Automatic Analysis of Industrial Robot Programs

OCaml Users and Developers Meeting 2012

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14.09.2012

Outline

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Industrial Robot Systems – Car Body Production Lines

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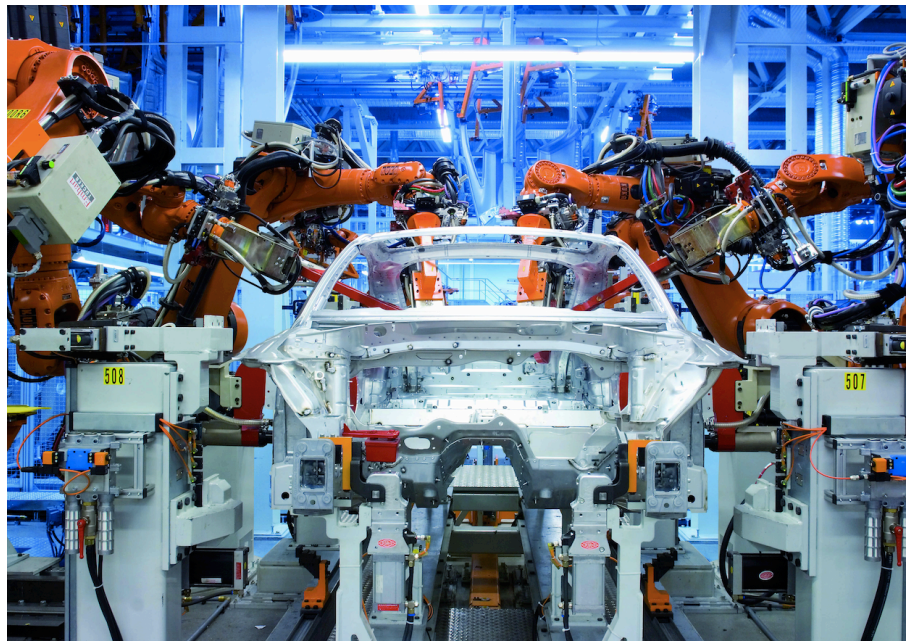

- Highly automated, complex systems
- Different car models on same production line
- Downtime extremely expensive
- Up to 12 robots working in a cell

Industrial Robot Systems – Topology

Distributed System of PLC and Robots

- Programming Logic Control (PLC) & robots work independently
- Incorrect handling of shared resources can lead to deadlocks and collisions (race conditions)

Robot Programming Language VKRC

Command	Semantics
variable = *expression*	Assignment of expression to variable
`GOTO LABEL` *id* = *expression*	Conditional jump to label *id*
`LABEL` *id*	Target of a jump
subroutine = *expression*	Conditional subroutine call
`REPEAT` *sub* = *n* `STOP` = *expr*	Call subroutine *n*-times
`WARTE BIS` *expression*	Wait until *expression* is met
n `PTP`	Move the robot arm to position *n*

