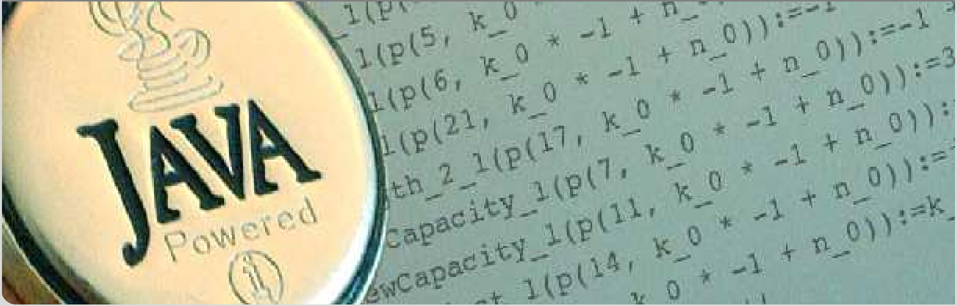
Applications of Formal Verification

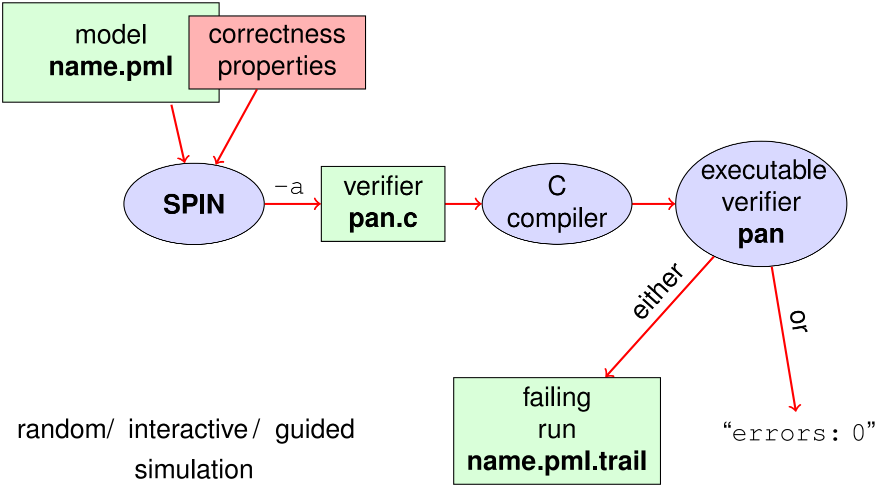
Model Checking with Temporal Logic

Bernhard Beckert · Mattias Ulbrich | SS 2019

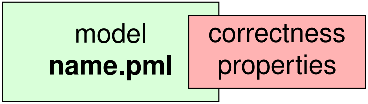
KIT – Institut für Theoretische Informatik



Model Checking with SPIN



Stating Correctness Properties



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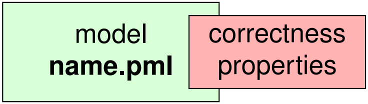

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- assertion statements

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

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stating properties outside model using

- never claims
- temporal logic formulas

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stating properties outside model using

- never claims
- *temporal logic formulas* (today's main topic)

Model Checking of Temporal Properties

many correctness properties not expressible by assertions

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model checking of properties formulated in temporal logic

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Remark:
in this course, "temporal logic" is synonymous to *"linear temporal logic" (LTL)*

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Assertions only talk about the state ‘at their own location’ in the code.

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Example: mutual exclusion expressed by adding assertion into *each* critical section.

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Drawbacks:

- no separation of concerns (model vs. correctness property)
- changing assertions is error prone (easily out of synch)
- easy to forget assertions:
  correctness property might be violated at unexpected locations
- many interesting properties not expressible via assertions

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“If some processes try to enter their critical section, eventually *one of them* does so.”

