Automata-Based Analysis of Recursive Programs with Threads

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Introduction

Threads & Recursion

Locks & monitors & joins

Optimal Analysis:

- Complete analysis of well-specified abstract model

Regular model checking

Reachability Analysis of Programs with Procedures and Thread Creation

Theorem [Ramalingam]

Reachability is undecidable in programs with two threads, synchronous communication, and procedures.

Proof:

Reduction of intersection problem ($L_1 \cap L_2 \neq \emptyset$) of contextfree languages L_1, L_2.

$\Rightarrow$ abstract from synchronous communication (for now).

A Model of Recursive Programs with Thread-creation: DPNs: Dynamic Pushdown-Networks

- A *dynamic pushdown-network (DPN)* over finite set of actions Act consists of:
  - P, a finite set of control symbols
  - Γ, a finite set of stack symbols
  - Δ, a finite set of rules of the following form

$$p\gamma \xrightarrow{a} p_1 w_1 \qquad [\text{ with } |w_1| \leq 2 \ ]$$

$$p\gamma \xrightarrow{a} p_1 w_1 \triangleright p_2 w_2 \qquad [\text{ with } |w_1| = 1 \text{ and } |w_2| = 1 \ ]$$

  (with $p, p_1, p_2 \in$ P, $\gamma \in \Gamma$, $w_1, w_2 \in \Gamma^*$, a$\in$ Act).

- DPNs can model recursive programs with thread-creation primitives using finite abstractions of (thread-local) global variables and local variables of procedures.

Execution-Semantics of DPNs on Word-Shaped Configurations

A configuration of a DPN is a word in $(P\Gamma^*)^+$:

$$p_1 w_1 p_2 w_2 \cdots p_k w_k \qquad \text{(with } p_i \in P, w_i \in \Gamma^*, k > 0\text{)}$$

... an infinite state space

The transition relation of a DPN:

$$\left(p\gamma \xrightarrow{a} p_1 w_1\right) \in \Delta: \qquad u\, p\, \gamma v \xrightarrow{a} u\, p_1\, w_1\, v$$

$$\left(p\gamma \xrightarrow{a} p_1 w_1 \rhd p_2 w_2\right) \in \Delta: \qquad u\, p\, \gamma v \xrightarrow{a} u\, p_2\, w_2\, p_1\, w_1\, v$$

Example

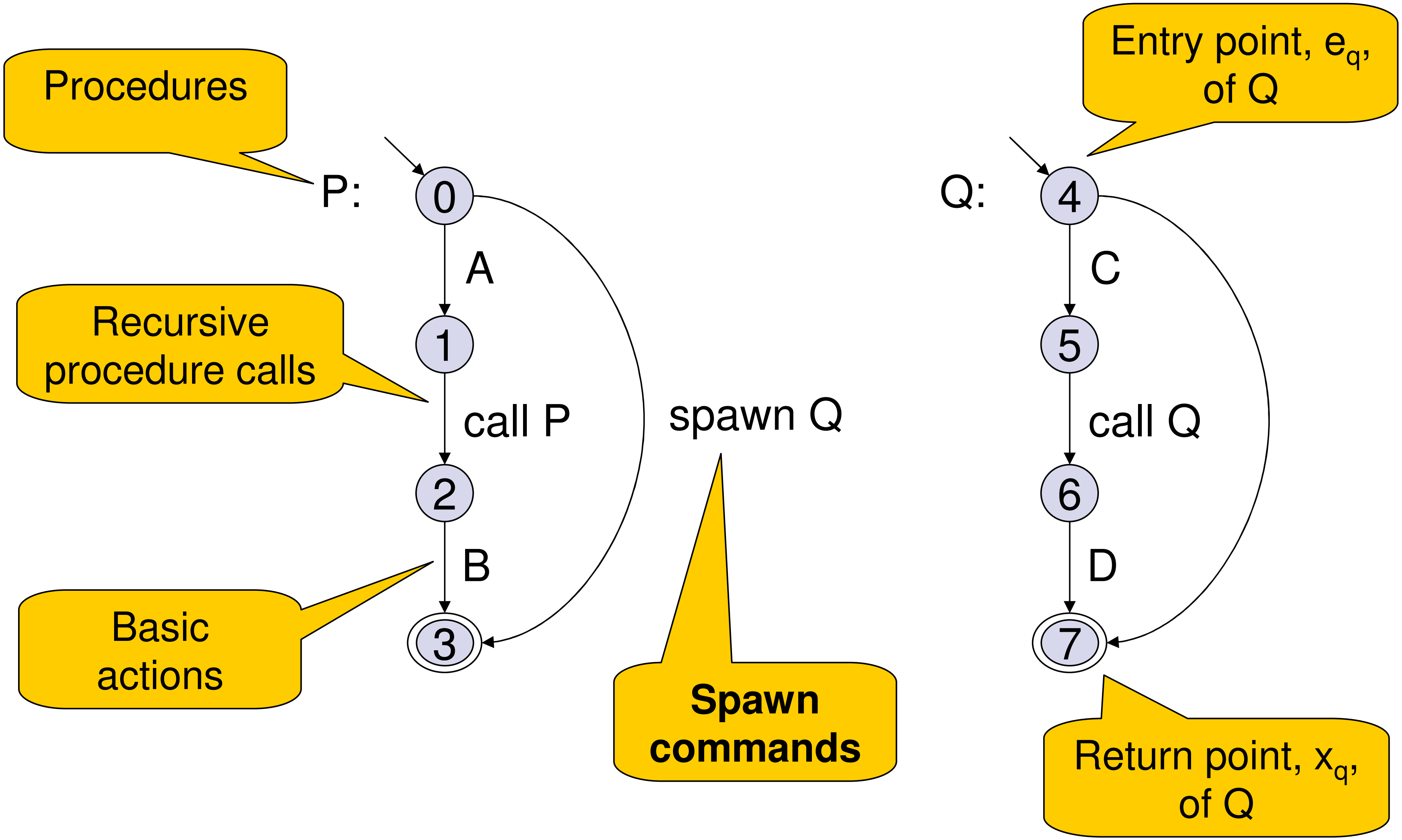
Consider the following DPN with a single rule

$$p\gamma \xrightarrow{a} p\gamma\gamma \triangleright q\gamma$$

Transitions:

$$p\gamma$$
$$q\gamma p\gamma\gamma$$
$$q\gamma q\gamma p\gamma\gamma\gamma$$
$$q\gamma q\gamma q\gamma p\gamma\gamma\gamma\gamma$$
$$q\gamma q\gamma q\gamma q\gamma p\gamma\gamma\gamma\gamma\gamma$$
$$\vdots$$

Recursive Programs with Thread Creation



+ finite-state abstraction of (thread-local) global and local variables

Modelling Programs with DPNs

à la [Esparza/Knoop, FOSSACS'99]

