);
release(l2);
acquire(l3);
acquire(l4);
release(l4);
release(l3);

acquire(l2);
acquire(l3);
release(l3);
release(l2);

acquire(l4);
acquire(l1);
release(l4);
release(l1);

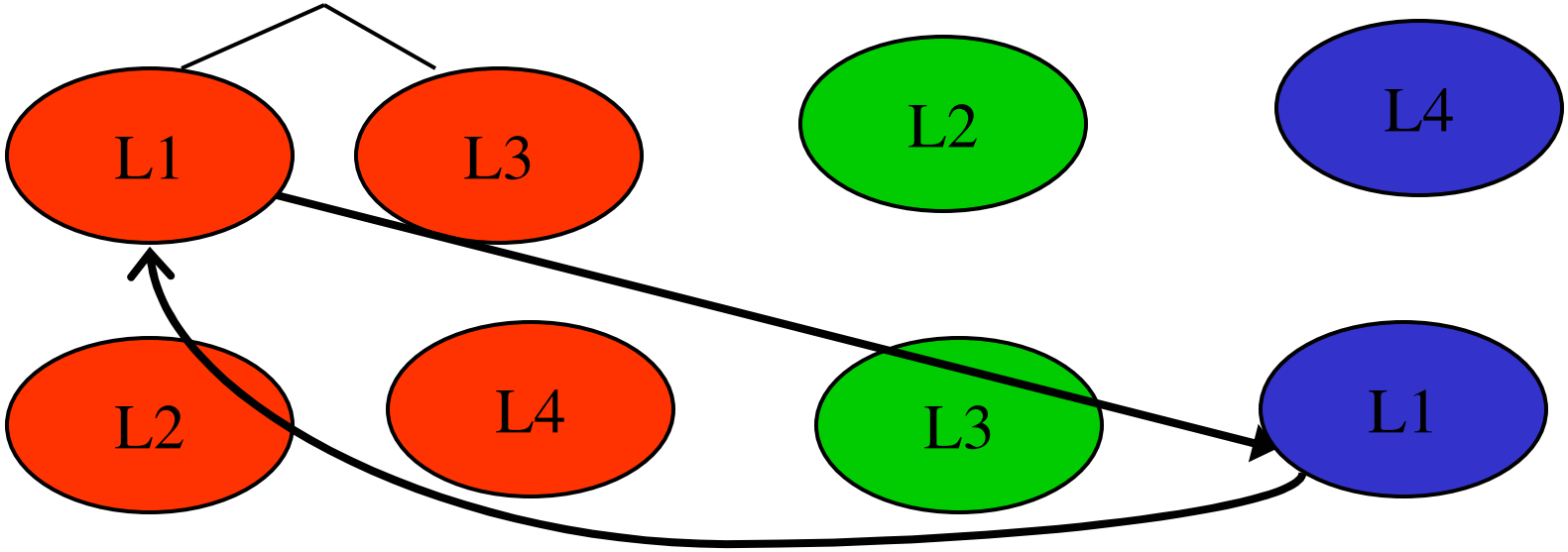


no valid cycles: no deadlocks

Example

Valid cycle is a cycle that

- does not contain consecutive inter edges, and
- nodes from each thread appear as at most one consecutive subsequence in the cycle.



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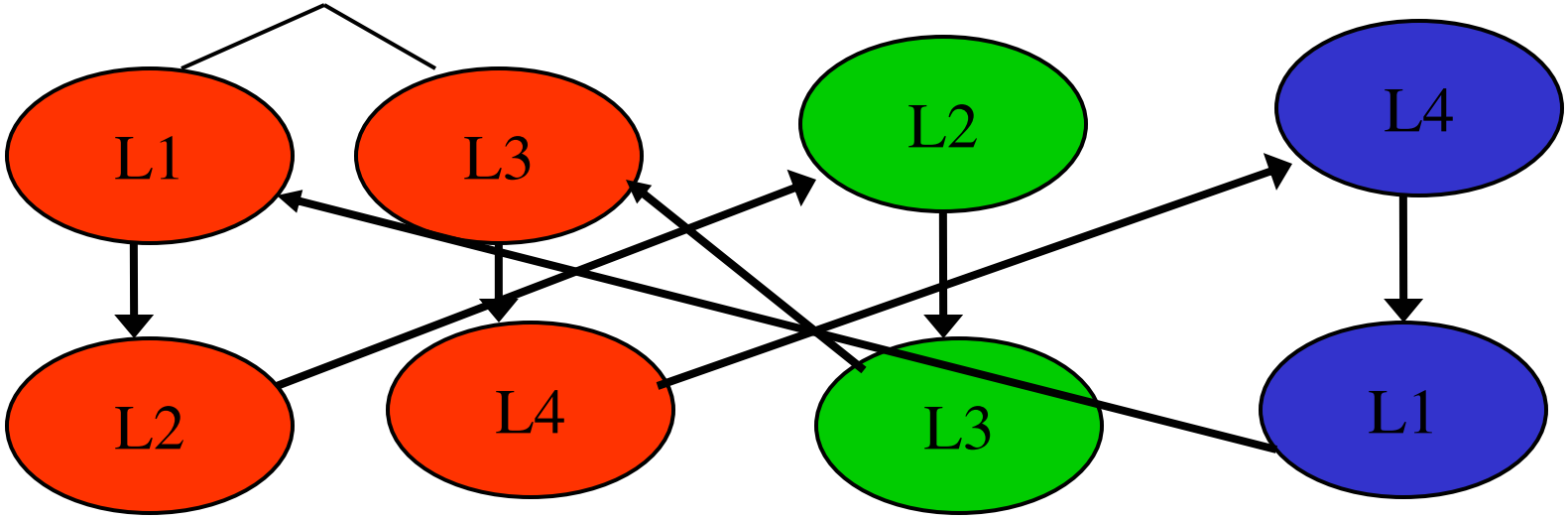


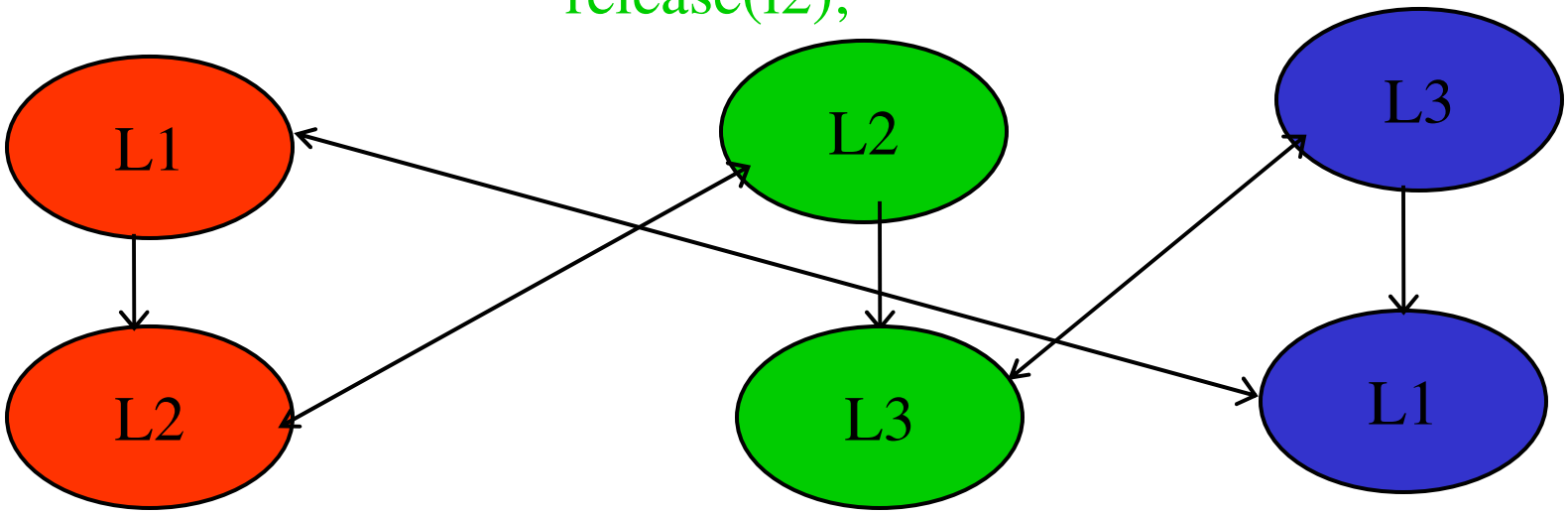
no valid cycles: no deadlocks

Example

acquire(l1);
acquire(l2);
release(l1);
release(l2);

acquire(l2);
acquire(l3);
release(l3);
release(l2);

acquire(l3);
acquire(l1);
release(l3);
release(l1);



