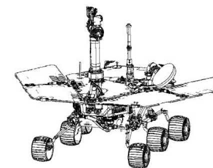
KESTREL TECHNOLOGY

Verimag

Scalable Dynamic Deadlock Analysis of Multi-Threaded Programs

I see a **deadlock** potential in that execution

log file
lock(T1,L1)
lock(T1,L2)
release(T1,L2)
release(T1,L1)
lock(T2,L2)
lock(T2,L1)



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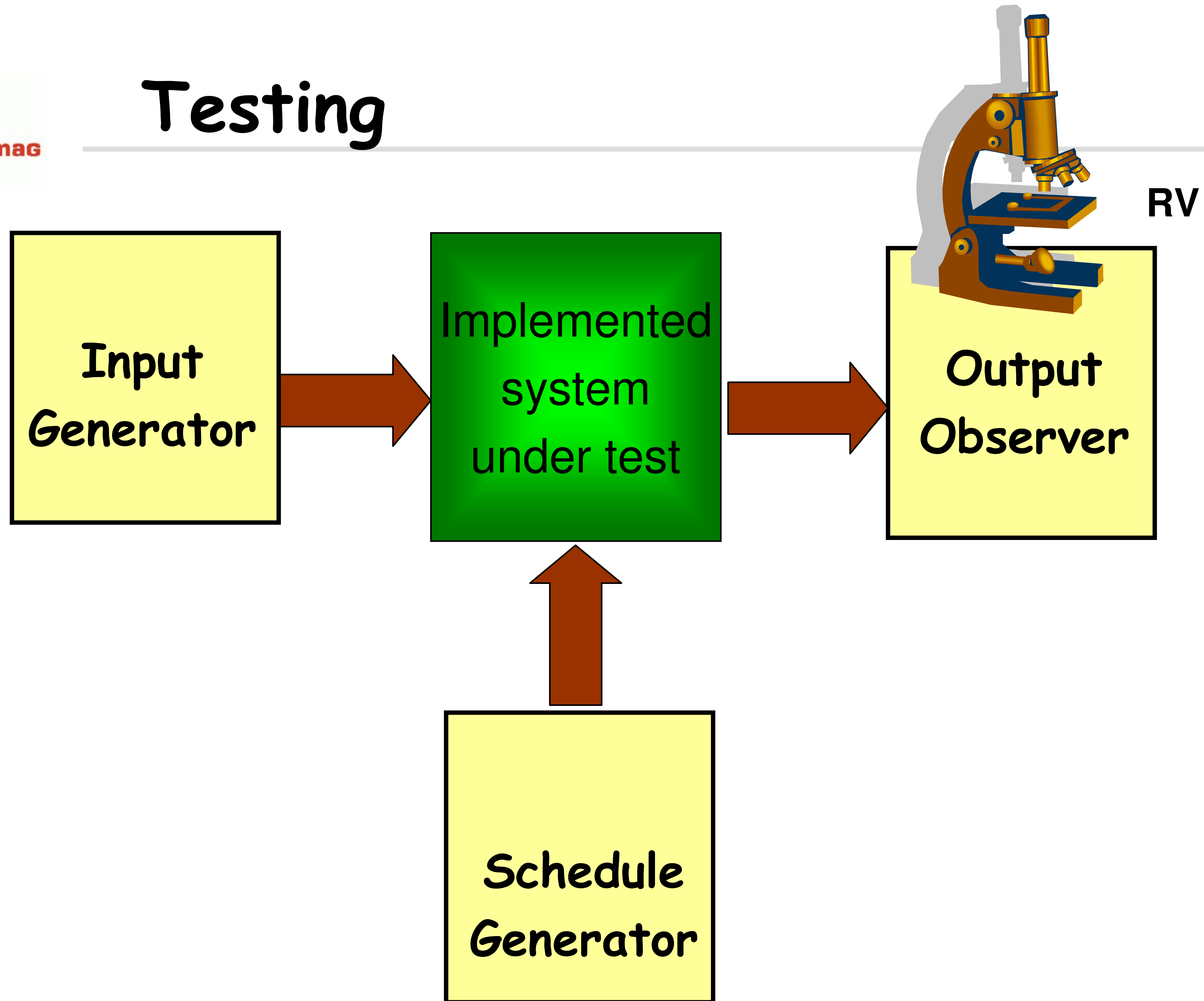
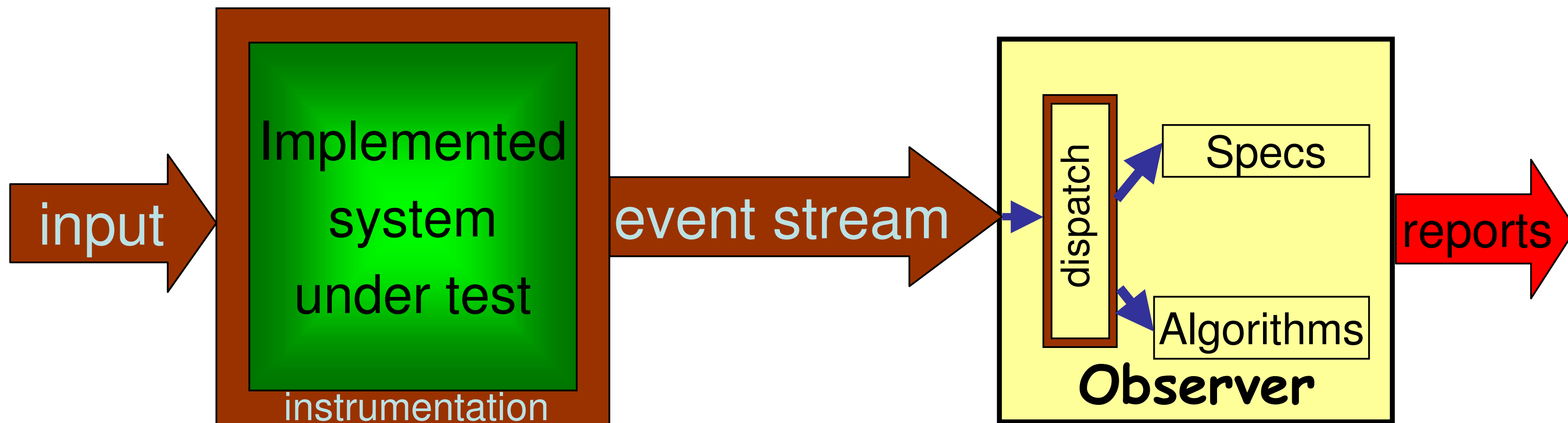
Testing



Runtime Verification



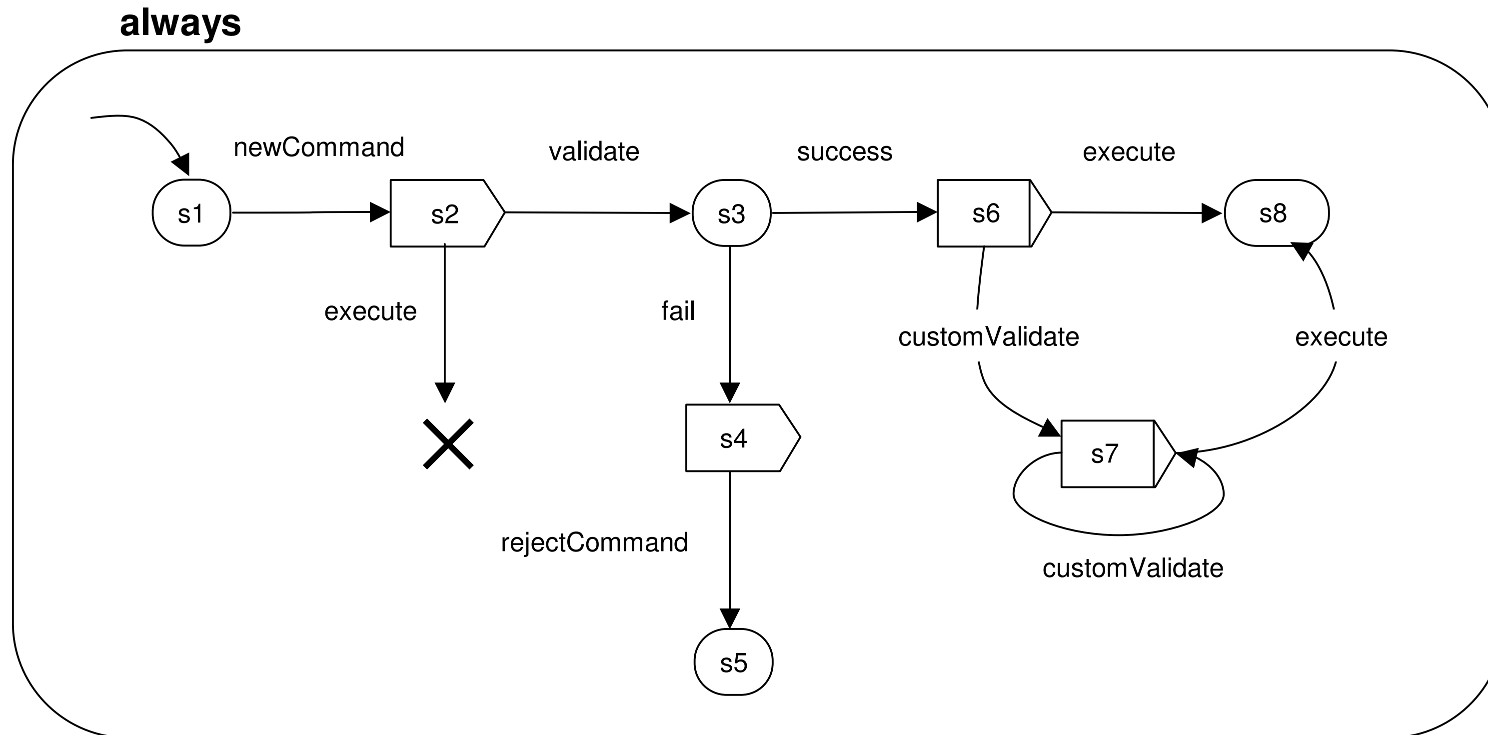
runtime monitoring
runtime checking
runtime validation
runtime analysis
dynamic analysis

Runtime Verification Tools

- Specification-based runtime verification
  - Eagle: A very powerful temporal logic
  - Rmor: A simple state machine-like language

- Algorithm-based runtime verification
  - Deadlocks - **this talk**
  - Low-level data races (Eraser)
  - High-level data races
  - Atomicity violations

Specification-Based Runtime Verification: RMOR



Two Kinds of Deadlocks

- Communication deadlocks

  Problems with **wait/notify**.

