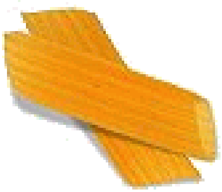
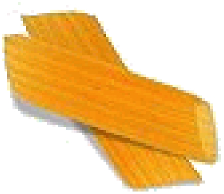


One hundred years of the PEPA tools

Stephen Gilmore
Laboratory for Foundations of Computer Science
The University of Edinburgh

12th June 2003



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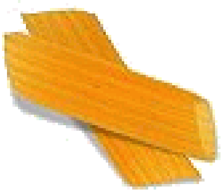
PEPA is ten years old!



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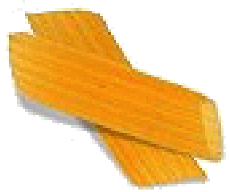
PEPA is ten years old!

One year programming in ML $\equiv$ ten years programming in Java



Background

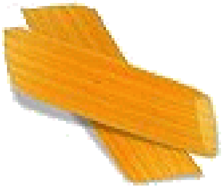
- Performance Evaluation Process Algebra (PEPA) is used as a formal description language for Markov chain modelling. PEPA is a compact language with a small number of primitive operations.

  Prefix: $(\alpha, r).P$ performs α at rate r to become P.

  Choice: $P + Q$ sets up a race between P and Q. The first to perform an action wins: the other is discarded.

  Cooperation: $P \underset{L}{\bowtie} Q$ runs P and Q in parallel, synchronising on activities in L.

  Hiding: P/L hides the activities in L, preventing cooperands from synchronising on them.



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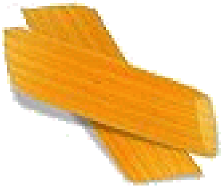

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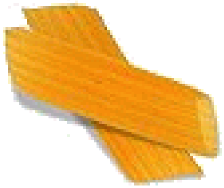

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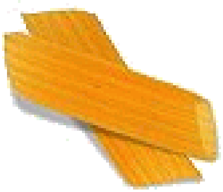

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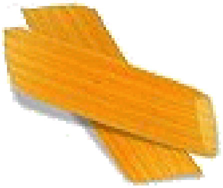

A first PEPA tool: The PEPA Workbench

- Our first PEPA tool was the PEPA Workbench, implemented in Standard ML.
- The PEPA syntax can be represented simply as an ML datatype.

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datatype Component =
     PREFIX of (Activity * Rate) * Component          (*  .  *)
   | CHOICE of Component * Component                  (*  +  *)
   | COOP of Component * Component * Activity list    (*  ⋈  *)
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   | VAR of Identifier                                (*  X  *)
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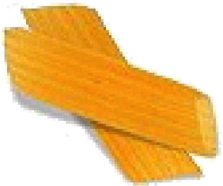

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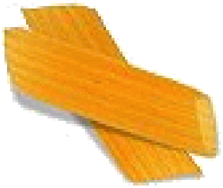

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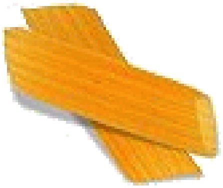

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The PEPA Workbench: derivatives

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fun derivative E (PREFIX (a as (alpha, rate), P)) = [(a, P)]
  | derivative E (CHOICE (P, Q)) =
         (derivative E P) @ (derivative E Q)
  | derivative E (COOP (P, Q, L)) =
         let
             val (dP, dQ) = (derivative E P, derivative E Q)
             val (fP, fQ) = (filterout dP L, filterout dQ L)
         in
             (map (fn (a, P')) => (a, COOP (P', Q, L))) fP)
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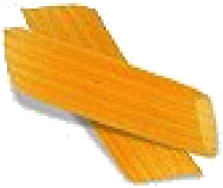

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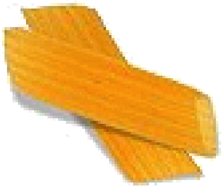

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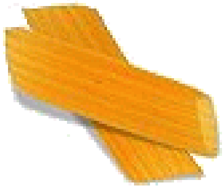

