State Space Reduction for Process Algebra Specifications

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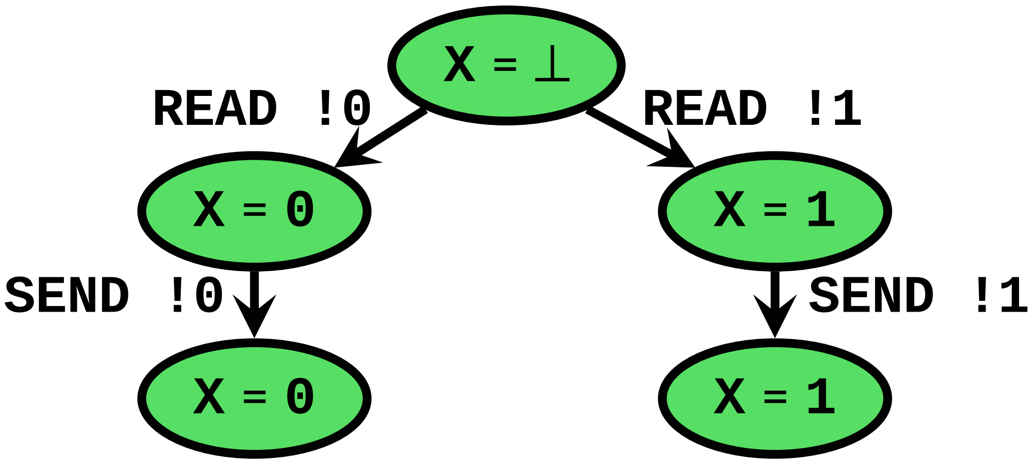
Context

- **CADP**: widespread verification toolbox
  - 307 licenses, 74 case studies, 17 tools using CADP
  - **http://www.inrialpes.fr/vasy/cadp**
- **LOTOS**: international standard (ISO 8807)
  - Based on algebraic methodology
  - Abstract data types and process algebra
- LOTOS-Compilers of CADP
  - CAESAR.ADT (data types), CAESAR (processes)
  - Generation of labeled transition systems (graphs)
  - Used in 32 demos and 60 case-studies

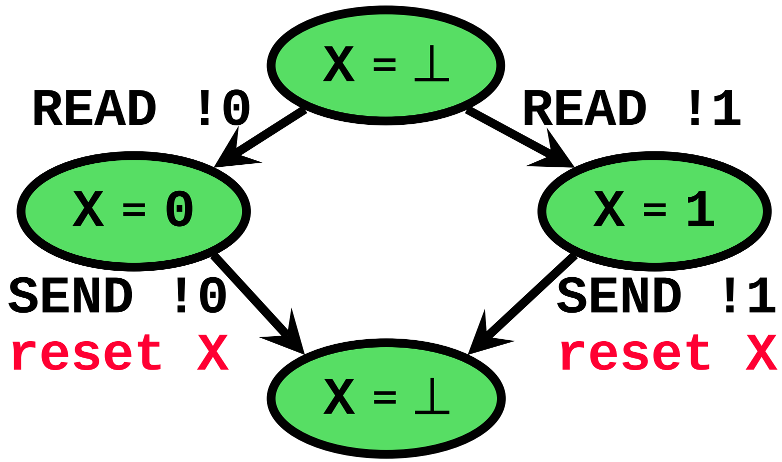
Enumerative Verification

- Classical problem: **state explosion**
- Several techniques – here **resetting variables**
- Graf-Richier-Rodríguez-Voiron 1989:

  Manual insertion of resets in an imperative language
- Example: “**`READ ?X:bit; SEND !X; stop`**”



without reset



with reset

Resetting Variables (1/3)

- Manual insertion of resets

  Error-prone and impossible in "assign-once" languages

- Garavel 1992
  - Translate LOTOS to structured Petri nets with variables

  - "Syntactic criterion":
    reset variables if places of a process loose their token
  - Significant state space reduction (CAESAR 4.2)