  Not analyzed in this work.

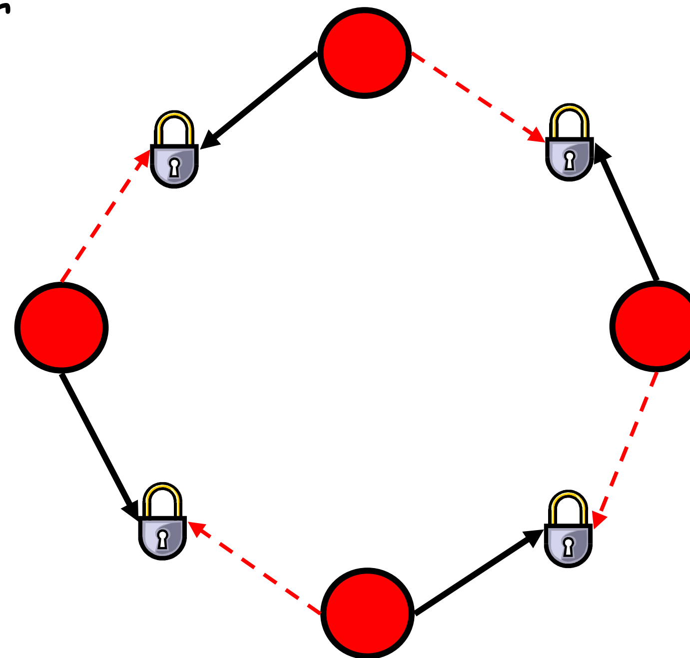
- Resource deadlocks

  Problems with **synchronized**.

  Analyzed in this work.

Resource Deadlocks

A resource deadlock can occur when two or more threads block each other in a cycle while trying to access synchronization locks (held by other threads) needed to continue their activities.



A Java Example

A basic scenario

synchronized statements

Deadlock: T1 takes L1 and
T2 takes L2

T1:

```
synchronized(L1){
   ...
   synchronized(L2){
      ...
   }
   ...
}
```

T2:

```
synchronized(L2){
   ...
   synchronized(L1){
      ...
   }
   ...
}
```

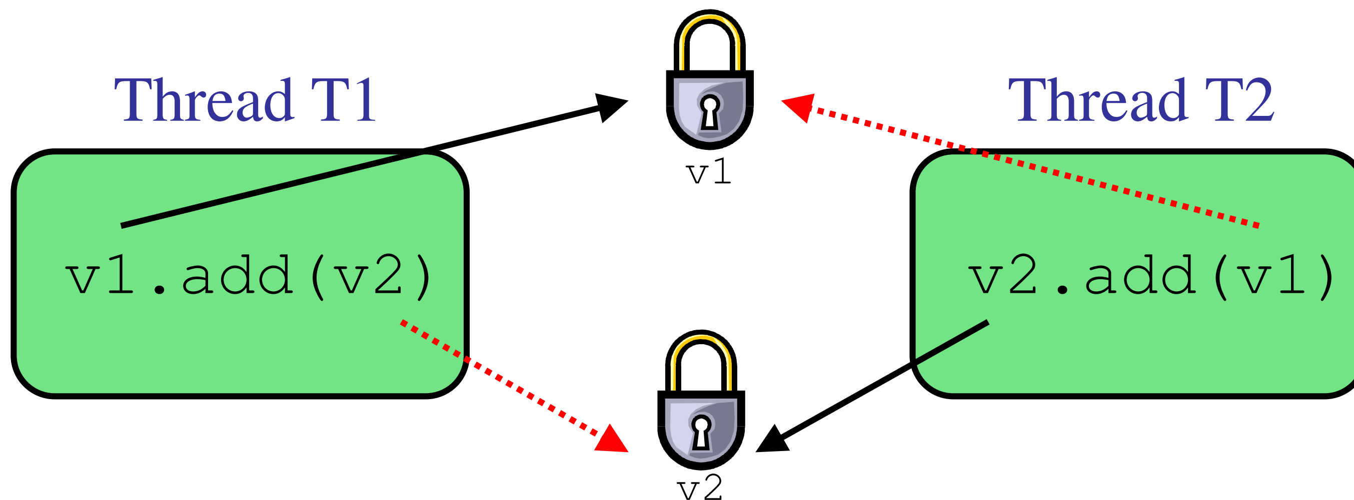
A Second Java Example

Dynamic locks

synchronized methods

```
class Value{
  int x = 1;
  synchronized void add(Value v){x = x + v.get();}
  synchronized int get(){return x;}
}
```

```
v1 = new Value();
v2 = new Value();
```



A Third Java Example

A challenge for static analysis

dynamic locking

N = number of philosophers

```
class Main{
  Fork[] forks = new Fork[N];
  ..
  for(int i=0;i<N;i++){
    new Phisosopher(forks[i],forks[(i+1)%N];
  };
}
```

arithmetic

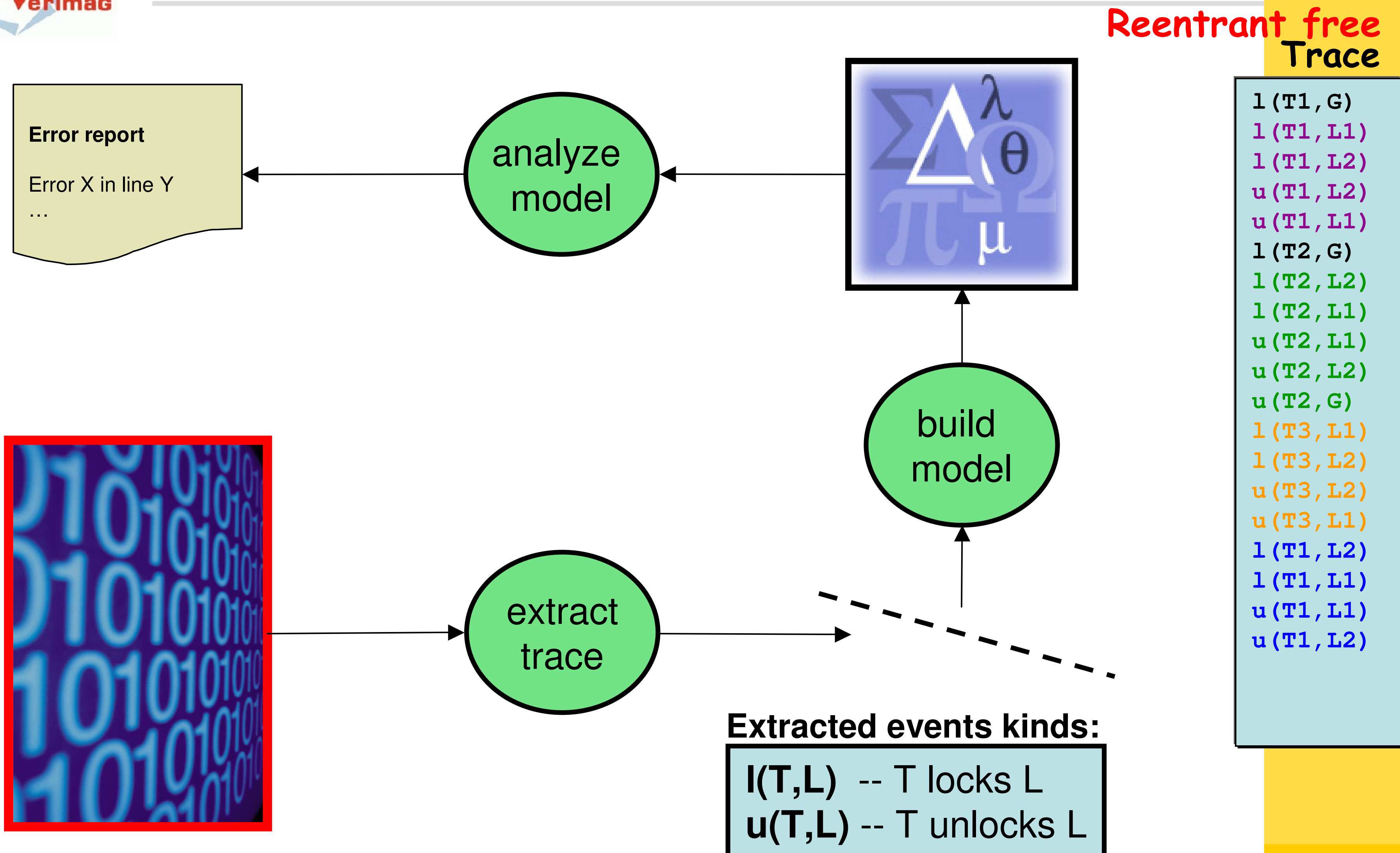
Philosopher:

```
  while(count<10){
    synchronized(salt_chaker)
    synchronized(left){
      synchronized(right){count++}
    }

  }
```