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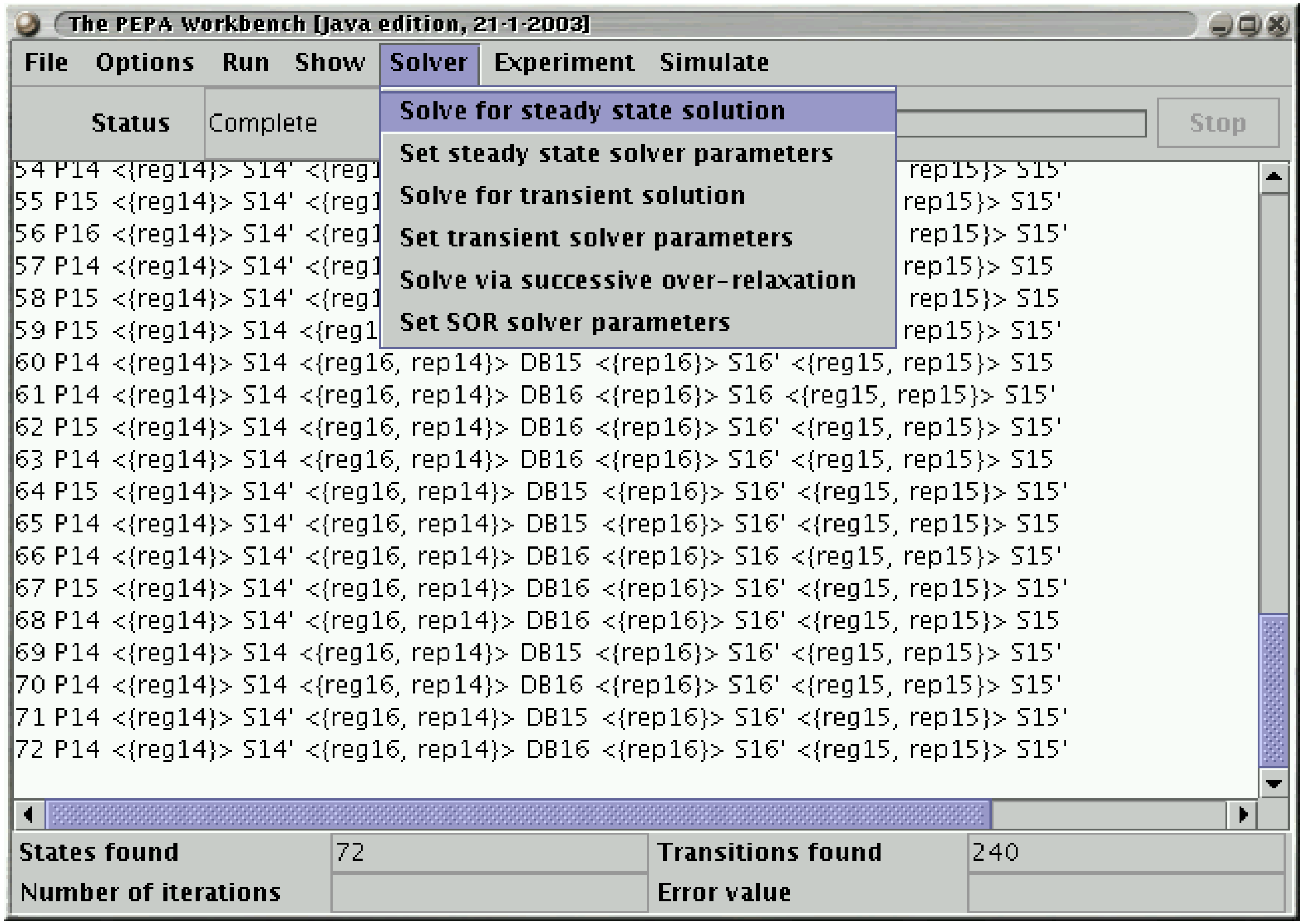
Beyond ML

- With the ML edition of the PEPA Workbench it was possible to solve small models using exterior solvers such as Maple and Matlab.

- However, users of the workbench wanted to make more detailed models (with larger state spaces).

- The ML edition of the PEPA Workbench could not solve Robert Holton's robotic workcell model efficiently enough so we interfaced it with an external solver written in C.

