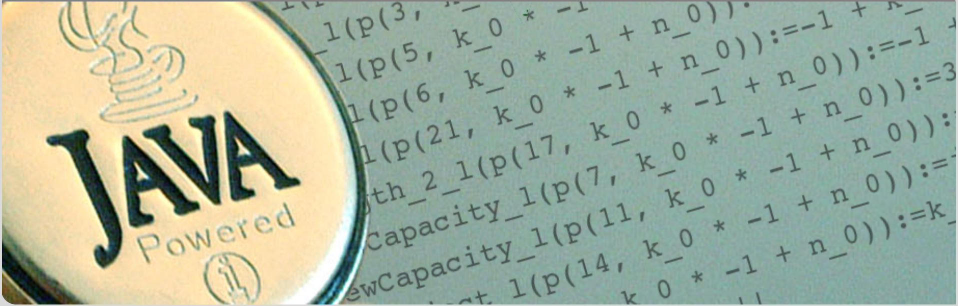
Karlsruhe Institute of Technology

Applications of Formal Verification

Model Checking: Introduction to SPIN

Dr. Vladimir Klebanov · Dr. Mattias Ulbrich | SS 2015

KIT – INSTITUT FÜR THEORETISCHE INFORMATIK



SPIN: Previous Lecture vs. This Lecture

Previous lecture

SPIN appeared as a PROMELA *simulator*

This lecture

Intro to SPIN as a *model checker*

What Does A Model Checker Do?

A Model Checker (MC) is designed to prove the user wrong.

MC tries its best to *find a counter example* to the correctness properties.
It is tuned for that.

MC does not try to prove correctness properties.
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MC's *search* for counter examples is *exhaustive*.

$\Rightarrow$ *Finding no counter example proves stated correctness properties.*

What does ‘exhaustive search’ mean here?

exhaustive search

=

resolving non-determinism in all possible ways

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=

resolving non-determinism in all possible ways

For model checking PROMELA code,
two kinds of non-determinism to be resolved:

- *explicit, local*:
  if/**do** statements

```
:: guardX -> ....
:: guardY -> ....
```

- *implicit, global*:
  scheduling of concurrent processes
  (see next lecture)

Model Checker for This Course: SPIN

SPIN: "*S*imple *P*romela *In*terpreter"

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The name is a serious understatement!

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- simulating a model (randomly/interactively)
- generating a *verifier*

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- in case the check is negative:
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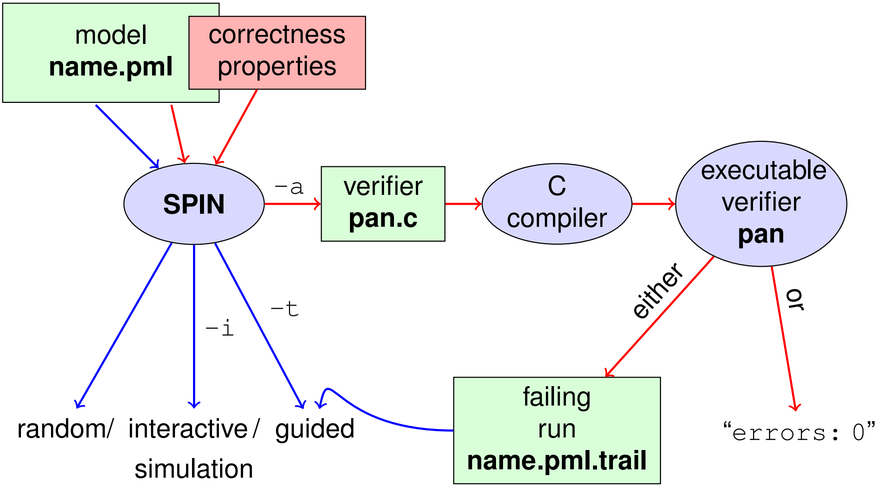
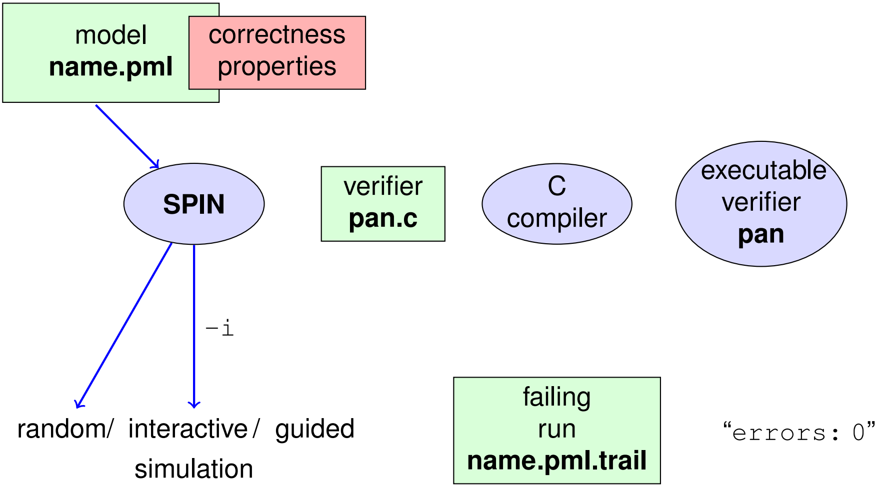
verifier generated by SPIN is a C program performing *model checking*:

- exhaustively *checks* PROMELA *model* against correctness properties
- in case the check is negative:
  generates a failing run of the model, to be simulated by SPIN

SPIN Workflow: Overview



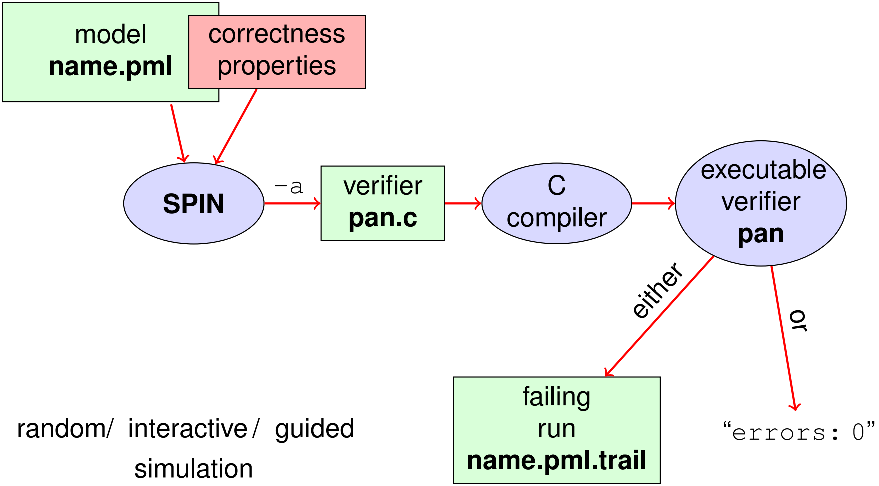
Plain Simulation with SPIN



Rehearsal: Simulation Demo

- run example, random and interactive
  `interleave.pml`, `zero.pml`

Model Checking with SPIN



Meaning of Correctness wrt. Properties

Given PROMELA model M, and correctness properties $C_1, \dots, C_n$.

- Be R_M the set of all possible runs of M.
- For each correctness property C_i,
  R_{M,C_i} is the set of all runs of M satisfying C_i.
  ($R_{M,C_i} \subseteq R_M$)
- M is correct wrt. $C_1, \dots, C_n$ iff $(R_{M,C_1} \cap \ldots \cap R_{M,C_n}) = R_M$.
- If M is not correct, then
  each $r \in (R_M \setminus (R_{M,C_1} \cap \ldots \cap R_{M,C_n}))$ is a counter example.

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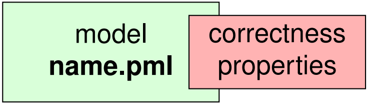
We know how to write models M.
But how to write Correctness Properties?