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Properties to verify

- Termination (deadlocks, ..)
- Freedom of collisions

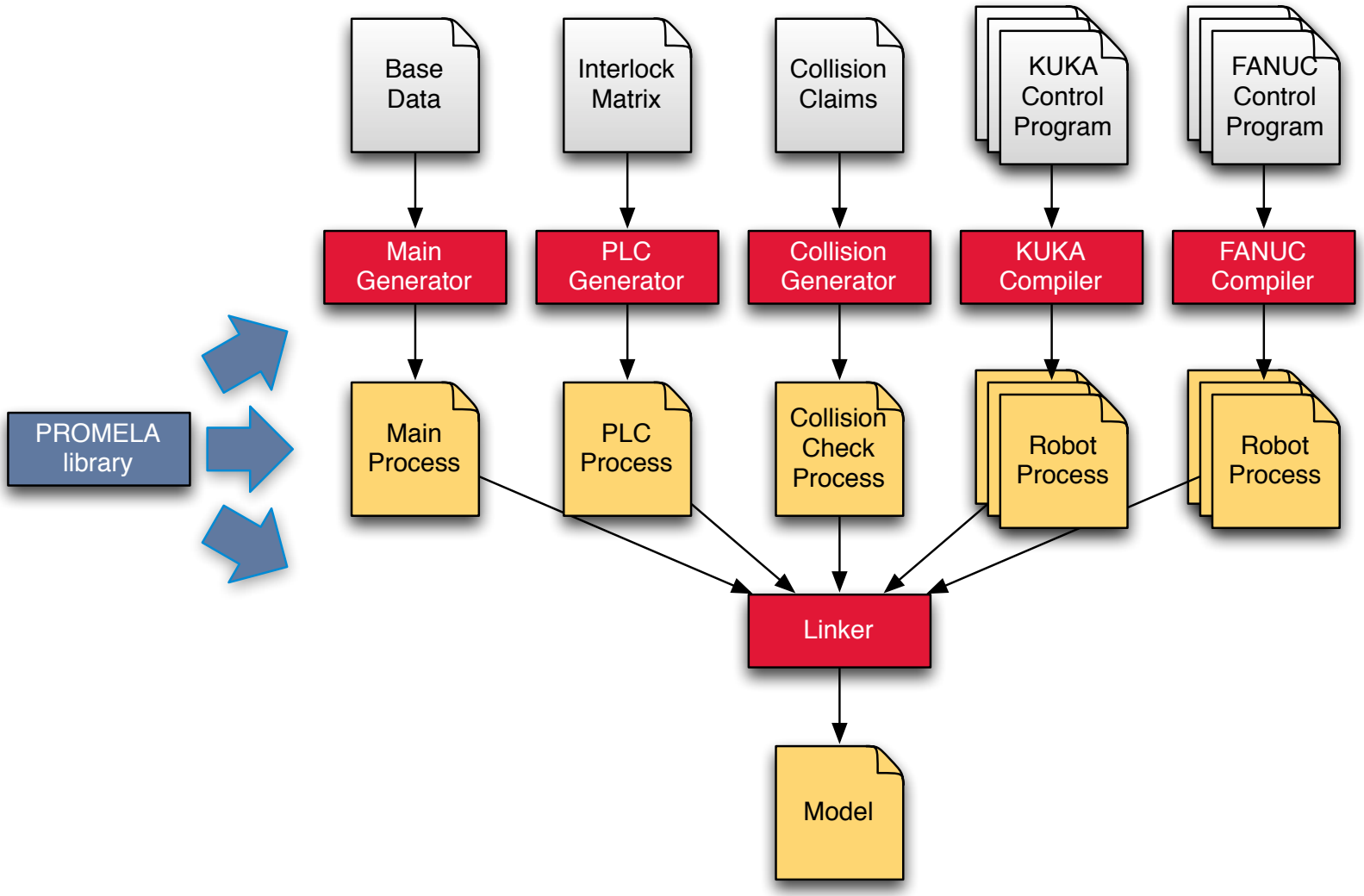
Robot 2

Robot 1	P1 -> P2	P2 -> P3	P3 -> P4
P1 -> P2	ok	⚡	⚡
P2 -> P3	ok	ok	⚡
P3 -> P4	ok	ok	ok