- Other users wanted to run the workbench on Solaris, Windows and Linux machines so we ported the Workbench and the solver to Java.



Status: Complete

```
54 P14 <{reg14}> S14' <{reg1                                    rep15}> S15'
55 P15 <{reg14}> S14' <{reg1                                    rep15}> S15'
56 P16 <{reg14}> S14' <{reg1                                    rep15}> S15'
57 P14 <{reg14}> S14' <{reg1                                    rep15}> S15
58 P15 <{reg14}> S14' <{reg1                                    rep15}> S15
59 P15 <{reg14}> S14 <{reg1                                     rep15}> S15'
60 P14 <{reg14}> S14 <{reg16, rep14}> DB15 <{rep16}> S16' <{reg15, rep15}> S15
61 P14 <{reg14}> S14 <{reg16, rep14}> DB16 <{rep16}> S16 <{reg15, rep15}> S15'
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64 P15 <{reg14}> S14' <{reg16, rep14}> DB15 <{rep16}> S16' <{reg15, rep15}> S15'
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72 P14 <{reg14}> S14' <{reg16, rep14}> DB16 <{rep16}> S16' <{reg15, rep15}> S15'
```
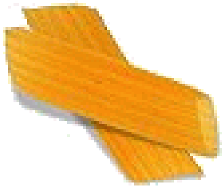

States found	72	Transitions found	240
Number of iterations		Error value	



Beyond the PEPA Workbench

- Graham Clark had extended the ML edition of the workbench and developed the Java edition of the workbench from his Peparoni simulator for PEPA.
- He then implemented an editor for PEPA in the Möbius multi-paradigm modelling framework, extending PEPA to PEPA$_k$ with guards and parameters.

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Consume[a,b] =    [a > 0] => (outa, ar).Consume[a-1,b]
 + [(b > 0) && (a == 0)] => (outb, br).Consume[a,b-1];

Breakdown = (outa, T).Breakdown
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System = Consume[0,0] <outa> Breakdown;
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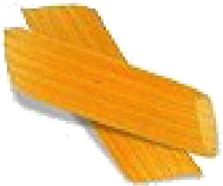

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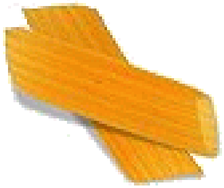

