Model Checking with SPIN

# A Bit More about SPIN

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# Content

- SPIN internal data structures
- SPIN result report
- Writing LTL formulas
- Containing state explosion
- Example

Acknowledgement: some slides are taken and adapted from Theo Ruys's SPIN Tutorials.

# Data structures involved in SPIN DFS

- Representation of a state.

- Stack for the DFS
  - To remember where to backtrack in DFS
  - It corresponds to the current "execution prefix" that is being inspected → used for reporting.

- Something to hold the set of visited states = "state space".

# State

- Each (global) state of a system is a “product” of the states of its processes.
- E.g.  Suppose we have:
  - One global var byte *x*
  - Process *P* with byte *y*
  - Process *Q* with byte z
- Each system state should describe:
  - all these variables
  - Program counter of each process
  - Other SPIN predefined vars
- Represent each global state as a tuple  … this tuple can be quite big.

# The stack, optimization

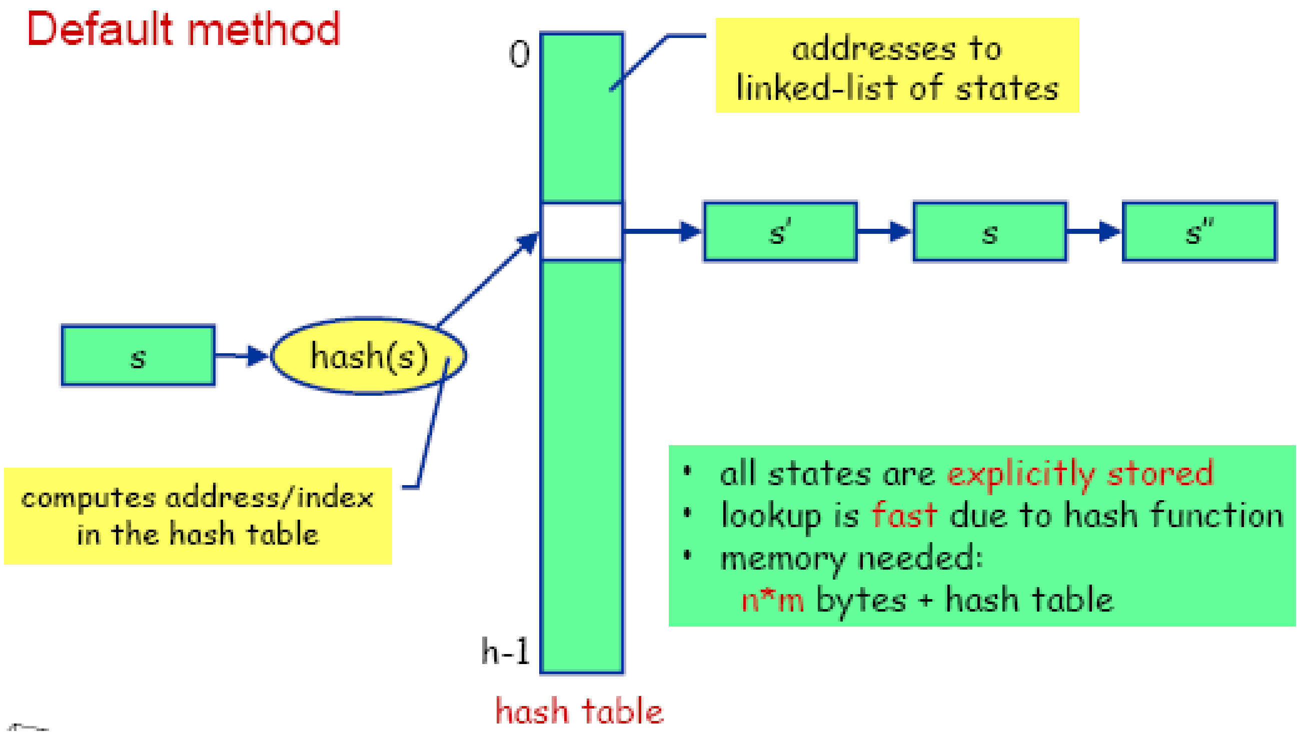
- To save space SPIN does not keep a stack of states (large), but rather a stack of action-IDs (smaller)

- But, when you backtrack you need to know the state!