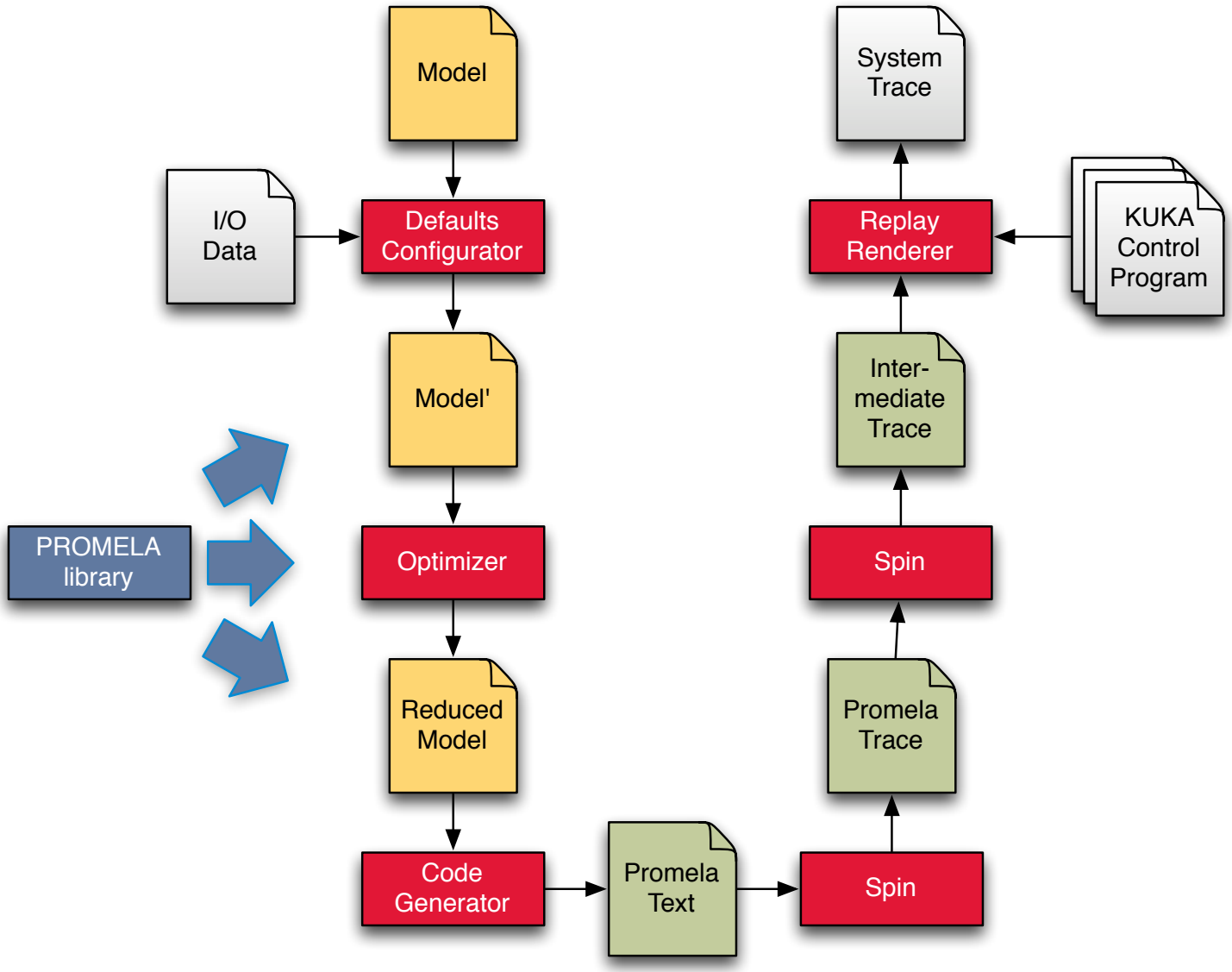
Claim for all potential collisions in Linear Temporal Logic

$$\square\neg((\text{target-position}_n = i) \wedge (\text{target-position}_m = k))$$