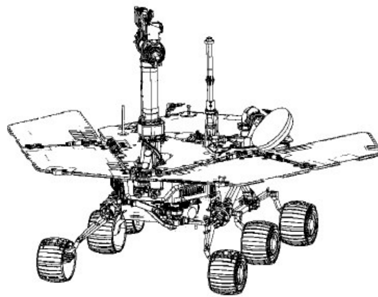
Analyzing the Dining Phil. with Static Analysis and Model checking

- **Jlint:** a static Java analyzer
  - No deadlocks found in deadlocking version
- **JPF:** a Java model checker
  - Deadlocking version:
    - N=15 (32 seconds)
    - N=20 (2.51 minutes)
    - N=21 (out of mem.)
  - Deadlock free version:
    - N=3 (3 minutes)
    - N=4 (26 minutes and out of mem.)
- **SPIN:** Similar experience as with JPF

Runtime Verification



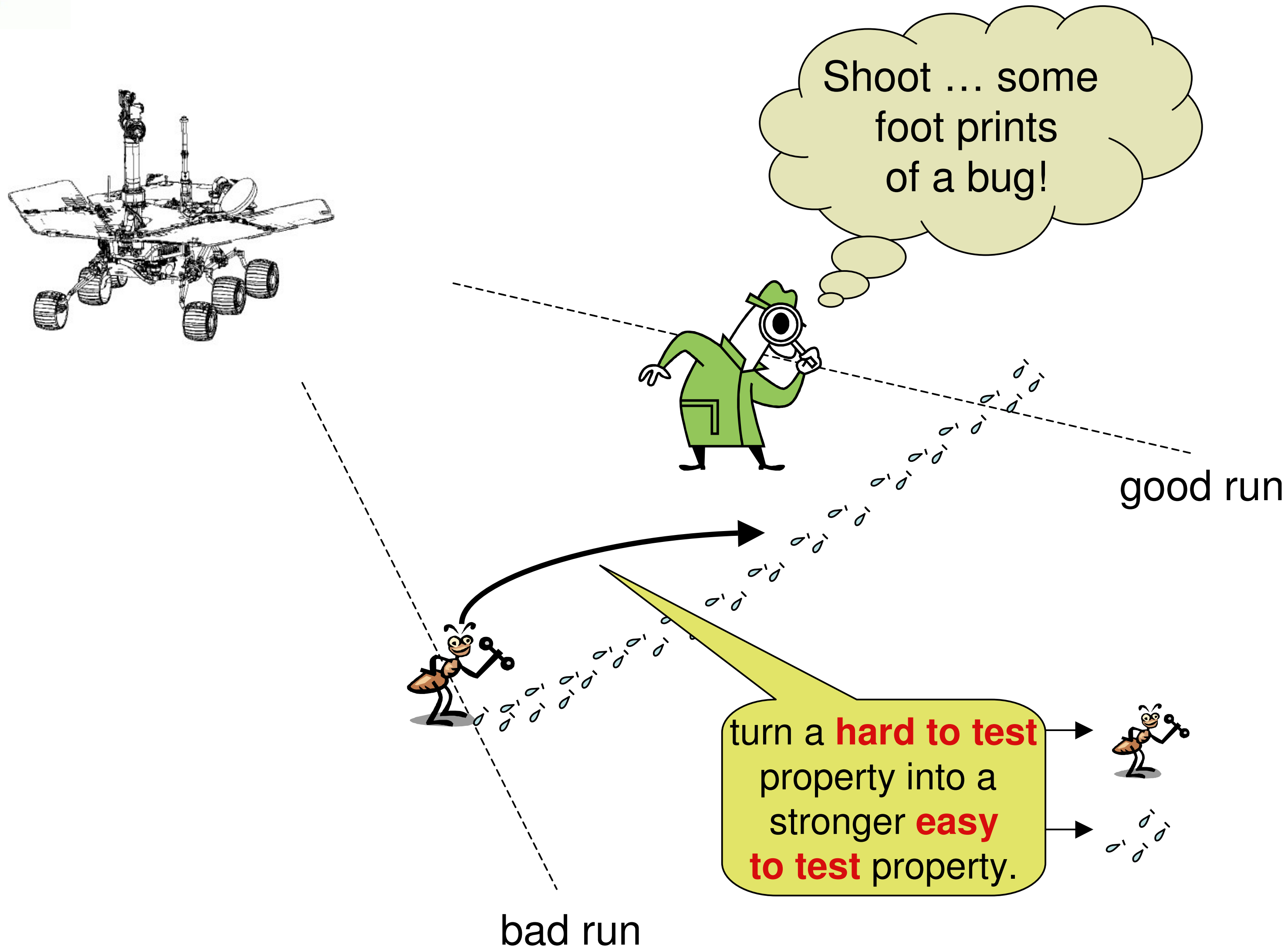
So Many Traces
So Little Time



good run

bad run

Algorithm-Based "Potential" Analysis



Pros and Cons

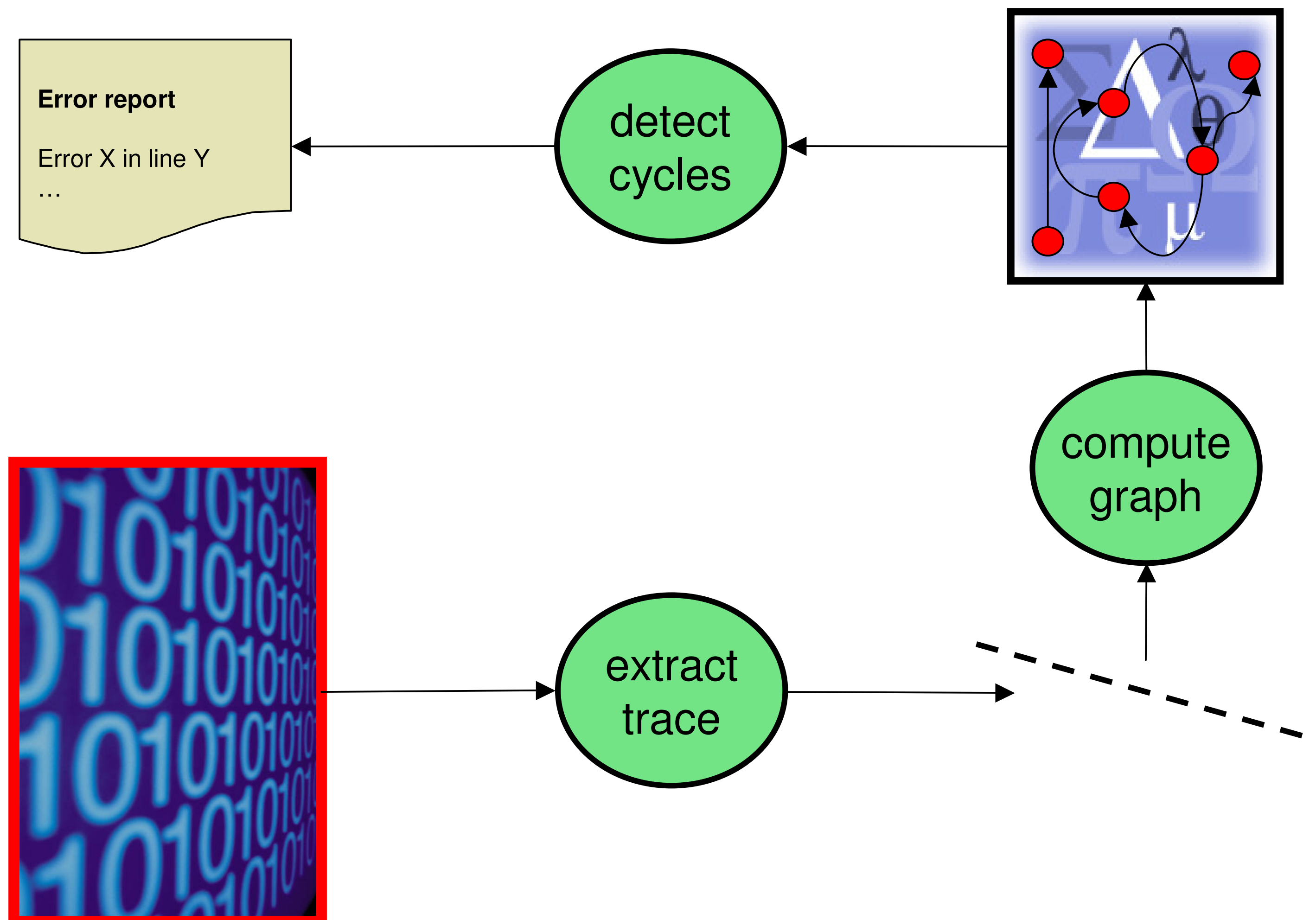
+ Scales well (one trace)
+ Often finds the bugs it is supposed to find

- Gives false positives
- Gives false negatives
- Only special bugs

Two Forms of Trace Analysis

- Build lock graph from trace and detect cycles in it.
- Build transition system from trace and model check it.

