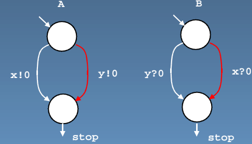
# Logic Model Checking

Lecture Notes 14:18
Caltech 118
**January-March 2006**

**Course Text:**
The Spin Model Checker: Primer and Reference Manual
Addison-Wesley 2003, ISBN 0-321-22862-6, 608 pgs.

## Promela semantics

```
chan x = [0] of { bit };
chan y = [0] of { bit };

active proctype A()
{
    x!0 unless y!0
}

active proctype B()
{
    y?0 unless x?0
}
```




what precisely does this mean?
what are the possible executions?

red arrows take priority over white arrows...

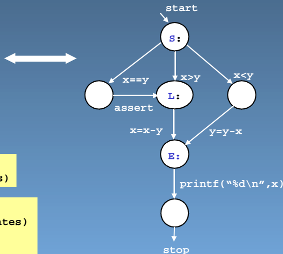
two rendezvous handshakes seem possible:
y!0 <-> y?0
and
x!0 <-> x?0
can you tell which can happen without running Spin....?

if you use this method and get a different answer from the Spin *simulator* and the Spin *verifier*, which answer is right?



## the semantics of Promela
### proctypes and automata

```
active proctype not_euclid()
{
S: if
   :: x == y ->    assert(x != y); goto L
   :: x > y  -> L: x = x - y
   :: x < y  ->    y = y - x
   fi;
E: printf("%d\n", x)
}
```




a Spin model defines a system of:
*states* and *state transformers* (transitions)

state is maintained in
sets of process counters (*control* flow states)
local and global variables and
message channels

';', '->', if-fi, do-od, goto, etc. are only used to define the *transition structure*
*(not the state transformers themselves)*
the only *state transformers* are the *basic* statements:
assignment, (expr), printf, assert, send, receive

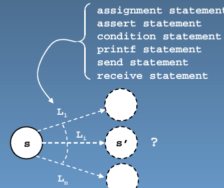


## operational model

- to define the semantics of the modeling language, we can define an operational model in terms of *states* and *state transformers (transitions)*
  - we have to define what a "*global system state*" is
  - we have to define what a "*state transition*" is
    - i.e., how the '*next-state*' relation is defined
- *global system states* are defined in terms of a small number of primitive objects:
  - we have to define: variables, messages, message channels, and processes
- *state transitions* are defined with the help of
  - basic statements that label transitions
    - the alphabet of the underlying automata
    - there are only 6 types of labels in the alphabet: assignment, condition, etc.
  - we have to define: transitions, transition selection, and transition execution



## transitions




given an arbitrary global state of the system, determine the set of possible immediate successor states

this means determining 3 things:
1. statement executability rules
2. statement selection rules
3. the effect of a statement execution

we only have to define single-step semantics to define the full language

the 3 parts of the semantics definition are defined over 4 types of objects:
1. variables
2. messages
3. message channels
4. processes

we'll define these first



## operational model
### *variables*, messages, channels, processes, transitions, global states

- a promela *variable* is defined by a five-tuple
  {name,scope,domain,inival,curval}

domain: e.g., $-2^{15}..2^{15}-1$
name
scope: global
inival x: 2

```
short x=2, y=1;

active proctype not_euclid()
{
S: if
   :: x > y  -> L: x = x - y
   :: x < y  ->    y = y - x
   :: x == y ->    assert(x != y); goto L
   fi;
E: printf("%d\n", x)
}
```

curval of x at S: 2
curval of x at E: 1

# operational model

variables, *messages*, channels, processes, transitions, global states

- a *message* is a finite, ordered set of variables
  (messages are stored in channels – *defined next*)

```
mtype = { req, resp, ack };

chan q = [2] of { mtype, bit };

active proctype not_very_useful()
{   bit p;

    do
    :: q?req,p  -> q!resp,p
    :: q?resp,p -> q!ack,1-p
    :: q?ack,_
    :: timeout -> break
    od
}
```

place names for values held in message channel:
$slot_1.field_1$
$slot_1.field_2$

domains:
mtype
bit

parallel value assignment



# operational model

variables, messages, *channels*, processes, transitions, global states

- a *message channel* is defined by a 3-tuple
  {ch_id, nslots, contents}

```
chan q = [2] of { mtype, bit };
```

