Formal Methods for Software Development

Modeling Concurrency

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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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http://www.youtube.com/watch?v=G8eqymwUFi8

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processes = vehicles, shared resource = crossing,
and a (data) race in progress.

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:

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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 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

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.**

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 mostly 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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(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()
  }
}
```

Atomic Start of Multiple Processes

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Effect: processes only start executing once all are created

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Effect: processes only start executing once all are created

(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); /* blocked until _nr_pr == 1 */
  printf("result␣=%d", result)
}
```

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byte result;

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  ...
}

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

`_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

init can be made implicit by using the **active** modifier:

```
active proctype P() {
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}
```

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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)
}
```

Interference on Global Data

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byte n = 0;

active proctype P() {
  n = 1;
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}

active proctype Q() {
  n = 2;
  printf("Proc␣Q,␣n␣=␣%d\n", n)
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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

Synchronization on Global Data

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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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(Recall: in alternatives, "`->`" syntactic sugar for "`;`")

(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 *C*urrently *R*unning *P*rocesses.
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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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 *C*urrently *R*unning *P*rocesses.
Let $NEL \subseteq CRP$ be the set of (currently running) processes which are *N*ot at a valid *E*nd *L*ocation.
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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Defined in PROMELA by **atomic**{$list\_of\_statements$}

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Can *only* be interrupted when a statement blocks.
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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)
  $\Rightarrow$ 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 When *all* processes try to enter their critical sections, *one* of them must succeed.

Absence of (individual) Starvation When *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␣noncritical␣actions\n");
        /* begin critical section */
        printf("P␣uses␣shared␣resourses\n")
        /* end critical section */
  od
}

active proctype Q() {
  do :: printf("Q␣noncritical␣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 when "waiting",
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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() {
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```

Verify Mutual Exclusion of this

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⇒ deadlock

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

Proving Mutual Exclusion

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
⇒ mutual exclusion is verified

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⇒ 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
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- 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)

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```
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.