Stating Correctness Properties

model
name.pml

correctness
properties

Stating Correctness Properties



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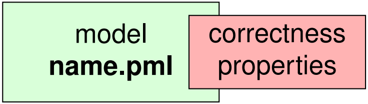

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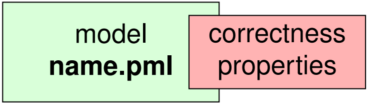

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- meta labels
  - `end` labels
  - `accept` labels
  - `progress` labels

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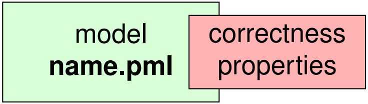

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stating properties outside the model, using

- never claims
- temporal logic formulas

Stating Correctness Properties

model **name.pml** | correctness properties

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stating properties within the model, using

- *assertion statements* (today)
- meta labels
  - `end` *labels* (today)
  - `accept` labels
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Assertion Statements

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Definition (Assertion Statements)

Assertion statements in PROMELA are statements of the form

`assert` (*expr*)

were *expr* is any PROMELA expression.

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```
...
stmt1;
assert(max == a);
stmt2;
...
```

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Typically, *expr* is of type **bool**.

Assertion statements can appear anywhere where a PROMELA statement is expected.

```
...
stmt1;
assert(max == a);
stmt2;
...
```

```
...
if
:: b1 -> stmt3;
         assert(x < y)
:: b2 -> stmt4
...
```

Meaning of Boolean Assertion Statements

`assert` (*expr*)

- has no effect if *expr* evaluates to true
- triggers an error message if *expr* evaluates to false

This holds in both, simulation and model checking mode.

Meaning of General Assertion Statements

`assert` (*expr*)

- has no effect if *expr* evaluates to non-zero value
- triggers an error message if *expr* evaluates to 0

This holds in both, simulation and model checking mode.

Meaning of General Assertion Statements

`assert` `(`*expr*`)`

- has no effect if *expr* evaluates to non-zero value
- triggers an error message if *expr* evaluates to 0

This holds in both, simulation and model checking mode.

Recall:

`bool true false` is syntactic sugar for

Meaning of General Assertion Statements

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Recall:

`bool`	**`true`**	**`false`**	is syntactic sugar for
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This holds in both, simulation and model checking mode.

Recall:

`bool`	**`true`**	**`false`**	is syntactic sugar for
`bit`	`1`	`0`	

⇒ general case covers Boolean case

Instead of using ‘printf’s for Debugging ...

```
/* after choosing a,b from {1,2,3} */
if
  :: a >= b -> max = a;
  :: a <= b -> max = b;
fi;
printf("the maximum of %d and %d is %d\n",
       a, b, max);
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Command Line Execution

(simulate, inject faults, add assertion, simulate again)

```
> spin max.pml
```

... we can employ Assertions

quoting from file **max.pml**:

```
/* after choosing a,b from {1,2,3} */
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Now, we have a first example with a formulated correctness property.

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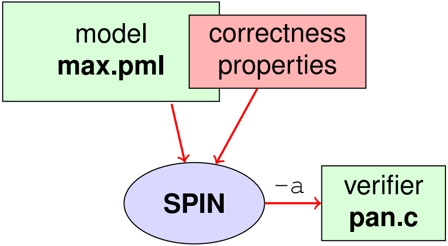
Now, we have a first example with a formulated correctness property.

We can do model checking, for the first time!

Generate Verifier in C



Command Line Execution

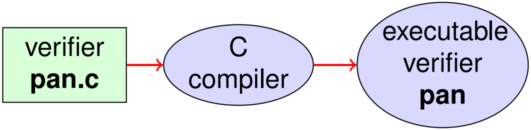
Generate Verifier in C

```
> spin -a max.pml
```

SPIN generates Verifier in C, called **pan.c**

(plus helper files)

Compile To Executable Verifier

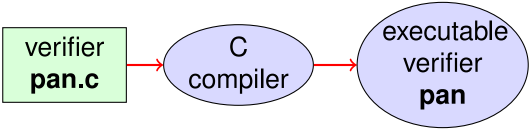


Command Line Execution

compile to executable verifier