Detecting Cycles in Lock Graphs



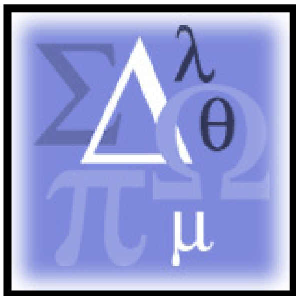
Basic Algorithm
Visiual Threads (Harrow 2000)

T1:

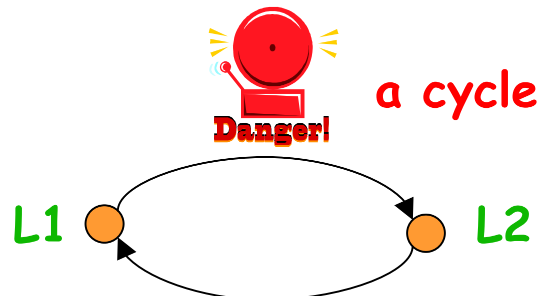
```
synchronized(L1){
   ...
   synchronized(L2){
      ...
   }
   ...
}
```

T2:

```
synchronized(L2){
   ...
   synchronized(L1){
      ...
   }
   ...
}
```



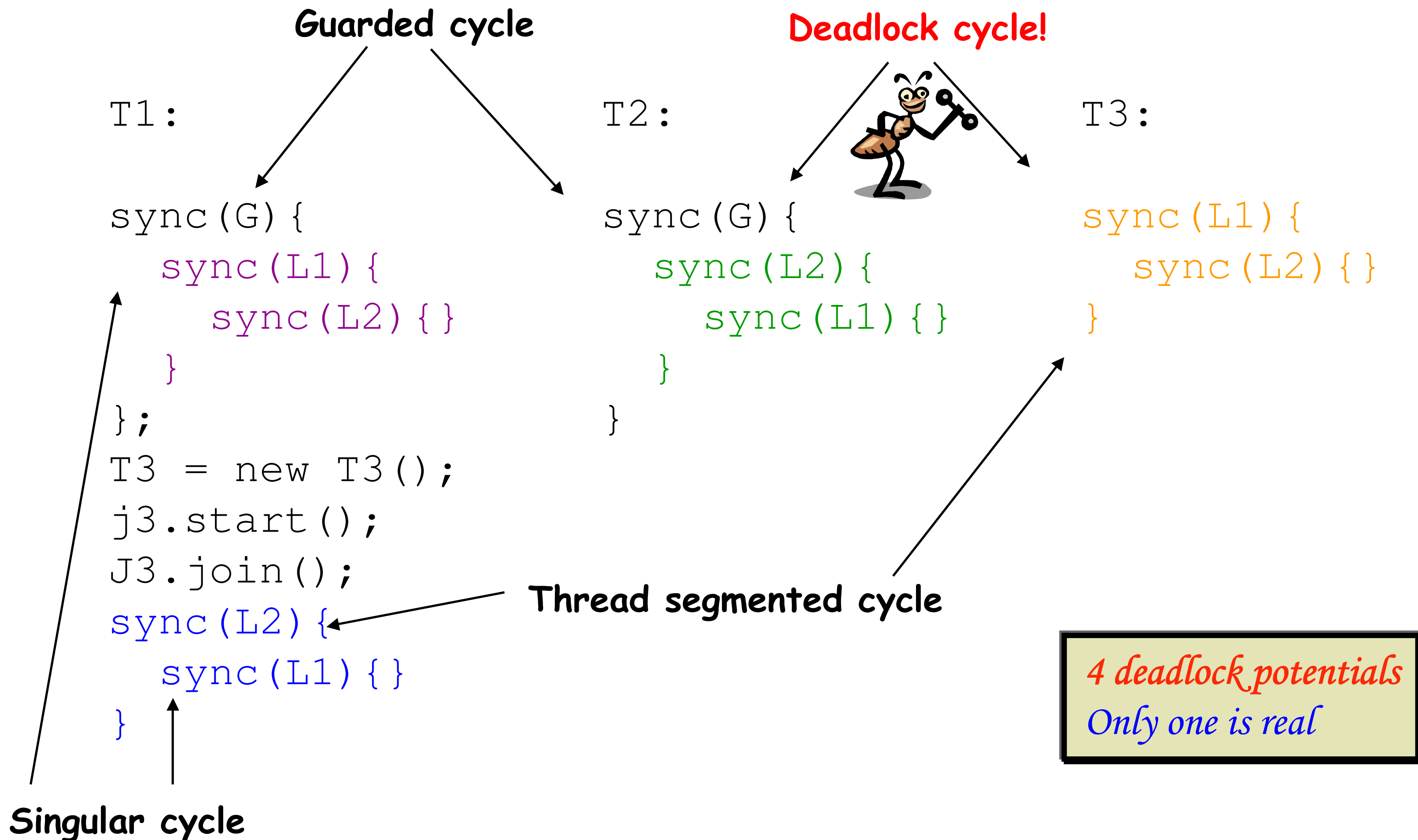
=



Basic Algorithm

```
Input: an execution trace δ

G_L : (Lock × Lock)-set        lock graph
C_L : [Thread → Lock-set]      lock context

for(i = 1..|δ|) do
  case δ[i] of
    l(t,o) →
      G_L := G_L ∪ { (o',o) | o' ∈ C_L(t) };
      C_L := C_L ⊕ [t ☞ C_L(t) ∪ {o} ];
    u(t,o) →
      C_L := C_L ⊕ [t ☞ C_L(t) \ {o} ];
  endcase
enddo

foreach c in cycles(G_L)
  print("deadlock potential: " + c);
```

Simple Algorithm Gives False Positives (False Warnings)



4 deadlock potentials
Only one is real

Extract Execution Trace

T1:

```
sync(G){
  sync(L1){
    sync(L2){}
  }
};
T3 = new T3();
j3.start();
J3.join();
sync(L2){
  sync(L1){}
}
```

T2:

```
sync(G){
  sync(L2){
    sync(L1){}
  }
}
```

T3:

```
sync(L1){
  sync(L2){}
}
```

Event format:

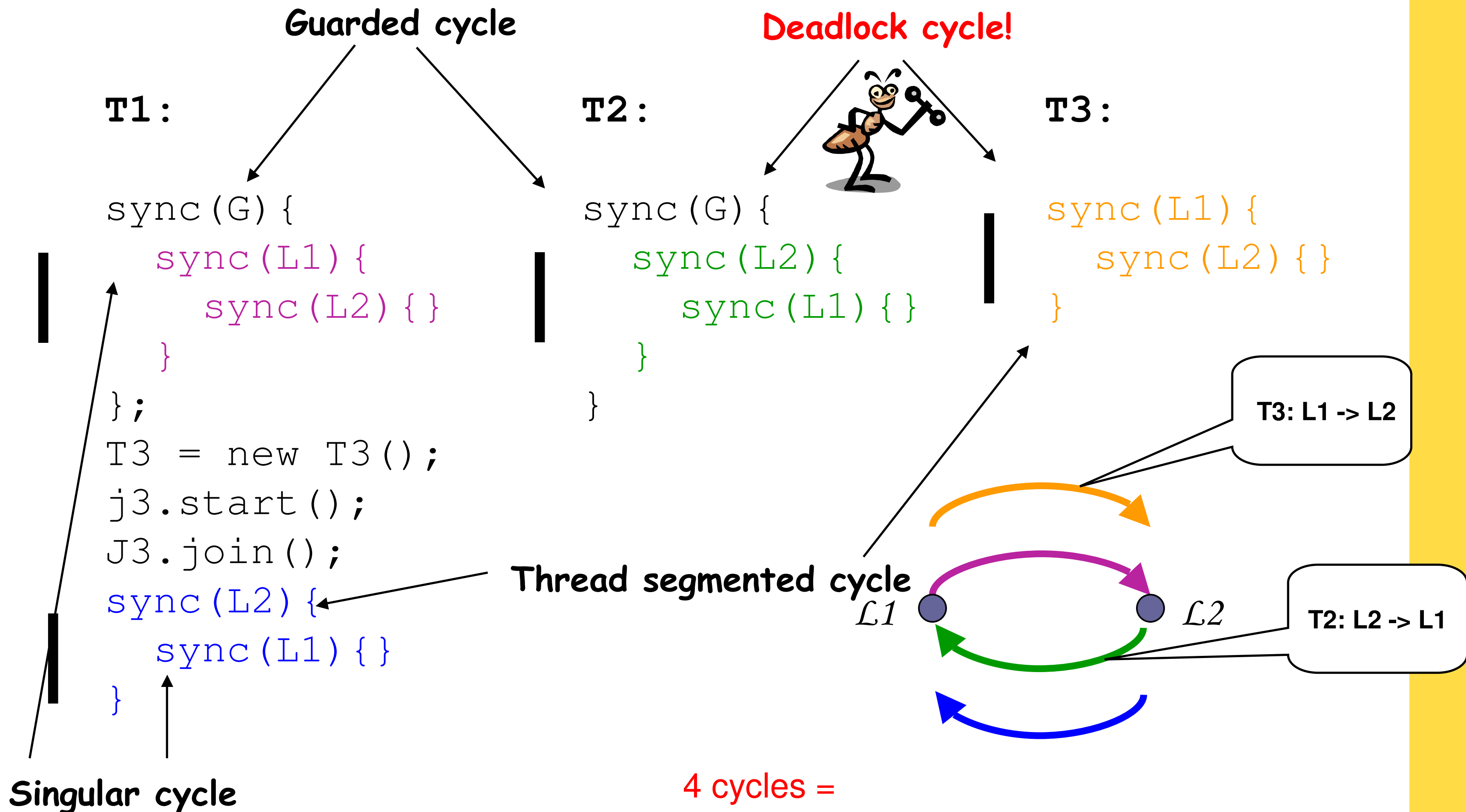
```
l(<thread>,<lock>)      - lock
u(<thread>,<lock>)      - unlock
s(<thread>,<thread>)    - start
j(<thread>,<thread>)    - join
```

Trace

```
l(T1,G)
l(T1,L1)
l(T1,L2)
u(T1,L2)
u(T1,L1)
s(T1,T3)
l(T2,G)
l(T2,L2)
l(T2,L1)
u(T2,L1)
u(T2,L2)
u(T2,G)
l(T3,L1)
l(T3,L2)
u(T3,L2)
u(T3,L1)
j(T1,T3)
l(T1,L2)
l(T1,L1)
u(T1,L1)
u(T1,L2)
```

Algorithm: build lock graph and detect cycles in graph.
An edge goes from X to Y if a thread holds X while locking Y.