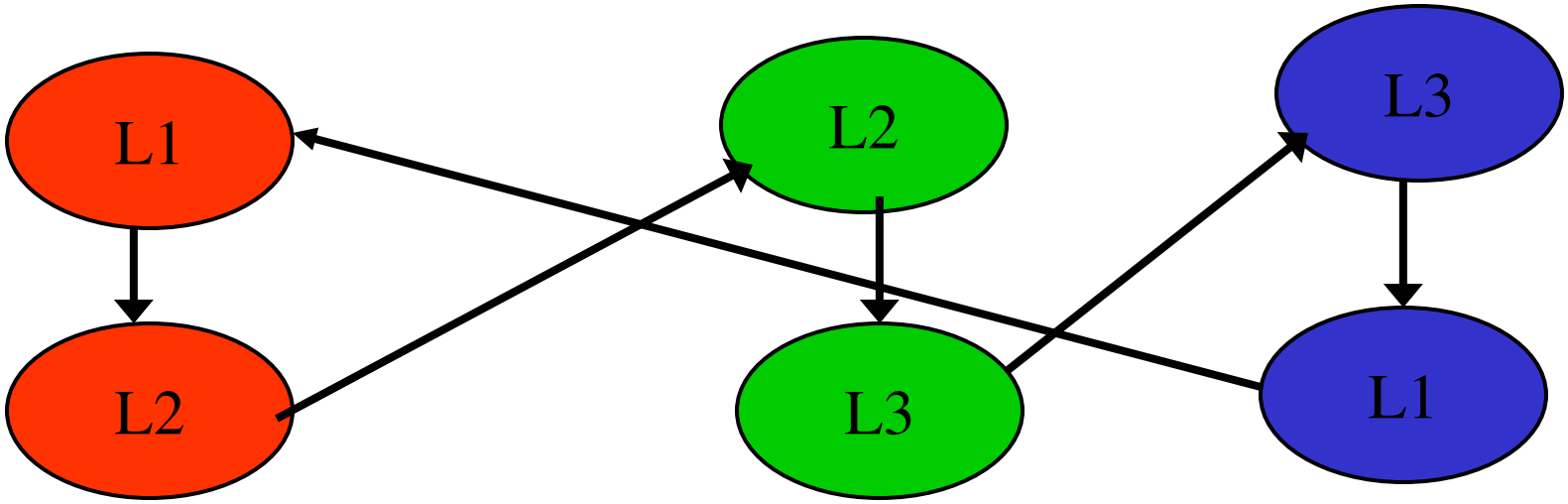
Warning: Potential Deadlock

Example

acquire(l1);
acquire(l2);
release(l1);
release(l2);

acquire(l2);
acquire(l3);
release(l3);
release(l2);

acquire(l3);
acquire(l1);
release(l3);
release(l1);



Valid cycle: Potential Deadlock

Detecting Valid Cycles

- Use a modified depth-first search algorithm.
- Presented optimizations to the algorithm [Agarwal+, 2005].
- Better complexity than checking for all feasible permutations of the trace.

Detecting Potential for Deadlock Due to Locks

- A cycle in the lock graph may be protected by a ***gate lock***, a common lock acquired by at least two threads involved in the cycle.
- For every valid cycle generated, we check whether there is a gate lock preventing the deadlock.
- Details in the paper.

Potential for Deadlock Due to Semaphores

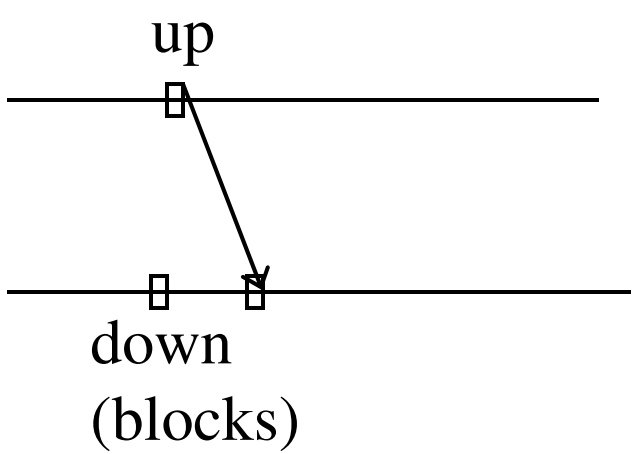
- An execution trace has potential for deadlock due to semaphores if some feasible permutation of trace restricted to operations on semaphores and operations on threads deadlocks.

Dual Nature of Semaphores

- Semaphores can be used to provide mutual exclusion or condition synchronization.
- We classify a semaphore *sem* as used for mutual exclusion if (∃ thread t. t:sem.down() t:sem.up())* (∃ thread t. t:sem.down())?
- Semaphores used for mutual exclusion are analyzed exactly like locks with `down` treated as `acquire` and `up` treated as `release`.

Happens-before Ordering Due to Semaphores

- Semaphores not used for mutual exclusion are analyzed based on their happens-before ordering.
- An up event e_u that unblocks a thread blocked on a down event e_d happens before $succ(e_d)$ where $succ(e)$ is the event immediately following e on the same thread.