Resetting Variables (2/3)

- Galvez-Garavel 1993 (MSc thesis, Grenoble)
  - Attempt of a more precise analysis
  - Local and global data-flow analysis
  - Automatic insertion of resets
  - Successful state space reduction

  But: **errors** in a small number of examples
  Strong bisimulation is not preserved!
  Reason not understood $\Rightarrow$ not embedded in CAESAR

- This paper
  - Understanding of the errors
  - Solution

Resetting Variables (3/3)

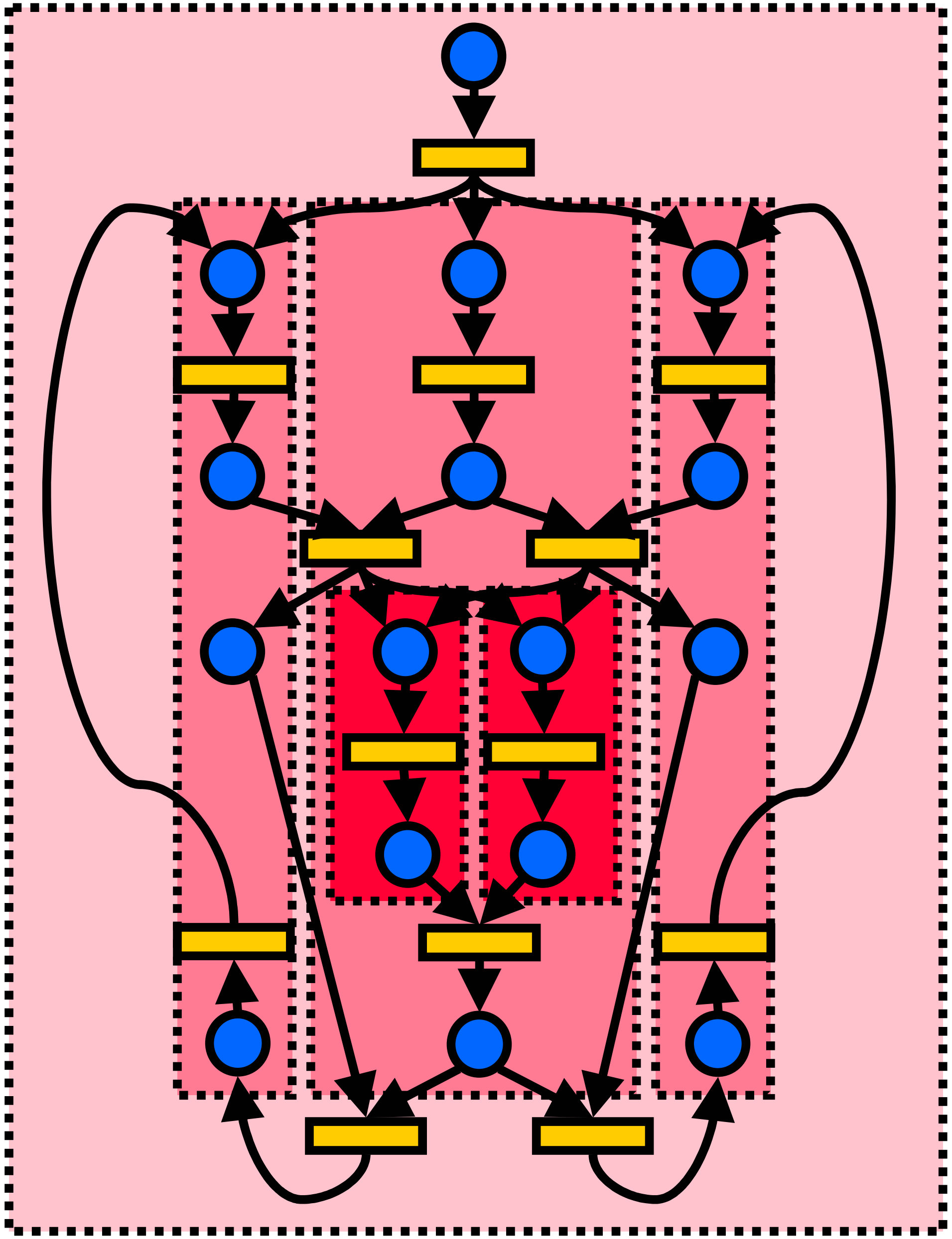
Related work

- Dong-Ramakrishnan 1999
  - Same syntactic criterion as CAESAR
  - Removing variables instead of resetting variables
- Holzmann 1999
  - Imperative language
  - Simpler model: *flat* collection of processes
- Bozga-Fernandez-Ghirvu 1999
  - Simpler model: *flat* collection of processes
  - But: Correctness proofs

Network Model of CAESAR

(section 2 of the paper)

Network Model of CAESAR (1/2)



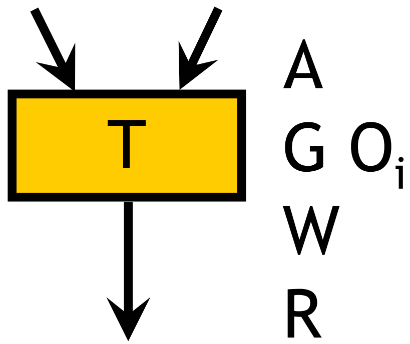
Structured Petri Nets

- Places
- Transitions
- Units
  - Partition of the places
  - Subunit relation: $\subseteq$

Properties of units

- Tree shaped hierarchy
- At most 1 marked place
- U_1 and $U_2 \subseteq U_1$ are not marked simultaneously

Network Model of CAESAR (2/2)



Typed variables

- Attached to units
- Modified by transitions:
  Action A, offer O, guard W, reaction R

Properties of variables

- Variables are defined before used
- Shared variables are read-only
  In the LOTOS behavior: "**G ?X:S; (P1 ||| P2)**"
  - "**X**" can be read by "**P1**" and "**P2**"