  SPIN pre-calculated the reverse/undo of every action. So, knowing the current state is sufficient.

# State-space is stored with a hash table

*The list of "visited states" is maintained by a Hash-table. So matching if a state occurring in the table is fast!*






*Optimization: bit state hashing ☺*

# Verifier’s output

```
assertion violated  !((crit[0]&&crit[1])) (at depth 5)     // computation depth
...
Warning: Search not completed

Full statespace search for:
        ...
        never-claim              - (not selected)
        assertion violations     +
        invalid endstates        +

State-vector 20 byte, depth reached 7, errors: 1          // max. stack depth
    24 states, stored                                    // states stored in hash table
    17 states, matched                                   // states found re-revisited
    41 transitions (= stored+matched)

hash conflicts: 0 (resolved)
(max size 2^19 states)

2.542       memory usage (Mbyte)
```

# Specifying LTL properties

- (Check out the Manual)

```
#define PinCritical    crit[1]
#define QinCritical    crit[2]

[]!(PinCritical &&  QinCritical)
```

- SPIN then generates the Buchi automaton for this LTL formula; called “Never Claim” in SPIN.

# Example of a Never Claim

To verify: <>[] *p*

SPIN generates this never-claim / Buchi of **[]<>¬*p***

```
never {
   init:
      if
      :: ¬p   → goto   accept
      :: else → goto   init
      fi;
   accept:
      skip; goto  init ;
}
```

# Neverclaim

- From SPIN perspective, a neverclaim is just another process, but it is executed in “*lock-step*” :
  - it is always executed first
  - After each step of the system, we execute a step from the neverclaim.

- Is used to express properties
  - E.g. by writing assertions inside a neverclaim
  - Or by useing acceptance states

# You can also manually write your custom NC …

```
never {
   do
   :: assert (b) ; assert (!b)
   od
}
```

*Expressing the value of b should be alternating.*

```
never {
    accept : do  :: (x==0) ; (x==1)  od
}
```

*recognize an execution where (x==0)(x==1) holds alternatingly, which would then be considered as error.*

# Watch out for state explosion!

```
int x,y,z ;

P  { do :: x++ od }
Q  { do :: y++ od }
R  { do ::  x/=y → z++ od }
```

- Size of each state: > 12 bytes
- Number of possible states $\approx (2^{32})^3 = 2^{96}$
- Using byte (instead of int) brings this down to 50 MB
- Focus on the critical aspect of your model; abstract from data when possible.

# Imposing a coarser grain atomicity

**atomic { guard → stmt_1; ... ; stmt_n }**

$$\textbf{active proctype P \{ x++ ; } \underbrace{\textbf{(y>0) ; y-- ; x=y}}_{\textbf{put in } \textit{atomic} \textbf{ ?}} \textbf{ \}}$$

- more abstract, less error prone, but less parallelism
- executable if the guard statement is executable
- none of stmt-i should be blocking; or rather : if any of then blocks, atomicity is lost