Cigarette Smokers Problem

Initially tob=0, pap=0, match=0, order = 1

Smoker 1: while(1) {tob.down(); pap.down(); order.up();}

Smoker 2: while(1) {pap.down(); match.down(); order.up();}

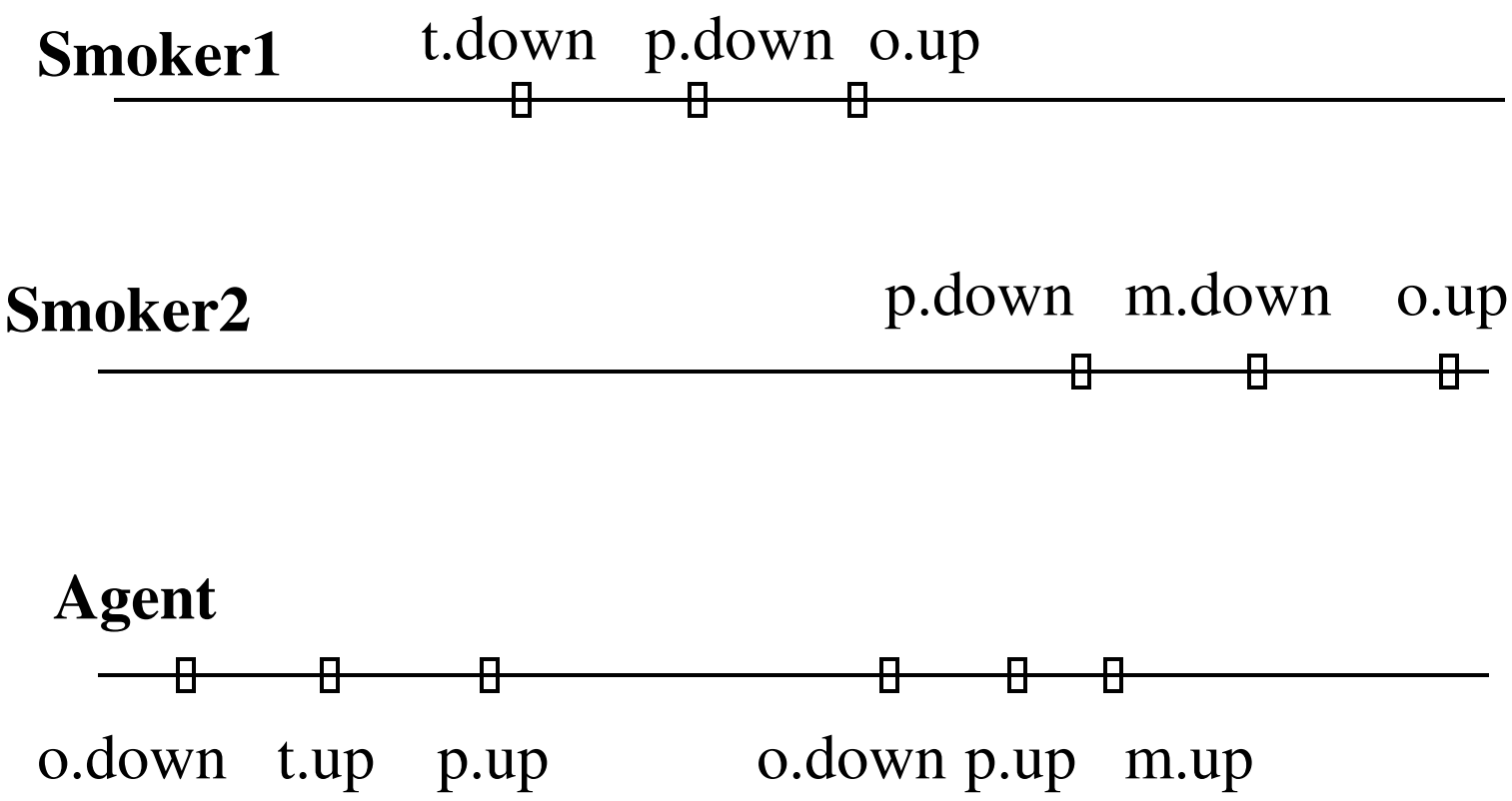
Smoker 3: while(1) {match.down(); tob.down(); order.up();}

Agent: while(1) {order.down();

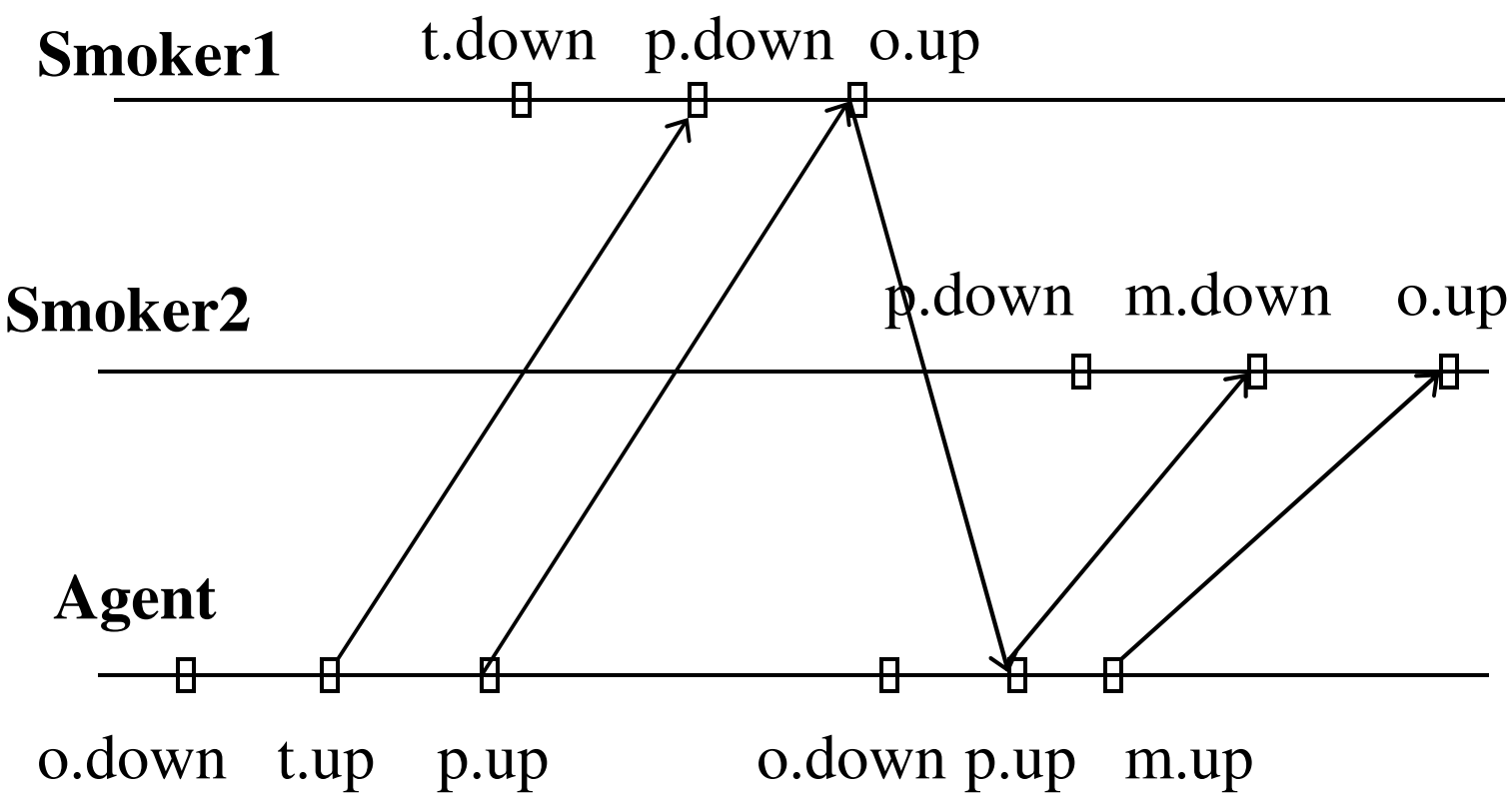
up on one of tob, paper, or match at random;