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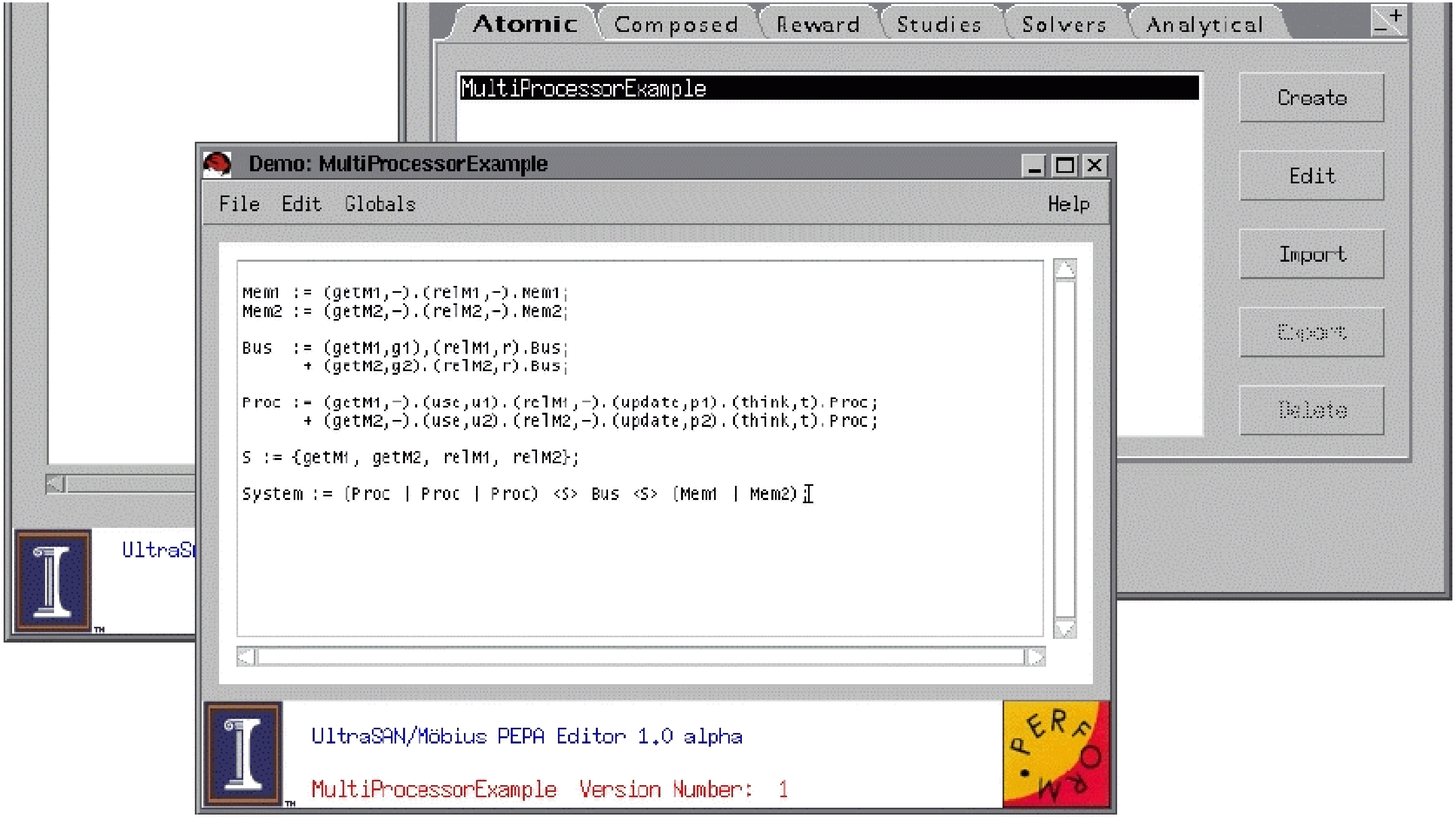


```
Mem1 := (getM1,-).(relM1,-).Mem1;
Mem2 := (getM2,-).(relM2,-).Mem2;

Bus  := (getM1,g1),(relM1,r).Bus;
      + (getM2,g2).(relM2,r).Bus;

Proc := (getM1,-).(use,u1).(relM1,-).(update,p1).(think,t).Proc;
      + (getM2,-).(use,u2).(relM2,-).(update,p2).(think,t).Proc;

S := {getM1, getM2, relM1, relM2};

System := (Proc | Proc | Proc) <S> Bus <S> (Mem1 | Mem2);
```