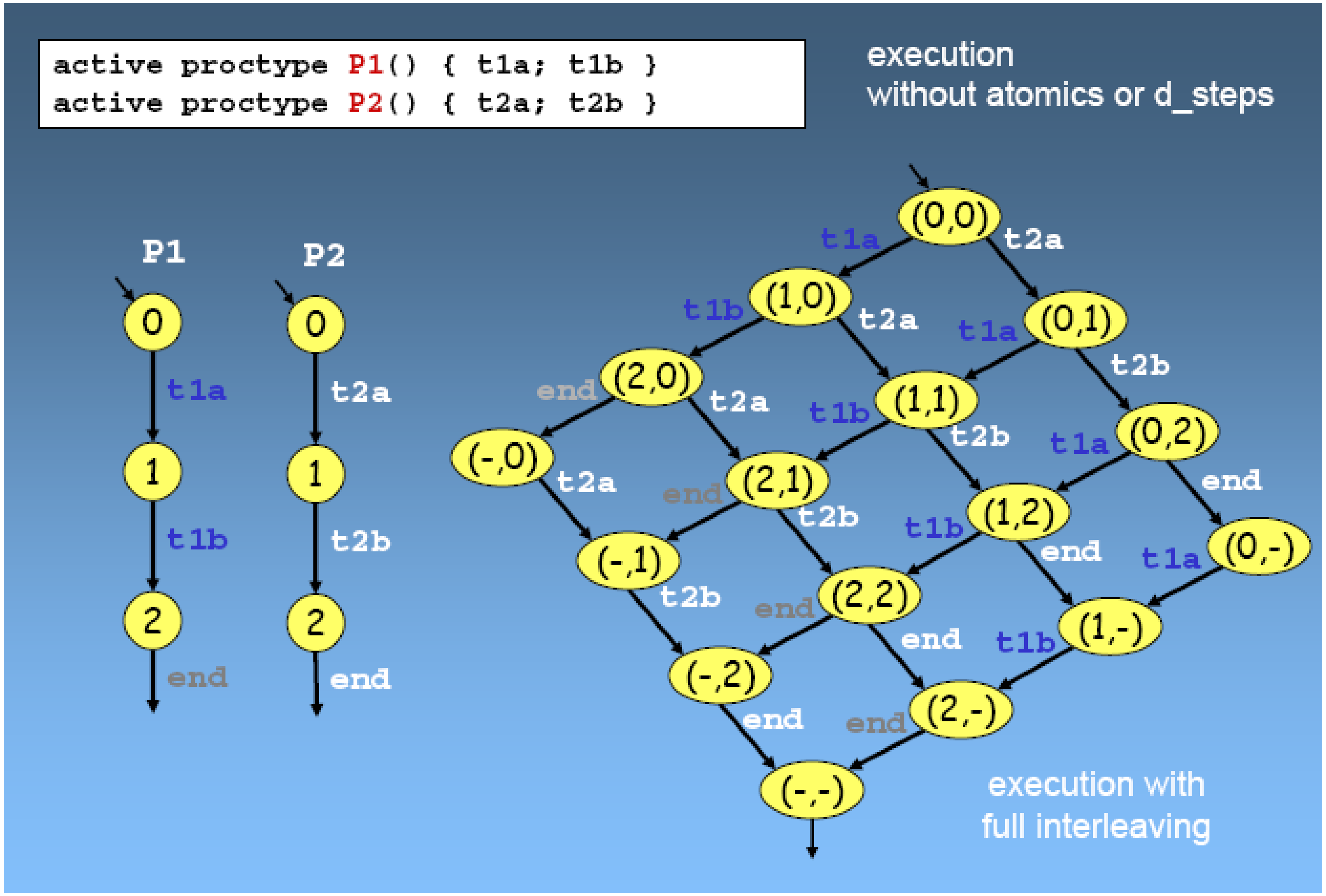
# d_step sequences

**d_step { guard → stmt_1; ... ; stmt_n }**

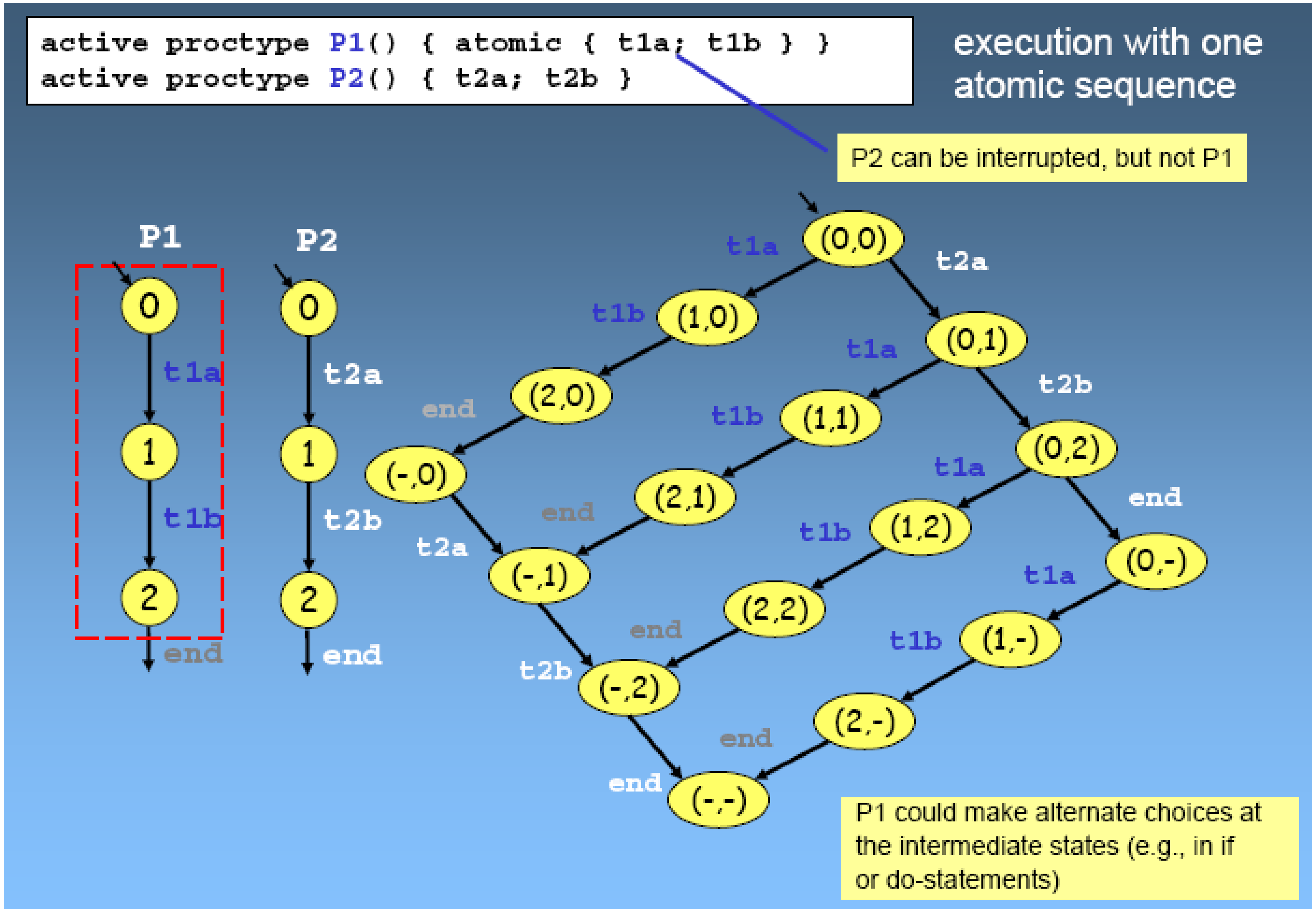
```
d_step {   /* reset array elements to 0 */
    i = 0;
    do
    :: i < N -> x[i] = 0; i++
    :: else -> break
    od;
    i = 0
}
```

- like an atomic, but *must be deterministic* and *may not block* anywhere
- atomic and d_step sequences are often used as a model reduction method, to lower complexity of large models (improving tractability)

