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
aim of SPIN-style model checking methodology:

- exhibit design flaws in software systems
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aim of \texttt{SPIN}-style model checking methodology:

- exhibit design flaws in \textit{concurrent} and \textit{distributed} software systems
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focus of this lecture:

- modeling and analyzing concurrent systems
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aim of $\text{SPIN}$-style model checking methodology:

- exhibit design flaws in concurrent and distributed software systems

focus of this lecture:

- modeling and analyzing concurrent systems

focus of next lecture:

- modeling and analyzing distributed systems
- (plus: starting with Temporal Logic Model Checking)
Concurrent/Distributed systems difficult to get right

problems:

- hard to predict, hard to form faithful intuition about
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  - reliability of communication mediums
We cannot exhaustively test concurrent/distributed systems

- lack of controllability
  - we miss failures in test phase
Testing Concurrent or Distributed System is Hard

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  - we miss failures in test phase
- lack of reproducability
  - even if failures appear in test phase,
    - often impossible to analyze/debug defect
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  ⇒ we miss failures in test phase
- lack of reproducability
  ⇒ 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.
Activities in \texttt{SPIN}-style Model Checking

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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
corner stone of modeling concurrent, and distributed, systems in SPIN approach are PROMELA processes
there is always an initial process prior to all others

often declared *implicitly* using ‘active’
there is always an initial process prior to all others

often declared *implicitly* using ‘active’

can be declared *explicitly* with key word ‘init’

```c
init {
    printf("Hello \n")
}
```

if *explicit*, `init` is used to start other processes with `run` statement
processes can be started *explicitly* using `run`

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

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

each `run` operator starts copy of process (with copy of local variables)
Starting Processes

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

```proctype P() {
    byte local;
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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

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

init {
    atomic {
        run P();
        run P();
    }
}
```
by convention, run operators enclosed in atomic block

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

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

effect: processes only start executing once all are created
Joining Processes

The following trick allows ‘joining’, i.e., waiting for all processes to finish:

```c
byte result;

proctype P() {
    ....
}

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

_nr_pr built-in variable holding number of running processes

_nr_pr = 1 only init is running (anymore)
Joining Processes

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init {
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    }
    (_nr_pr == 1) ->
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_nr_pr built in variable holding number of running processes
_nr_pr = 1 only init is running (anymore)
Processes may have formal parameters, instantiated by `run`:

```plaintext
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
c PROCEDURE P() {
  ...
}
```

implicit init will run one copy of P
init can be made implicit by using the active modifier:

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

implicit init will run one copy of P

```c
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.

```java
byte n;

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

n is global
temp is local
```
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)
byte n = 0;

active proctype P() {
    n = 1;
    printf("Process P, n = \%d\n", n);
}

active proctype Q() {
    n = 2;
    printf("Process Q, n = \%d\n", n);
}
Interference on Global Data

byte n = 0;

active proctype P() {
    n = 1;
    printf("Process P, n = %d\n", n);
}

active proctype Q() {
    n = 2;
    printf("Process Q, n = %d\n", n);
}
byte  n = 0;

active proctype P() {
    n = 1;
    printf("Process P, n = \%d\n", n);
}

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

how many outputs possible now?
byte n = 0;

active proc type P() {
    n = 1;
    printf("Process P, n = %d\n", n);
}

active proc type Q() {
    n = 2;
    printf("Process Q, n = %d\n", n);
}

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
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
Atomicity

limit the possibility of sequences being interrupted by other processes

**weakly atomic sequence**
- can *only* be interrupted if a statement is not executable
- 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
  \( \Rightarrow \) 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

\[
d\text{_step} \{ \\
  \text{stmt1;} \leftarrow \text{guard} \\
  \text{stmt2;} \\
  \text{stmt3}
\}
\]

if stmt1 blocks, d_step is *not entered*, and blocks as a whole
it is an error if stmt2 or stmt3 block
apply \texttt{d\_step} to interference example
**Promela** has *no synchronization primitives*, like semaphores, locks, or monitors.
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Executability addresses many issues in the interplay of processes
Each statement has the notion of executability.

<table>
<thead>
<tr>
<th>statement type</th>
<th>executable</th>
</tr>
</thead>
<tbody>
<tr>
<td>assignments</td>
<td>always</td>
</tr>
<tr>
<td>assertions</td>
<td>always</td>
</tr>
<tr>
<td>print statements</td>
<td>always</td>
</tr>
<tr>
<td>expression statements</td>
<td>iff value not 0/\texttt{false}</td>
</tr>
<tr>
<td>send/receive statements</td>
<td>(coming soon)</td>
</tr>
</tbody>
</table>
Executability (Cont’d)

Executability of compound statements:
Executability of **compound statements**:

- Atomic resp. d_step statement is executable iff
- guard (the first statement within) is executable
Executability (Cont’d)

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  - an alternative is executable
    iff
    its guard (the first statement) is executable
Executability (Cont’d)

Executability of *compound statements*:

- **atomic resp. d_step statement** is executable iff guard (the first statement within) is executable

- **if resp. do statement** is executable iff any of its alternatives is executable

  - 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.

For each step of execution, the scheduler nondeterministically chooses a process to execute.
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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:

- Mutual Exclusion
  - At most one process is executing its critical section 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
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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
for demonstration, and simplicity:
(non)critical sections only `printf` statements

```c
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
}
```

Formal Specification and Verification: Concurrency
need more infrastructure to achieve it:
adding two Boolean flags:

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

```c
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
}
```

```c
active proctype Q() {
    ...correspondingly...
}
```
Show Mutual Exclusion Violation with \texttt{SPIN}

adding assertions

\texttt{bool inCriticalP = false;}
\texttt{bool inCriticalQ = false;}

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

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

active proctype Q() { ...correspondingly... }
Mutual Exclusion by Blocking

instead of Busy Waiting, process should

- release control
- continuing to run only when exclusion properties are fulfilled
Mutual Exclusion by Blocking

instead of Busy Waiting, process should

▶ release control
▶ continuing to run only when exclusion properties are fulfilled

We can use expression statement \(!inCriticalQ\)
to let process \(P\) block where it should not proceed!
bool inCriticalP = false;
bool inCriticalQ = false;

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

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

still errors (invalid end state)
⇒ deadlock
can make pan ignore the deadlock: ./pan -E
Spin then proves mutual exclusion
Deadlock Hunting
find Deadlock with \texttt{SPIN}
solution:

checking and setting the flag in one atomic step
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```
atomic {
    !inCriticalQ;
    inCriticalP = true
}
```
Variations of Critical Section Problem

the example was simplistic indeed
variations:

▶ use other means for verification:
  ▶ ghost variables (verification only)
  ▶ temporal logic
  ▶ max $n$ processes allowed in critical section
    modeling possibilities include:
      ▶ counters instead of booleans
      ▶ semaphores (see demo)
      ▶ more fine grained exclusion conditions, e.g.
        ▶ several critical sections (Leidestraat in Amsterdam)
        ▶ writers exclude each other and readers
        ▶ readers exclude writers, but not other readers
      ▶ FIFO queues for entering sections (full semaphores)
      ▶ ... and many more
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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!