Formal Methods for Software Development

Model Checking with Temporal Logic

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20th September 2019

Model Checking

Check whether a formula is valid in all runs of a transition system.

Given a transition system $\mathcal{T}$ (e.g., derived from a PROMELA program).

Verification task: is the LTL formula ϕ satisfied in all traces of $\mathcal{T}$, i.e.,

$$\mathcal{T} \models \phi \quad ?$$

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this lecture

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next lecture

1. translating LTL into generalised Büchi automata
2. generalised Büchi automata and their normalisation

A model checking graph is a directed graph with initial and accepting nodes.

Definition (Model Checking Graph)

A model checking graph $(N, \rightarrow, N_0, N_a)$ is composed of:

- finite, non-empty set of nodes N
- an 'arrow' relation $\rightarrow \subseteq N \times N$
- a non-empty set of initial nodes $N_0 \subseteq N$
- a set of accepting nodes $N_a \subseteq N$

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1. transition systems without terminal states:
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Can always be achieved by adding 'trap states' or 'trap locations', resp.

Product of Transition System and Büchi Automaton

We assume a set of atomic propostions AP.

Definition (Product of Transition System and Büchi Automaton)

Let $\mathcal{T} = (S, \rightarrow, S_o, L)$ be a transition system over AP and $\mathcal{B} = (Q, \delta, Q_0, F)$ be a Büchi automaton over the alphabet 2^{AP}.
Then, $\mathcal{T} \otimes \mathcal{B}$ is the following model checking graph:

$$\mathcal{T} \otimes \mathcal{B} = (S \times Q, \rightarrow', N_0, N_a)$$

where:

- $\langle s, q \rangle \rightarrow' \langle s', q' \rangle$ iff $s \rightarrow s'$ and $(q, L(s'), q') \in \delta$

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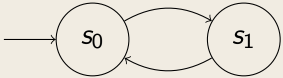
Model Checking Example

Assume $AP = \{red, green\}$

$\mathcal{T}$:



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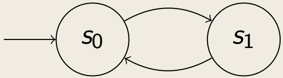

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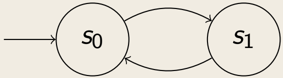

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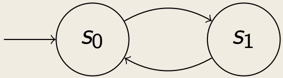

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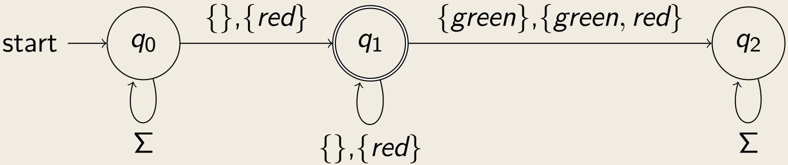

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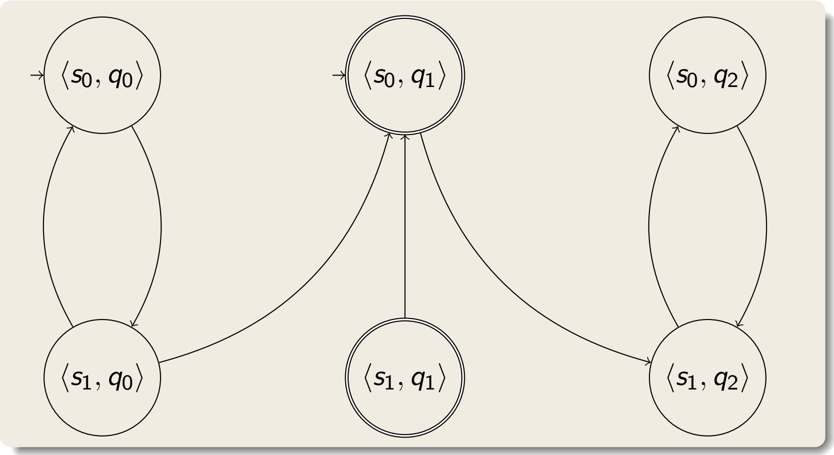