**an ordered set of messages maximally with nslots elements:**

{
$\{slot_1.field_1,\ slot_1.field_2\}$,
$\{slot_2.field_1,\ slot_2.field_2\}$
}

a ch_id is an integer 1..MAXQ that can be stored in a *variable*

*(ch_id's <= 0 or > MAXQ do not correspond to any instantiated channel, so the default initial value of a chan variable 0 is not a valid ch_id)*

***channels*** always have global scope

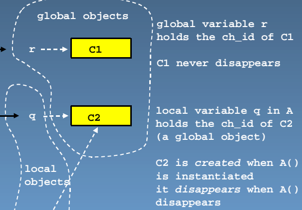
but ***variables*** of type chan are either local or global,

(so, ch_id's are always meaningful when passed from one process to another)



# channel scope

```
chan r = [0] of { chan };

active proctype A()
{
    chan q = [0] of { int };

    r!q;
    q?100
}

active proctype B()
{
    chan s;

    r?s;
    s!100
}
```




global variable r holds the ch_id of C1

C1 never disappears

local variable q in A holds the ch_id of C2 (a global object)

C2 is *created* when A() is instantiated
it *disappears* when A() disappears

local variable s in B is initialized to 0 (not a valid ch_id)

it is set to C2 in the receive from r == C1

C2 is a globally visible object with a limited lifetime...

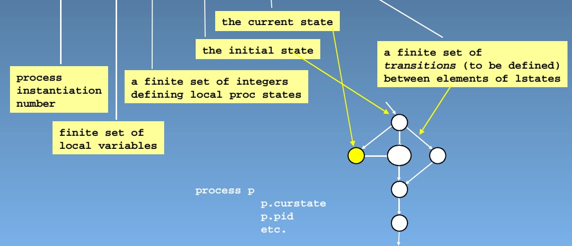
**in the initial system state r, q, s, C1, and C2 all exist r points to C1, q points to C2**



# operational model

variables, messages, channels, *processes*, transitions, global states

- a *process* is defined by a six-tuple
  {pid, lvars, lstates, inistate, curstate, transitions}



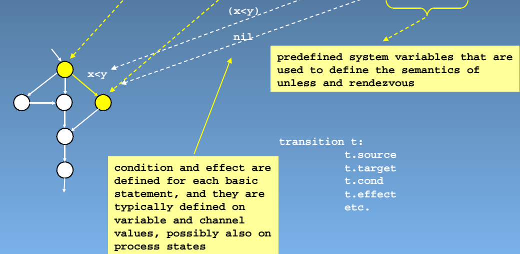

process p
p.curstate
p.pid
etc.



# operational model

variables, messages, channels, processes, *transitions*, global states

- a *transition* is defined by a seven-tuple
  {tri_id, source-state, target-state, cond, effect, priority, rv}




transition t:
t.source
t.target
t.cond
t.effect
etc.

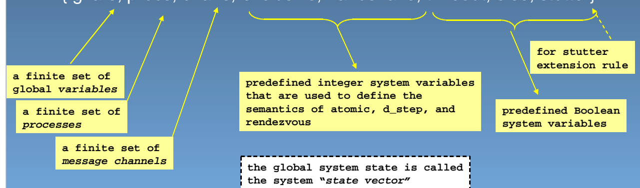
**condition and effect are defined for each basic statement, and they are typically defined on variable and channel values, possibly also on process states**



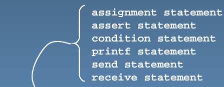
# operational model

variables, messages, channels, processes, transitions, *global states*

- a *global state* is defined by a eight-tuple
  { gvars, procs, chans, exclusive, handshake, timeout, else, stutter}