```
> gcc -o pan pan.c
```

Compile To Executable Verifier



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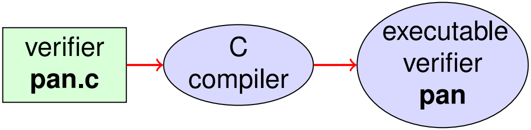

Command Line Execution

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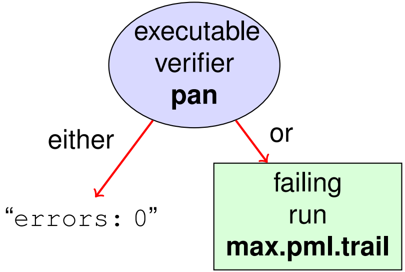
C compiler generates executable verifier **pan**

pan: historically “**p**rotocol **an**alyzer”, now “**p**rocess **an**alyzer”

Run Verifier (= Model Check)

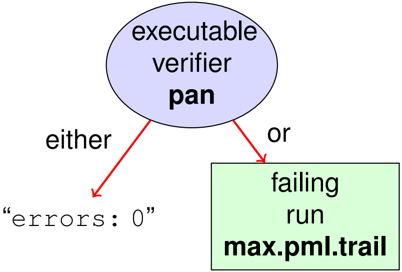


Command Line Execution

run verifier ***pan***

```
> ./pan
```

Run Verifier (= Model Check)



Command Line Execution

*run verifier **pan***

```
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```

- prints “`errors: 0`”

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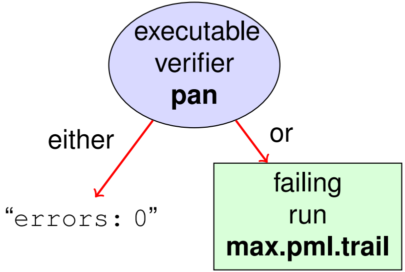

Command Line Execution

*run verifier **pan***

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- prints "`errors: 0`" ⇒ Correctness Property verified!

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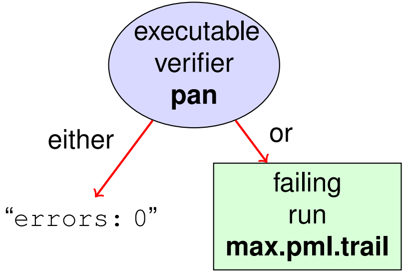

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```

- prints "`errors: 0`", or
- prints "`errors:` *n*" ($n > 0$)

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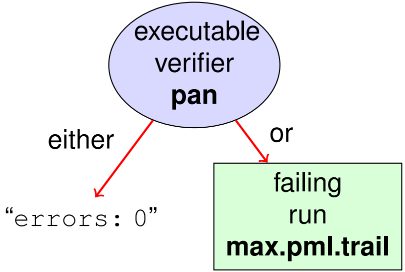

Command Line Execution

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- prints "errors: 0", or
- prints "errors: n" ($n > 0$) $\Rightarrow$ counter example found!

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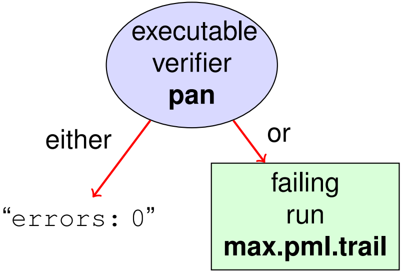