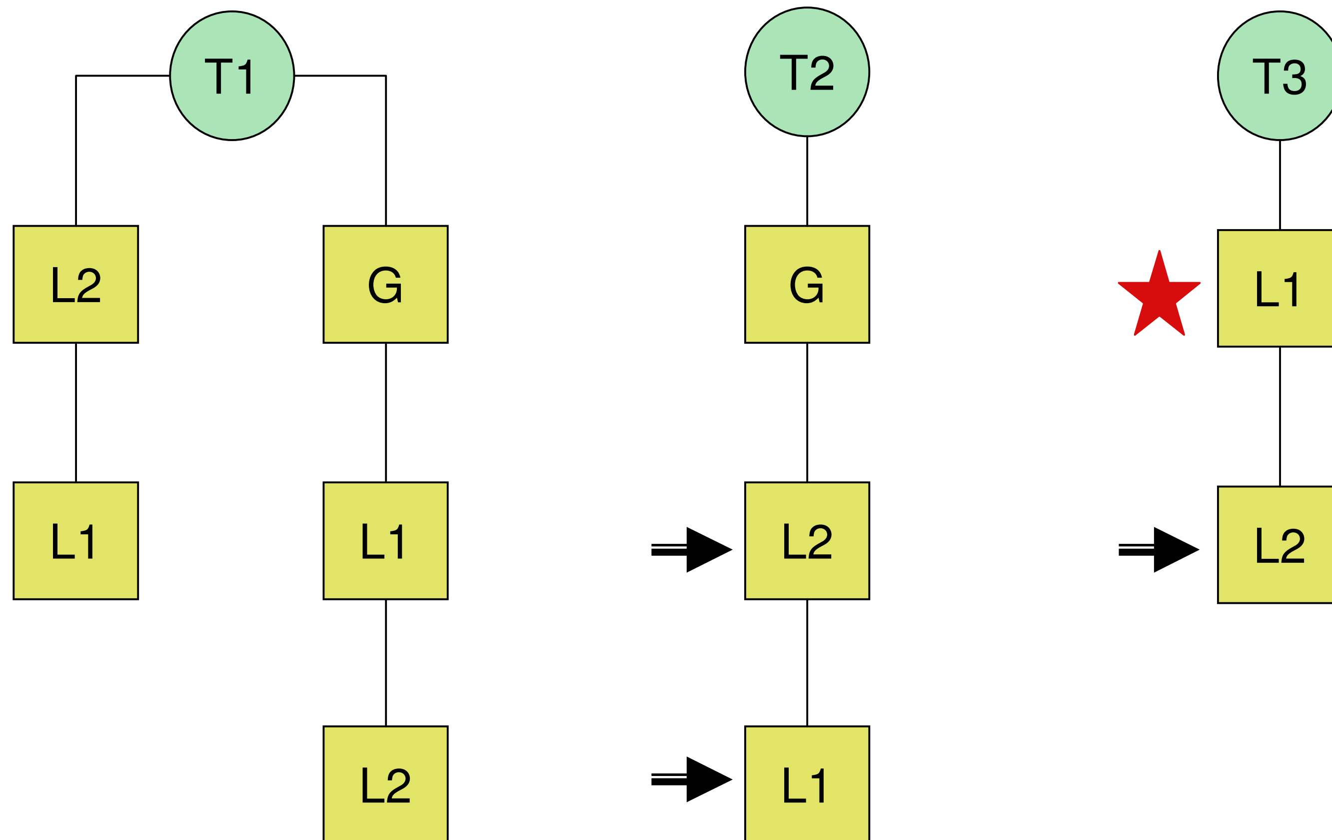
Basic Algorithm



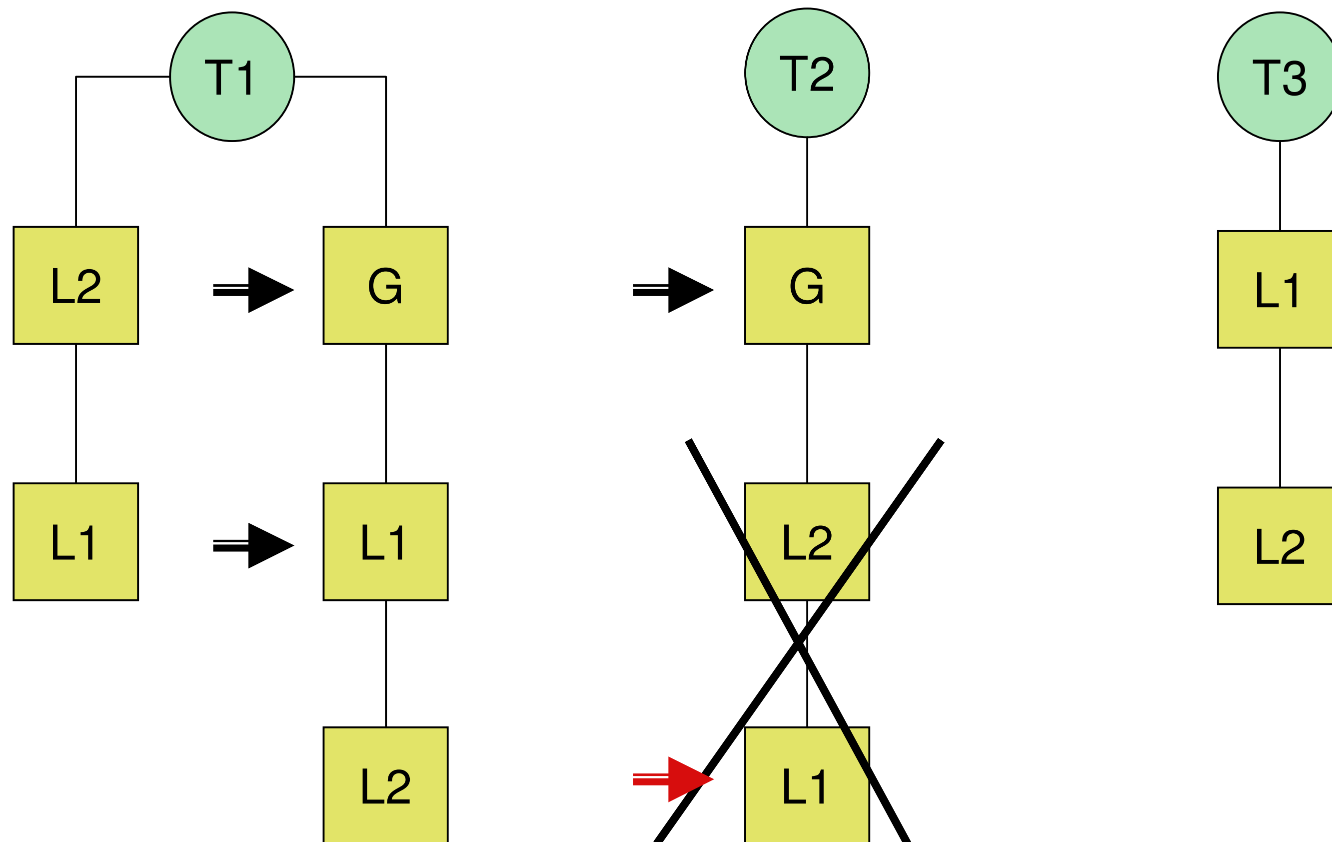
4 cycles =
4 deadlock potentials reported (Visual Threads).

1 real deadlock! (3 false positives)

The GoodLock Algorithm (Havelund 2000)



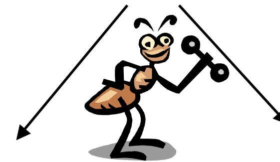
The GoodLock Algorithm (Havelund 2000)



Algorithm: extend lock graph with labeled edges: which thread, and set of guard locks.

Guarded Algorithm

Deadlock cycle!



T1:

```
sync(G){
  sync(L1){
    sync(L2){}
  }
};
T3 = new T3();
j3.start();
J3.join();
sync(L2){
  sync(L1){}
}
```

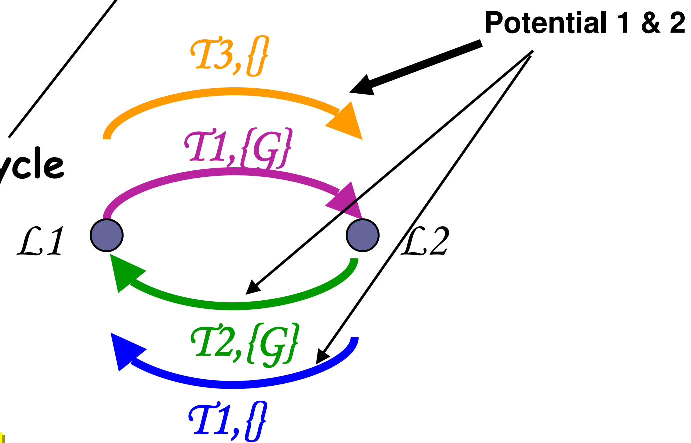
T2:

```
sync(G){
  sync(L2){
    sync(L1){}
  }
}
```

T3:

```
sync(L1){
  sync(L2){}
}
```

Thread segmented cycle



2 cycles =
2 deadlock potentials reported.