up on one of three at random but not one above;}

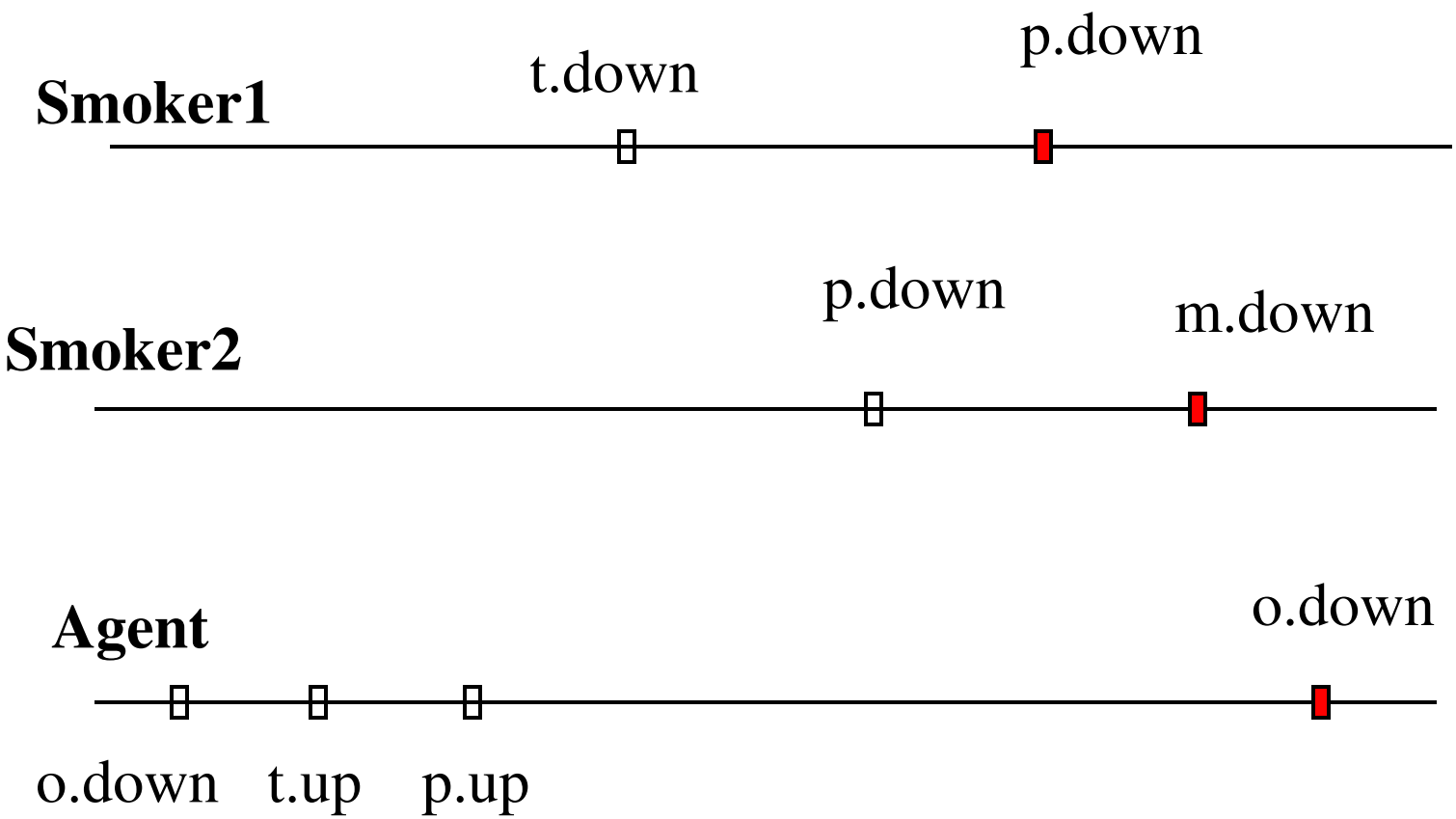
Deadlock Free Trace



Happens-before Ordering for the Trace



Feasible Permutation that Deadlocks



The original trace has potential for deadlock.

Lost Notifies

- A notify is lost if it occurs before the thread it should wake actually calls wait.
- As a result, the notify has no effect, and when that thread does call wait, it may wait forever.

Potential for Lost Notify

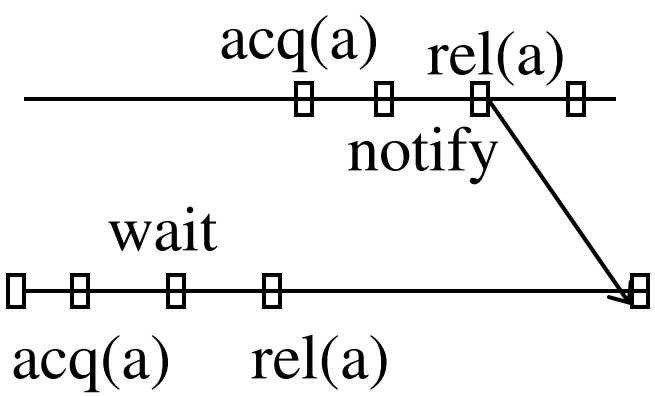
- An execution trace has potential for lost notify if it contains a notify or notifyall event *e* such that there is a feasible permutation of *tr* in which *e* wakes up fewer threads than it does in *tr*.
  - This is possible when the wait event of one of the threads woken in *tr* is not constrained to happen before *e*.

Example

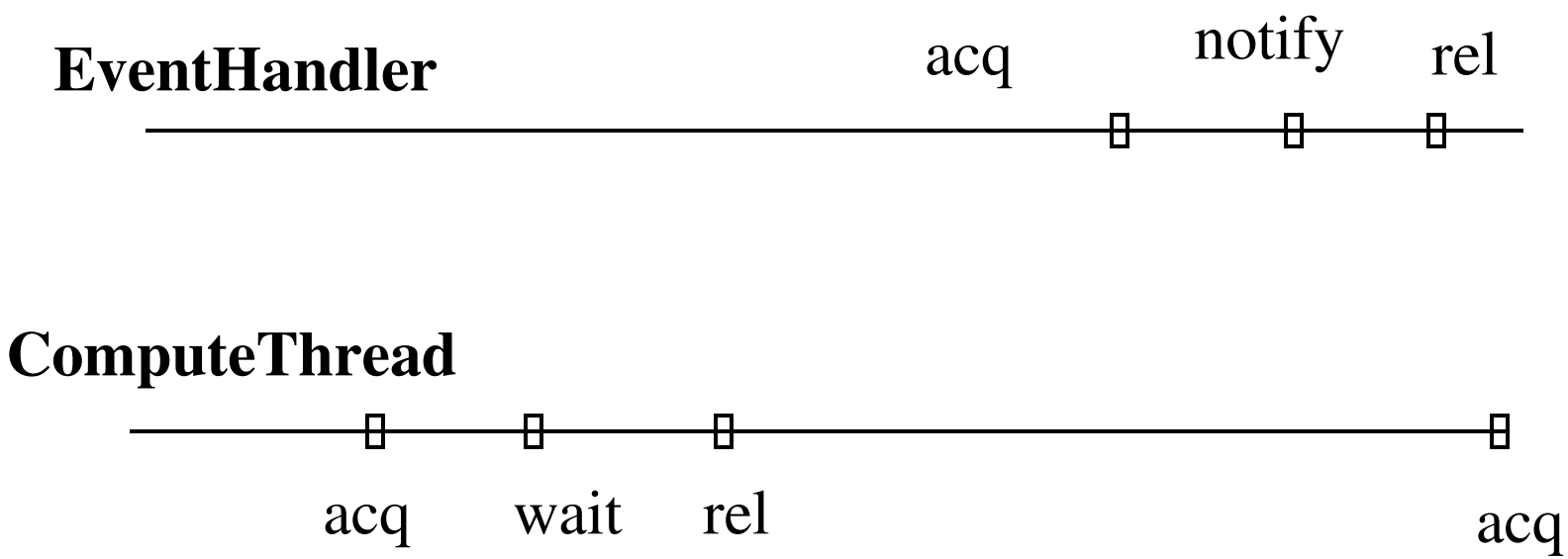
```
class EventHandler extends …. {
  public void handleEvent(Event e) {
    switch(e.type) {
     update: data.update();
                sync(computeThread){computeThread.notify();}
                break; }}}

class ComputeThread extends Thread {
  public void run () {
    while (true) {
     sync(this) {this.wait(); compute();}}}}
```