Command Line Execution

run verifier ***pan***

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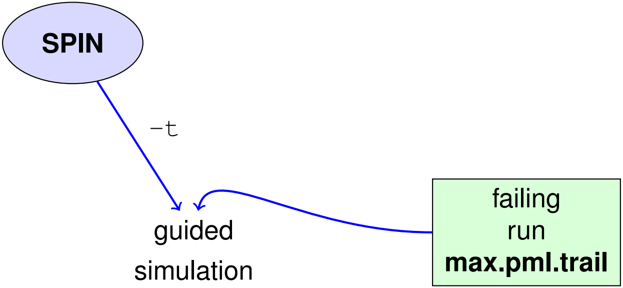
```

- prints "`errors: 0`", or
- prints "`errors:` *n*" ($n > 0$) ⇒ counter example found!
  records failing run in **max.pml.trail**

Guided Simulation

To examine failing run: employ simulation mode, “guided” by trail file.



Command Line Execution

inject a fault, re-run verification, and then:

```
> spin -t -p -l max.pml
```

Output of Guided Simulation

can look like:

```
Starting P with pid 0
1: proc 0 (P) line  8 "max.pml" (state 1) [a = 1]
                  P(0):a = 1
2: proc 0 (P) line 14 "max.pml" (state 7) [b = 2]
                  P(0):b = 2
3: proc 0 (P) line 23 "max.pml" (state 13) [((a<=b))]
3: proc 0 (P) line 23 "max.pml" (state 14) [max = a]
                  P(0):max = 1
spin: line  25 "max.pml", Error: assertion violated
spin: text of failed assertion:
      assert(( ((a>b)) -> ((max==a)) : ((max==b)) ))
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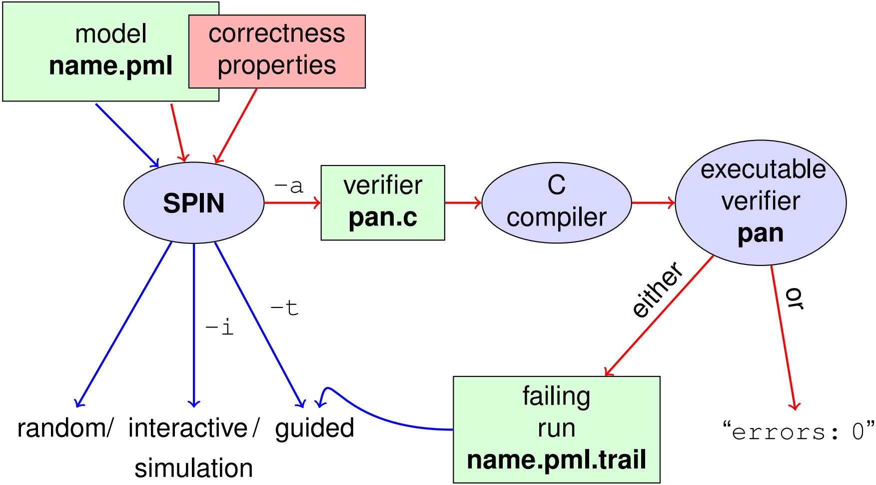
assignments in the run
values of variables whenever updated

What did we do so far?

following whole cycle (most primitive example, assertions only)



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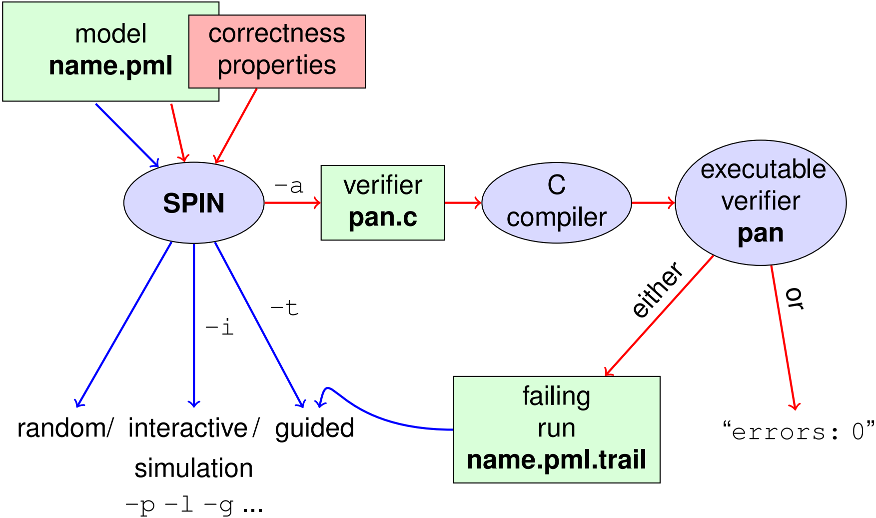