Valid Cycles:

1. *Threads: must differ*
2. *Guard sets: must not overlap*

Guarded Algorithm

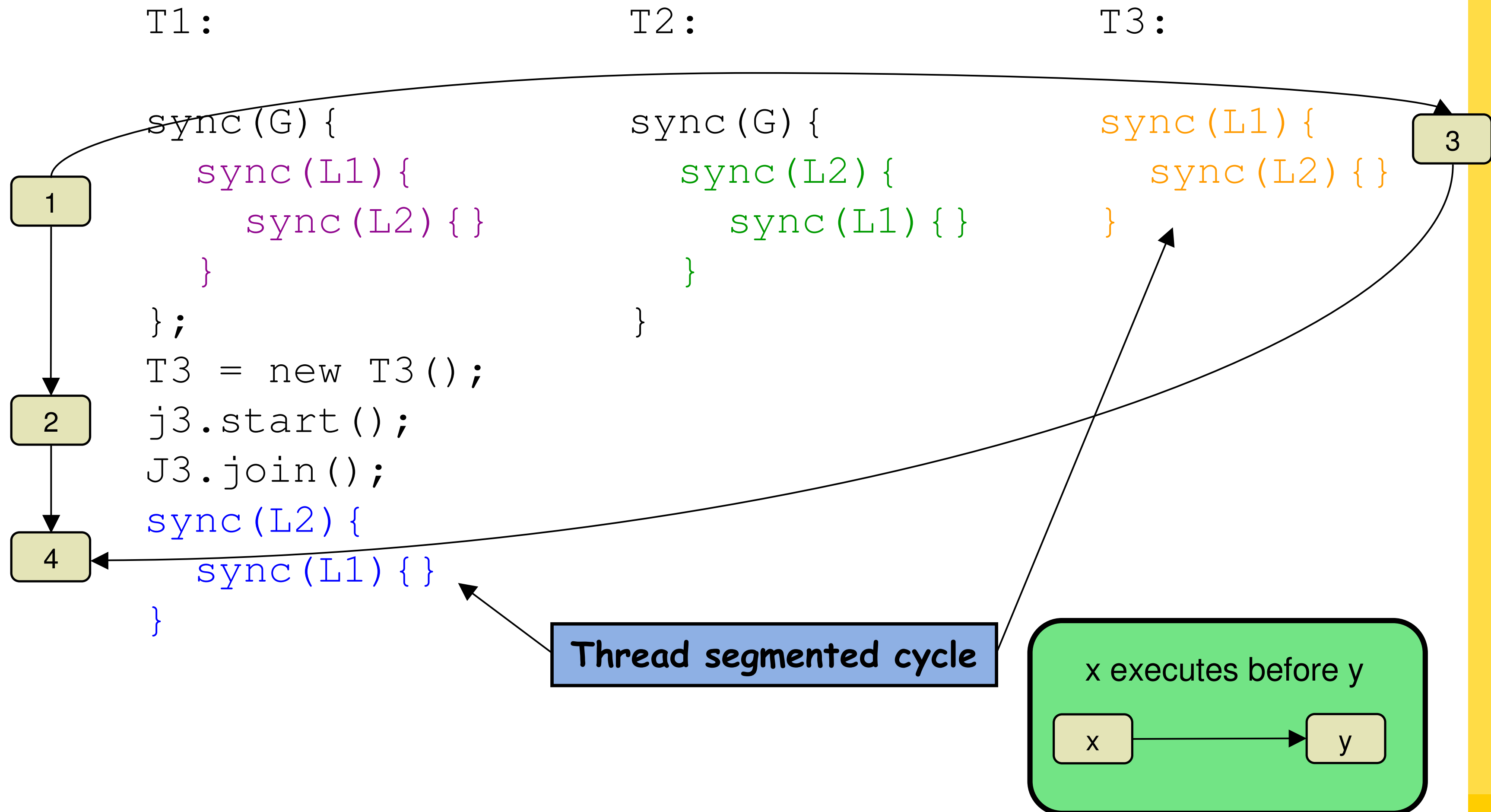
```
Input: an execution trace δ
type Label = Thread × Lock-set
G_L : (Lock × Label × Lock)-set            lock graph
C_L : [Thread → Lock-set]                  lock context

for(i = 1..|δ|) do
  case δ[i] of
    l(t,o) →
      G_L := G_L ∪ { (o',(t,g),o) |
                       o' ∈ C_L(t) ∧
                       g = { o'' | o'' ∈ C_L(t) }};
      C_L := C_L ⊕ [t ☞ C_L(t) ∪ {o} ];
    u(t,o) →
      C_L := C_L ⊕ [t ☞ C_L(t) \ {o} ];
  endcase
enddo

foreach c in valid-cycles(G_L)
  print("deadlock potential: " + c);
```

thread : Label → Thread
thread(t,g) = t

guards : Label → Lock-set
guards(t,g) = g

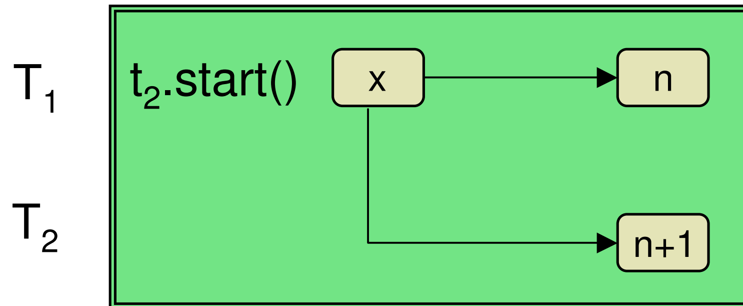
valid-cycle(c) =
$\forall e_1, e_2 \in c \bullet$
$thread(e_1) \neq thread(e_2) \wedge$
$guards(e_1) \cap guards(e_2) = \{\ \}$

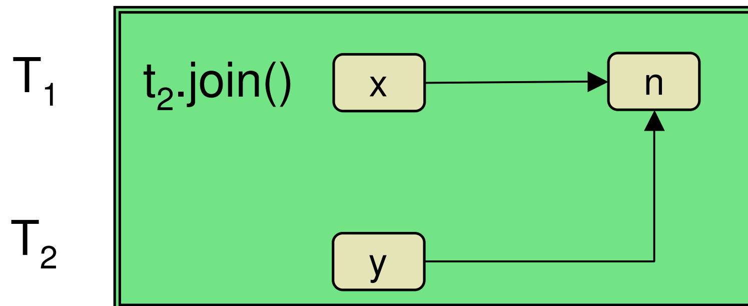
Dividing Code Into Segments



Effect of start() and join() on the Segmentation Graph 'S'

n : next free segment





Let S^* be the transitive closure of segmentation graph S.

The happens-before relation is defined as:

x ➲ y = $(x,y) \in S^*$

The in-parallel relation is defined as:

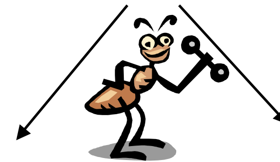
x || y = ¬(x ➲ y) ∧ ¬(y ➲ x)

Algorithm: extend lock graph with segment labels: which segments of a thread locks are taken.

Final Algorithm

```
M:
• new T1().start();
• new T2().start();
```

Deadlock cycle!

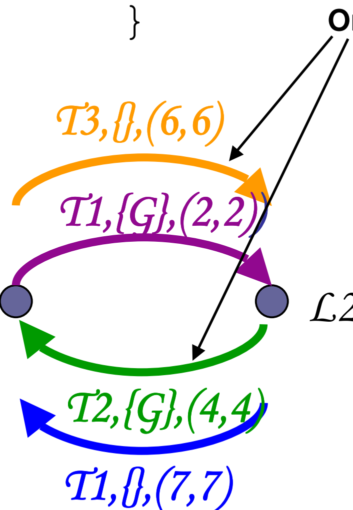


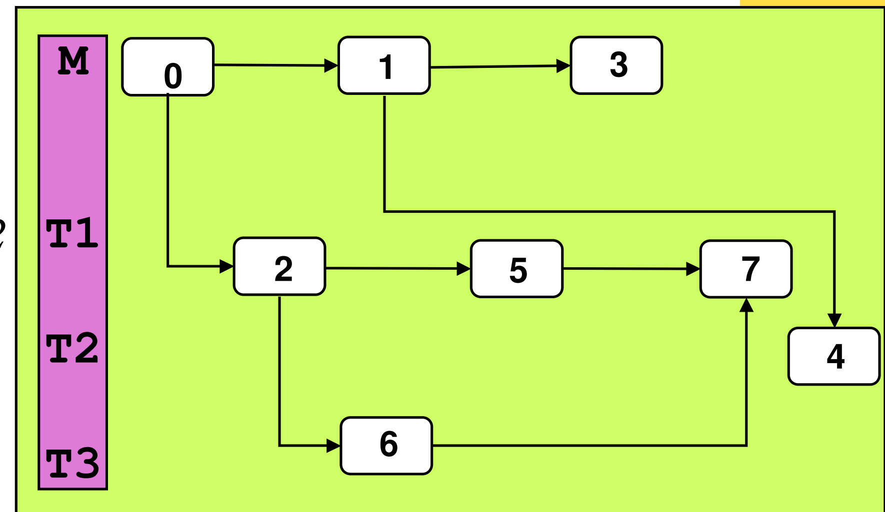
```
T1:

sync(G){
   sync(L1){
      sync(L2){}
   }
};
T3 = new T3();
• j3.start();
• J3.join();
sync(L2){
   sync(L1){}
}
```

```
T2:

sync(G){
   sync(L2){
      sync(L1){}
   }
}
```

```
T3:

sync(L1){
   sync(L2){}
}
```

One potential left, the real deadlock!