  - "**X**" cannot be modified by "**P1**" or "**P2**"

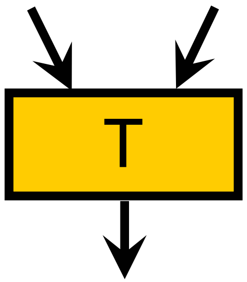
Local Data-Flow Analysis

(section 3 of the paper)

Local Data-Flow Analysis

- Intra-transition
- Predicates on transition T and variable X

  defined by structural induction on T (i.e., A, O, W, R)
  - ***use*(T, X)**: value of X accessed by T
  - ***def*(T, X)**: value of X defined *at the end* of T
  - ***use_before_def*(T, X)**: value of X accessed *at the beginning* of T, i.e., *before* a possible *redefinition*
- Example




```
COUNT := COUNT+1
READ ?VALUE
when VALUE > COUNT
```

def(T, **COUNT**), *def*(T, **VALUE**)
use(T, **COUNT**), *use*(T, **VALUE**)
use_before_def(T, **COUNT**)

Global Data-Flow Analysis

(section 4 of the paper)

Global Data-Flow Analysis

- Inter-transition: combine local results
- Classically (sequential programs) compute fixed point on (control-flow) graph
- Principal difference: Concurrency Petri nets instead of graphs
- Idea: abstract Petri nets to graphs
  - Nodes: transitions
  - Arcs: successor relation "$T_1 \rightarrow T_2$"

Abstracting Networks to Graphs

Several possibilities:

- Good precision: based on reachable markings
  - "$T_1 \rightarrow_M T_2$" iff exists firable sequence "..., T_1, T_2"
  - State explosion possible
- Poor precision: connection by places
  - "$T_1 \rightarrow T_2$" iff $(\exists\ Q)$ Q output of T_1 and Q input of T_2
  - Simple, but imprecise
- Improvement: analyze variables one by one
  - "$T_1 \rightarrow_X T_2$" iff $(\exists\ Q)$ as above and Q in unit of X
  - Chosen approach