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all these are temporal properties $\Rightarrow$ *use temporal logic*

Boolean Temporal Logic

talking about numerical variables (like in `critical <= 1` or `0 <= i <= len-1`) requires variation of *propositional temporal logic* which we call Boolean temporal logic:

- Boolean expressions (over PROMELA variables), rather than *propositions*, form basic building blocks of the logic

Boolean Temporal Logic over PROMELA

Set For_{BTL} of Boolean Temporal Formulas (simplified)

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- if ϕ and ψ are formulas $\in For_{BTL}$, then all of

$$\neg\phi, \quad \phi \wedge\wedge \psi, \quad \phi \vee\vee \psi, \quad \phi \rightarrow \psi, \quad \phi \longleftrightarrow \psi$$

$$[\,]\phi, \quad <>\phi, \quad \phi\, \mathtt{U}\, \psi$$

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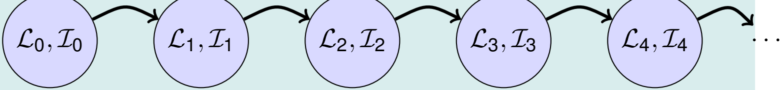
Semantics of Boolean Temporal Logic

A run σ through a PROMELA model M is a chain of states



$\mathcal{L}_j$ maps each running process to its current location counter.
From $\mathcal{L}_j$ to $\mathcal{L}_{j+1}$, only one of the location counters has advanced (exception: channel rendezvous).
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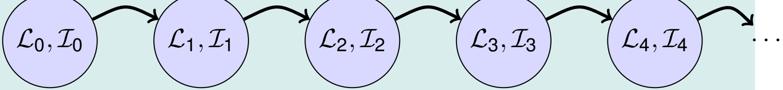

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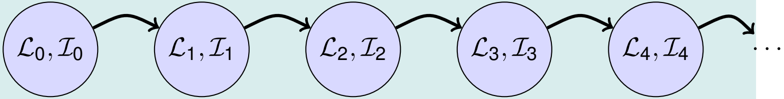

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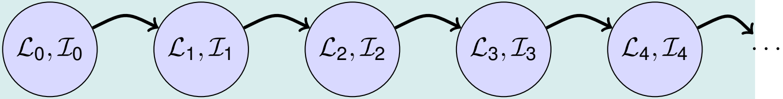

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$\mathcal{L}_j, \mathcal{I}_j \models \mathtt{P@l}$ iff $\mathcal{L}_j(\mathtt{P})$ is the location labeled with $\mathtt{l}$.

Evaluating other formulas $\in$ For_{BTL} in a run σ: as usual (see the book / “Formale Systeme”).

Boolean Temporal Logic Support in SPIN

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instead

Boolean expressions must be abbreviated using **`#define`**

Temporal Logic Quiz

What does the following LTL formula mean?

[]((Q & !R & <>R) -> (P -> (!R U (S & !R))) U R)

Temporal Logic Quiz

What does the following LTL formula mean?

`[](( Q & !R & <>R) -> (P -> (!R U (S & !R))) U R)`

P triggers S between Q (e.g., end of system initialization) and R (start of system shutdown).

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example: ‘`[](critical <= 1)`’

“it is guaranteed throughout each run that at most one process is in its critical section”

or equivalently:
“more than one process being in its critical section will never happen”

Applying Temporal Logic to Critical Section Problem

We want to verify `'[](critical<=1)'` as correctness property of:

```
active proctype P() {
  do :: /* non-critical activity */
        atomic {
          !inCriticalQ;
          inCriticalP = true
        }
        critical++;
        /* critical activity */
        critical--;
        inCriticalP = false
  od
}

/* similarly for process Q */
```

Model Checking a Safety Property with JSPIN

1. add ‘`#define mutex (critical <= 1)`’ to PROMELA file
2. open PROMELA file
3. enter `[]mutex` in `LTL` text field
4. select `Translate` to create a ‘never claim’, corresponding to the negation of the formula
5. ensure `Safety` is selected
6. select `Verify`
7. (if necessary) select `Stop` to terminate too long verification

Never Claims

you may ignore them, but if you are interested:

- a never claim tries to show the user wrong
- it defines, in terms of PROMELA, all violations of a wanted correctness property
- it is semantically equivalent to the negation of the wanted correctness property
- JSPIN adds the negation for you
- using SPIN directly, you have to add the negation yourself

Model Checking a Safety Property with SPIN directly

Command Line Execution

make sure ‘**#define** mutex (critical <= 1)’ *is in* safety1.pml

```
> spin -a -f "!([] mutex)" safety1.pml
> gcc -DSAFETY -o pan pan.c
> ./pan
```

Temporal MC Without Ghost Variables

We want to verify mutual exclusion without using ghost variables

```
#define mutex !(P@cs && Q@cs)

bool inCriticalP = false, inCriticalQ = false;

active proctype P() {
  do :: atomic {
          !inCriticalQ;
          inCriticalP = true
        }
cs:     /* critical activity */
        inCriticalP = false
  od
}
/* similarly for process Q */
/* with same label cs:     */
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Verify ‘`[]mutex`’ with JSPIN.

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Liveness properties are formulas where potential counterexamples are necessarily infinite runs.

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example: ‘`<>csp`’

(with `csp` a variable only true in the critical section of `P`)

“in each run, process `P` visits its critical section eventually”

Applying Temporal Logic to Starvation Problem

We want to verify ‘`<>csp`’ as correctness property of:

```
active proctype P() {
  do :: /* non-critical activity */
        atomic {
          !inCriticalQ;
          inCriticalP = true
        }
        csp = true;
        /* critical activity */
        csp = false;
        inCriticalP = false
  od
}

/* similarly for process Q */
/* here using csq          */
```

Model Checking a Liveness Property with JSPIN

1. open PROMELA file
2. enter `<>csp` in `LTL` text field
3. select `Translate` to create a 'never claim', corresponding to the negation of the formula
4. ensure that `Acceptance` is selected
   (SPIN will search for *accepting* cycles through the never claim)
5. *for the moment* uncheck `Weak Fairness` (see discussion below)
6. select `Verify`

Verification Fails

Verification fails.

Why?

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Why?

The liveness property on one process ‘had no chance’.
The scheduler can unfairly select the other process all the time.

Fairness

Does the following PROMELA model necessarily terminate?

```
byte n = 0;
bool flag = false;

active proctype P() {
  do :: flag -> break;
     :: else -> n = 5 - n;
  od
}
active proctype Q() {
  flag = true
}
```

Fairness

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Termination guaranteed only if scheduling is (weakly) fair!

Definition (Weak Fairness)

A run is called weakly fair iff the following holds:
each continuously executable statement is executed eventually.

Model Checking Liveness with Weak Fairness!

Always switch Weak Fairness on when checking for liveness!

1. open PROMELA file
2. enter `<>csp` in `LTL` text field
3. select `Translate` to create a 'never claim', corresponding to the negation of the formula
4. ensure that `Acceptance` is selected
   (SPIN will search for *accepting* cycles through the never claim)
5. ensure `Weak Fairness` is checked
6. select `Verify`

Model Checking Liveness with SPIN directly

Command Line Execution

```
> spin -a -f "!csp" liveness1.pml
> gcc -o pan pan.c
> ./pan -a -f
```

Verification Fails

Verification fails again.

Why?

Verification Fails

Verification fails again.

Why?

Weak fairness is still too weak.

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Verification fails again.

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Note that `!inCriticalQ` is not continuously executable!

Verification Fails

Verification fails again.

Why?

Weak fairness is still too weak.

Note that `!inCriticalQ` is not continuously executable!

Designing a fair mutual exclusion algorithm is complicated.

Literature for this Lecture

Ben-Ari Chapter 5

Progress Labels

- name starts with `progress`.
- must be traversed (infinitely often) in any infinite execution,
- otherwise: “non-progress cycle”.

Accept Labels

- name starts with `accept`.
- state cannot persist forever, and
- cannot be revisited infinitely often