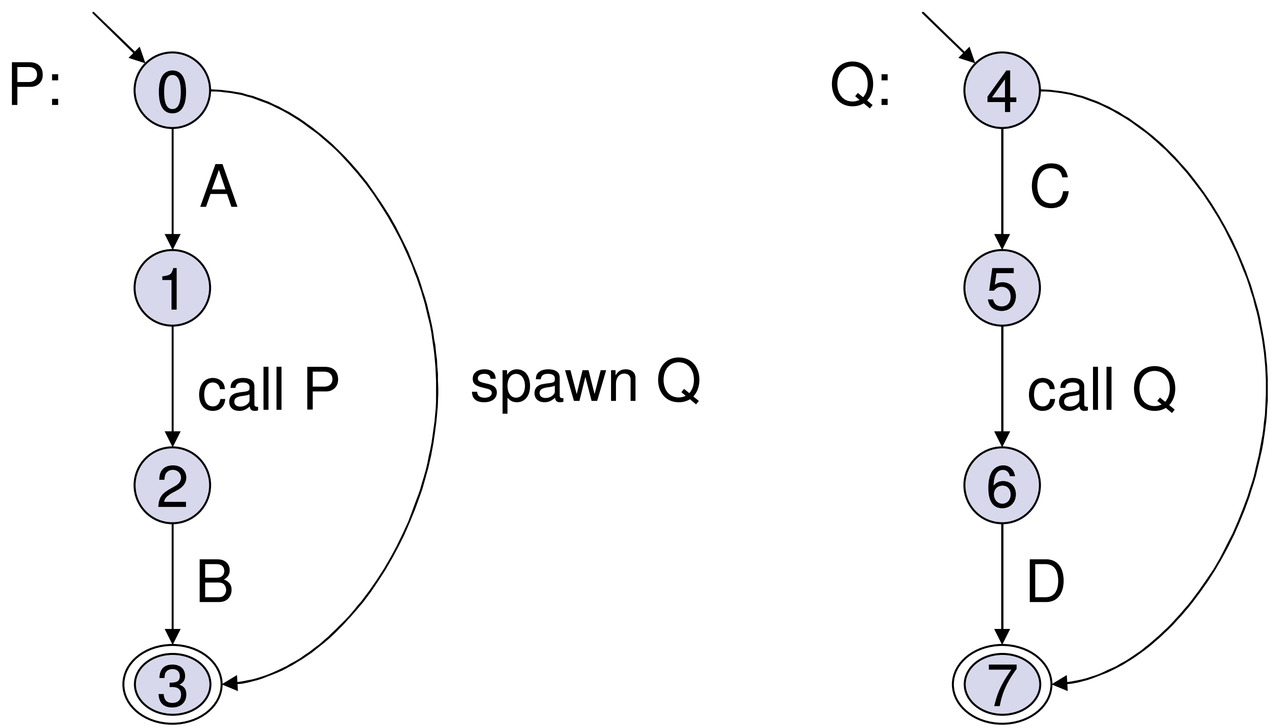
abstraction of global state

abstraction of local state

current control point

for basic edge e:	$u \xrightarrow{A} v$	$g\langle l,u\rangle \xrightarrow{e} g'\langle l',v\rangle, \quad \text{if } ((g,l),(g',l')) \in [\![A]\!]^{\#}$
for call edge e:	$u \xrightarrow{\text{call } P} v$	$g\langle l,u\rangle \xrightarrow{e} g\langle l_{\text{init}}, e_P\rangle\langle l,v\rangle$
for return point of each procedure	r_P	$g\langle l,r_P\rangle \xrightarrow{ret} g$
for spawn edge e:	$u \xrightarrow{\text{spawn P}} v$	$g\langle l,u\rangle \xrightarrow{e} g\langle l,v\rangle \triangleright g_{\text{init}}\langle l_{\text{init}}, e_P\rangle$

Spawns are Fundamentally Different



P induces trace language: $L = \bigcup \{ A^n \cdot (B^m \otimes (C^i \cdot D^j) \mid n \geq m \geq 0,\ i \geq j \geq 0 \}$

Cannot characterize L by constraint system with „·“ and „⊗“.

Trace languages of DPNs differ from those of PA processes.

[Bouajjani, MO, Touili: CONCUR 2005]

Basic Results on Reachability Analysis of DPNs

[Bouajjani, MO, Touili, CONCUR 2005]

Definition

$$\mathrm{pre}^*[L](C) := \{c \mid \exists d \in C, w \in L : c \xrightarrow{w}{}^* d\}$$

$$\mathrm{post}^*[L](C) := \{d \mid \exists c \in C, w \in L : c \xrightarrow{w}{}^* d\}$$

Forward-Reachability

1) post*[Act*](C) is in general non-regular for regular C.
2) post*[Act*](C) is effectively context-free for context-free C (in polyn. time).
3) Membership in post*[L](C) is in general undecidable for regular L.

Backward-Reachability

1) pre*[A*](C) is effectively regular for regular C and A $\subseteq$ Act (in polyn. time).
2) Membership in pre*[L](C) is in general undecidable for regular L.

Single Steps

1) pre*[A](C) and post*[A](C) are effectively regular for regular C and A $\subseteq$ Act (in polyn. time).

Example: Backward Reachability Analysis for DPNs

Consider again DPN with the rule

$$p\gamma \xrightarrow{a} p\gamma\gamma \triangleright q\gamma$$

and the infinite set of states

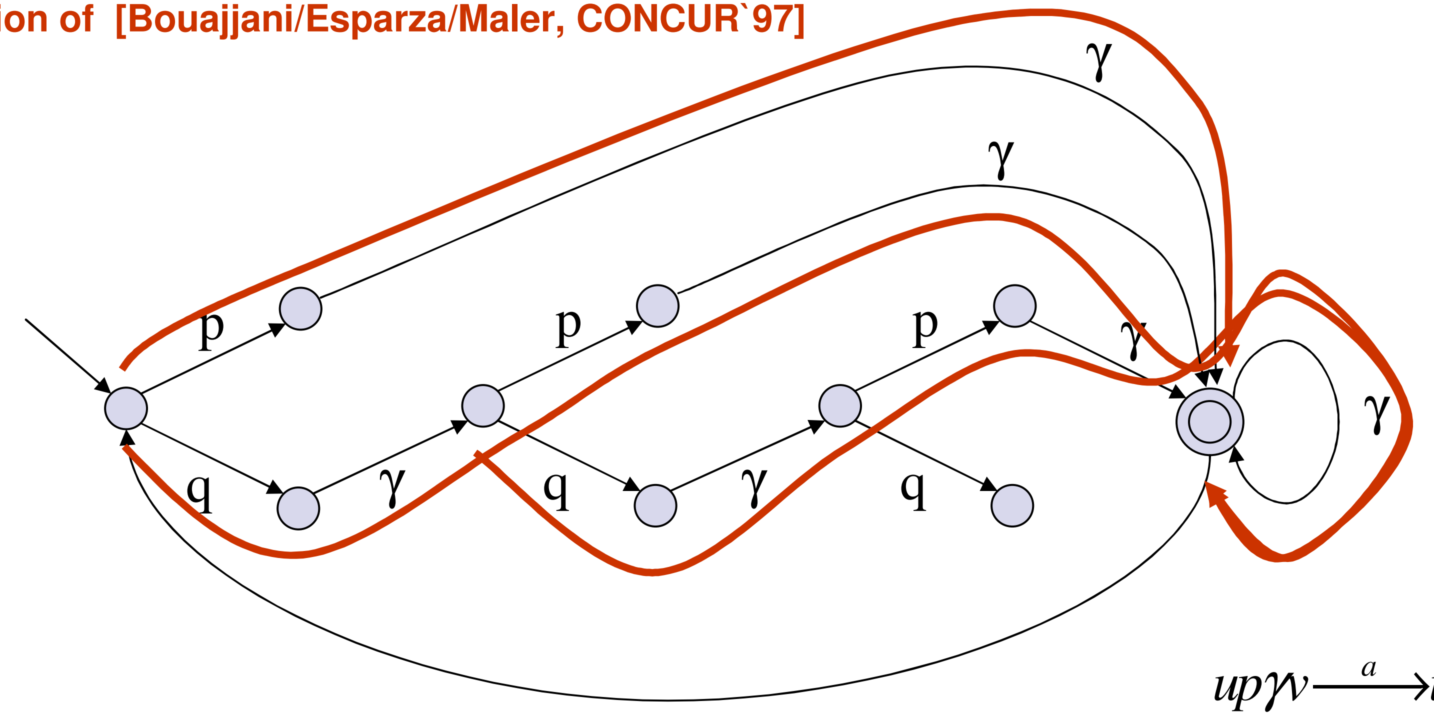
$$\text{Bad} = \left(q\gamma q\gamma p\gamma^{+}\right)^{+} = L(A)$$

Analysis problem: can Bad be reached from pγ ?