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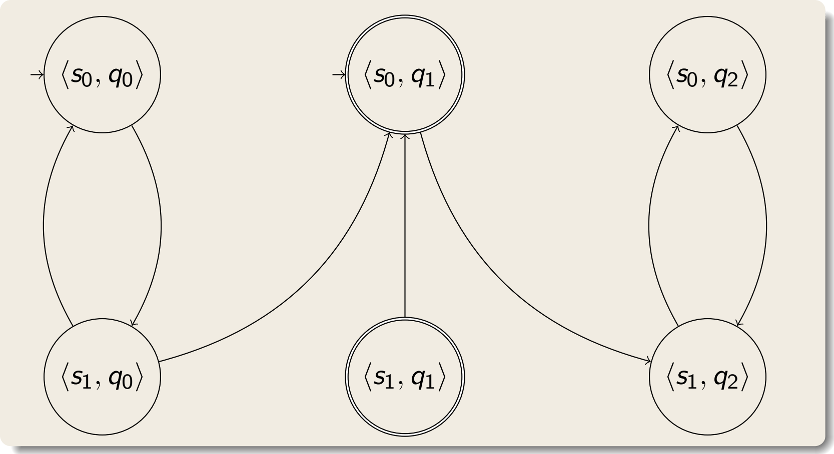

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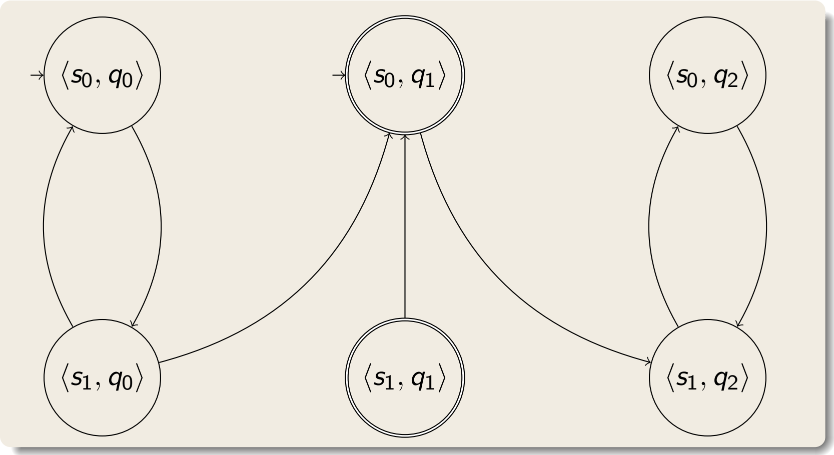

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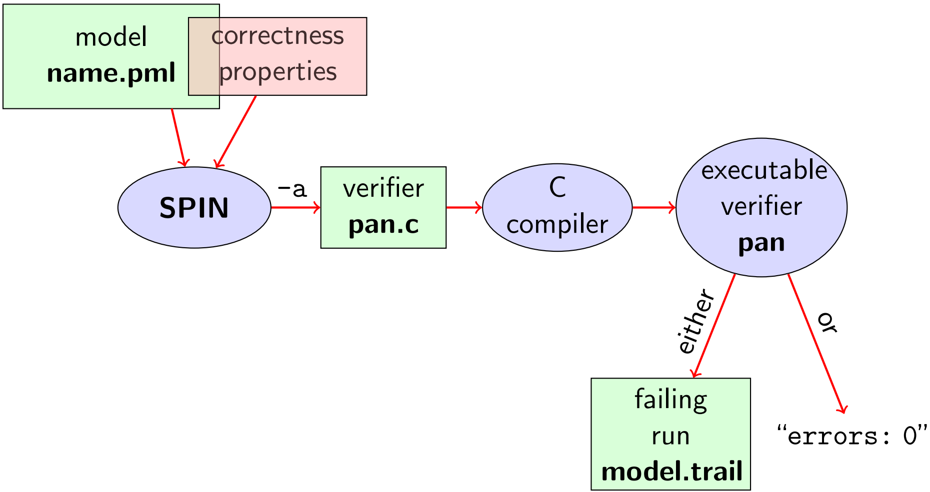
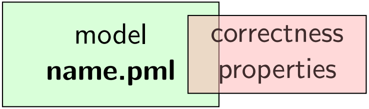
Model Checking with SPIN



Stating Correctness Properties



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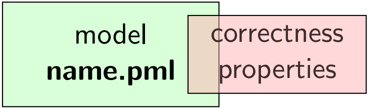

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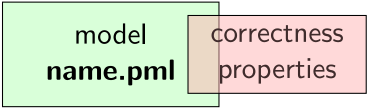

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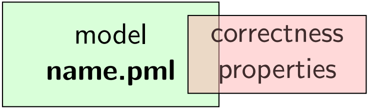

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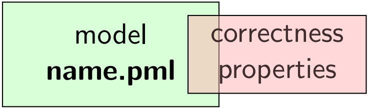

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Preliminaries

1. Accept labels in PROMELA $\leftrightarrow$ Büchi automata
2. Fairness

Preliminaries 1: Acceptance Cycles

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Accept locations can be used to specify cyclic behavior

Definition (Acceptance Cycle)

A run which infinitely often passes through an accept location is called an acceptance cycle.