Valid Cycles:

1. *Threads: must differ*
2. *Guard sets: must not overlap*
3. *Segments: must be parallel*

Final Algorithm

```
Input: an execution trace δ
type Label = nat × Thread × Lock-set × nat
G_L : (Lock × Label × Lock)-set         lock graph
G_S : (nat × nat)-set                   seg. Graph
C_L : [Thread → (Lock × nat)-set]       lock context
C_S : [Thread → nat]                    segm. Context
n : nat = 1;                            next available segm.

for(i = 1..|δ|) do
  case δ[i] of
    l(t,o) →
      G_L := G_L ∪ { (o',(s_1,t,g,s_2),o) |
                     (o', s_1) ∈ C_L(t) ∧
                     g = { o'' | (o'', *) ∈ C_L(t) } ∧
                     s_2 = C_S(t)};
      C_L := C_L ⊕ [t ☞ C_L(t) ∪ {(o,C_S(t))} ];
    u(t,o) →
      C_L := C_L ⊕ [t ☞ C_L(t) \ {(o,*)} ];
    s(t_1, t_2) →
      G_S := G_S ∪ { (C_S(t_1),n), (C_S(t_1),n+1)}
      C_S := C_S ⊕ [t_1 ☞ n, t_2 ☞ n+1];
      n := n + 2;
    j(t_1, t_2) →
      G_S := G_S ∪ { (C_S(t_1),n), (C_S(t_2),n)};
      C_S := C_S ⊕ [t_1 ☞ n];
      n := n + 1;
  endcase
enddo

foreach c in valid-cycles(G_L)
  print("deadlock potential: " + c);
```

thread : Label → Thread
$thread(s_1,t,g,s_2) = t$

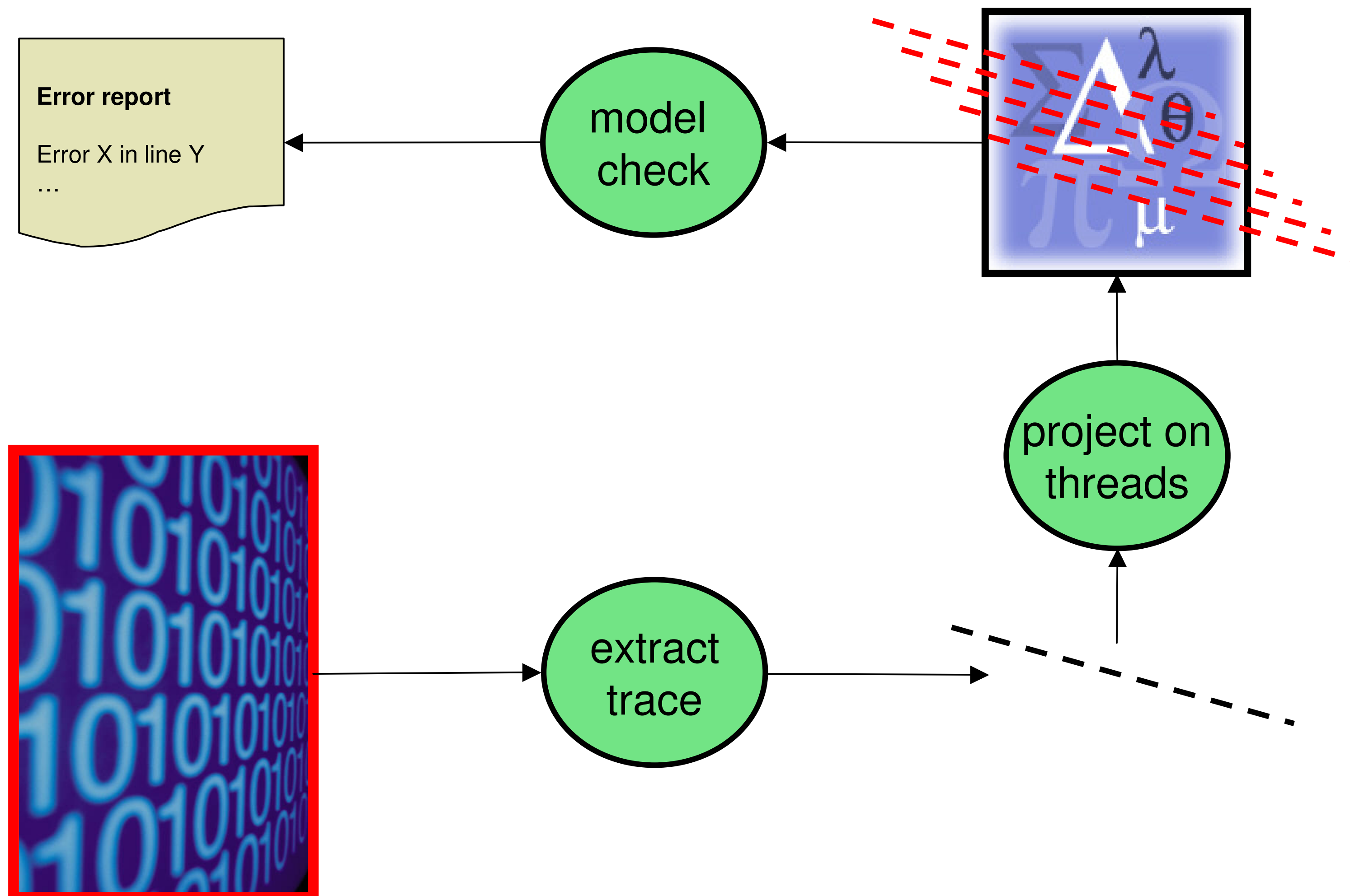
guards : Label → Lock-set
$guards(s_1,t,g,s_2) = g$

source : Label → nat
$source(s_1,t,g,s_2) = s_1$

target : Label → nat
$target(s_1,t,g,s_2) = s_2$

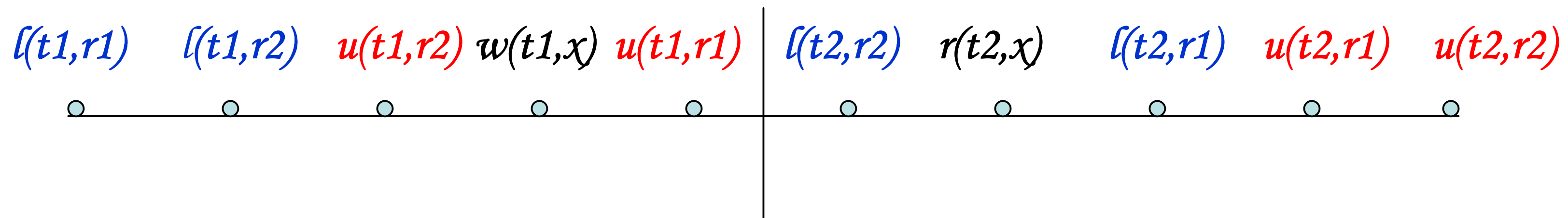
valid-cycle(c) =
$\forall e_1,e_2 \in c \bullet$
$thread(e_1) \neq thread(e_2) \wedge$
$guards(e_1) \cap guards(e_2) = \{ \} \wedge$
$target(e_1) \neg\supset target(e_2)$

Model Checking Traces



Model Checking Traces

- Execute instrumented version of program and extract "random" execution trace:



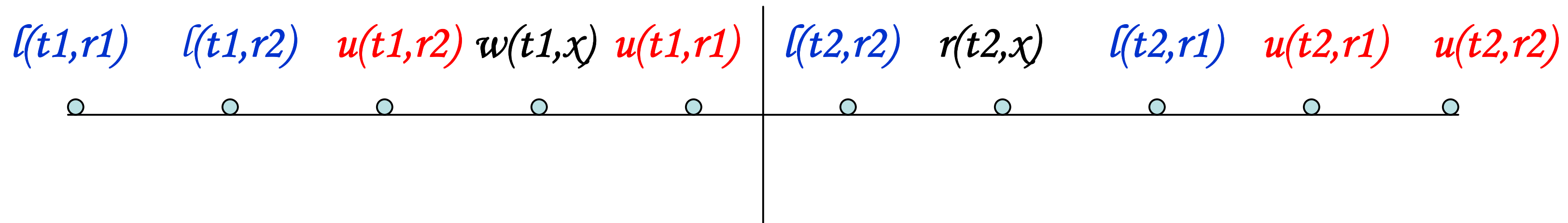
T1:

```
long x;
synchronized(R1){
  synchronized(R2){};
  x = big1*big2;
}
```

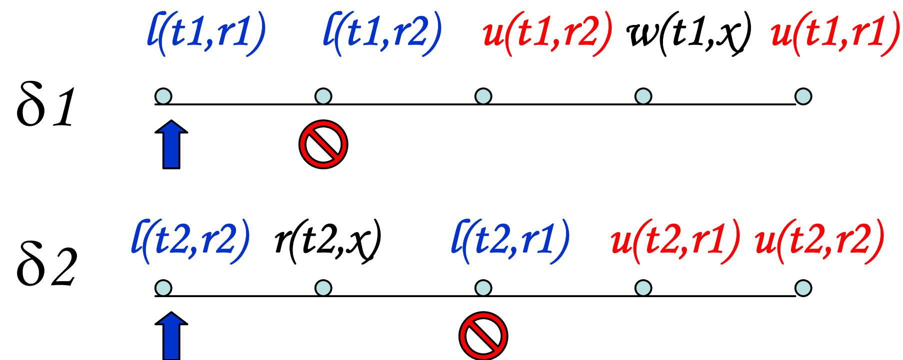
T2:

```
synchronized(R2){
  System.out.println(x);
  synchronized(R1){};
}
```

Model Checking Traces



project on threads



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Deadlocking Transition Systems

An execution path ρ of $||S_i$ is a sequence:

$$\rho = s_0 \xrightarrow{e_0} s_1 \xrightarrow{e_1} s_2 \xrightarrow{e_2} \ldots \xrightarrow{e_{k-1}} s_k$$

such that s_0 is the initial state (1,1,…,1,{})
and there are no further moves from s_k.

deadlocking(ρ) = *last_state(ρ) $\neq$ ($k_1, k_2, \ldots, k_M$,{})*
That is: not all threads have reached their final state.

Deadlocking($||S_i$) = $\exists\ \rho \in ||S_i \bullet$ deadlocking(ρ)

DEADLOCKING(δ) = Deadlocking($||S_i$)

Experiment with Model Checking of Traces

better

- Deadlocking philosophers: for N=47 deadlock found in 5 minutes
- For *deadlock free* philosophers (recall that each eats 10 times):
  - for N=3 verified correct in 38 seconds
  - For N=4 out of memory (1.5 GB memory)

N=3: faster
N=4: out of mem.