Happens-before Ordering Due to Condition Variables

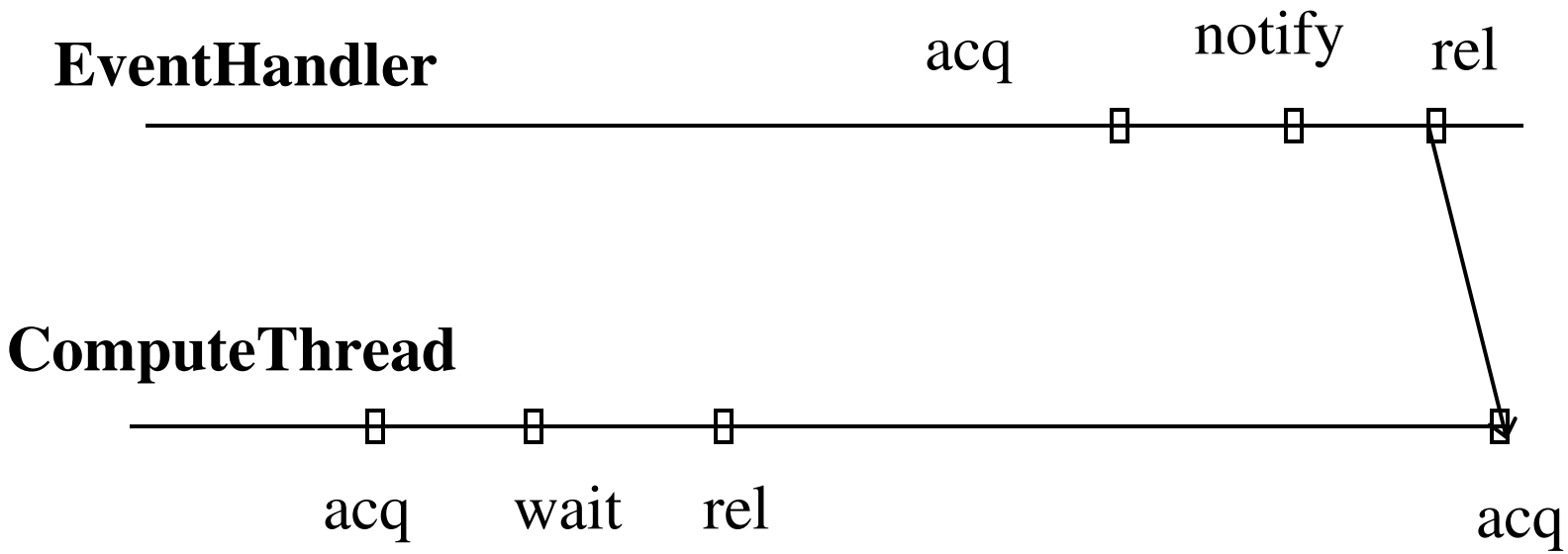
- For each notify or notifyAll event e_n and each wait event e_w that is notified by e_n, e_n happens-before $succ(e_w)$, where $succ(e)$ is the event immediately after e on the same thread.
  - Since, the same lock l must be held when e_w and e_n occur and only one thread can hold a given lock at a time, this is equivalent to saying that the release of l after e_n happens-before $succ(e_w)$.



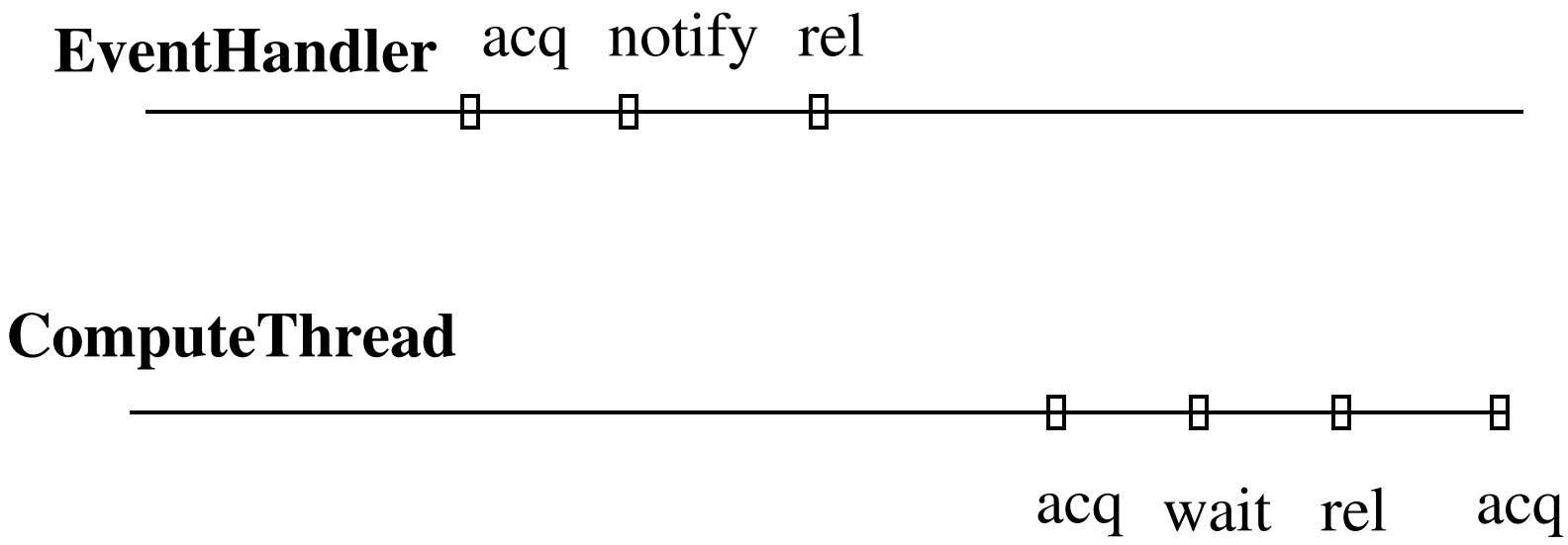
Trace without Lost Notify



Happens-before Ordering for the Trace

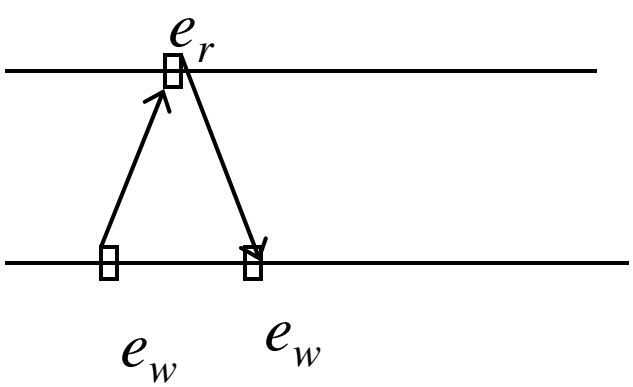


Feasible Permutation with Lost Notify



Happens-before Ordering Due to Condition Variables

- Orderings due to control dependencies on access to shared variables which is useful for condition sync.
  - A read event e_r on some shared variable that occurs in boolean condition of if or while statement happens after the previous write event e_w (e_w happens before e_r) and happens-before the next write event to that variable.

