Karlsruhe Institute of Technology

Applications of Formal Verification

Model Checking: Introduction to SPIN

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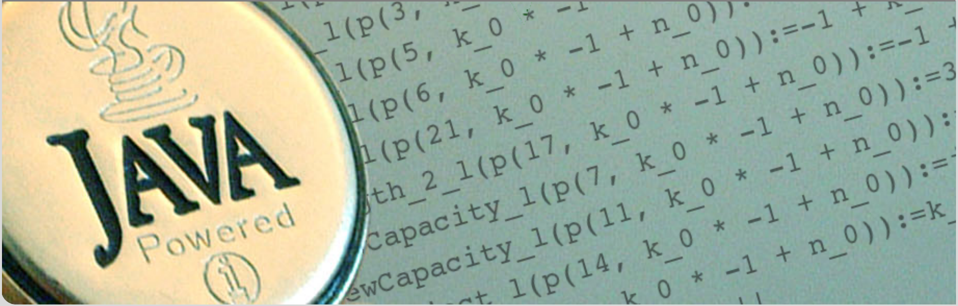
KIT – INSTITUT FÜR THEORETISCHE INFORMATIK



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.
It tries the opposite.

But why then can a MC also *prove* correctness properties?

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

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"

If this was all, you would have seen most of it already.
The name is a serious understatement!

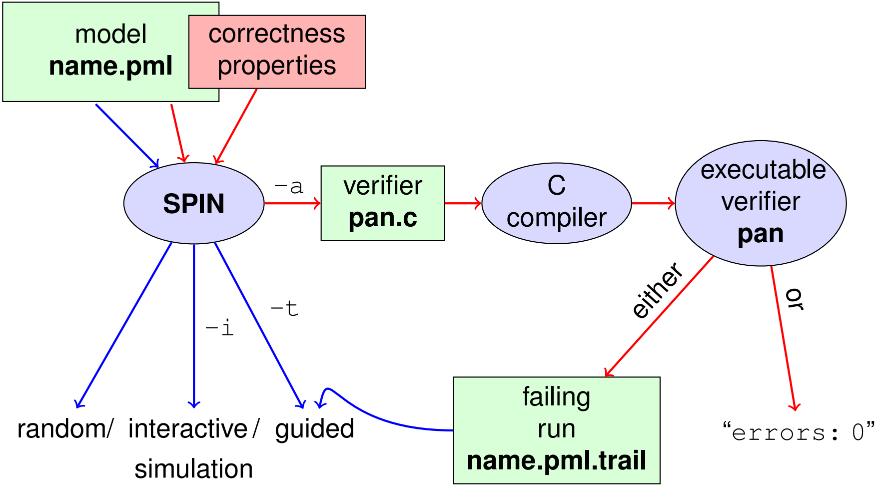
Main functionality of SPIN:

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

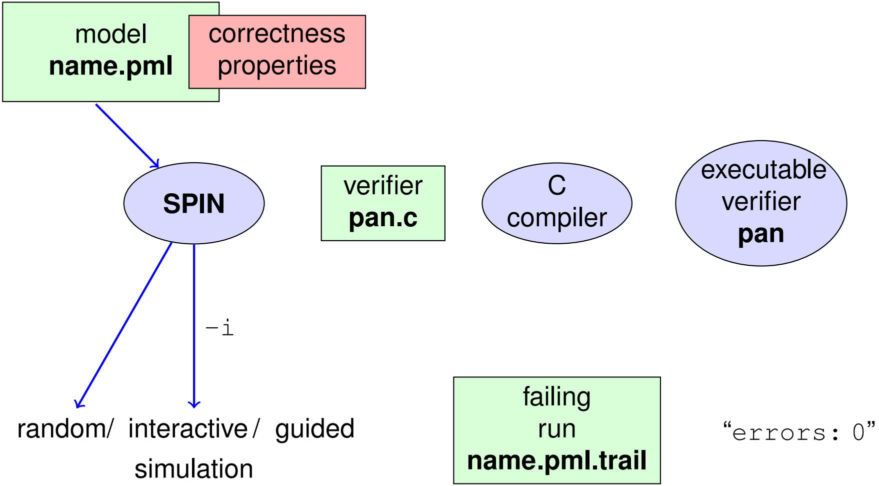
verifier generated by SPIN is a C program performing *model checking*:

- 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**



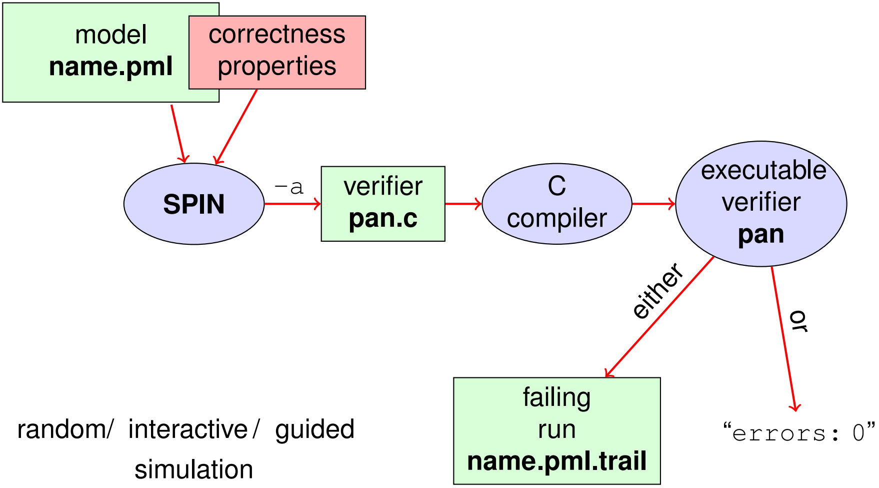
Plain Simulation with SPIN



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 $C_1, \ldots, C_n$.

