CS477 Formal Software Development Methods

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Slides mostly a reproduction of Theo C. Ruys – SPIN Beginners' Tutorial

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SPIN Commandline Options

The following are some useful commandline options:

- `-a`: Generate code for project-specific verifier
  - Default: run SPIN as a simulator
- `-p`: Print at each state which process took which step
- `-s`: Print send statements and their effects
- `-r`: Print receive statements and their effects
- `-v`: verbose
- `-n`*N*: Use *N* as random seed, instead of clock (good for reproducibility)
- `l` Show changes to local variables
- `g` Show changes to global variables
- `-u`*N* Limit number of steps taken to *N*
- `-t` Run simulation driven by an error trail
- `-k`*`filename`* use the trail file stored in *filename*

Common SPIN Workflow

- Write SPIN model; put in file *filename*
- Debug syntax with: spin -u1000 *filename*
- Check assertions, bad end states with:
  - spin -a *filename*
  - gcc -o pan pan.c
  - ./pan
  - Read the output
  - If you have an error trail: spin -t -p *filename*
- To see if an LTL formula does not hold:
  - Put LTL formula in file *ltlfile*
  - spin -F *ltlfile* > *neverclaimfile*
  - spin -a -N *neverclaimfile* *filename*
  - gcc -o pan pan.c
  - ./pan
  - Read the output
  - If you have an error trail: spin -t -p *filename*

never Claims

- never claims used to describe systemwide behavior that *should* be impossible
- monitor process show similar idea
  - monitor checks property is true in some interleaved fashion
  - never claim check a proerty does not happen (anywhere in any exectuion)
  - never claim takes a step after every step of every other process

Never Claims: mutextwrong1a.pml

```
bit flag; /* signal entering/leaving the section */
byte mutex; /* # procs in the critical section. */
proctype P(bit i) {
  flag != 1;
  flag = 1;
  mutex++;
  printf("MSC: P(%d) has entered section\n", i);
  mutex--;
  flag = 0
}

never{ do
       :: ((mutex != 0)&&(mutex != 1)) -> break
       :: else
       od }
init { atomic { run P(0); run P(1) } }
```

SPIN Checking never claim

```
bash-3.2$ spin -p -v -n123 -l -g -k mutexwrong1a.pml.trail mut
spin: mutexwrong1a.pml:0, warning, proctype P, 'bit   i' varia
starting claim 1
using statement merging
  1: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
Never claim moves to line 15 [else]
Starting P with pid 2
  2: proc  0 (:init:) mutexwrong1a.pml:20 (state 1) [(run P(0)
Starting P with pid 3
  3: proc  0 (:init:) mutexwrong1a.pml:20 (state 2) [(run P(1)
  4: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
  5: proc  2 (P) mutexwrong1a.pml:4 (state 1) [((flag!=1))]
  6: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
  7: proc  1 (P) mutexwrong1a.pml:4 (state 1) [((flag!=1))]
  8: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
```

```
  9: proc  2 (P) mutexwrong1a.pml:5 (state 2) [flag = 1]
flag = 1
 10: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
 11: proc  2 (P) mutexwrong1a.pml:6 (state 3)
[mutex = (mutex+1)]
mutex = 1
 12: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
                  MSC: P(1) has entered section.
 13: proc  2 (P) mutexwrong1a.pml:7 (state 4)
[printf('MSC: P(%d) has entered section.\n',i)]
 14: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
 15: proc  1 (P) mutexwrong1a.pml:5 (state 2) [flag = 1]
 16: proc  - (never_0) mutexwrong1a.pml:15 (state 3) [else]
 17: proc  1 (P) mutexwrong1a.pml:6 (state 3)
[mutex = (mutex+1)]
mutex = 2
```

```
 18: proc  - (never_0) mutexwrong1a.pml:14 (state 1)
[(((mutex!=0)&&(mutex!=1)))]
Never claim moves to line 14 [(((mutex!=0)&&(mutex!=1)))]
spin: trail ends after 19 steps
#processes: 3
flag = 1
mutex = 2
 19: proc  2 (P) mutexwrong1a.pml:8 (state 5)
 19: proc  1 (P) mutexwrong1a.pml:7 (state 4)
 19: proc  0 (:init:) mutexwrong1a.pml:21 (state 4) <valid enc
 19: proc  - (never_0) mutexwrong1a.pml:17 (state 7) <valid er
3 processes created
```