Global Data-Flow Predicates

live(T_0, X) iff
$(\exists\, T_0 \rightarrow_X \dots \rightarrow_X T_n)$
use_before_def(T_n, X)
and
$(\forall i \in \{1, \dots, n\text{-}1\})$
$\neg$*def*(T_i, X)

Backward fixed point

available(T_n, X) iff
$(\exists\, T_0 \rightarrow_X \dots \rightarrow_X T_n)$
def(T_0, X)
and
$(\forall i \in \{0, \dots, n\text{-}1\})$
live(T_i, X)

Forward fixed point

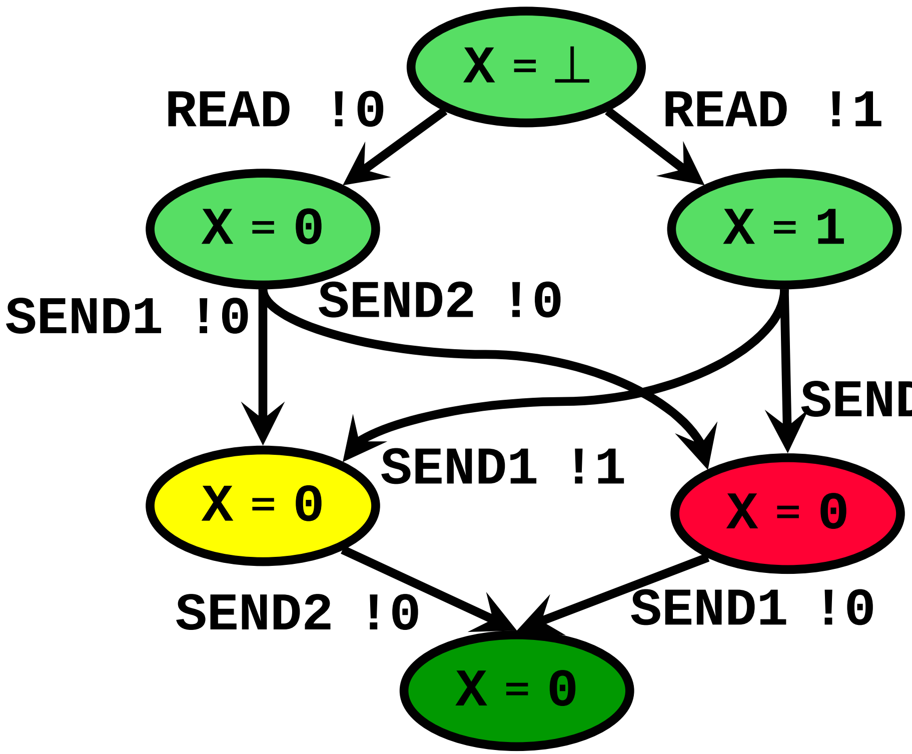
reset(T, X) iff *available*(T, X) and $\neg$*live*(T, X)