- 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. $C_1, \ldots, C_n$ 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.

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

Stating Correctness Properties

model
name.pml

correctness
properties

Correctness properties can be stated (syntactically) within or outside the model.

stating properties within the model, using

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

stating properties outside the model, using

- never claims
- temporal logic formulas

Assertion Statements

Definition (Assertion Statements)

Assertion statements in PROMELA are statements of the form

assert (*expr*)

were *expr* is any PROMELA expression.

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 General Assertion Statements

assert (*expr*)

- has no effectno effect if *expr* evaluates to truenon-zero value
- triggers an error messageerror message if *expr* evaluates to false0

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);
```

Command Line Execution

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

```
> spin max.pml
```

... we can employ Assertions

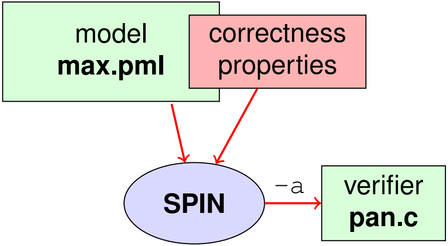
quoting from file **max.pml**:

```
/* after choosing a,b from {1,2,3} */
if
  :: a >= b -> max = a;
  :: a <= b -> max = b;
fi;
assert( a > b -> max == a : max == b )
```

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

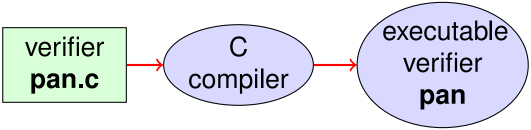
Generate Verifier in C

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

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

(plus helper files)

Compile To Executable Verifier



Command Line Execution

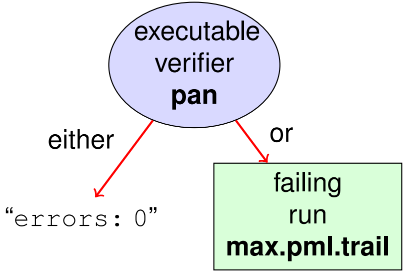
compile to executable verifier

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

C compiler generates executable verifier **pan**

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

Run Verifier (= Model Check)



Command Line Execution

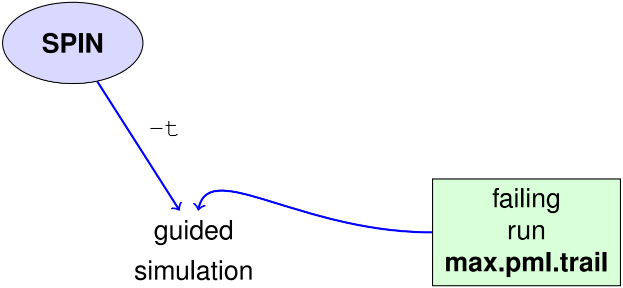
run verifier ***pan***

> ./pan

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

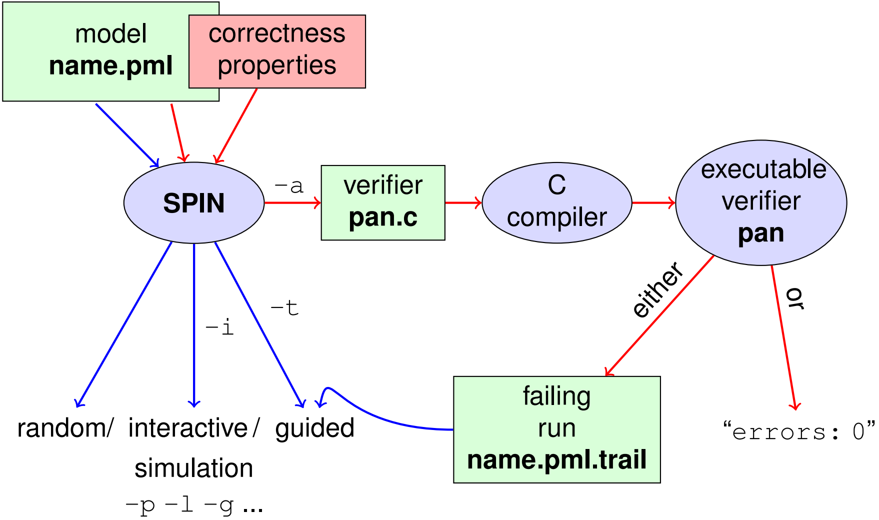
can look like:

```
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)) ))
```

assignments in the run
values of variables whenever updated

What did we do so far?

following whole cycle (most primitive example, assertions only)



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);
```

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)
```

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
```

interactive simulation

```
spin -i name.pml
```

model checking

```
spin -a name.pml
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
- 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:

```
> jspin
```

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);
```

simulate a few times
⇒ crazy “`timeout`” message sometimes

generate and execute **pan**
⇒ reports “`errors: 1`”

????

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.

Blocking for letting others proceed is useful, and typical, for concurrent and distributed models (i.p. protocols).

But

it's an error if a process blocks while no other process can proceed

$\Rightarrow$ "Deadlock"

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

Valid End States

Definition (Valid End State)

An end state of a run is valid iff the location counter of each processes is at an end location.

Definition (End Location)

End locations of a process `P` are:

- `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

Karlsruhe Institute of Technology

Ben-Ari Chapter 2, Sections 4.7.1, 4.7.2