# one-step semantics



```
assignment statement
assert statement
condition statement
printf statement
send statement
receive statement
```

?

we've defined the only 4 types of objects that hold state:
1. variables
2. messages
3. channels and
4. processes

to define a one-step semantics, we have to define 3 more things:
1. transition executability rules
2. transition selection rules
3. the effect of transition

we do so by defining an algorithm: an implementation-independent semantics interpretation "engine" for Spin

given an arbitrary global state of the system, determine the set of possible immediate successor states



# defining the *next-state* relation

the Promela *semantics engine*

the easy part: state updating

```
global states s, s'
processes     p, p'
transitions   t, t'               to be defined
E a set of pairs {p,t}

 1 while ((E = executable(s)) != {})
 2 {
 3     for-some (process p and transition t) from E
 4     {   s' = apply(t.effect, s)
 5
 6
 7         {   s = s'
 8             p.curstate = t.target
 9
10
...
20     }     }
21 }
23 while
```



# executability rules

the hard part: transition selection

```
global states s, s'
processes     p, p'
transitions   t, t'
 1 Set
 2 executable(State s)
 3 {  new Set E
 4    new Set e
 5
 6
 7
 8 AllProcs:
 9
29
30
...
38
39
40    return E      /* executable transitions */
41 }

 9    for each active process p
10    {
11
12
13        {  e = {};
14 OneProc:  for each transition t in p.trans
15           {  if (t.source == p.curstate
16
17
18
19                 and  eval(t.cond) == true)
20              {    add (p,t) to set e
21           }  }
22
23            add all elements of e to E
...
29    }    }
```

next: extensions for timeout, else, rendezvous, atomic, unless, stutter



# executability rules

the hard part: transition selection

```
global states s, s'
processes     p, p'
transitions   t, t'
 1 Set
 2 executable(State s)
 3 {  new Set E
 4    new Set e
 5
 6    E = {}
 7    timeout = false
 8 AllProcs:
 9
29
30
...
34
35    if (E == {} and timeout == false)
36    {   timeout = true
37        goto AllProcs
38    }
39
40    return E      /* executable transitions */
41 }

 9    for each active process p
10    {
11
12
13        {  e = {};
14 OneProc:  for each transition t in p.trans
15           {  if (t.source == p.curstate
16
17
18
19                 and  eval(t.cond) == true)
20              {    add (p,t) to set e
21           }  }
22
23            add all elements of e to E
...
29    }    }
```

next: extension for else



# executability rules

the hard part: transition selection

```
global states s, s'
processes     p, p'
transitions   t, t'
 1 Set
 2 executable(State s)
 3 {  new Set E
 4    new Set e
 5
 6    E = {}
 7    timeout = false
 8 AllProcs:
 9
29
30
...
34
35    if (E == {} and timeout == false)
36    {   timeout = true
37        goto AllProcs
38    }
39
40    return E      /* executable transitions */
41 }

 9    for each active process p
10    {
11
12
13        {  e = {};  else = false
14 OneProc:  for each transition t in p.trans
15           {  if (t.source == p.curstate
16
17
18
19                 and  eval(t.cond) == true)
20              {    add (p,t) to set e
21           }  }
22           if (e != {})
23           {   add all elements of e to E
24               continue  /* on to next process */
25           } else if (else == false)
26           {   else = true
27               goto OneProc
28           }
29    }    }
```

next: extension for rendezvous semantics



# adding semantics for rendezvous 1:2

the predefined variable handshake

```
global states s, s'
processes     p, p'
transitions   t, t'

 1 while ((E = executable(s)) != {})
 2 {
 3     for-some (process p and transition t) from E
 4     {   s' = apply(t.effect, s)   <----- can set handshake
 5
 6         if (handshake == 0)
 7         {   s = s'
 8             p.curstate = t.target
 9         } else
10         {   /* try to complete a rv handshake */
11             E' = executable(s')
12             /* if E' is {}, s is unchanged */
13
14             for-some (process p' and transition t') from E'
15             {   s = apply(t'.effect, s')
16                 p.curstate  = t.target
17                 p'.curstate = t'.target
19             }
18             handshake = 0
20     }     }
21 }
22
```