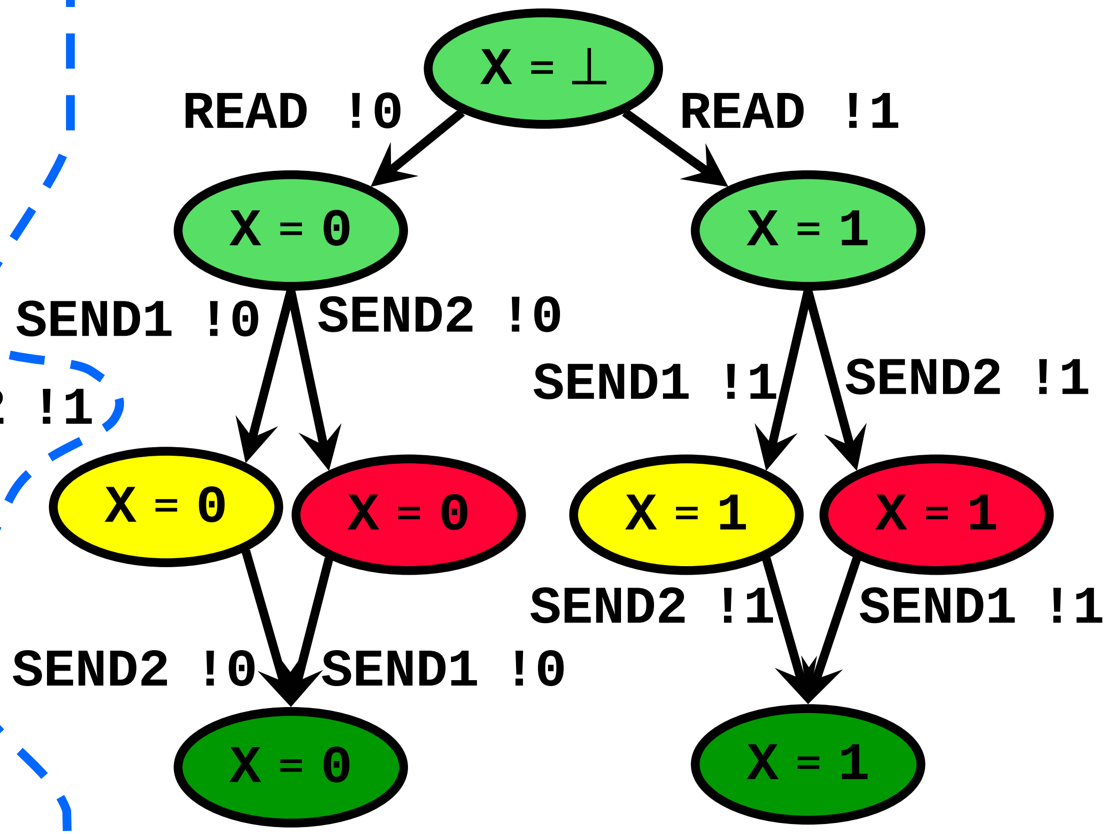
Treatment of Inherited Shared Variables

(section 5 of the paper)

Resetting Shared Variables (1/3)