Acceptance cycles are mainly used in never claims (see below), to define (undesired) infinite behavior

Preliminaries 2: Fairness

Does this model terminate in each run?

Simulate: `start/fair.pml`

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byte n = 0;
bool flag = false;

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Definition (Weak Fairness)

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

Model Checking of Temporal Properties

Many correctness properties not expressible by assertions

- All properties that involve state changes
- Temporal logic expressive enough to characterize many (but not all) Linear Time properties

In this course: "temporal logic" synonymous with "linear temporal logic"

Today: model checking of properties formulated in temporal logic

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- Many interesting properties not expressible via assertions

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These are temporal properties $\Rightarrow$ use temporal logic

Boolean Temporal Logic

Numerical variables in expressions

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In Boolean Temporal Logic, atomic building blocks are *Boolean expressions* over PROMELA variables

Boolean Temporal Logic over PROMELA

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

$$!\,\phi, \quad \phi \;\&\&\; \psi, \quad \phi \;||\; \psi, \quad \phi \;\text{->}\; \psi, \quad \phi \;\text{<->}\; \psi$$
$$[\,]\phi, \quad <>\phi, \quad \phi\,\mathtt{U}\,\psi$$

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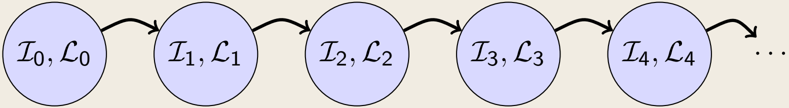
Semantics of Boolean Temporal Logic

A trace τ through a PROMELA model M



- $\mathcal{I}_j$ maps each variable in M to its current value
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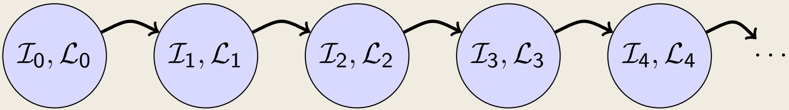

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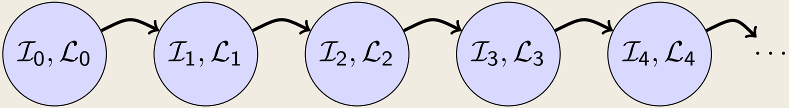

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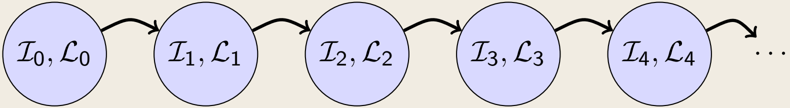

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Evaluating other formulas $\in For_{BTL}$ in traces τ: see previous lecture

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Any violating run would have `(critical > 1)` after *finite* time

Applying Temporal Logic to Critical Section Problem

We want to verify `[](critical<=1)` as a 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 SPIN

Command Line Execution

Add definition of TL formula to PROMELA file

Example `ltl atMostOne { [](critical <= 1) }`

General `ltl` *name* `{` *TL-formula* `}`

can define more than one formula

```
> spin -a file.pml
> gcc -DSAFETY -o pan pan.c
> ./pan -N name
```

Demo: `target/safety1.pml`

Model Checking a Safety Property with SPIN

Command Line Execution

Add definition of TL formula to PROMELA file

Example `ltl atMostOne { [](critical <= 1) }`

General `ltl` *name* `{` *TL-formula* `}`

can define more than one formula

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> spin -a file.pml
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> ./pan -N name
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Demo: `target/safety1.pml`

- The '`ltl` *name* `{` *TL-formula* `}`' construct must be part of your lab submission!

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> ./pan -N name
```

Demo: `target/safety1.pml`

- The '`ltl` *name* `{` *TL-formula* `}`' construct must be part of your lab submission!

`ltl` definitions not part of Ben Ari's book (SPIN$\leq$ 6): ignore 5.3.2, etc.

Model Checking a Safety Property using Web Interface

1. add definition of TL formula to PROMELA file

   Example `ltl atMostOne { [](critical <= 1) }`

   General `ltl` *name* { *TL-formula* }

   can define more than one formula
2. load PROMELA file into web interface
3. ensure `Safety` is selected
4. enter name of LTL formula in according field
5. select `Verify`

Demo: `safety1.pml`

Model Checking a Safety Property using jSpin

1. add definition of TL formula to Promela file

   Example `ltl atMostOne { [](critical <= 1) }`

   General `ltl` *name* { *TL-formula* }

   can define more than one formula

2. load Promela file into jSpin
3. write *name* in 'LTL formula' field
4. ensure `Safety` is selected
5. select `Verify`
   - (corresponds to command line `./pan -N` *name* `...`)
6. (if necessary) select `Stop` to terminate too long verification

Demo: `safety1.pml`

Temporal Model Checking without Ghost Variables

We want to verify mutual exclusion without using ghost variables.