UltraSAN/Möbius PEPA Editor 1.0 alpha

MultiProcessorExample Version Number: 1

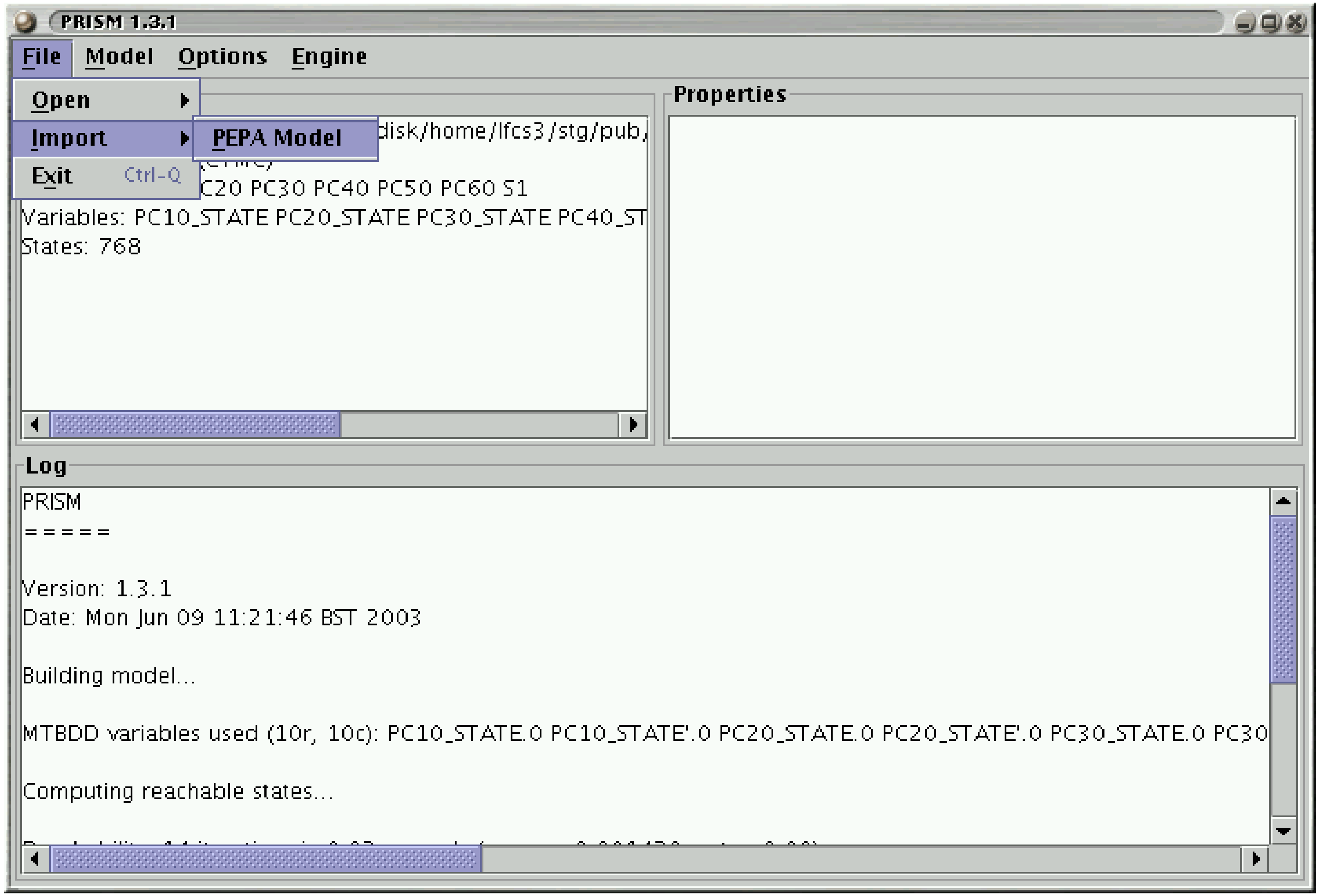
PEPA and PRISM

- PRISM is a probabilistic model checker which supports modelling in DTMCs, CTMCs and MDPs with PTCL and CSL model checking.

- The matrix storing the state space of the system is expressed as an MTBDD built using the CUDD package.

- Support for the PEPA language in PRISM was provided in two steps:

  1. extending the PRISM input language with a new **system** construct providing the PEPA composition operators for synchronisation over activity sets and hiding; and
  2. compiling the PEPA language into the extended PRISM language.



```
disk/home/lfcs3/stg/pub/
C20 PC30 PC40 PC50 PC60 S1
Variables: PC10_STATE PC20_STATE PC30_STATE PC40_ST
States: 768
```

```
PRISM
=====

Version: 1.3.1
Date: Mon Jun 09 11:21:46 BST 2003

Building model...

MTBDD variables used (10r, 10c): PC10_STATE.0 PC10_STATE'.0 PC20_STATE.0 PC20_STATE'.0 PC30_STATE.0 PC30

Computing reachable states...
```

PEPA modelling with PRISM

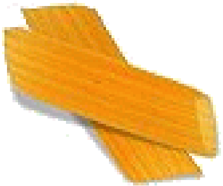
- PEPA modelling with PRISM has proved to be very effective in practice. The largest PEPA model so far solved has been solved with PRISM.

- However, there are a number of places where the user needs to understand the tool chain thoroughly:
  - The PEPA-to-PRISM compiler rejects (valid) PEPA models which use active/active synchronisation or anonymous components;
  - The compiler can fail during compilation with Java stack overflow;
  - PRISM can reject models which the PEPA-to-PRISM compiler outputs;
  - The CUDD package can fail with out-of-memory errors and need to be reconfigured.