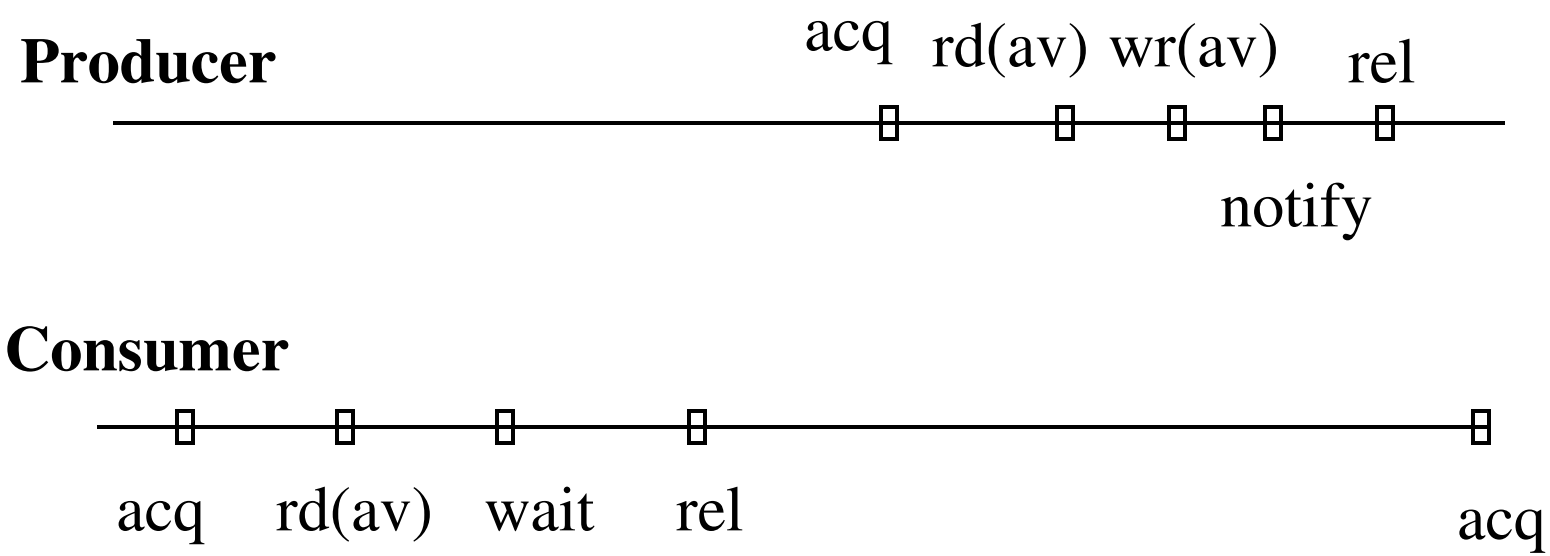


Producer Consumer

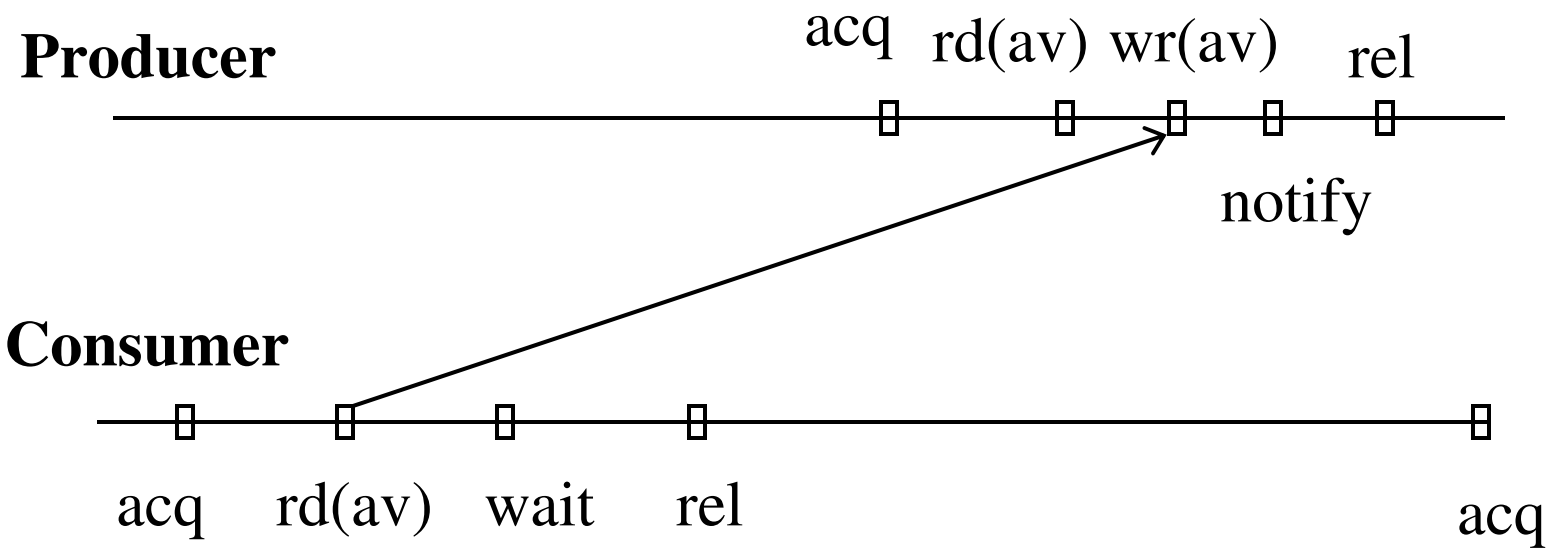
```
public synchronized int get()
  while (available == false) {
    wait();
  }
  available = false;
  notifyAll();
  return contents; }
```

```
public synchronized void put(int value) {
  while (available == true) {
    wait();
  }
  contents = value;
  available = true;
  notifyAll();}
```

Trace for Producer Consumer



Happens-Before Ordering for the Trace



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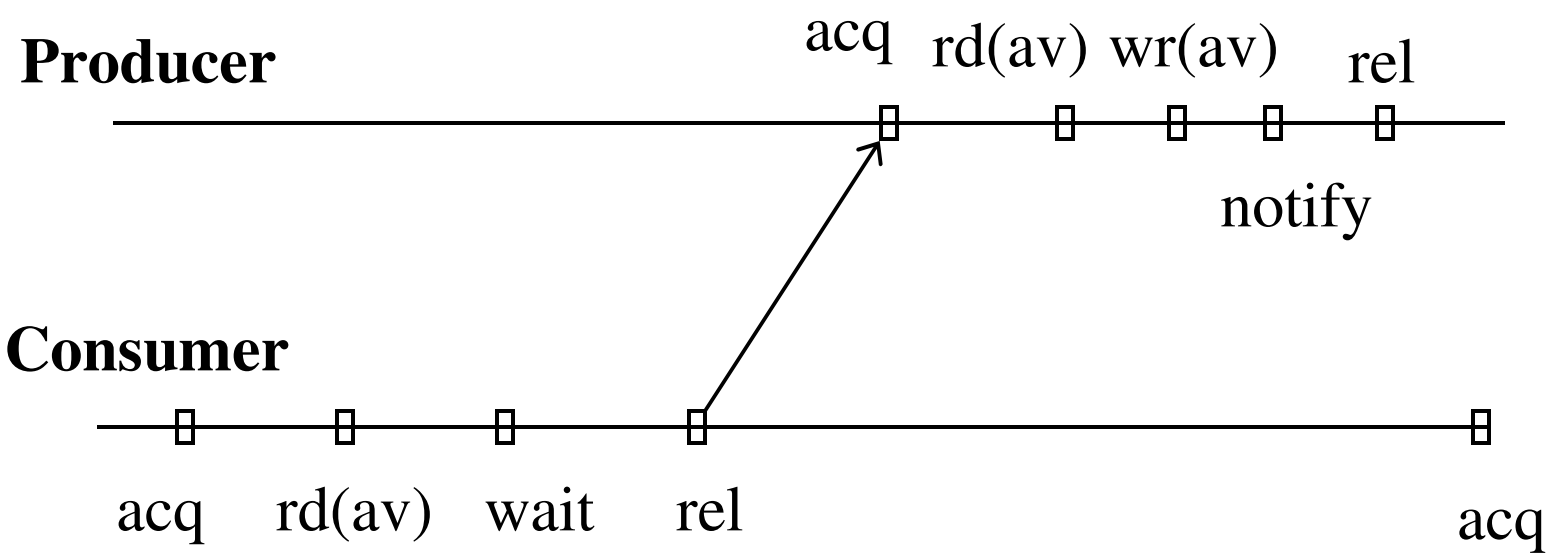


No lost notifies !!