```
bool inCriticalP = false , inCriticalQ = false;

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

/* similar for process Q with same label cs: */

ltl mutualExcl { []!(P@cs && Q@cs) }
```

Demo: `start/noGhost.pml`

Never Claims: Processes trying to show user wrong

Büchi automaton, as PROMELA process, for negated property

1. Negated TL formula translated to '**never**' process
2. Accepting locations in Büchi automaton represented with help of accept labels ("`accept`*xxx*`:`")
3. If one of these reached infinitely often, the orig. property is violated

Never Claims: Processes trying to show user wrong

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1. Negated TL formula translated to '**never**' process
2. Accepting locations in Büchi automaton represented with help of accept labels ("accept*xxx*:")
3. If one of these reached infinitely often, the orig. property is violated

Example (Never claim for `<>p`, simplified for readability)

```
never {  /* !<>p */
  accept_xyz: /* passed ∞ often iff !<>p holds */
  do
  :: !p
  od
}
```

Liveness Properties

Liveness Properties

- state that something good (ϕ) eventually happens in each run
- each violating requires *infinitely* many steps

Liveness Properties

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- state that something good (ϕ) eventually happens in each run
- each violating requires *infinitely* many steps

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 a 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 */
/* there, using csq         */
```

Model Checking a Liveness Property using jSPIN

1. open PROMELA file `liveness1.pml`
2. write `ltl pWillEnterC { <>csp }` in PROMELA file
   (as first `ltl` formula)
3. ensure that `Acceptance` is selected (for liveness properties)
   (SPIN will search for *accepting* cycles through the never claim)
4. *for the moment* uncheck `Weak Fairness` (see discussion below)
5. select `Verify`

Verification Fails

Demo: `start/liveness1.pml`

Verification fails!

Why?

Verification Fails

Demo: `start/liveness1.pml`

Verification fails!

Why?

The liveness property on one process "had no chance".
Not even weak fairness was switched on!

Model Checking Liveness with Weak Fairness using JSPIN

Always check `Weak fairness` when verifying liveness

1. open PROMELA file
2. write `ltl pWillEnterC { <>csp }` in PROMELA file
   (as first `ltl` formula)
3. ensure that `Acceptance` is selected (for liveness properties)
   (SPIN will search for *accepting* cycles through the never claim)
4. ensure `Weak fairness` is checked
5. select `Verify`

Model Checking Liveness using Web Interface

1. add definition of TL formula to PROMELA file

   Example `ltl pWillEnterC { <>csp }`

   General `ltl` *name* `{` *TL-formula* `}`

   can define more than one formula

2. load PROMELA file into web interface
3. ensure `Acceptance` is selected (for liveness properties)
4. enter name of LTL formula in according field
5. ensure `Weak fairness` is checked
6. select `Verify`

Demo: `liveness1.pml`

Model Checking Liveness using SPIN directly

Command Line Execution

Make sure `ltl` *name* { *TL-formula* } is in *file*.pml

```
> spin -a file.pml
> gcc -o pan pan.c
> ./pan -a -f [-N name]
```

`-a` acceptance cycles, `-f` weak fairness

Demo: `start/liveness1.pml`

Limitation of Weak Fairness

Verification fails again!

Why?

Limitation of Weak Fairness

Verification fails again!

Why?

Weak fairness is too weak . . .

Definition (Weak Fairness)

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

Limitation of Weak Fairness

Verification fails again!

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Weak fairness is too weak . . .

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

Note that `!inCriticalQ` is not continuously executable!

Limitation of Weak Fairness

Verification fails again!

Why?

Weak fairness is too weak ...

Definition (Weak Fairness)

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

Note that `!inCriticalQ` is not continuously executable!

Restriction to weak fairness is principal limitation of Spin

Here, liveness needs strong fairness, which is not supported by Spin.

Revisit `fair.pml`

- Specify liveness of `fair.pml` using labels

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- Prove termination

Demo: `target/fair.pml`

Revisit `fair.pml`

- Specify liveness of `fair.pml` using labels
- Prove termination
- Here, weak fairness is needed, *and sufficient*

Demo: `target/fair.pml`

Literature for this Lecture

Ben-Ari Chapter 5
except Sections 5.3.2, 5.3.3, 5.4.2
(`ltl` construct replaces **#define** and `-f` option of SPIN)