PEPA and IPC/Dnamaca

The Imperial PEPA compiler (IPC) compiles PEPA models into Petri nets which are solved with the Dnamaca solver. Dnamaca provides a number of numerical solvers and outperforms PRISM on small PEPA models.

```
                          \transition{P1_start} {
                              %% PEPA action type { start }
                              \condition{ P1 > 0 }
                              \action {
                                  next -> P1 = P1 - 1;
P1 = (start, r1).P2;  =           next -> P2 = P2 + 1;
                              }
                              \priority{1}
                              \rate{ PEPA_r1 }
                          }
```

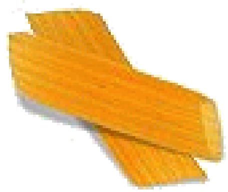


Synchronisation in Dnamaca

Suppose that two copies of P synchronise on the run activity.

```
P2 = (run, r2).P3; =
```

```
\transition{P2_run__P2_1_run} {
    %% PEPA action type { run }
    \condition{ P2 > 0 && P2_1 > 0 }
    \action {
        next -> P2_1 = P2_1 - 1;
        next -> P3_1 = P3_1 + 1;
        next -> P2 = P2 - 1;
        next -> P3 = P3 + 1;
    }
    \priority{1}
    \rate{ PEPA_r2 }
}
```



PEPA modelling with IPC and Dnamaca

- More of the PEPA language is supported by IPC/Dnamaca than by PRISM. Active/active synchronisation and anonymous components are supported.

- However, there are still a number of places where the user needs to understand the tool chain thoroughly:
  - The IPC compiler can fail during compilation with Haskell memory exhaustion;
  - Dnamaca can reject models which IPC outputs; and
  - Dnamaca's numerical procedures can fail to converge.

Dnamaca features and PEPA extensions

- Because Dnamaca supports non-Markovian modelling, beyond the models which are expressible in PEPA, it would be possible to support PEPA extensions with Dnamaca:
  - PEPA$_k$ guards and parameters; *[Clark, Sanders, '01]*
  - Weighted (WSCCS-style) PEPA; *[Bradley, '02]*
  - PEPA nets with priorities; *[Gilmore, Hillston, Ribaudo, Kloul, '03]*
  - Semi-Markov PEPA; *[Bradley, '03]*
  - . . .

PEPA nets

- PEPA nets are Petri nets with PEPA tokens. An example token is

$$\begin{aligned}
\mathsf{Agent} &\stackrel{\mathit{def}}{=} (\mathbf{go}, \lambda).\mathsf{Agent}' \\
\mathsf{Agent}' &\stackrel{\mathit{def}}{=} (\mathsf{interrogate}, \mathsf{r_i}).\mathsf{Agent}'' \\
\mathsf{Agent}'' &\stackrel{\mathit{def}}{=} (\mathbf{return}, \mu).\mathsf{Agent}''' \\
\mathsf{Agent}''' &\stackrel{\mathit{def}}{=} (\mathsf{dump}, \mathsf{r_d}).\mathsf{Agent}
\end{aligned}$$

  go and **return** are *firings* of the PEPA net. interrogate and dump are local transitions.

- A PEPA net can be processed with the PEPA Workbench for PEPA nets or compiled to PEPA using the PEPA net compiler.

The PEPA nets compiler

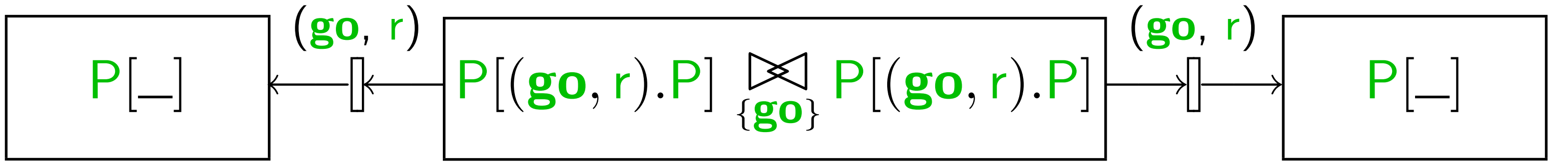
- The PEPA nets compiler compiles out token movement.