Traffic Light Example

```
mtype {NS, EW, Red, Yellow, Green}

bit Turn = 0;
mtype Color[2];

proctype Light(bit myId) {
  mtype otherId = 1 - myId;
  do
  :: Turn == myId && Color[myId] == Red
     -> Color[myId] = Green
  :: Color[myId] == Green -> Color[myId] = Yellow
  :: Color[myId] == Yellow
     -> Color[myId] = Red; Turn = otherId
  od
}
```

```
init { Color[0] = Red;
       Color[1] = Red;
       atomic{run Light(0); run Light(1)}
     }
```

```
bash-3.2$ spin -f '[]((Color[0] = Red) || (Color[1] = Red))'
         >& trafficlightnever.pml
bash-3.2$ cat trafficlightnever.pml
never  {    /* []((Color[0] = Red) || (Color[1] = Red)) */
accept_init:
T0_init:
do
:: (((Color[0] = Red) || (Color[1] = Red)))
          -> goto T0_init
od;
}
```

Traffic Light Example

```
/* File: trafficlight.pml */

mtype = {NS, EW, Red, Yellow, Green};
bit Turn = 0;
mtype Color[2];

proctype Light(bit myId) {
  bit otherId = 1 - myId;
  do
  :: Turn == myId && Color[myId] == Red
     -> Color[myId] = Green
  :: Color[myId] == Green
     -> Color[myId] = Yellow
  :: Color[myId] == Yellow
     -> Color[myId] = Red; Turn = otherId
  od
}
```

```
init { atomic{Color[0] = Red; Color[1] = Red};
       atomic{run Light(0); run Light(1)}
     }
/* End of File: trafficlight.pml */
```

Can test this with

```
bash-3.2$ spin -p -l -g -u50 trafficlight.pml
  0: proc  - (:root:) creates proc  0 (:init:)
  1: proc  0 (:init:) trafficlight.pml:18 (state 1) [Color[0] = Red]
Color[0] = Red
Color[1] = 0
  2: proc  0 (:init:) trafficlight.pml:19 (state 2) [Color[1] = Red]
Color[0] = Red
Color[1] = Red
Starting Light with pid 1
  3: proc  0 (:init:) creates proc  1 (Light)
  3: proc  0 (:init:) trafficlight.pml:20 (state 5) [(run Light(0))]
Starting Light with pid 2
  4: proc  0 (:init:) creates proc  2 (Light)
  4: proc  0 (:init:) trafficlight.pml:20 (state 4) [(run Light(1))]
```

LTL to Never Claim

```
bash-3.2$ spin -f '<>(!(Color[0] == Red
 || Color[1] == Red))' >& trafficlightnever.pml
bash-3.2$ cat trafficlightnever.pml
never      /* <>(!(Color[0] == Red || Color[1] == Red))  */
T0_init:
do
:: atomic  ((!(Color[0] == Red || Color[1] == Red)))
           -> assert(!((!(Color[0] == Red || Color[1] == Red))))
:: (1) -> goto T0_init
od;
accept_all:
skip
```

Using never Claim in Separate File

To use file containing `never` claim:

```
bash-3.2$ spin -a -N trafficlightnever.pml trafficlight.pml
bash-3.2$ gcc -o pan pan.c
bash-3.2$ ./pan    omissions
Full statespace search for:
never claim            + (never_0)
assertion violations + (if within scope of claim)
acceptance   cycles  - (not selected)
invalid end states - (disabled by never claim)

State-vector 44 byte, depth reached 26, errors: 0
       13 states, stored
        1 states, matched
       14 transitions (= stored+matched)
        1 atomic steps
hash conflicts:          0 (resolved)
```

```
unreached in proctype Light
./trafficlight.pml:17, state 17, "-end-"
(1 of 17 states)
unreached in init
(0 of 4 states)
unreached in claim never_0
./trafficlightnever.pml:9, state 10, "-end-"
(1 of 10 states)

pan: elapsed time 0.02 seconds
pan: rate       650 states/second
```

- Process `Light` never ends, so its end state never reached

Properties (1)

- Model checking tools automatically verify whether

  $M \models \phi$

  holds, where M is a (finite-state) model of a system and property ϕ is stated in some formal notation.