Example: Backward Reachability Analysis for DPNs

1. Step: Saturate automaton for Bad with the DPN rule: $p\gamma \xrightarrow{a} p\gamma\gamma \rhd q\gamma$

Generalization of [Bouajjani/Esparza/Maler, CONCUR`97]



$up\gamma v \xrightarrow{a} uq\gamma p\gamma\gamma v$

Resulting automaton A_{pre*} represents pre*(Bad) !

2. Step: Check, whether pγ is accepted by A_{pre*} or not

Result: Bad is reachable from pγ, as A_{pre*} accepts pγ !

Some Applications of pre*-Computations with unrestricted L (i.e. L = Act*)

Reachability of regular sets of configurations

Set Bad of configurations is reachable from initial configuration $p_0\gamma_0$

iff

$p_0\gamma_0 \in$ pre*[Act*](Bad)

Bounded model checking

used in JMoped of Schwoon/Esparza

By iterated pre*-computations alternating with single steps corresponding to synchronizations/communications

Bit-vector data-flow analysis problems

à la [Esparza/Knoop, FOSSACS'99]

Variable x is live at program point u

iff

$$e_{Main} \in pre^*[Act^*]\big(At_u \cap pre^*[NonDef_x{}^*]\big(pre^*[Use_x](Conf)\big)\big)$$

Exploiting a Tree-Shaped View of Configurations
CDPNs: Constrained Dynamic Pushdown-Networks

Idea:

Add (regular, stable) pre-conditions over current control symbols of children threads to DPN rules.

A *constrained dynamic pushdown-network* (CDPN) consists of:

- P, a finite set of control symbols
- Γ, a finite set of stack symbols
- Δ, a finite set of rules of the following form

$$\phi: p\gamma \xrightarrow{a} p_1 w_1 \qquad \text{where } \phi \subseteq P^*$$

$$\phi: p\gamma \xrightarrow{a} p_1 w_1 \rhd p_2 w_2 \qquad \text{where } \phi \subseteq P^*$$

(with $p, p_1, p_2 \in$ P, $\gamma \in \Gamma$, $w_1, w_2 \in \Gamma^*$, a$\in$ Act)

Example: A CDPN

1. Phase: $p\gamma \xrightarrow{a} p\gamma\gamma \triangleright q_0\gamma$

$\phi: p\gamma \xrightarrow{b} p'$ with $\phi = ((q_1 + q_2)q_2)^*$

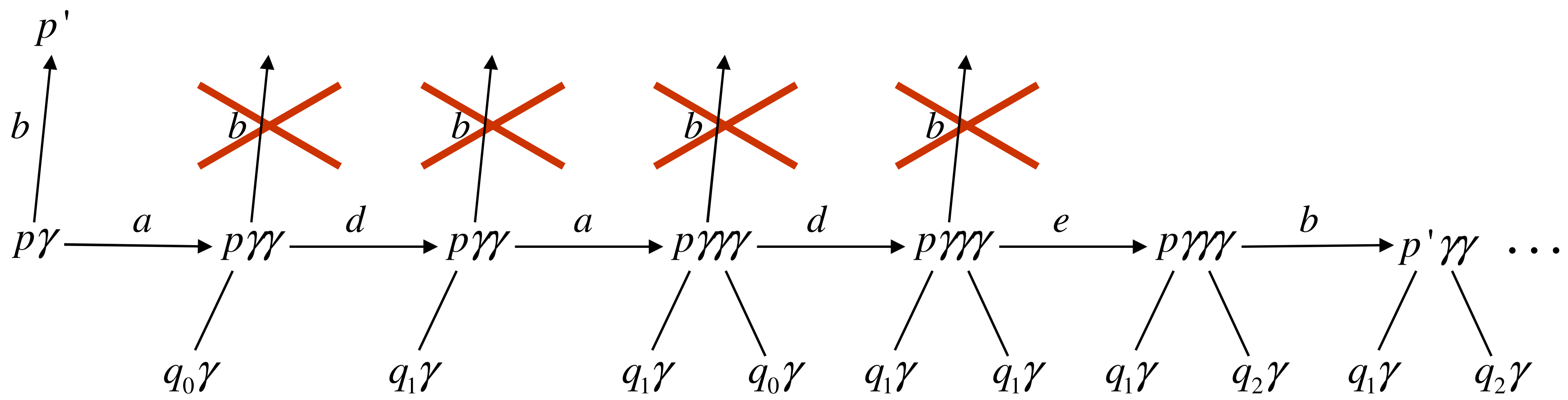
2. Phase: $p'\gamma \xrightarrow{c} p'$

$q_0\gamma \xrightarrow{d} q_1\gamma$

$q_1\gamma \xrightarrow{e} q_2\gamma$

Constraint ϕ means: Proceed to second phase only if:

- an even number of children threads has been created,
- each second child has terminated, and
- each child has performed at least one step.



Reachability Analysis of CDPNs

Definition

Constraint ϕ is called stable for Δ if:

$$upv \in \phi\,,\ (\psi : p\gamma \xrightarrow{a} p_1 w_1) \in \Delta \quad \text{implies} \quad up_1 v \in \phi, \text{ and}$$

$$upv \in \phi\,,\ (\psi : p\gamma \xrightarrow{a} p_1 w_1 \triangleright p_2 w_2) \in \Delta \quad \text{implies} \quad up_1 v \in \phi$$

Theorem for CDPNs [Bouajjani, MO, Touili, CONCUR 2005]

pre*[Act*](C) is effectively regular for regular C and A $\subseteq$ Act,
if all constraints ϕ occuring in rules of the CDPN are regular and stable for Δ.

Problem at least PSPACE-hard

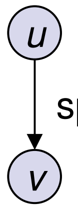
Modelling power of stable constraints:

Parallel procedure calls, various join-statements, return values from parallel procedure calls, phased execution.

Modelling Power of Stable Regular Constraints

As a preparation: Indicate termination of son threads by a special control state §:

for spawn edge e:



spawn P

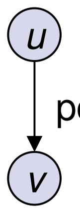
$$g\left\langle l,u\right\rangle \xrightarrow{e} g\left\langle l,v\right\rangle \triangleright g_{\text{init}}\left\langle l_{\text{init}},e_P\right\rangle \$$$

one special type of rules:

$$p\$ \xrightarrow{e} §$$

Model parallel call to two procedures:

for parallel call edge e:



pcall(P,Q)

$$g\left\langle l,u\right\rangle \xrightarrow{P\|.} g\left\langle l,u^1\right\rangle \triangleright g_{\text{init}}\left\langle l_{\text{init}},e_P\right\rangle \$$$

$$g\left\langle l,u^1\right\rangle \xrightarrow{.\|Q} g\left\langle l,u^2\right\rangle \triangleright g_{\text{init}}\left\langle l_{\text{init}},e_Q\right\rangle \$$$

$$P*§§ : g\left\langle l,u^2\right\rangle \xrightarrow{P\|Q} g\left\langle l,v\right\rangle$$

Modelling Power of Stable Regular Constraints (Ctd.)

Model various types of join-statements:

- proceed if all children have terminated: $\S^*$: ...
- proceed if last child has terminated: $P^*\S$: ...
- proceed if some child has terminated: $P^*\S P^*$: ...
- proceed if every second child has terminated: $(P\S)^*(P+\varepsilon)$: ...
- ...

Model return values of parallel procedures (beyond PA!):

$$P^*\S_p\S_q : g\left\langle l,u^2\right\rangle \xrightarrow{P||Q} g_{pq}\left\langle l,v\right\rangle$$

Model phased execution

...