# adding semantics for rendezvous 2:2

## the predefined variable handshake

```
global states s, s'
processes     p, p'
transitions   t, t'
 1 Set
 2 executable(State s)
 3 {  new Set E
 4    new Set e
 5
 6    E = {}
 7    timeout = false
 8 AllProcs:
 9
29
30
31
32
33
34
35    if (E == {} and timeout == false)
36    {  timeout = true
37       goto AllProcs
38    }
39
40    return E     /* executable transitions */
41 }
```

```
 9    for each active process p
10    {
11
12
13          {  e = {};  else = false
14 OneProc:    for each transition t in p.trans
15             {  if (t.source == p.curstate
16
17                and (handshake == 0
18                or   handshake == t.rv)
19                and  eval(t.cond) == true)
20                {    add (p,t) to set e
21             }  }
22             if (e != {})
23             {  add all elements of e to E
24                break   /* on to next process */
25             } else if (else == false)
26             {  else = true
27                goto OneProc
28             }
29    }  }
```

next:
extensions for atomic and d_step sequences



# adding semantics for atomic sequences

## the predefined variable exclusive

```
global states s, s'
processes     p, p'
transitions   t, t'
 1 Set
 2 executable(State s)
 3 {  new Set E
 4    new Set e
 5
 6    E = {}
 7    timeout = false
 8 AllProcs:
 9
29
30
31    if (E == {} and exclusive != 0)
32    {  exclusive = 0
33       goto AllProcs
34    }
35    if (E == {} and timeout == false)
36    {  timeout = true
37       goto AllProcs
38    }
39
40    return E     /* executable transitions */
41 }
```

```
 9    for each active process p
10    {  if (exclusive == 0
11       or  exclusive == p.pid)
12       {
13          {  e = {};  else = false
14 OneProc:    for each transition t in p.trans
15             {  if (t.source == p.curstate
16
17                and (handshake == 0
18                or   handshake == t.rv)
19                and  eval(t.cond) == true)
20                {    add (p,t) to set e
21             }  }
22             if (e != {})
23             {  add all elements of e to E
24                break   /* on to next process */
25             } else if (else == false)
26             {  else = true
27                goto OneProc
28             }
29    }  }  }
```

next:
extension for unless sequences



# adding semantics for unless

## statement priority levels

```
global states s, s'
processes     p, p'
transitions   t, t'
 1 Set
 2 executable(State s)
 3 {  new Set E
 4    new Set e
 5
 6    E = {}
 7    timeout = false
 8 AllProcs:
 9
29
30
31    if (E == {} and exclusive != 0)
32    {  exclusive = 0
33       goto AllProcs
34    }
35    if (E == {} and timeout == false)
36    {  timeout = true
37       goto AllProcs
38    }
39
40    return E     /* executable transitions */
41 }
```

```
 9    for each active process p
10    {  if (exclusive == 0
11       or  exclusive == p.pid)
12       {  for u from high to low    /* priority */
13          {  e = {};  else = false
14 OneProc:    for each transition t in p.trans
15             {  if (t.source == p.curstate
16                and t.prty == u
17                and (handshake == 0
18                or   handshake == t.rv)
19                and  eval(t.cond) == true)
20                {    add (p,t) to set e
21             }  }
22             if (e != {})
23             {  add all elements of e to E
24                break   /* on to next process */
25             } else if (else == false)
26             {  else = true
27                goto OneProc
28             } /* else lower the priority */
29    }  }  }
```

