Formal Methods for Software Development

Modeling Concurrency

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10 September 2019

Concurrent Systems – The Big Picture

Concurrency: different processes trying not to run into each others' way

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Main problem of concurrency: sharing computational resources

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processes = vehicles, shared resource = crossing,
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Solutions to this must be carefully designed and verified, otherwise...

Concurrent Systems – The Big Picture

Focus of this Lecture

Aim of SPIN-style model checking methodology:

exhibit flaws in software systems

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Aim of SPIN-style model checking methodology:

exhibit design flaws in software systems

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Aim of Spin-style model checking methodology:

exhibit design flaws in concurrent and distributed software systems

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- Modeling and analyzing concurrent systems

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Focus of next lecture:

- Modeling and analyzing distributed systems

Concurrent/Distributed systems difficult to get right

Problems:

- hard to predict, hard to form faithful intuition

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- lack of controllability
  $\Rightarrow$ we miss failures in test phase
- lack of reproducability
  $\Rightarrow$ even if failures appear in test phase,
  often impossible to analyze/debug defect
- lack of time
  exhaustive testing exhausts the testers long before it exhausts behavior of the system...

Mission of Spin-style Model Checking

Offer an efficient methodology to

- improve the design
- exhibit defects

of concurrent and distributed systems

Activities in SPIN-style Model Checking

1. model (critical aspects of) concurrent/distributed system with PROMELA
2. state crucial properties with assertions, temporal logic, ...
3. use SPIN to check all possible runs of the model
4. analyze result, possibly re-work **1.** and **2.**

Activities in SPIN-style Model Checking

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Separate concerns of model vs. property! Check the property you want the model to have, not the one it happens to have.

Main Challenges of Modeling

expressiveness
: Model must be expressive enough to 'embrace' defects the real system could have

simplicity
: Model must be simple enough to be 'model checkable', theoretically and practically

Modeling Concurrent Systems in Promela

In the SPIN approach,
the cornerstone of modeling concurrent/distributed systems are

PROMELA processes.

Initializing Processes

Can be instantiated *implicitly* using '**active**'.

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Can be instantiated *implicitly* using '**active**'.

Can be instantiated *explicitly* with key word '**init**'

```
init {
  printf("Hello␣world\n")
}
```

init is used to start other processes with **run** statement.

Starting Processes

Processes can be started *explicitly* using **run**

```
proctype P() {
  byte x;
  ...
}

init {
  run P();
  run P()
}
```

Each **run** operator starts copy of process (with copy of local variables)

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run `P()` does *not* wait for `P` to finish

(PROMELA's **run** corresponds to JAVA's **`start`**, *not* to JAVA's **`run`**)

Atomic Start of Multiple Processes

By convention, **run** operators enclosed in **atomic** block

```
proctype P() {
  byte x;
  ...
}

init {
  atomic {
    run P();
    run P()
  }
}
```

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Effect: processes only start executing once all are created

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(More on **atomic** later)

Joining Processes

joining: waiting for all other processes to finish

```
byte result;

proctype P() {
  ...
}

init {
  atomic {
    run P();
    run P()
  }
  (_nr_pr == 1); /*blocks until join*/
  printf("result␣=%d", result)
}
```

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}
```

`_nr_pr`	built-in variable holding number of running processes
`_nr_pr == 1`	only ‘this’ process (**init**) is running

Process Parameters

Processes may have formal parameters, instantiated by **run**:

```
proctype P(byte id; byte incr) {
  ...
}

init {
  run P(7, 10);
  run P(8, 15)
}
```

Active (Sets of) Processes

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```

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```
active [n] proctype P() {
  ...
}
```

Implicit **init** will **run** *n* copies of P

Local and Global Data

Variables declared outside of the processes are global to all processes.

Variables declared inside a process are local to that processes.

```
byte n;

proctype P(byte id; byte incr) {
  byte t;
  ...
}
```

`n` is global

`t` is local

Modeling with Global Data

Pragmatics of modeling with global data:

Shared memory of concurrent systems often modeled
by global variables of numeric (or array) type

Status of shared resources (printer, traffic light, ...) often modeled
by global variables of Boolean or enumeration type
(**bool**/**mtype**).