Synchronization via Locks

- Assume finite set of locks
- Have acquire- and release actions
  - acq L, rel $L \in$ Act f.a. locks L
- Intuition: At any time a lock can be hold by at most one thread
- Goal of lock-sensitive analysis

The Results of Kahlon and Gupta

Theorem 1 [Kahlon/Gupta, LICS 2006]

Reachability is undecidable for two pushdown-systems running in parallel and synchronizing by release- and acquire-operations used in an unstructured way.

Idea: Can simulate synchronous communication

Theorem 2 [Kahlon/Gupta, LICS 2006]

Reachability is decidable for two pushdown-systems running in parallel and synchronizing by release- and acquire-operations used in a nested fashion.

Idea: Collect information about lock usage of each process in **„acquisition histories“** and check mutual consistency of the collected histories.

Our goal: Lock-sensitive analysis for **systems with thread creation**

Example: Locksets are not Precise Enough

Thread 1:
- acquire L1
- acquire L2
- release L2

X:

Thread 2:
- acquire L2;
- acquire L1;
- release L1;

Y:

Must-Lockset computed at X: { L1 }

Must-Lockset computed at Y: { L2 }

We have disjoint locksets at X and Y: { L1 } $\cap$ { L2 } = { } .

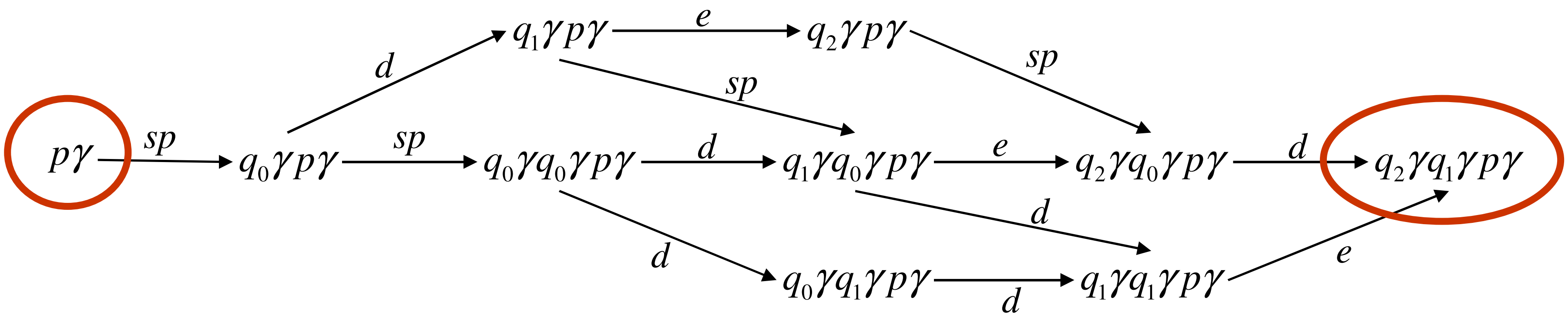
Nevertheless, X and Y are not reachable simultaneously !

A Tree-Based View of Executions: Action Trees

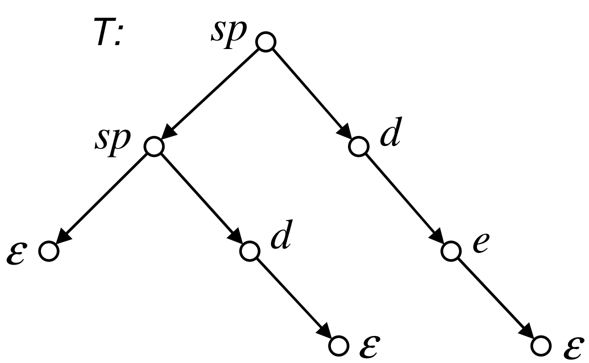
A DPN: $p\gamma \xrightarrow{sp} p\gamma \rhd q_0\gamma$ $\quad$ $q_0\gamma \xrightarrow{d} q_1\gamma$

$q_1\gamma \xrightarrow{e} q_2\gamma$

Action sequences:



Action tree:



We write: $p\gamma \xrightarrow{T}{}^{*} q_2\gamma q_1\gamma p\gamma$

A Tree-Based View of Executions

Definition

$$\mathrm{pre}^*[L](C) \quad := \{c \mid \exists d \in C, w \in L : c \xrightarrow{w}{}^* d\} \qquad \text{where } L \subseteq Act^*$$

$$\mathrm{preT}^*[M](C) := \{c \mid \exists d \in C, T \in M : c \xrightarrow{T}{}^* d\} \qquad \text{where } M \subseteq Trees(Act)$$

Recall:

Membership in pre*[L](C) is undecidable for regular L already for very simple languages C (e.g. singletons).

Theorem for DPNs [Lammich, MO, Wenner, CAV 2009]

preT*[M](C) is effectively regular for regular C and regular M (on trees).

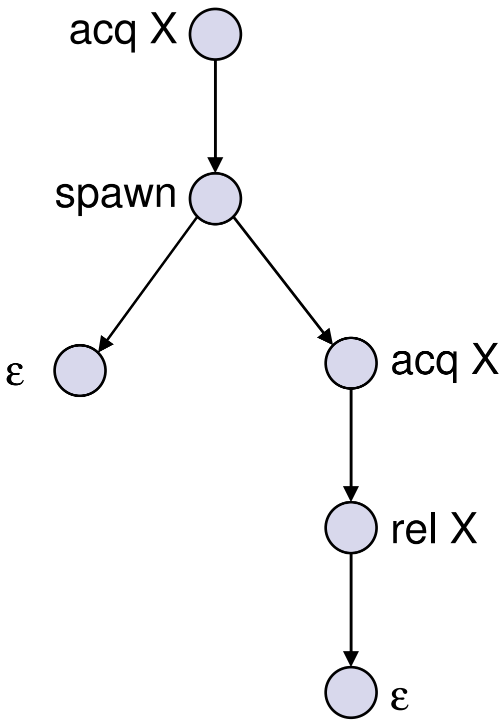
Theorem 2 [Lammich, MO, Wenner, CAV 2009]

In a DPN that uses locks in a well-nested and non-reentrant fashion:
Set of tree-shaped executions having a lock-sensitive schedule is regular.

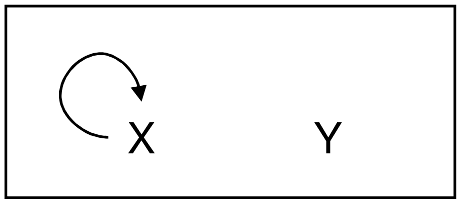
Idea of proof: Generalize Kahlon and Gupta‘s acquisition histories.

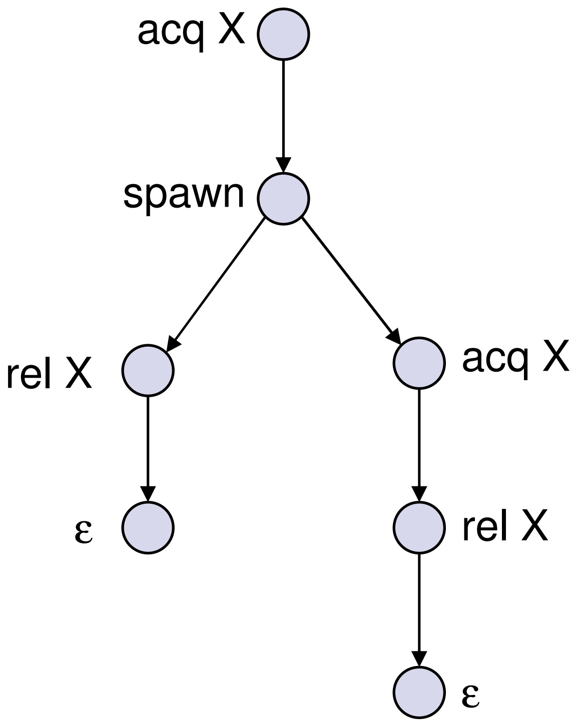
Size of automaton exponential in number of locks...

