Formal Specification and Verification

Modeling Concurrency

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Based on a lecture by Wolfgang Ahrendt and Reiner Hähnle at Chalmers University, Göteborg

Focus of this Lecture

aim of SPIN-style model checking methodology:

exhibit flaws in software systems

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focus of this lecture:

- modeling and analyzing concurrent systems

focus of next lecture:

- modeling and analyzing distributed systems
- (plus: staring with Temporal Logic Model Checking)

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  - reliability of communication mediums

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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. use assertions, temporal logic, ... to model crucial properties
3. use Spin to check all possible runs of the model
4. analyze result, and possibly re-work **1.** and **2.**

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I claim:
The hardest part of Model Checking is **1.**

Main Challenges of Modeling

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

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

Modeling Concurrent Systems in Promela

corner stone of
modeling concurrent, and distributed, systems in SPIN approach are

PROMELA processes

Initializing Processes

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often declared *implicitly* using '**active**'

can be declared *explicitly* with key word '**init**'

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

if *explicit*, **init** is used to start other processes with **run** statement

Starting Processes

processes can be started *explicitly* using **run**

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

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 local;
  ....
}

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

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init {
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}
```

effect: processes only start executing once all are created

Joining Processes

following trick allows 'joining', i.e., waiting for all processes to finish

```
byte result;

proctype P() {
  ....
}

init {
  atomic {
    run P();
    run P()
  }
  (_nr_pr == 1) ->
     printf("result␣=%d", result)
}
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```

`_nr_pr` built in variable holding number of running processes

`_nr_pr = 1` only **init** is running (anymore)

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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```
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 temp;
  ...
}
```

`n` is global

`temp` 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("Process␣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("Process␣Q,␣n␣=␣%d\n", n);
}
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how many outputs possible now?

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```

how many outputs possible now?

different processes can interfere on global data

Examples

1. `interleave0.pml`
   SPIN simulation, SPINSPIDER automata + transition system
2. `interleave1.pml`
   SPIN simulation, SPINSPIDER automata + transition system
3. `interleave5.pml`
   SPIN simulation, SPIN model checking, trail inspection

Atomicity

limit the possibility of sequences being interrupted by other processes

weakly atomic sequence

can *only* be interrupted if a statement is not executable

strongly atomic sequence

can not be interrupted at all

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defined in PROMELA by **atomic{ ... }**

strongly atomic sequence

can not be interrupted at all
defined in PROMELA by **d_step{ ... }**

Deterministic Sequences

d_step:

- strongly atomic
- deterministic
- nondeterminism resolved in fixed way
  ⇒ good style to avoid nondeterminism 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

Prohibit Interference by Atomicity

apply $\mathbf{d\_step}$ to interference example

Synchronization on Global Data

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executability addresses many issues in the interplay of processes

Executability

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

statement type	*executable*
assignments	always
assertions	always
print statements	always
expression statements	iff value not 0/**false**
send/receive statements	(coming soon)

Executability (Cont'd)

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atomic resp. **d_step** statement is executable
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an alternative is executable
iff
its guard (the first statement) is executable

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

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
(to be discussed in following)

The Critical Section Problem

archetypical problem of concurrent systems

given a number of looping processes, each containing a critical section design an algorithm such that:

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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:
(non)critical sections only **printf** statements

```
active proctype P() {
  do :: printf("Noncritical␣section␣P\n");
        /* begin critical section */
        printf("Critical␣section␣P\n");
        /* end critical section */
  od
}

active proctype Q() {
  do :: printf("Noncritical␣section␣Q\n");
        /* begin critical section */
        printf("Critical␣section␣Q\n");
        /* end critical section */
  od
}
```

No Mutual Exclusion Yet

need more infrastructure to achieve it:
adding two Boolean flags:

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

active proctype P() {
  do :: printf("Non-critical␣section␣P\n");
        /* begin critical section */
        inCriticalP = true;
        printf("Critical␣section␣P\n");
        inCriticalP = false
        /* end critical section */
  od
}

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

Show Mutual Exclusion Violation with SPIN

adding assertions

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

active proctype P() {
  do :: printf("Non-critical␣section␣P\n");
        /* begin critical section */
        inCriticalP = true;
        printf("Critical␣section␣P\n");
        assert(!inCriticalQ);
        inCriticalP = false
        /* end critical section */
  od
}

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

Mutual Exclusion by Busy Waiting

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

active proctype P() {
  do :: printf("Non-critical␣section␣P\n");
        /* begin critical section */
        inCriticalP = true
        do :: !inCriticalQ -> break
           :: else -> skip
        od;
        printf("Critical␣section␣P\n");
        assert(!inCriticalQ);
        inCriticalP = false
        /* end critical section */
  od
}

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

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Verify Mutual Exclusion of this

SPIN
still errors (`invalid end state`)
$\Rightarrow$ deadlock
can make `pan` ignore the deadlock: `./pan -E`
SPIN then proves mutual exclusion

Deadlock Hunting

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find Deadlock with SPIN

Atomicity against Deadlocks

solution:

checking and setting the flag in one atomic step

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```
atomic {
  !inCriticalQ;
  inCriticalP = true
}
```

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the example was simplistic indeed

variations:

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- … and many more

Solving CritSectPr with atomic/d_step only?

actually possible in this case (demo)
also in interleaving example (counting via `temp`, see above)
But:

- does not carry over to variations (see previous slide)
- **atomic** only weakly atomic!
- **d_step** excludes any nondeterminism!