Further Examples: Integer Division

```
int dividend = 15;
int divisor  = 4;
int quotient, remainder;

quotient = 0;
remainder = dividend;
do
  :: remainder > divisor ->
     quotient++;
     remainder = remainder - divisor
  :: else ->
     break
od;
printf("%d divided by %d = %d, remainder = %d\n",
       dividend, divisor, quotient, remainder);
```

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```

simulate, put assertions, verify, change values, ...

Further Examples: Greatest Common Divisor

```
int x = 15, y = 20;
int a, b;
a = x; b = y;
do
  :: a > b -> a = a - b
  :: b > a -> b = b - a
  :: a == b -> break
od;
printf("The GCD of %d and %d = %d\n", x, y, a)
```

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full functional verification not possible here (why?)

still, assertions can perform sanity check

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```

full functional verification not possible here (why?)

still, assertions can perform sanity check

⇒ typical for model checking

Typical Command Lines

typical command line sequences:

random simulation

```
spin name.pml
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interactive simulation

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spin -i name.pml
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model checking

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gcc -o pan pan.c
./pan
```

and in case of error

```
spin -t -p -l -g name.pml
```

SPIN Reference Card

Ben-Ari produced Spin Reference Card, summarizing

- typical command line sequences
- options for
  - SPIN
  - gcc
  - pan
- PROMELA
  - datatypes
  - operators
  - statements
  - guarded commands
  - processes
  - channels
- temproal logic syntax

Why SPIN?

- SPIN targets software, instead of hardware verification
- based on standard theory of ω-automata and linear temporal logic
- 2001 ACM Software Systems Award (other winning software systems include: Unix, TCP/IP, WWW, Tcl/Tk, Java)
- used for safety critical applications
- distributed freely as research tool, well-documented, actively maintained, large user-base in academia and in industry
- annual SPIN user workshops series held since 1995

Why SPIN? (Cont'd)

- PROMELA and SPIN are rather simple to use
- good to understand a few system really well, rather than many systems poorly
- availability of good course book (Ben-Ari)
- availability of front end JSPIN (also Ben-Ari)

What is JSPIN?

- graphical user interface for SPIN
- developed for pedagogical purposes
- written in Java
- simple user interface
- SPIN options automatically supplied
- fully configurable
- supports graphics output of transition system

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- simple user interface
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- makes back-end calls transparent

JSPIN **Demo**

Command Line Execution

calling JSPIN

```
> java -jar /usr/local/jSpin/jSpin.jar
```

(with path adjusted to your setting)

or use shell script:

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> jspin
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JSPIN **Demo**

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play around with similar examples ...

Catching A Different Type of Error

quoting from file **max2.pml**:

```
/* after choosing a,b from {1,2,3} */
if
  :: a >= b -> max = a;
  :: b <= a -> max = b;
fi;
printf("the maximum of %d and %d is %d\n",
       a, b, max);
```

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generate and execute **pan**
⇒ reports "`errors: 1`"

Note: no **`assert`** in **max2.pml**.

Catching A Different Type of Error

Further inspection of **pan** output:

```
...
pan: invalid end state (at depth 1)
pan: wrote max2.pml.trail
...
```

Legal and Illegal Blocking

A process may legally block, as long as some other process can proceed.

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$\Rightarrow$ "Deadlock"

in **max1.pml**, no process can take over.

Valid End States

Definition (Valid End State)

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Valid End States

Karlsruhe Institute of Technology

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- `P`'s textual end
- each location marked with an end label: "`end`*xxx*`:`"

End labels are not useful in **max1.pml**, but elsewhere, they are.
Example: `end.pml`

Literature for this Lecture

Ben-Ari Chapter 2, Sections 4.7.1, 4.7.2