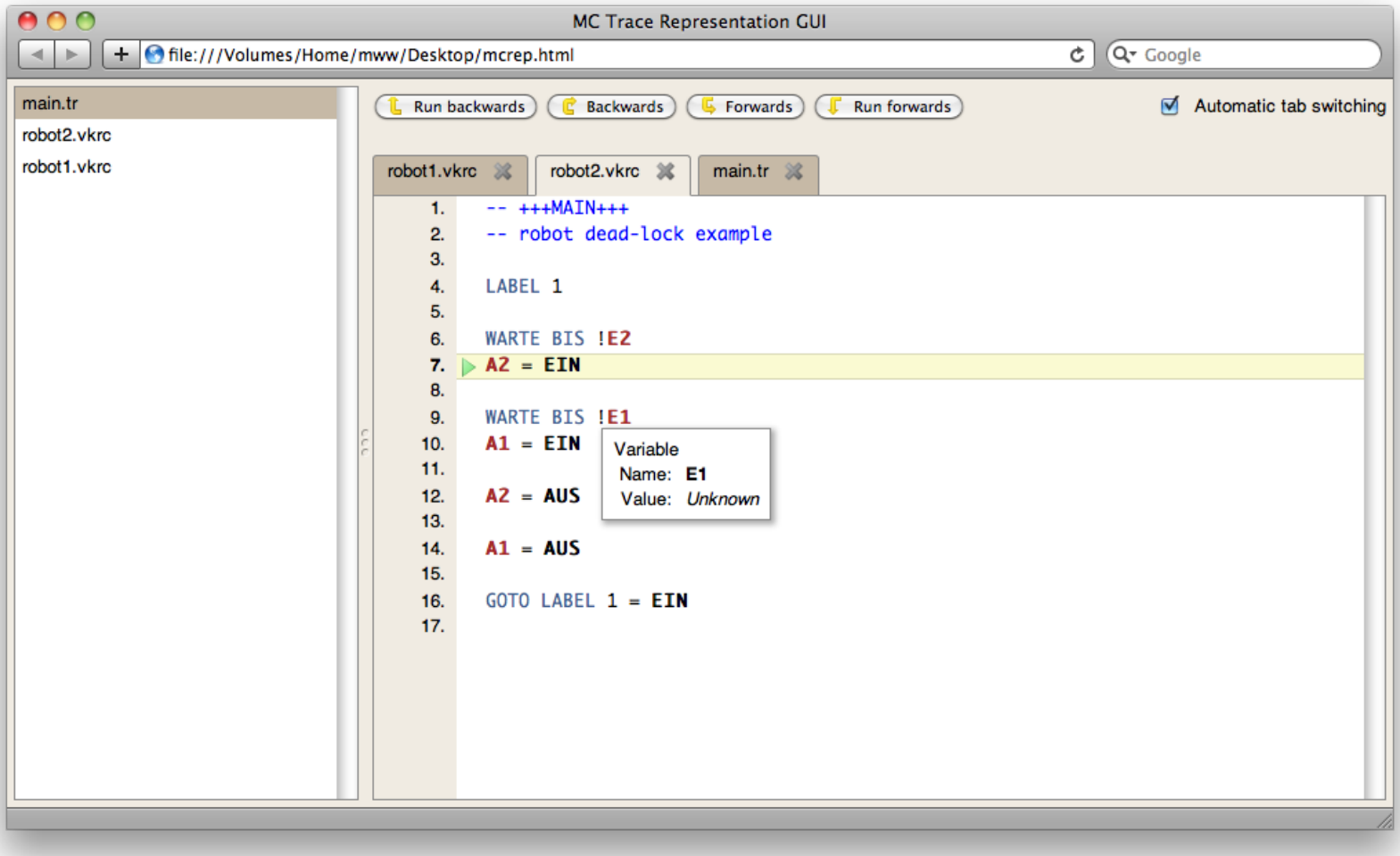
Model Generation and Extraction



Model Verification and Trace



Replay Renderer



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Benchmarks

#r	#proc	state size	result	time	#states
4	5	112 bit	deadlock	1 sec	6.2×10^6
3	4	152 bit	non-termination	<1 sec	196
4	5	184 bit	ok	2 sec	1.5×10^6
4	5	196 bit	ok	6 sec	$3{,}5 \times 10^6$
4	5	202 bit	ok	50 sec	2.4×10^7
4	5	208 bit	deadlock	4 sec	10^6
9	11	678 bit	deadlock	<1 sec	5129
9	10	132 bit	assertion	<1 sec	32
10	11	506 bit	out-of-memory	~50 min	10^9