Which of these trees have a lock-sensitive schedule?

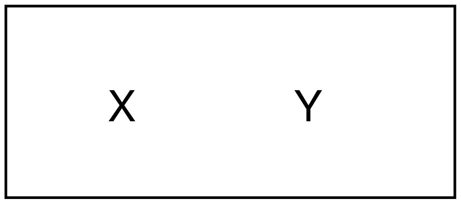


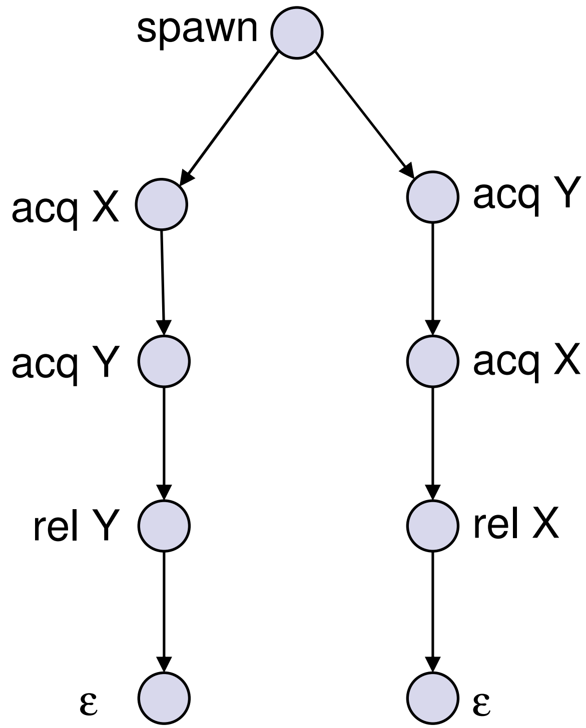
No!



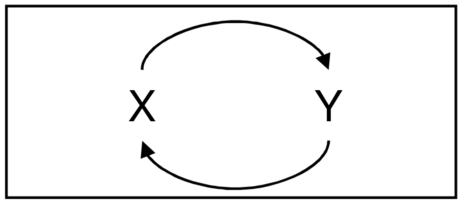


Yes: (0,acq X),(0,sp),(0,rel X),
(1,acq X),(1,rel X)





No!

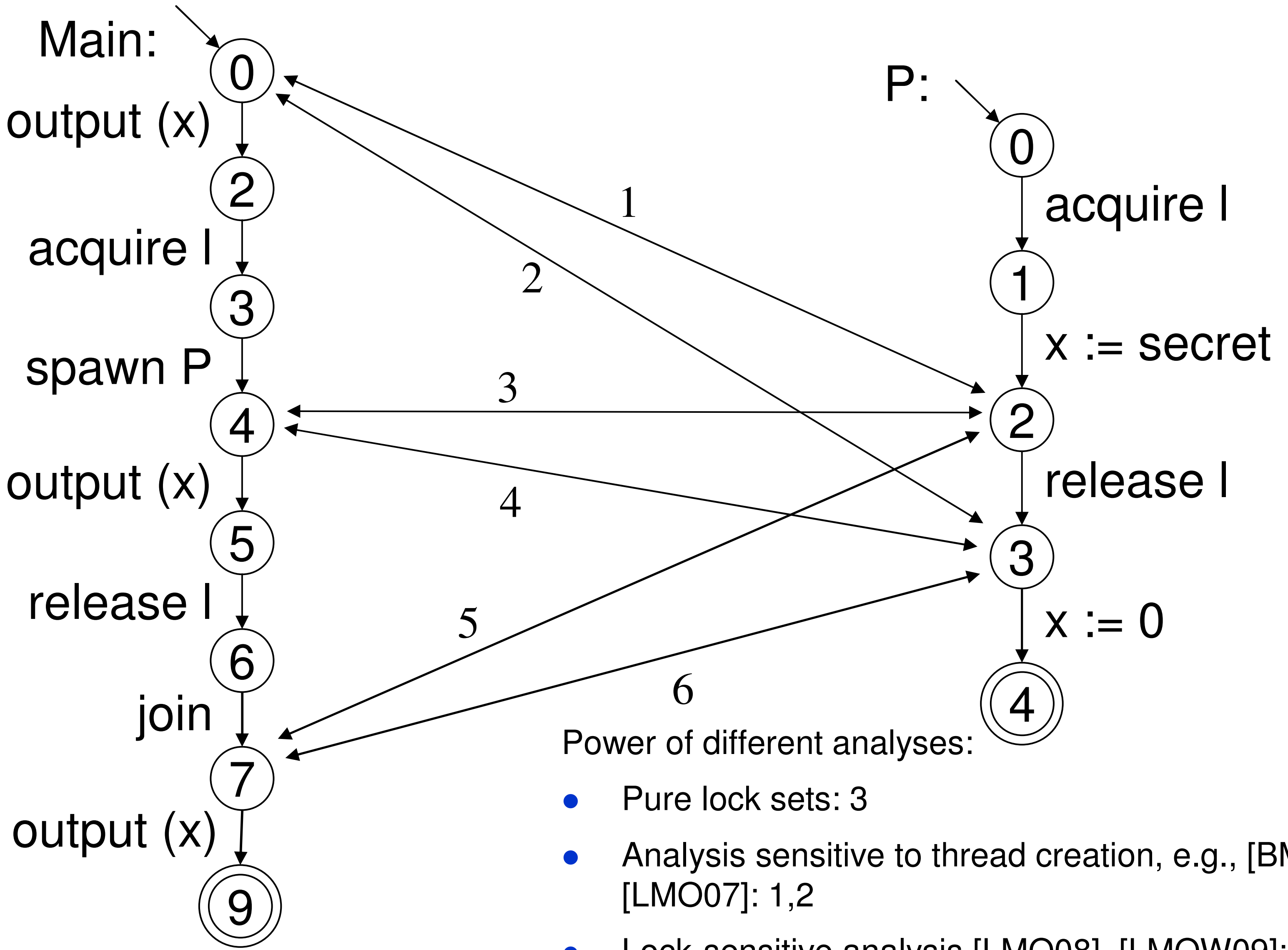


Applications

Lock-(join-)sensitive ...

- ... reachability analysis to regular sets of configurations
- ... bounded model checking
- ... DFA of bitvector problems

Lock-join-sensitive Analysis



Power of different analyses:

- Pure lock sets: 3
- Analysis sensitive to thread creation, e.g., [BMOT05], [LMO07]: 1,2
- Lock-sensitive analysis [LMO08], [LMOW09]: 1,2,3,4
- Lock-join-sensitive analysis [GLMOSW11]: 1,2,3,4,5, 6

Of course, also treat branching, loops, recursion !