- With SPIN one may check the following type of properties:
  - deadlocks (invalid endstates)
  - assertions
  - unreachable code
  - LTL formulae
  - liveness properties
    - non-progress cycles (livelocks)
    - acceptance cycles

Historical Classification

Properties (2)

safety property
- "nothing bad ever happens"

- invariant
  x is always less than 5
- deadlock freedom
  the system never reaches a state where no actions are possible

- SPIN: find a trace leading to the "bad" thing. If there is not such a trace, the property is satisfied.

liveness property
- "something good will eventually happen"

- termination
  the system will eventually terminate
- response
  if action X occurs then eventually action Y will occur

- SPIN: find a (infinite) loop in which the "good" thing does not happen. If there is not such a loop, the property is satisfied.

Properties (3)

- LTL formulae are used to specify liveness properties.
  LTL ≡ propositional logic + temporal operators
  - `[]P` always P
  - `<>P` eventually P
  - `P U Q` P is true until Q becomes true

Xspin contains a special "LTL Manager" to edit, save and load LTL properties.

- Some LTL patterns
  - invariance `[] (p)`
  - response `[] ((p) -> (<> (q)))`
  - precedence `[] ((p) -> ((q) U (r)))`
  - objective `[] ((p) -> <>((q) || (r)))`

Properties (4)

- Suggested further reading (on temporal properties):

  [Bérard et. al. 2001]
  - Textbook on model checking.
  - One part of the book (six chapters) is devoted to "Specifying with Temporal Logic".
  - Also available in French.

  [Dwyer et. al. 1999]
  - classification of temporal logic properties
  - pattern-based approach to the presentation, codification and reuse of property specifications for finite-state verification.

Note: although this tutorial focuses on how to construct an effective Promela model M, the definition of the set of properties which are to be verified is equally important!

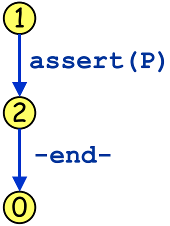
Invariance

- `[]P` where `P` is a state property
  - safety property
  - invariance ≡ global universality or global absence [Dwyer et. al. 1999]:
    - 25% of the properties that are being checked with model checkers are invariance properties
    - BTW, 48% of the properties are response properties
  - examples:
    - `[] !aflag`
    - `[] mutex != 2`
- SPIN supports (at least) 7 ways to check for invariance.

variant 1+2 - monitor process (single assert)

- proposed in SPIN's documentation
- add the following monitor process to the Promela model:

```
active proctype monitor()
{
  assert(P);
}
```



- Two variations:
  - 1. monitor process is created first
  - 2. monitor process is created last

If the monitor process is created last, the -end- transition will be executable after executing assert(P).

variant 3 - guarded monitor process

- Drawback of solution “1+2 monitor process” is that the **`assert`** statement is enabled in every state.

```
active proctype monitor()
{
  assert(P) ;
}
```

```
active proctype monitor()
{
  atomic {
    !P -> assert(P) ;
  }
}
```

- The **`atomic`** statement only becomes executable when P itself is not true.

> We are searching for a state where `P` is not true. If it does not exist, `[]P` is true.

variant 4 - monitor process (do assert)

- From an operational viewpoint, the following monitor process seems less effective:

```
active proctype monitor()
{
  do
  :: assert(P)
  od
}
```

- But the number of states is clearly advantageous.

variant 5 - never claim (do assert)

- also proposed in SPIN's documentation

```
never {
  do
  :: assert(P)
  od
}
```

SPIN will synchronise the never claim automaton with the automaton of the system. SPIN uses never claims to verify LTL formulae.

… but SPIN will issue the following unnerving warning:

warning: for p.o. reduction to be valid the never claim must be stutter-closed (never claims generated from LTL formulae are stutter-closed)

… and this never claim has not been generated…

variant 6 - LTL property

- The logical way...
- SPIN translates the LTL formula to an accepting **never** claim.

```
never { ![]P
TO_init:
  if
  :: (!P) -> goto accept_all
  :: (1)  -> goto TO_init
  fi;
accept_all:
  skip
}
```

variant 7 - `unless {!P -> ...}`

- Enclose the ***body*** of (at least) one of the processes into the following `unless` clause:

```
{ body } unless { atomic { !P -> assert(P) ; } }
```

- Discussion
  + no extra process is needed: saves 4 bytes in state vector
  + local variables can be used in the property P
  – definition of the process has to be changed
  – the `unless` construct can reach inside `atomic` clauses
  – partial order reduction may be invalid if rendez-vous communication is used within body
  – the ***body*** is not allowed to end

This is quite restrictive

Note: disabling partial reduction (`-DNOREDUCE`) may have severe negative consequences on the effectiveness of the verification run.