$$
\begin{aligned}
\mathsf{Agent\_\_at\_\_P2} &\stackrel{\mathit{def}}{=} (\mathsf{go\_\_to\_\_P1}, \lambda).\mathsf{Agent'\_\_at\_\_P1} \\
&\phantom{\stackrel{\mathit{def}}{=}}\!\!\!\!+ (\mathsf{go\_\_to\_\_P3}, \lambda).\mathsf{Agent'\_\_at\_\_P3} \\
\mathsf{Agent'\_\_at\_\_P1} &\stackrel{\mathit{def}}{=} (\mathsf{interrogate\_\_at\_\_P1}, \mathsf{r_i}).\mathsf{Agent''\_\_at\_\_P1} \\
\mathsf{Agent'\_\_at\_\_P3} &\stackrel{\mathit{def}}{=} (\mathsf{interrogate\_\_at\_\_P3}, \mathsf{r_i}).\mathsf{Agent''\_\_at\_\_P3} \\
\mathsf{Agent''\_\_at\_\_P1} &\stackrel{\mathit{def}}{=} (\mathsf{return\_\_to\_\_P2}, \mu).\mathsf{Agent'''\_\_at\_\_P2} \\
\mathsf{Agent''\_\_at\_\_P3} &\stackrel{\mathit{def}}{=} (\mathsf{return\_\_to\_\_P2}, \mu).\mathsf{Agent'''\_\_at\_\_P2} \\
\mathsf{Agent'''\_\_at\_\_P2} &\stackrel{\mathit{def}}{=} (\mathsf{dump\_\_at\_\_P2}, \mathsf{r_d}).\mathsf{Agent\_\_at\_\_P2}
\end{aligned}
$$

- (Strictly speaking, tokens must specify their cells within places. Different cells at the same place fall under different synchronisation sets.)

Loss of expressivity

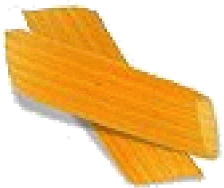
- In PEPA nets it is possible for tokens to synchronise on their exit actions from a place:



$P[\_]$ $\quad (\mathbf{go}, r) \quad$ $P[(\mathbf{go}, r).P] \underset{\{\mathbf{go}\}}{\bowtie} P[(\mathbf{go}, r).P]$ $\quad (\mathbf{go}, r) \quad$ $P[\_]$

- The PEPA nets compiler cannot compile this idiom because the two tokens must go to different cells—cells can only contain a single token—and their exit activities must specify the destination cell. Therefore these activity renamings are distinct and so synchronisation is not possible.

- We consider this to be a small loss of expressivity.



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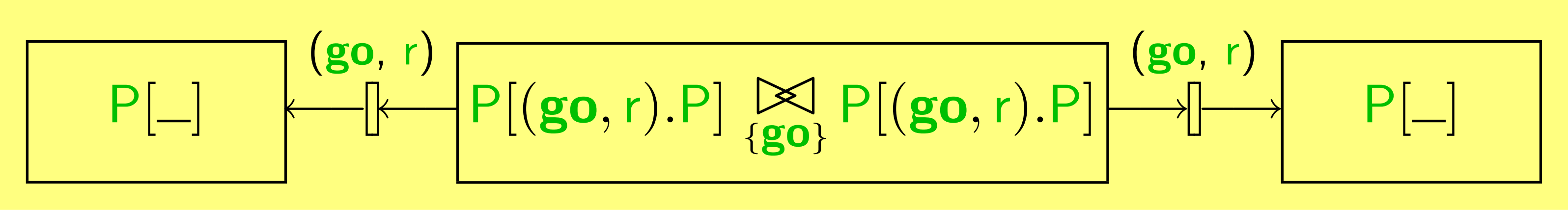