next:
adding the stutter extension rule



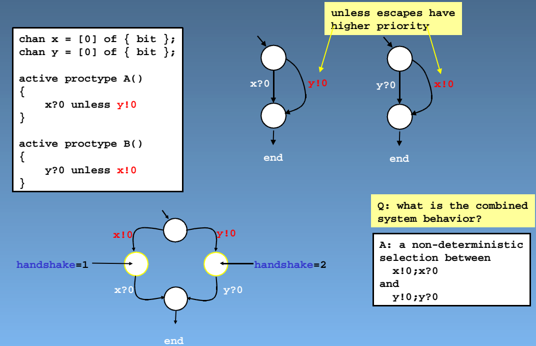
# the stutter extension rule

```
global states s, s'
processes     p, p'
transitions   t, t'

 1 while ((E = executable(s)) != {})
 2 {
 3      for some (process p and transition t) from E
 4      {    s' = apply(t.effect, s)
 5
 6           if (handshake == 0)
 7           {    s = s'
 8                p.curstate = t.target
 9           } else
10           {     /* try to complete rv handshake */
11                E' = executable(s')
12                /* if E' is {}, s is unchanged  */
13
14                for some (process p' and transition t') from E'
15                {    s = apply(t'.effect, s')
16                     p.curstate  = t.target
17                     p'.curstate = t'.target
18                     handshake = 0
19                     break
20      }     }   }
21 }
22 while (stutter) { s = s }  /* stutter extension rule */
```



# example 1:3

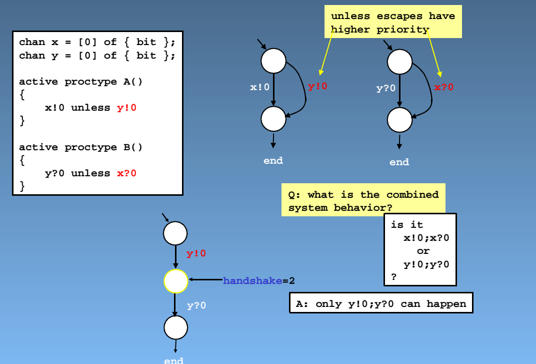
## using the semantics engine






# example 2:3

## using the semantics engine

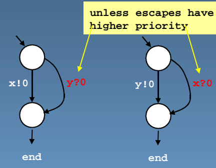


# example 3:3

## using the semantics engine

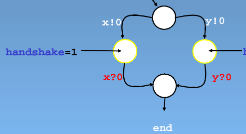
```
chan x = [0] of { bit };
chan y = [0] of { bit };

active proctype A()
{
    x!0 unless y?0
}

active proctype B()
{
    y!0 unless x?0
}
```

unless escapes have higher priority




Q: what is the combined system behavior?

is it
x!0;x?0
or
y!0;y?0
?



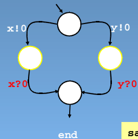

A: a non-deterministic selection between
x!0;x?0
and
y!0;y?0



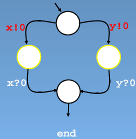
# compare

```
chan x = [0] of { bit };
chan y = [0] of { bit };

active proctype A()
{
    x!0 unless y?0
}

active proctype B()
{
    y!0 unless x?0
}
```

```
chan x = [0] of { bit };
chan y = [0] of { bit };

active proctype A()
{
    x?0 unless y!0
}

active proctype B()
{
    y?0 unless x!0
}
```




same global behavior but for very different reasons....






# what about never claims, etc.?

## meta-semantics

- *correctness properties* do not define new behavior, they just monitor it
  - and complain bitterly when interesting things are seen
- a *verification engine* can make pronouncements on properties of behavior
  - this is at a *higher* level of semantics: it interprets the goodness or badness of a behavior instead of defining the behavior itself
- a *never claim* is designed to *select* those behaviors that could possibly lead to “interesting” behavior
  - the distinction between “good” and “bad”, “interesting” and “uninteresting” is a meta-statement *about* behavior: not part of the behavior itself, and therefore not part of the operational semantics....