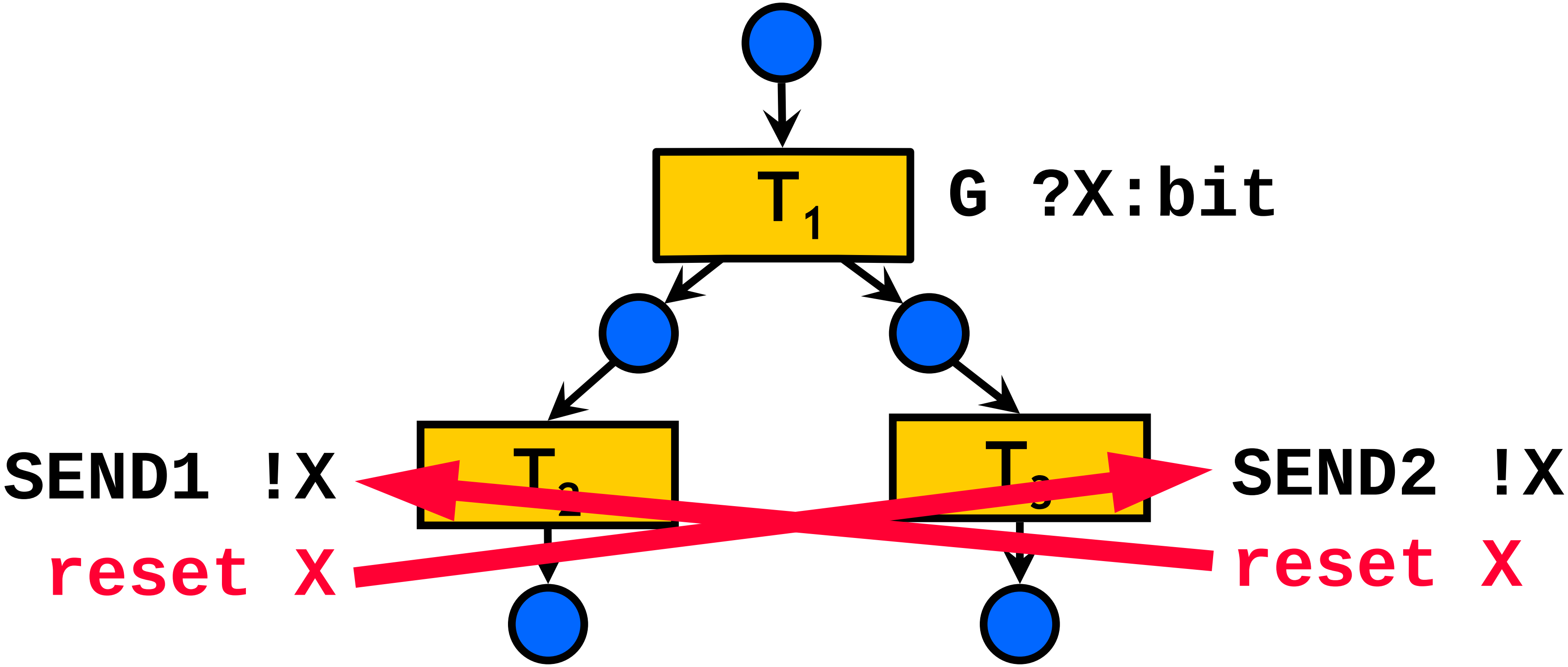
```
READ ?X: bit;
     (SEND1 !X; stop ||| SEND2 !X; stop)
```