More Recent Work (VMCAI 2011): An Even More Regular View to Executions: Execution Trees

Joint work with:

- Thomas Gawlitza, Helmut Seidl (TU München)
- Peter Lammich, Alexander Wenner (WWU Münster)

Realised for Java analysis: Benedikt Nordhoff's diploma thesis

Example:

$$Call_0: \quad p\gamma \xrightarrow{cl} p'\gamma\gamma$$

$$Spawn_1: \quad p'\gamma \xrightarrow{sp} p\gamma \triangleright q\gamma$$

$$Ret_2: \quad p\gamma \xrightarrow{ret_2} p''$$

$$Ret_3: \quad p''\gamma \xrightarrow{ret_3} p''$$

$$Ret_4: \quad q\gamma \xrightarrow{ret_4} q$$

Execution Tree vs. Action Tree

The DPN:

$$Call_0 : \quad p\gamma \xrightarrow{cl} p'\gamma\gamma$$

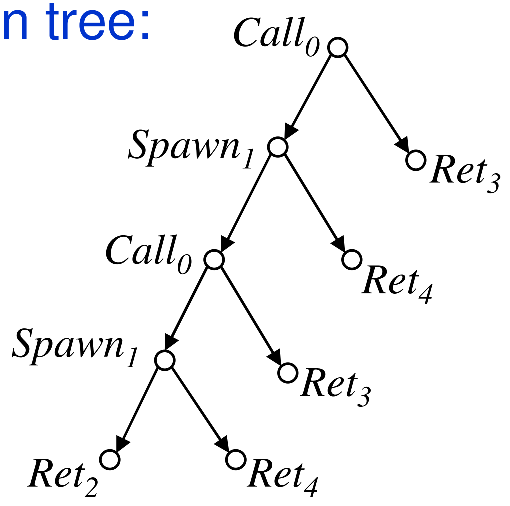
$$Spawn_1 : \quad p'\gamma \xrightarrow{sp} p\gamma \triangleright q\gamma$$

$$Ret_2 : \quad p\gamma \xrightarrow{ret_2} p''$$

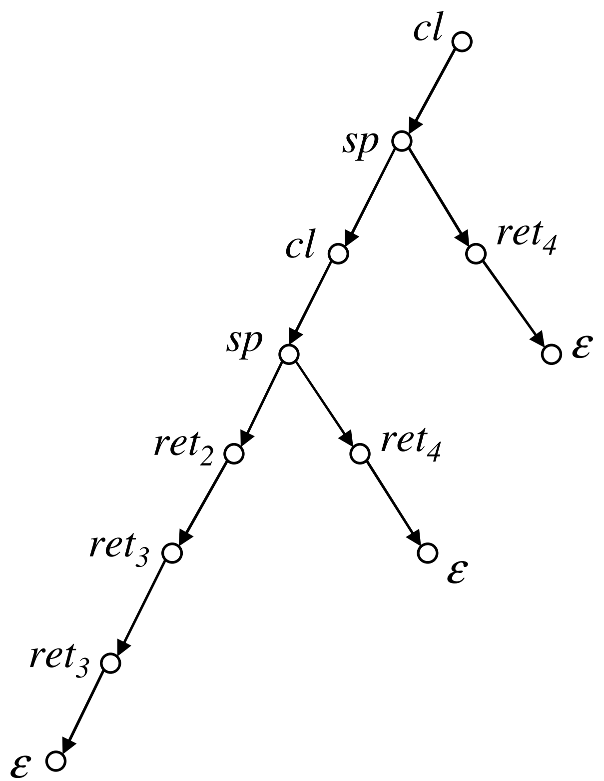
$$Ret_3 : \quad p''\gamma \xrightarrow{ret_3} p''$$

$$Ret_4 : \quad q\gamma \xrightarrow{ret_4} q$$

Execution tree:



Action tree:



Execution Trees

Recall: post*[Act*]($p_0\gamma_0$) is non-regular in general.

Observation 1:

Set of all execution trees from given initial config., postE*($p_0\gamma_0$), is regular !

Observation 2:

Set of execution trees that have a lock-sensitive schedule is regular, e.g. for:

- nested non-reentrant locking with structured form of joins
- reentrant block-structured locking (monitors, synchronized-blocks)

Observation 3:

Set of execution trees reaching a given regular set C of configs is regular

Obtain homogenous approach to, e.g., lock-sensitive reachability:

Reg. set C is lock-sensitively reachable from start config $p_0\gamma_0$

iff

postE*($p_0\gamma_0$) $\cap$ LockSensTrees $\cap$ ExecTrees(C) is non-empty.

(Finite) Tree-Automata

Definition

Let Σ be a finite ranked alphabet.

(Finite bottom-up) tree automaton (over Σ):

A structure $T = (Q, Q_F, \delta)$ with:

- Q: finite set of states
- $Q_F \subseteq Q$: accepting states
- δ: set of rules of the form:

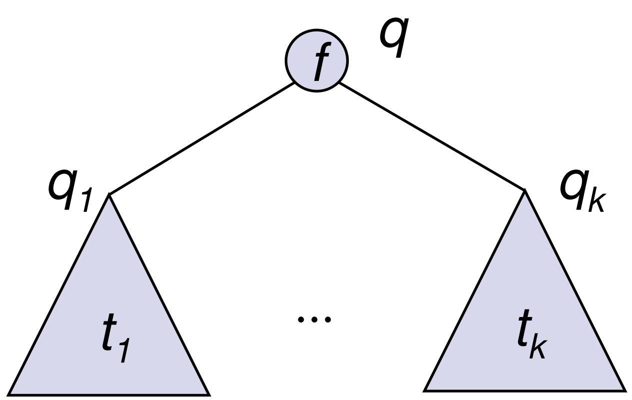
  $f(q_1,\ldots,q_k) \to q$ with $q, q_1,\ldots,q_k \in Q$, $f \in \Sigma$ of rank $k \geq 0$

Acceptance:

a) If
- T accepts trees $t_1,\ldots,t_k$ in states $q_1,\ldots,q_k$ and
- T has rule $f(q_1,\ldots,q_k) \to q$

then
- T accepts tree $f(t_1,\ldots,t_k)$ in state q

b) T accepts a tree t
if T accepts t in an accepting state $q \in Q_F$



Example: (Finite) Tree-Automaton

Ranked alphabet Σ:

Rank 0: true, false   Rank 1: not   Rank 2: and, or

Tree automaton:

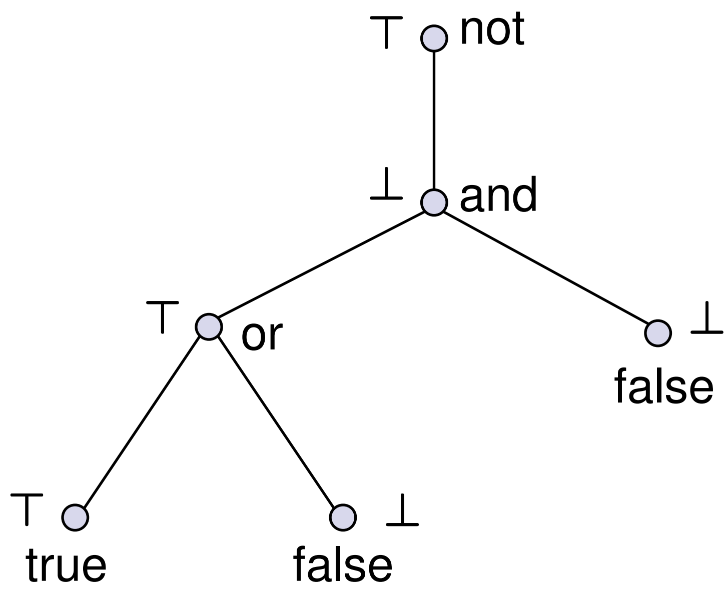
$T = (\{\perp,\top\}, \{\top\}, \delta)$ with

δ :

true $\to \top$	not($\perp$) $\to \top$	or($\perp$,$\perp$) $\to \perp$	and($\perp$,$\perp$) $\to \perp$
false $\to \perp$	not($\top$) $\to \perp$	or($\perp$,$\top$) $\to \top$	and($\perp$,$\top$) $\to \perp$
		or($\top$,$\perp$) $\to \top$	and($\top$,$\perp$) $\to \perp$
		or($\top$,$\top$) $\to \top$	and($\top$,$\top$) $\to \top$