Communication mediums of distributed systems often modeled
by global variables of channel type (**chan**). (next lecture)

Interference on Global Data

```
byte n = 0;

active proctype P() {
  n = 1;
  printf("Proc␣P,␣n␣=␣%d\n", n)
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Interference on Global Data

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byte n = 0;

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  n = 2;
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How many outputs possible?

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How many outputs possible?

Different processes can interfere on global data

Examples

1. `interleave0.pml`
   Spin simulation, SpinSpider automata + transition system
2. `interleave1.pml`
   Spin simulation, adding assertion, fine-grained execution model, model checking
3. `interleave5.pml`
   Spin simulation, Spin model checking, trail inspection

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Executability addresses many issues in the interplay of processes.

Most synchronization primitives
(test & set, compare & swap, semaphores, ...)
can be modeled w. *executability and atomicity*.

Executability

Each statement has the notion of executability.
Executability of basic statements:

statement type	*executable*
assignment	always
assertion	always
print statement	always
expression statement	
send/receive statement	

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(Inspect `end.pml`)

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Executability and Blocking

Definition (Blocking)

A statement blocks iff it is *not* executable.
A process blocks iff its location counter points to a blocking statement.

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Executability, resp. blocking are the key to PROMELA-style modeling of solutions to synchronization problems.

Deadlock

Definition (Deadlock (simplified))

Let CRP be the set of currently running processes.
A deadlock is a point in the execution where

- $CRP \neq \emptyset$
- all $p \in CRP$ are blocking

(Model check `end.pml`)

Valid End States

Definition (End Location)

End locations of a process `P` are:

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Definition (End Location)

End locations of a process `P` are:

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

Deadlock

Definition (Deadlock (full version))

Let CRP be the set of currently running processes.
Let $NEL \subseteq CRP$ be the set of (currently running) processes which are *not* at a valid end location.
A deadlock is a point in the execution where

- $NEL \neq \emptyset$
- all $p \in NEL$ are blocking

Deadlock Detection

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(Fix `end.pml`)

Atomicity

limit the possibility of sequences being interrupted by other processes

weakly atomic sequence

can *only* be interrupted when a statement blocks

strongly atomic sequence

cannot be interrupted at all

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can *only* be interrupted when a statement blocks
defined in PROMELA by **atomic**{*list_of_statements*}

strongly atomic sequence

cannot be interrupted at all
defined in PROMELA by **d_step**{*list_of_statements*}

Executability (Cont'd)

atomic resp. **d_step** statement is executable

iff

guard (i.e., the first inner statement) is executable

Deterministic Sequences

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Deterministic Sequences

d_step:

- strongly atomic
- **d**eterministic (like a single **step**)
- choices resolved in fixed way (always take the first possible option)
  ⇒ avoid choices in **d_step**
- it is an error if any statement within **d_step**,
  other than the first one (called *'guard'*), blocks

```
d_step {
    stmt1; ← guard
    stmt2;
    stmt3
}
```

If `stmt1` blocks, **d_step** is not entered, and blocks as a whole.

It is an error if `stmt2` or `stmt3` block.

(Weakly) Atomic Sequences

atomic:

- weakly atomic
- can be non-deterministic

```
atomic {
    stmt1; ← guard
    stmt2;
    stmt3
}
```

If *guard* blocks, **atomic** is not entered, and blocks as a whole.

Once **atomic** is entered, control is kept until a statement blocks, and only in this case passed to another process.

The Critical Section Problem

Archetypal problem of concurrent systems

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Mutual Exclusion At most one process is executing its critical section at any time.

Absence of Deadlock If *some* processes are trying to enter their critical sections, then *one* of them must eventually succeed.

Absence of (individual) Starvation If *any* process tries to enter its critical section, then *that* process must eventually succeed.

Critical Section Pattern

For demonstration and simplicity:
Noncritical and critical sections only **printf** statements here

```
active proctype P() {
  do :: printf("P␣non-critical␣actions\n");
        /* begin critical section */
        printf("P␣uses␣shared␣resourses\n")
        /* end critical section */
  od
}

active proctype Q() {
  do :: printf("Q␣non-critical␣actions\n");
        /* begin critical section */
        printf("Q␣uses␣shared␣resourses\n")
        /* end critical section */
  od
}
```

No Mutual Exclusion Yet

More infrastructure to achieve ME.

Adding two Boolean flags:

```
bool P_in_CS = false;
bool Q_in_CS = false;

active proctype P() {
  do :: printf("P␣non-critical␣actions\n");
        P_in_CS = true;
        /* begin critical section */
        printf("P␣uses␣shared␣resourses\n");
        /* end critical section */
        P_in_CS = false
  od
}

active proctype Q() {
  ...correspondingly...
}
```

Show Mutual Exclusion VIOLATION with SPIN

adding assertions

```
bool P_in_CS = false;
bool Q_in_CS = false;

active proctype P() {
  do :: printf("P␣non-critical␣actions\n");
        P_in_CS = true;
        /* begin critical section */
        printf("P␣uses␣shared␣resourses\n");
        assert(!Q_in_CS);
        /* end critical section */
        P_in_CS = false
  od
}

active proctype Q() {
    ........assert(!P_in_CS);........
}
```

Mutual Exclusion by Busy Waiting

```
bool P_in_CS = false;
bool Q_in_CS = false;

active proctype P() {
  do :: printf("P␣non-critical␣actions\n");
        P_in_CS = true;
        do :: !Q_in_CS -> break
           :: else -> skip
        od;
        /* begin critical section */
        printf("P␣uses␣shared␣resourses\n");
        assert(!Q_in_CS);
        /* end critical section */
        P_in_CS = false
  od
}

active proctype Q() { ...correspondingly... }
```

Mutual Exclusion by Blocking

Instead of Busy Waiting, process should

1. yield control,
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What can we do instead?

We use expression statement `!Q_in_CS`
to let process `P` block where it should not proceed!

Mutual Exclusion by Blocking

```
active proctype P() {
  do :: printf("P␣non-critical␣actions\n");
        P_in_CS = true;
        !Q_in_CS;
        /* begin critical section */
        printf("P␣uses␣shared␣resourses\n");
        assert(!Q_in_CS);
        /* end critical section */
        P_in_CS = false
  od
}

active proctype Q() {
  ...correspondingly...
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Verify Mutual Exclusion of this

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can make `pan` ignore the deadlock: `./pan -E`

SPIN still reports assertion violation(!)

Proving Mutual Exclusion

In this example:

- mutual exclusion (ME) cannot be shown by SPIN

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- `P/Q_in_CS` *not* sufficient for *proving* ME

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In this example:

- mutual exclusion (ME) cannot be shown by SPIN
- `P/Q_in_CS` sufficient for *achieving* ME
- `P/Q_in_CS` *not* sufficient for *proving* ME

Need more infrastructure.

Ghost variables: variables for verification, not for modeling

Show Mutual Exclusion with Ghost Variable

```
int critical = 0;

active proctype P() {
  do :: printf("P␣non-critical␣actions\n");
        P_in_CS = true;
        !Q_in_CS;
        /* begin critical section */
        critical++;
        printf("P␣uses␣shared␣resourses\n");
        assert(critical < 2);
        critical--;
        /* end critical section */
        P_in_CS = false
  od
}

active proctype Q() {
  ...correspondingly...
}
```

Verify Mutual Exclusion of this

SPIN (`./pan -E`) shows no assertion is violated
$\Rightarrow$ mutual exclusion is verified

Verify Mutual Exclusion of this

SPIN (`./pan -E`) shows no assertion is violated
⇒ mutual exclusion is verified

Still SPIN (without `-E`) reports (`invalid end state`)
⇒ deadlock

Deadlock Hunting

Invalid End State:

- A process does not finish at its end
- OK if it is not crucial to continue – add end lables (see `end.pml`)
- If it is crucial to continue:
  Real deadlock

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- A process does not finish at its end
- OK if it is not crucial to continue – add end lables (see `end.pml`)
- If it is crucial to continue:
  Real deadlock

Address Deadlock with SPIN:

- Verify to produce a failing run trail
- Simulate to see how the processes get to the interlock
- Fix the model (not using the end labels nor `-E` option)

Atomicity against Deadlocks

solution:

checking and setting the flag in one atomic step

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(demonstrate that in `csGhost.pml`)

Atomicity against Deadlocks

solution:

checking and setting the flag in one atomic step

(demonstrate that in csGhost.pml)

```
atomic {
  !Q_in_CS;
  P_in_CS = true
}
```

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- ... and many more

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Using **atomic** and **d_step** too heavily, for too large blocks, can result in well-behaved models, while modeling the wrong system.