Resetting Shared Variables (2/3)

```
READ ?X:bit;
     (SEND1 !X; stop ||| SEND2 !X; stop)
```

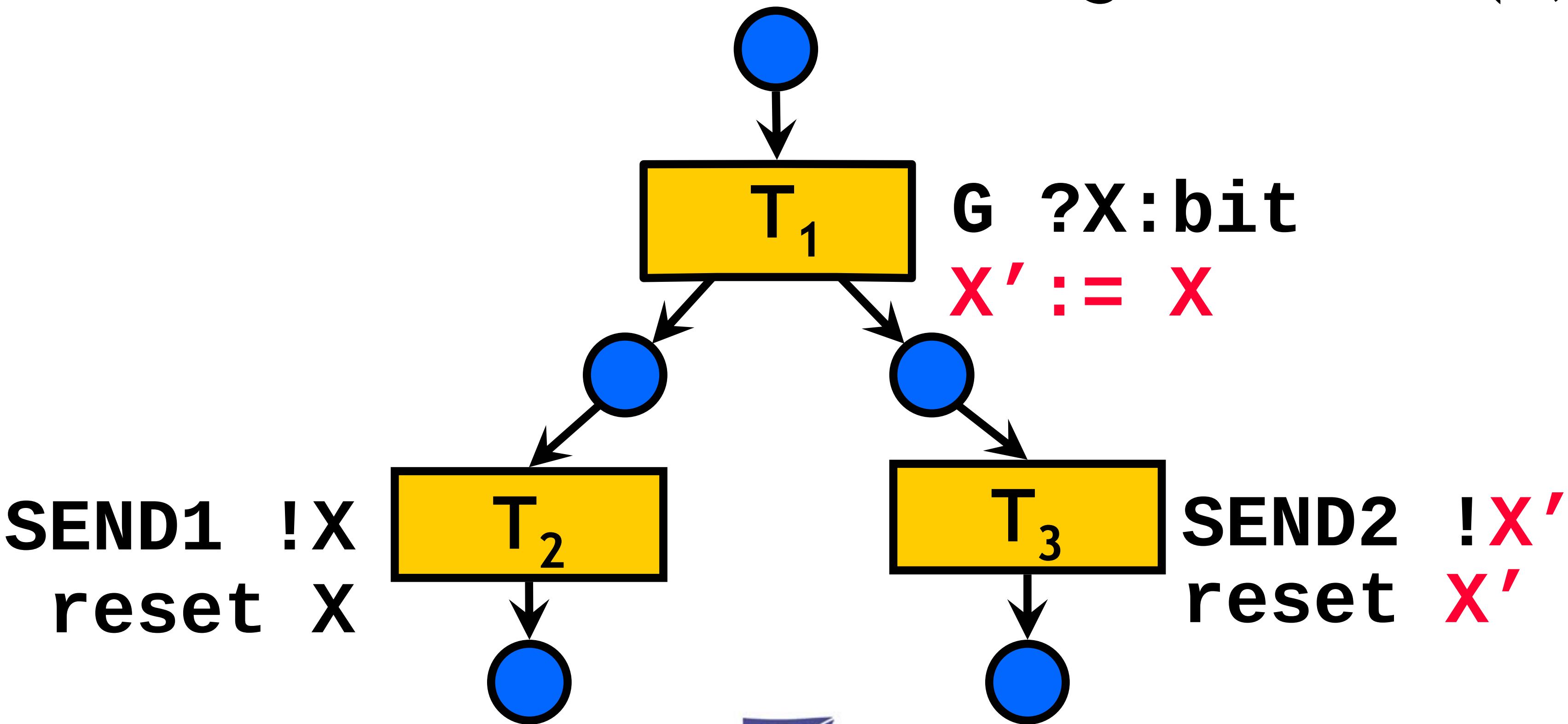


- Without resets, shared variables are read-only
- Inserting resets creates read/write(reset) conflicts

Resetting Shared Variables (3/3)

Solution: Duplication of "X" in unit "U"

- Create a new variable X′ attached to U
- Replace X by X′ in all transitions of U
- Insert "X′ := X" in all T entering U s.t. *Live*(T, **X**)