Acceptance of example tree:

not (and (or (true, false), false))



Tree Automaton for Execution Trees of a DPN

States:

(p, γ, c) with $p \in P, \gamma \in \Gamma, p' \in P \cup \{\mathrm{N}\}$

Idea:

(p, γ, c) accepts tree T

iff

a) $c \in P$ and T represents terminating executions from $p\gamma$ to c, or

b) $c = \mathrm{N}$ and T represents non-terminating executions from $p\gamma$

Rules:

$$\text{Nil}: \quad [nil_{p\gamma}] \rightarrow (p, \gamma, N)$$

$$\text{Base rules}: \quad [p\gamma \xrightarrow{a} p'\gamma']((p', \gamma', c)) \rightarrow (p, \gamma, c)$$

$$\text{Call rules}: \quad [p\gamma \xrightarrow{X} p'\gamma'\gamma'']((p', \gamma', p''), (p'', \gamma'', c)) \rightarrow (p, \gamma, c)$$

$$[p\gamma \xrightarrow{X} p'\gamma'\gamma'']((p', \gamma', N)) \rightarrow (p, \gamma, N)$$

$$\text{Return rules}: \quad [p\gamma \xrightarrow{a} p'] \rightarrow (p, \gamma, p')$$

$$\text{Spawn rules}: \quad [p\gamma \xrightarrow{a} p'\gamma' \triangleright p''\gamma'']((p', \gamma', c), (p'', \gamma'', \_)) \rightarrow (p, \gamma, c)$$

Tree Automaton for Execution Trees with Lock-Sensitive Schedule

States: (G, A, U) with $A, U \subseteq Locks$, $G \subseteq Locks \times Locks$, accepting if G is acyclic

Idea: (G, A, U) accepts tree T

iff

a) no lock is finally acquired more than once in T,

b) G contains edge $x \to y$ if lock y is used in T after lock x has been finally acquired,

c) A is the set of finally acquired locks, and

d) U is the set of used locks.

Rules: Nil: $[nil_{p\gamma}] \to (\emptyset, \emptyset, \emptyset)$

Base rules: $[p\gamma \xrightarrow{a} p'\gamma']((G, A, U)) \to (G, A, U)$

Call rules: $[p\gamma \xrightarrow{X} p'\gamma'\gamma''](((G, A, U), (G', A', U')) \to$

$$\text{if } A \cap A' = \emptyset$$

$$[p\gamma \xrightarrow{X} p'\gamma'\gamma''](((G, A, U)) \to (G \cup X \times A, A \cup X, U)$$

$$\text{if } A \cap X = \emptyset$$

Return rules: $[p\gamma \xrightarrow{a} p'] \to (\emptyset, \emptyset, \emptyset)$

Spawn rules: $[p\gamma \xrightarrow{a} p'\gamma' \triangleright p''\gamma''](((G, A, U), (G', A', U')) \to (G \cup G', A \cup A', U \cup U')$

$$\text{if } A \cap A' = \emptyset$$

Realization for Java

Diploma thesis of Benedikt Nordhoff

Uses:

- WALA from IBM: T.J. Watson Libraries for Analysis
- XSB: A Prolog-like system with tabulating evaluation

Identifies object references that can be used as locks

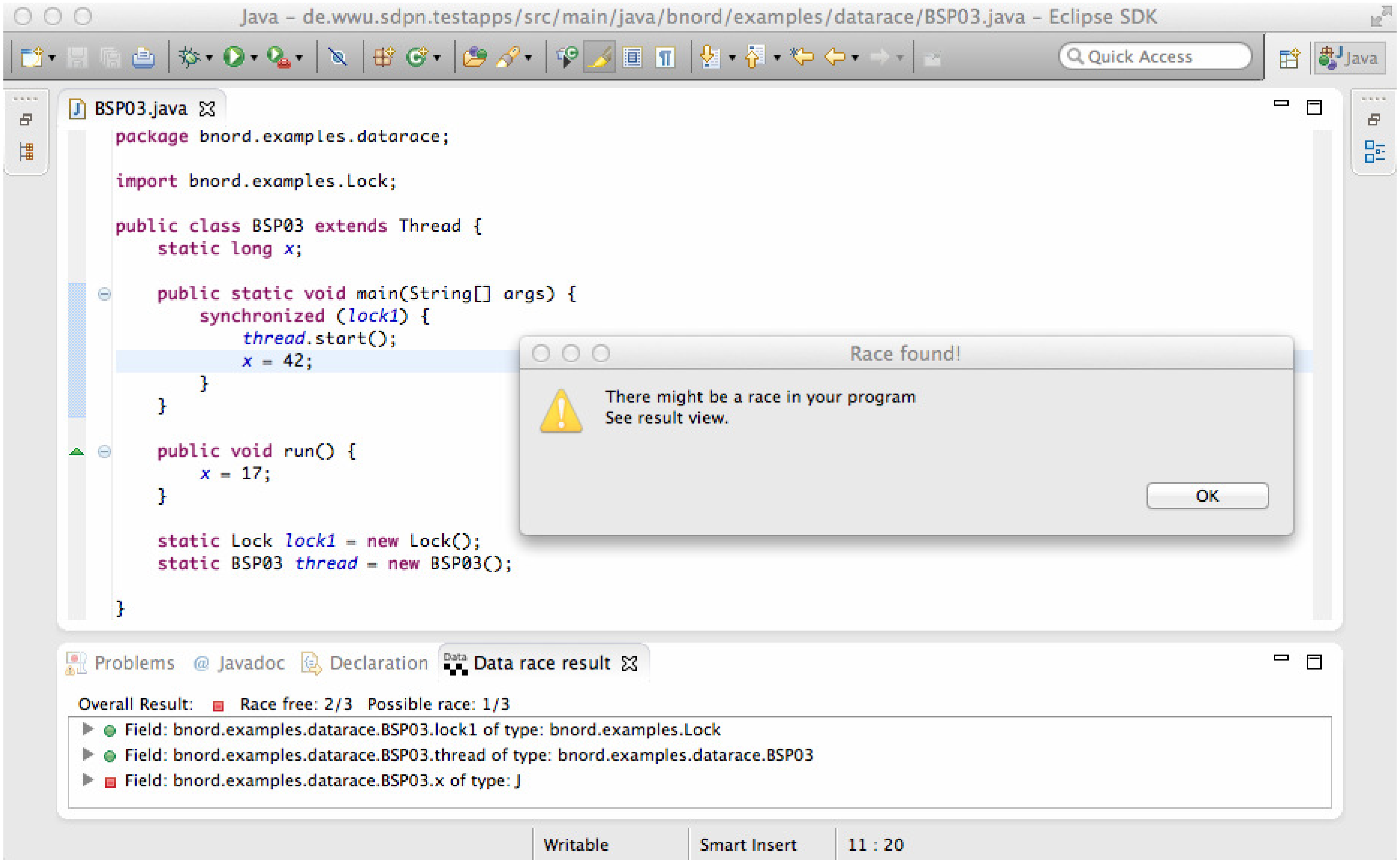
For practicality:

- Pre-analysis of WALA flow graph and (massive) pruning
- Modular reformulation of automata-based analysis
- Clever evaluation strategy for tree automata construction