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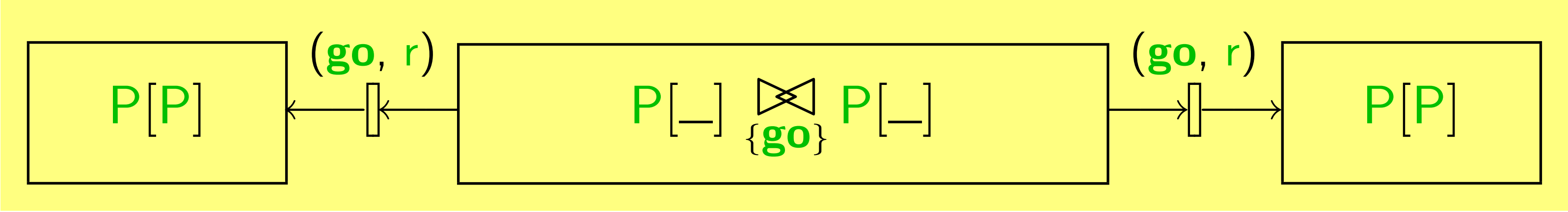

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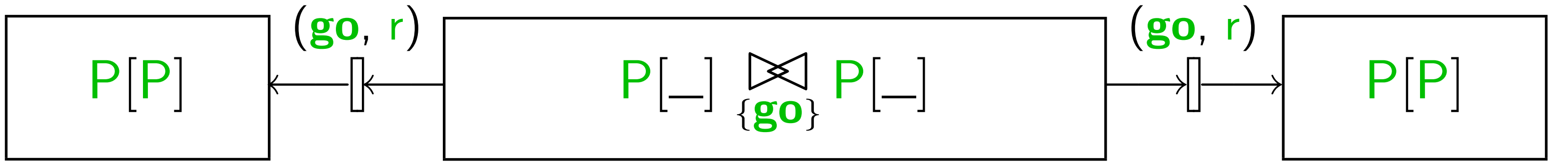

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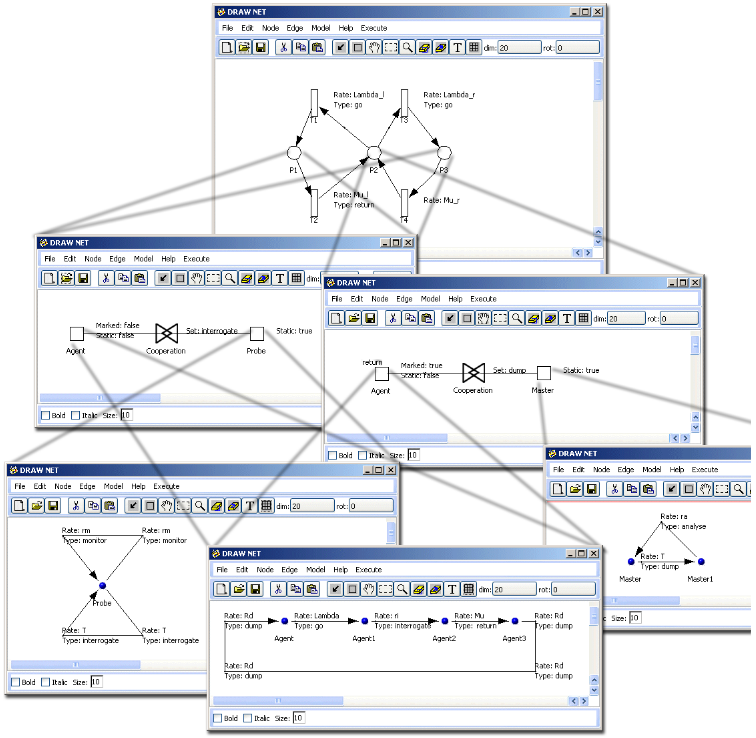
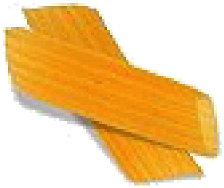
PEPA nets in DrawNET





Conclusions

- Compiling PEPA and PEPA net models to other formalisms seems to be a very profitable activity.
- However, there are typically many small details in the translation which need to be taken care of.
- It is tempting to lift features of the host tool back to the PEPA level but sometimes desirable properties of the PEPA language are lost.
- It is important to strike a balance between exploiting opportunities and losing theoretical properties.