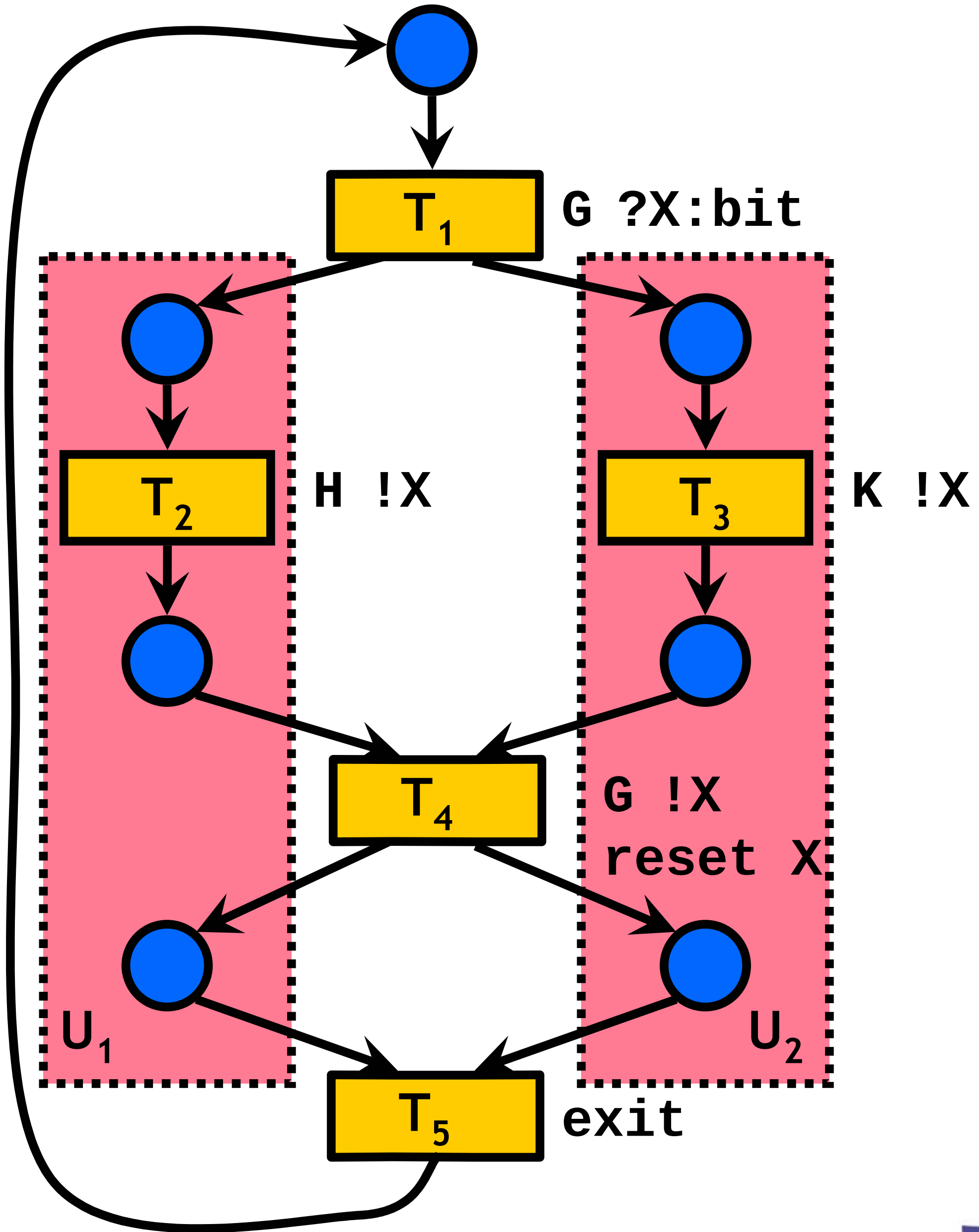


Which Variables to Duplicate? (1/2)

- Variable duplication increases the representation of a state!
- **Goal**: minimal number of duplicated variables
- **Concurrent Units**: "U_1 ||| U_2"
  U_1, U_2 separate and simultaneously marked
- **Conflict** *use*(T_1, X) versus *reset*(T_2, X) iff
  T_1 transition of U_1, T_2 transition of U_2, and U_1 ||| U_2

Too rough!

Which Variables to Duplicate? (2/2)



- *use*(T_2, **X**), *use*(T_3, **X**), *use*(T_4, **X**)
- *reset*(T_4, **X**)
- T_2 transition of U_1
- T_3 transition of U_2
- T_4 transition of U_1 and U_2
- U_1 ||| U_2

Conflict T_2 (T_3) with T_4?

NO:

- T_4 synchronizes U_1, U_2
- "**reset X**" in T_4 correct

Algorithm

compute *concurrent units* and *synchronizing transitions*

VARS := { X_1 … X_n }

while *VARS* not empty **do**

choose **X** in *VARS*

repeat

compute local and global data-flow

compute conflicts

U := choose conflicting unit

if U <> NULL then

duplicate **X** in **U** (yields **X’**)

VARS := *VARS* ∪ { **X’**}

until U = NULL (i.e., no more conflicts)

insert “**reset X**” in all **T** such that “*reset*(**T, X)**”

Experimental Results

(section 6 of the paper)

Experimental Results

- Tests: 544 LOTOS value-passing specifications
- State space reduction for 120 examples (22%)
- Average reduction factors

  States: **9** (max 220), Transitions: **12** (max 360)
- 3 examples: generation impossible before

  reduction factor > 10^4
- Generating all graphs: 4 times faster
- Only 24 examples (4%) requiring duplication
- Increase of state representation outweighed by state space reduction

Conclusion

- Resetting variables in process algebra
  - Translation to structured Petri nets with variables
  - Local and global data-flow analysis
- Rich model: Hierarchy of nested processes
- Tests on 544 examples: reductions up to 10^4

Open issues

- Unrestricted creation/destruction of processes
- Handling of shared read-write variables