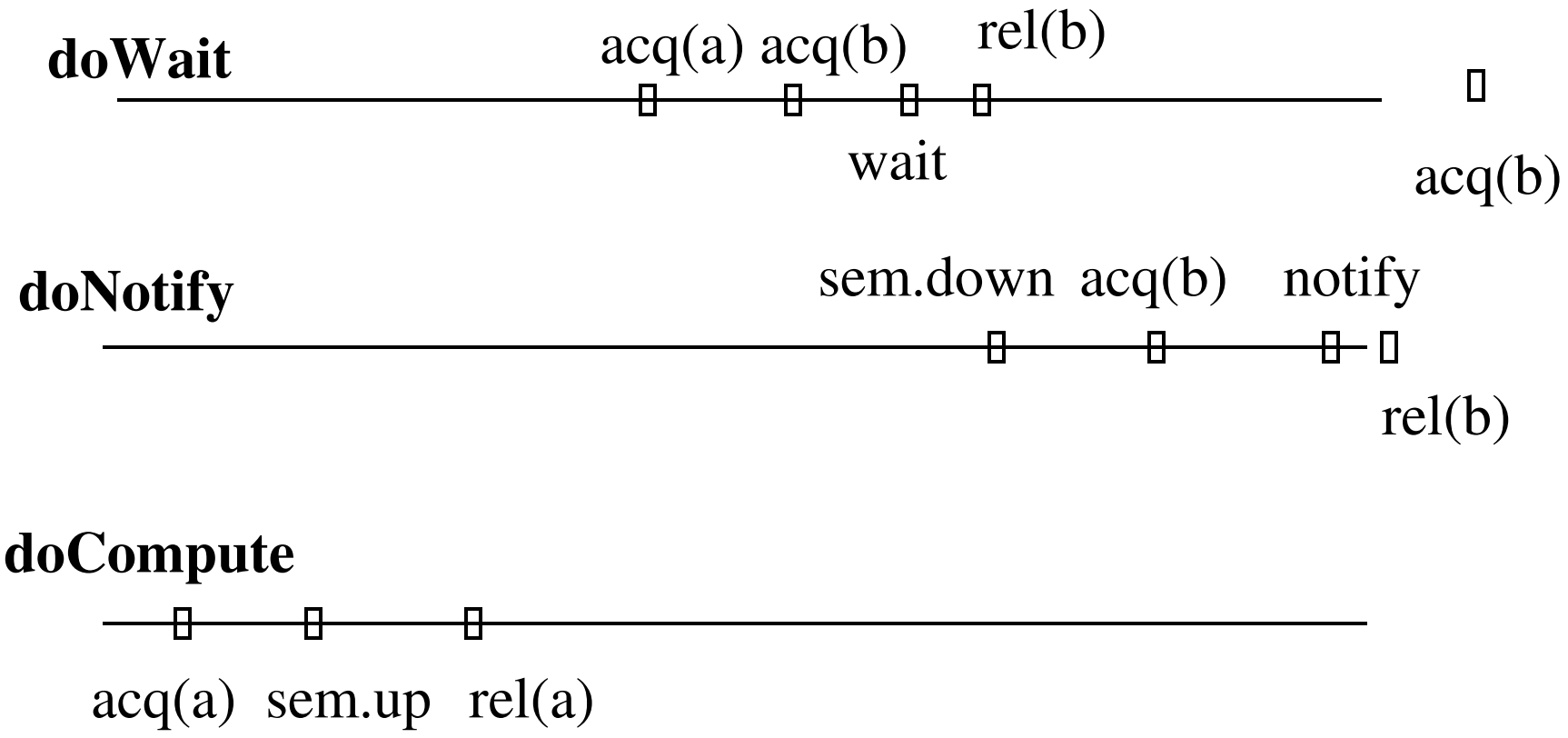
Detection of Potential Deadlocks Due to Locks, Condition Variables, and Semaphores

- Classify semaphore as used for mutual exclusion or used as condition variable.
- All ordering constraints so far are imposed.
- Check if a feasible permutation of the trace deadlocks.

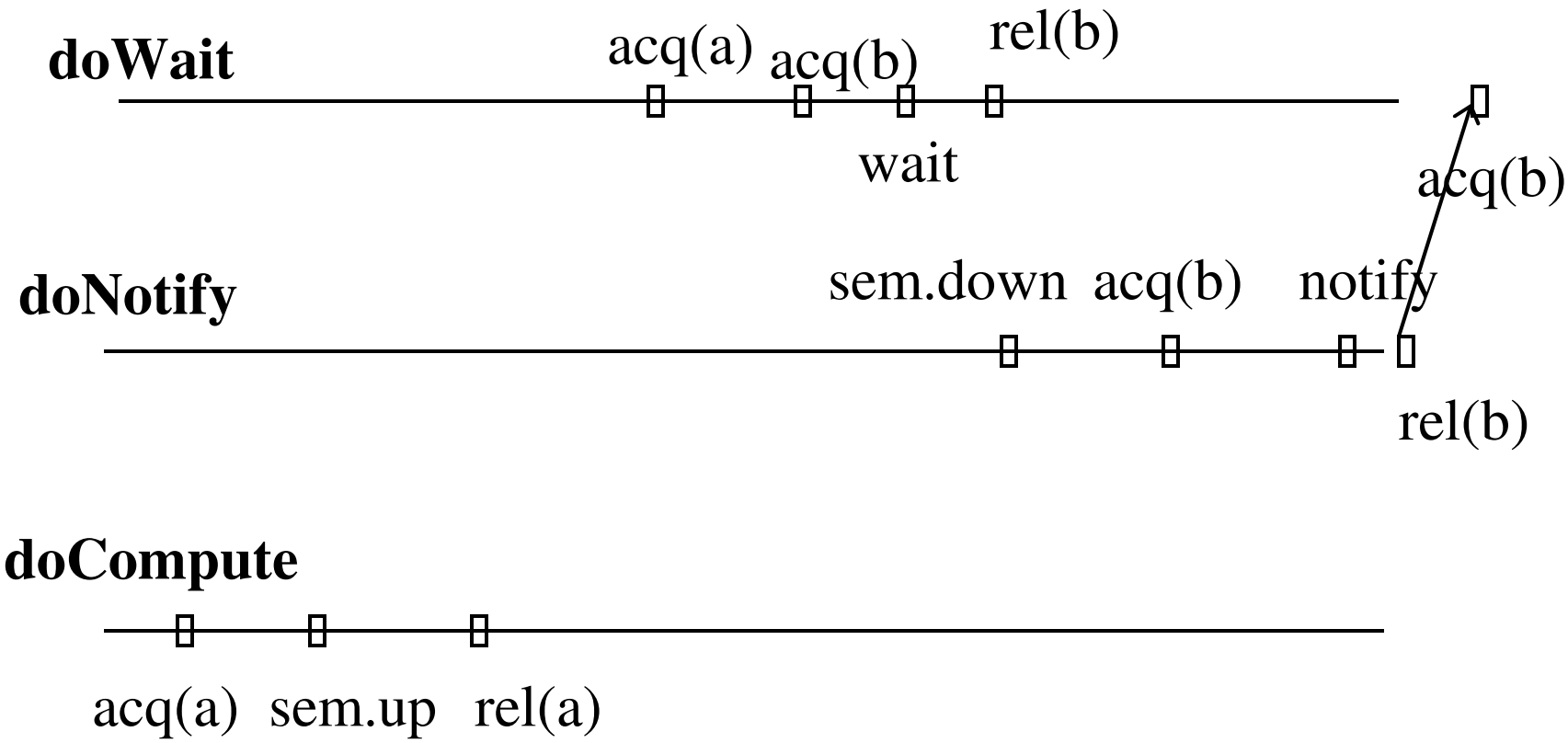
Example

```
public sync doWait(B b) { //this: Class A object.
   compute();
   sync(b) {b.wait();}
}

public doNotify(B b) {
  sem.down();
  sync(b) {b.notify();}}

public sync doCompute() { //this: Class A object
  compute();
  sem.up();}
```