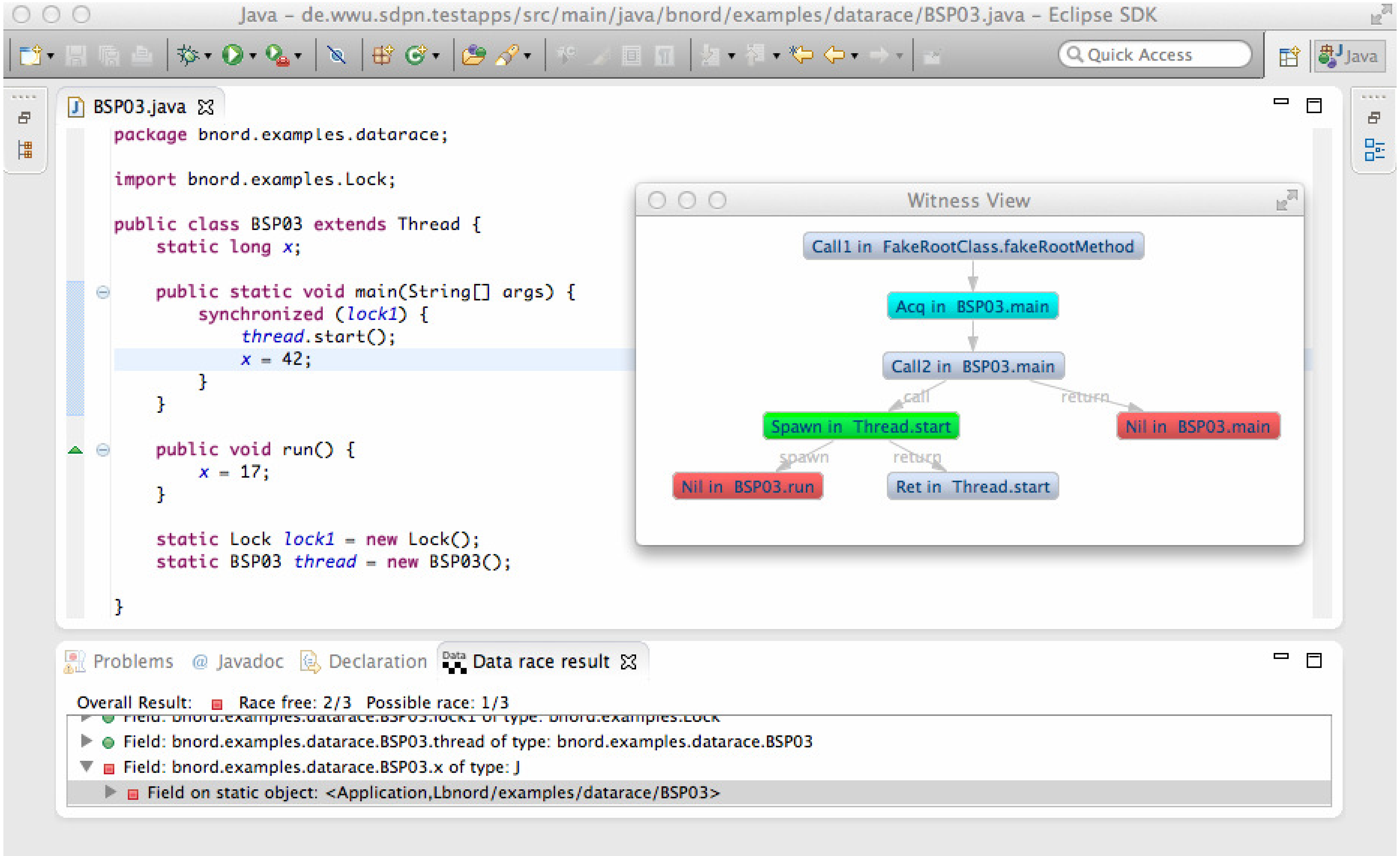
Experimental applications:

- Monitor-sensitive data-race analyzer for Java
- RS3 context: Improve PDG-based IFC analysis of concurrent Java

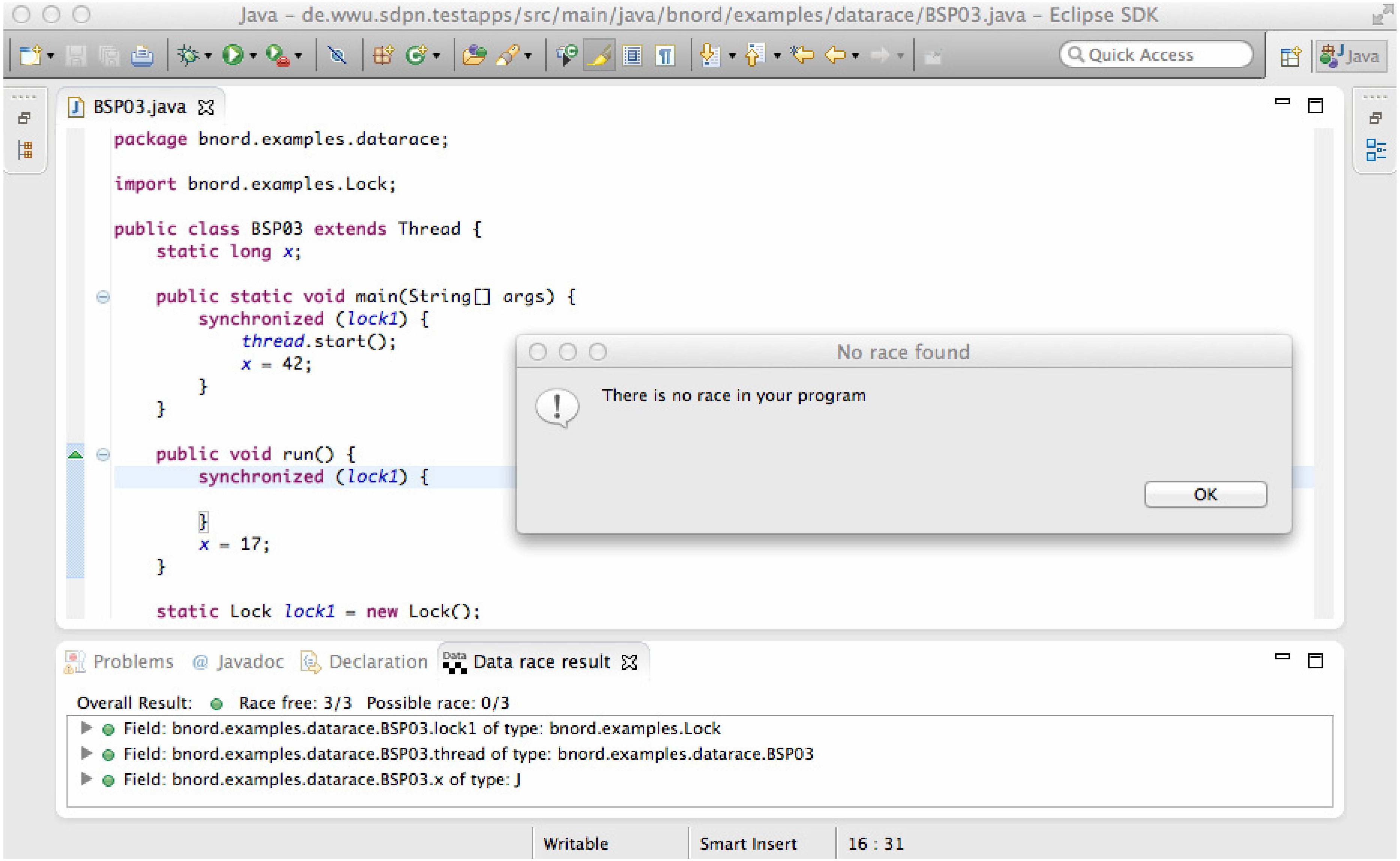
Java Data-Race Finder: Screenshot 1



Java Data-Race Finder: Screenshot 2



Java Data-Race Finder: Screenshot 3



Conclusion

- Lock-join-sensitive analysis using automata
- Finite state + recursion + thread creation + locks + joins
- Experimental applications for Java
- Trees are better than words
- Keeping more structure in the trees is even better