8-core Intel Xeon E5630 (2.53 GHz)
64 GByte of main memory

Locking Protocol – Normal Operation

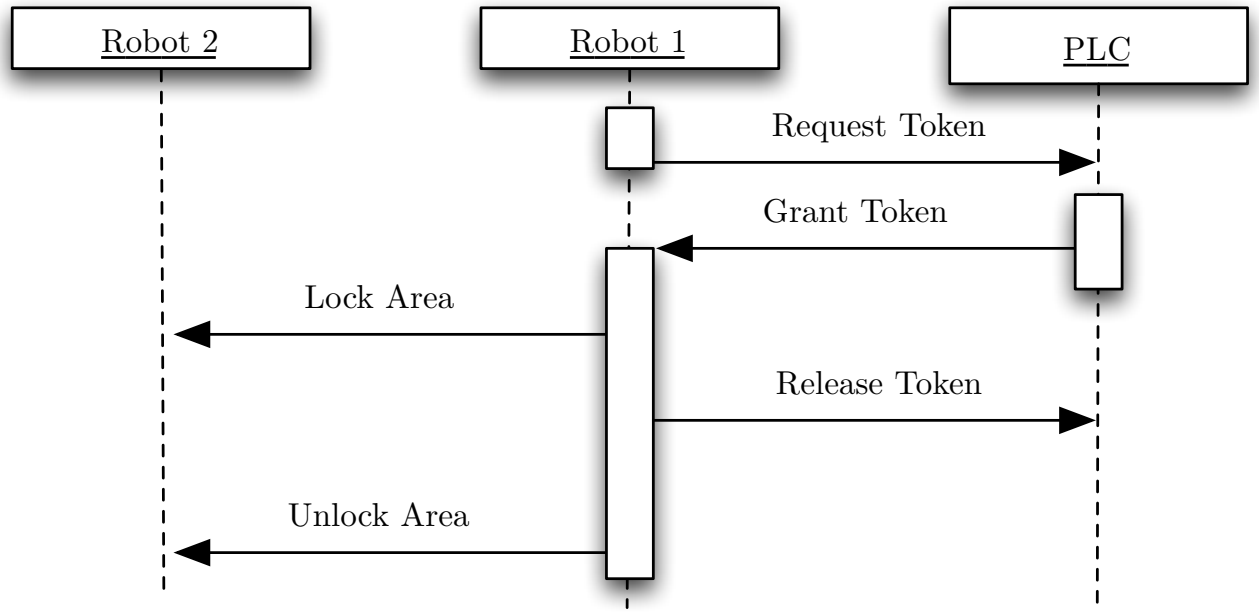

Figure 2: Robot 1 locks a resource for Robot 2

Locking Protocol – Potential Deadlock

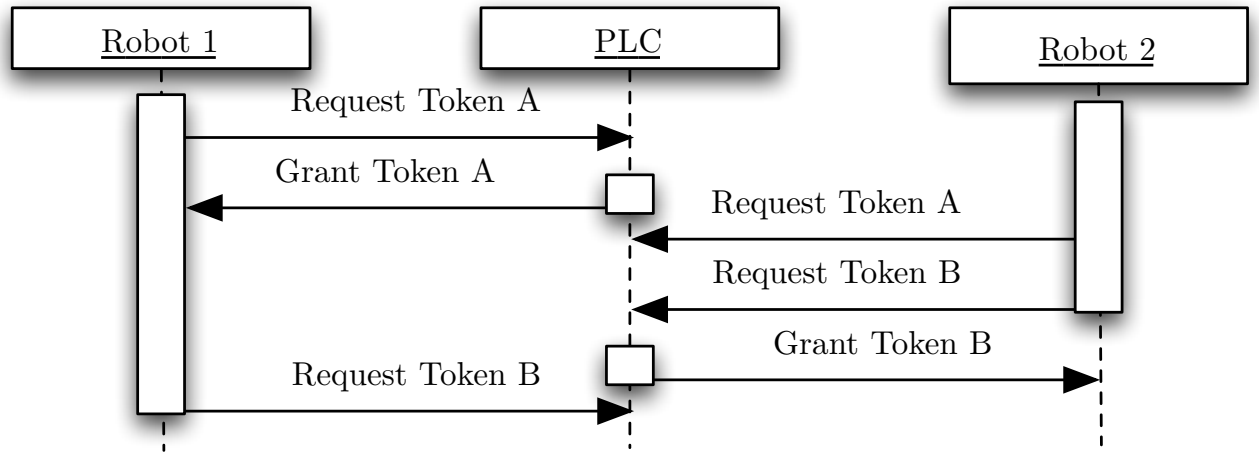

Figure 3: Robot can request second token without grant

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OCaml Code

we use

- menhir
- ocamlgraph – control flow graph in compilers, code analysis
- ocaml-csv – vital to read Microsoft Excel exports
- bolt
- extlib
- qtest (from batteries) – for testing our own code
- oasis

and provide

- PROMELA library + tools (BSD3, OCamlForge)
- boolean expression simplifier (BSD3, OCamlForge)
- ocamlgraph algorithms: Fixpoint, Leaderlist, Contraction

PROMELA library example

```
(* Create one dining philosopher process *)
let dp_process ~max_id id =
  let module PE = Promela.Expression in
  let forkl, forkr = id, (id + 1) mod max_id in
  let check x =
    `Guard (PE.Binop (PE.Eq,
      (PE.Variable (fork_id x)), (PE.ConstInt 0))) in
  let assign v x =
    `Assign (fork_id x, None,(PE.ConstInt v)) in
  let take =  assign 1 in
  let release = assign 0 in
  let check_and_take x =
    `Atomic ((check x)::(take x)::[]) in
  Promela.Process.create ~active:true (pid "PHIL%d" id)
    [check_and_take forkl; check_and_take forkr;
      release forkl; release forkr]
```

ocamlgraph – fixpoint for data flow analysis

```
(* compute reachability on a directed graph *)
module Reachability = Graph.Fixpoint.Make(G)
(struct
  type vertex = G.E.vertex
  type edge = G.E.t
  type g = G.t
  type data = bool
  let direction = Graph.Fixpoint.Forward
  let equal = (=)
  let join = (||)
  let analyze _ = (fun x -> x)
end)

..
let vertex_is_reachable =
  Reachability.analyze is_root_vertex graph in
```

Outline

Experiences with OCaml

On the team

- strong OCaml community at TUM
- no OO in use
- try to write pure code
- refactoring is a breeze
- finding students for projects is hard

and with industrial partner

- Audi management feels strongly about results
- People in plant engineering are engineers, not computer scientists
- It is a research project

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Conclusion

- Found multiple deadlock errors – even in protocol
- Formal Verification can even be cheaper than testing
- It is an option for analyzing large industrial robot systems
- Using OCaml for this project was a very good choice

Weißmann et al., Model Checking Industrial Robot Systems, SPIN 2011