Correctness Theorem

Let δ be an execution trace.
Let G_L be its lock graph.
Let $||S_i$ be its transition system.

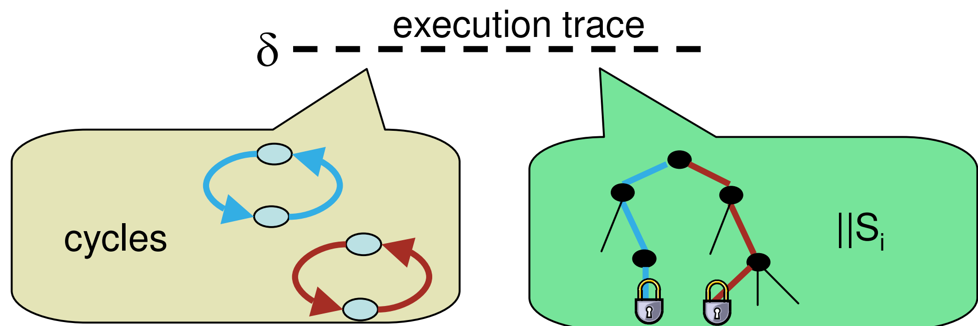
reflects : Cycle $\times$ Path $\rightarrow$ **Bool**
reflects(c,ρ) =
  $\forall$ (l_1,(_,t,_,_),l_2) $\in$ c •
   t **holds** l_1 **in** ρ $\wedge$
   t **next wants** l_2 **in** ρ

soundness wrt. execution trace δ:

$$\forall\ c \in \text{valid-cycles}(G_L) \bullet \exists\ \rho \in ||S_i \bullet \text{Deadlocking}(\rho) \wedge \text{reflects}(c,\rho)$$

completeness wrt. execution trace δ:

$$\forall\ \rho \in ||S_i \bullet \text{Deadlocking}(\rho) \Rightarrow \exists\ c \in \text{valid-cycles}(G_L) \bullet \text{reflects}(c,\rho)$$



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Missed Warnings

Guarded cycle?

T1:

```
sync(G){
  sync(L1){
    sync(L2){}
  }
};
T3 = new T3();
j3.start();
J3.join();
sync(L2){
  sync(L1){}
}
```

T2:

```
if(p)
  X := G
else
  X := H;
sync(X){
  sync(L2){
    sync(L1){}
  }
}
```

T3:

```
sync(L1){
  sync(L2){}
}
```

If p evaluates to true
Cycle becomes guarded
and error is missed.

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The Problem of False Negatives

- Added covererage module reporting synchronization statements not executed per thread in a run.
- Will work better when combined with test case generation and more sophisticated coverage criteria.
- However, tool works surprisingly well on tried test cases (finds known bugs immediately).

The Testing Problem: Non-determinism

Prog(k,n):

```
synchronized(L1){
  if(random(1,n)==1)
    synchronized(L2){}
}

synchronized(L2){
  if(random(1,n)==1)
    synchronized(L3){}
}

...

synchronized(Lk){
  if(random(1,n)==1)
    synchronized(L1){}
}
```

Probability for deadlock to occur:

$P_D(k,n)$ = P(**Prog(k,n)** deadlocks in a run)

= 1/n * P(deadlock | random == 1)

= 1/n * (1 * (k-1)/k * (k-2)/k * … * 1/k)

= 1/n * k!/k^k

Example:

$P_D(k=4,n=3) = 0.03$

Runtime Verification on this Example is 10 times more Effective

Prog(k,n):

```
synchronized(L1){
  if(random(1,n)==1)
    synchronized(L2){}
}

synchronized(L2){
  if(random(1,n)==1)
    synchronized(L3){}
}

...

synchronized(Lk){
  if(random(1,n)==1)
    synchronized(L1){}
}
```

Probability for deadlock to occur:

$P_C(k,n)$ = P(**Prog(k,n)** generates cycle in a run)

= 1/n * P(cycle | random == 1)

= 1/n * 1

= 1/n

Example:

$P_C(k=4,n=3) = 0.33$

$= 10 * P_D(k=4,n=3)$ < 1

KESTREL TECHNOLOGY

Verimag

The Dining Philosophers

model checking

Deadlocking version:
- N=15 (32 seconds),
- N=20 (2.51 minutes),
- N=21 (out of mem.)

Deadlock free version:
- N=3 (3 minutes),
- N=4 (out of mem.)

trace model checking

Deadlocking version:
- N=47 (5 minutes),

Deadlock free version:
- N=3 (38 seconds),
- N=4 (out of mem.)

runtime analysis

Deadlocking version:
- N=100 (8 seconds),
- N=300 (22 seconds)
- …

Deadlock free version:
- N=4 (7 seconds)
- N=100 (30 seconds)
- N=300 (2 minutes)
- …

Real Case Studies

NASA's K9 Rover controller:

35,000 lines of C++

Found 1 deadlock in first run.

NASA K9 Java Rover controller:

8,000 lines of Java (small Java version of C++ version)

Found 2 planted deadlocks in first run. Did well in "competition".

NASA IDEA plan-runner:

C++

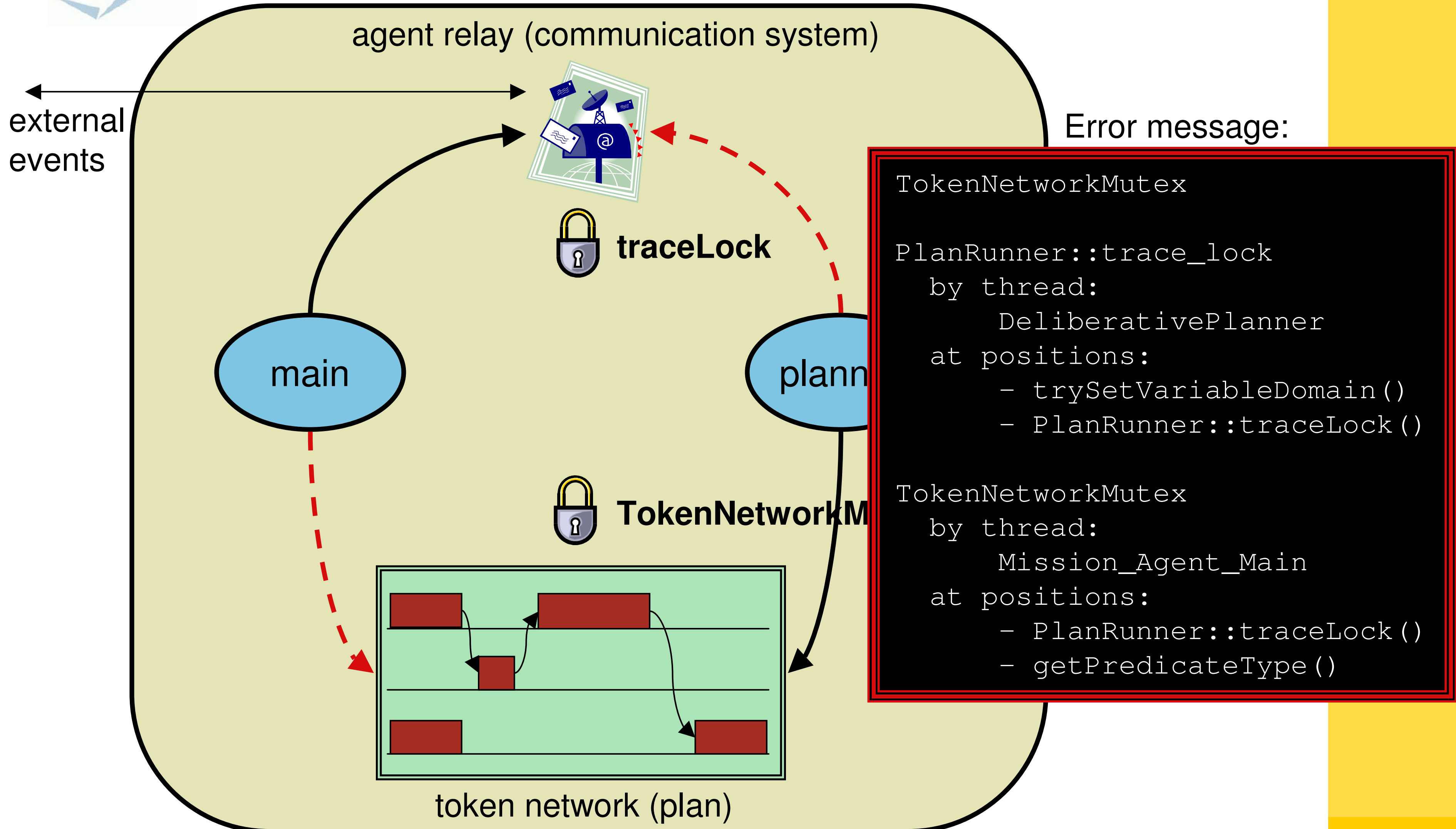
Found 2 deadlocks.

NASA attitude controller:

No deadlocks found (but Java version of Eraser found a data race).

Deadlock Analysis of the NASA 'IDEA' Planner

With Chuck Fry,
QSS, NASA Ames



Observations

- **Dynamic Analysis**
  - It's very easy to instrument code for this analysis. Static analysis is much more complicated to implement (consider fx. C++, it took programmer only 20 min. to instrument rover code for dynamic analysis).
  - Detects bugs very efficiently, usually in first run.
  - However, combine with test case generation for better results.
  - Study is needed to explore relationship with coverage criteria.

- **Static analysis:**
  - Some dynamic cases seem hard to catch statically (Dining Phil. modulo).
  - However, static analysis might be used to detect "as much as possible". Combine with dynamic analysis. Systematic comparison needed.
  - Type systems.

- **Preventive meassures:**
  - Multiple locking operations:

    ```
    synchronized(A,B){…}
    ```

  - A planning oriented approach, where programmer states intentions.

End