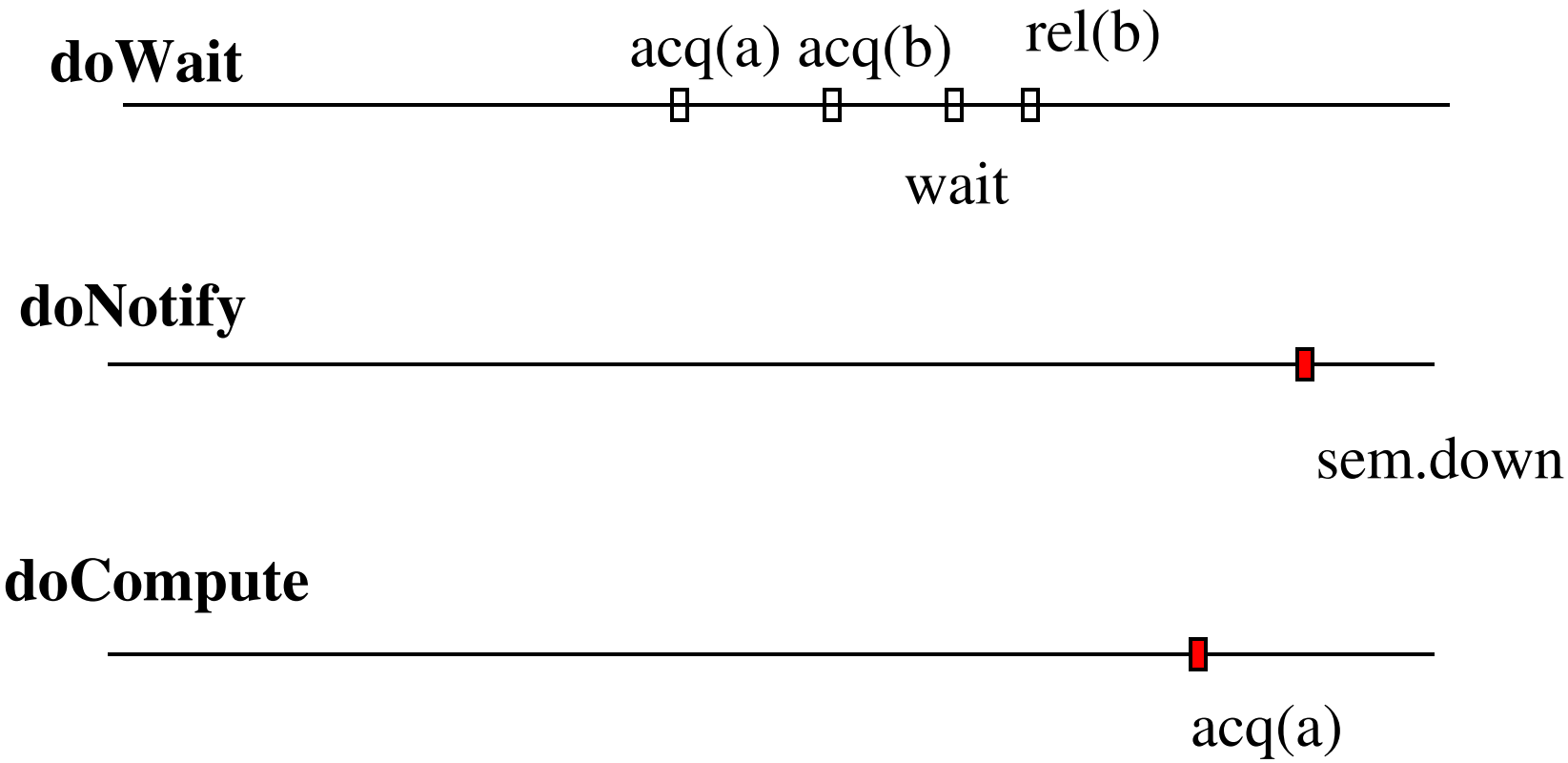
Deadlock Free Trace



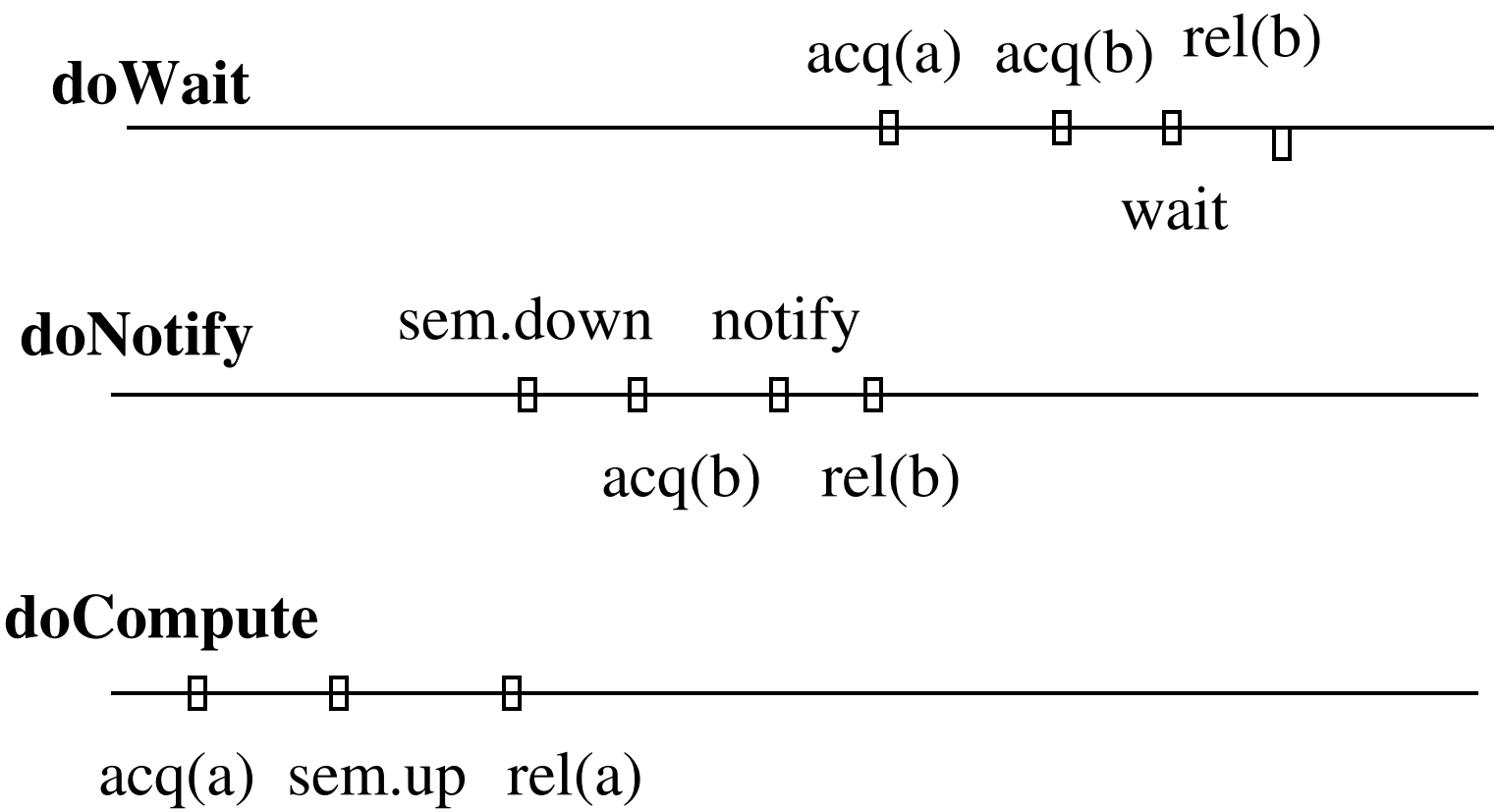
Partial Order for the Trace



Feasible Permutation that Deadlocks



Feasible Permutation that has Lost Notifies



Related Work

- Run-time analysis
  - GoodLock Algorithm [Havelund, 2000]
  - MultiThread GoodLock Algorithm [Bensalem+, 2005, Agarwal+, 2005]
  - ConTest [Edelstein+, 2003]
  - JMPaX [Sen+, 2005]
- Static Analysis
  - SafeJava [Boyapati+, 2002]
  - RacerX [Engler+, 2003]
  - Williams et. al., 2005