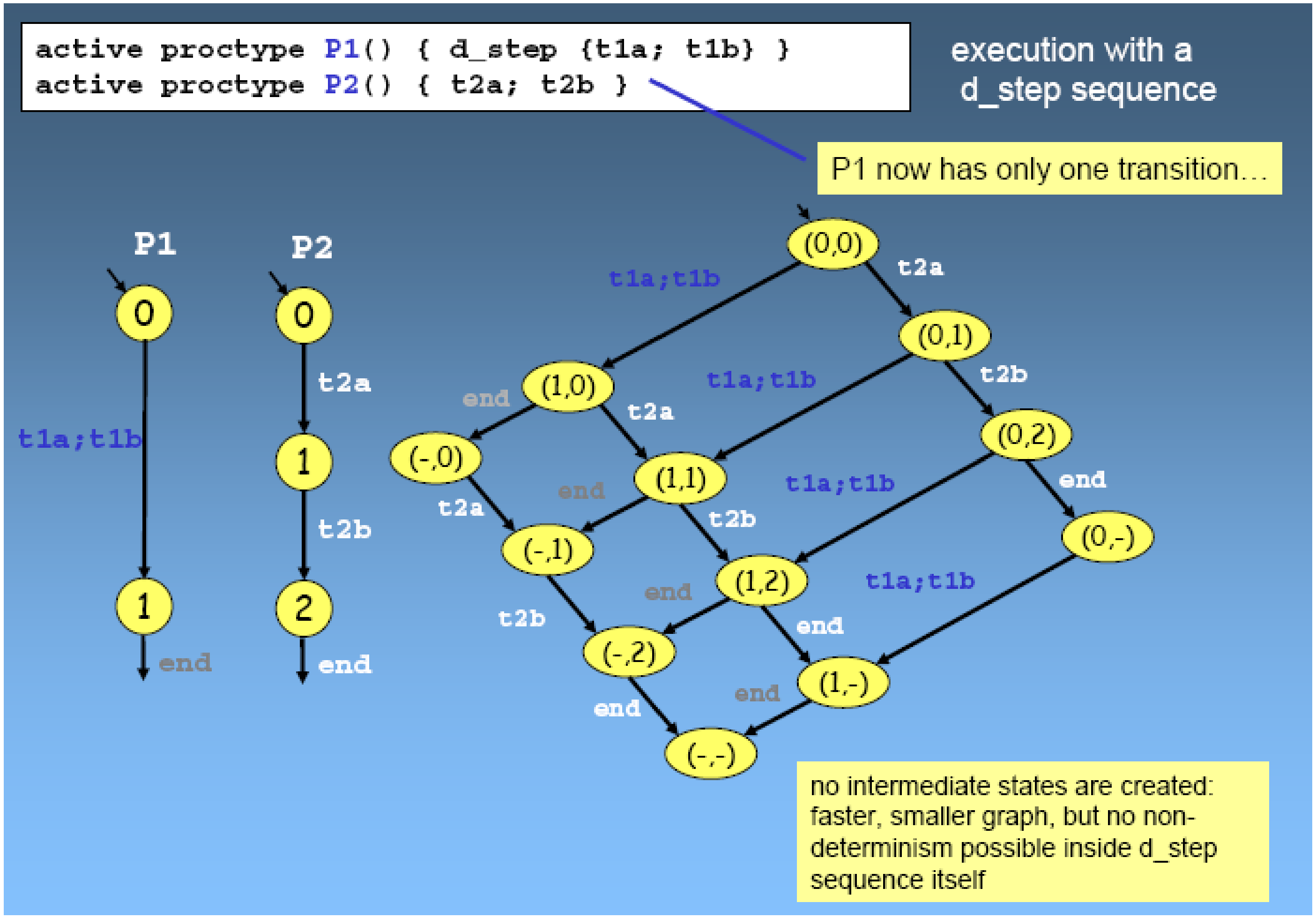
# execution without atomics or d_steps



# execution with one atomic sequence



# execution with a d_step sequence



# atomic vs d_step

- d_step:
  - translated to a single piece of C code
  - executed as *one* block
  - therefore is deterministic
  - blocking or non-termination would hang you ☺
  - no way verifier can peek into intermediate states

- atomic:
  - translated to a series of actions
  - executed step-by-step, but without interleaving
  - it can make non-deterministic choices
  - verifies sees intermediate states

# Partial Order Reduction

- The validity of a property $\phi$ is often insensitive to the order in which ‘independent’ actions are interleaved.

  e.g. stutter invariant $\varphi$ (does not contain X) that only refers to global variables, is insensitive to the relative order of actions that only access local variables.

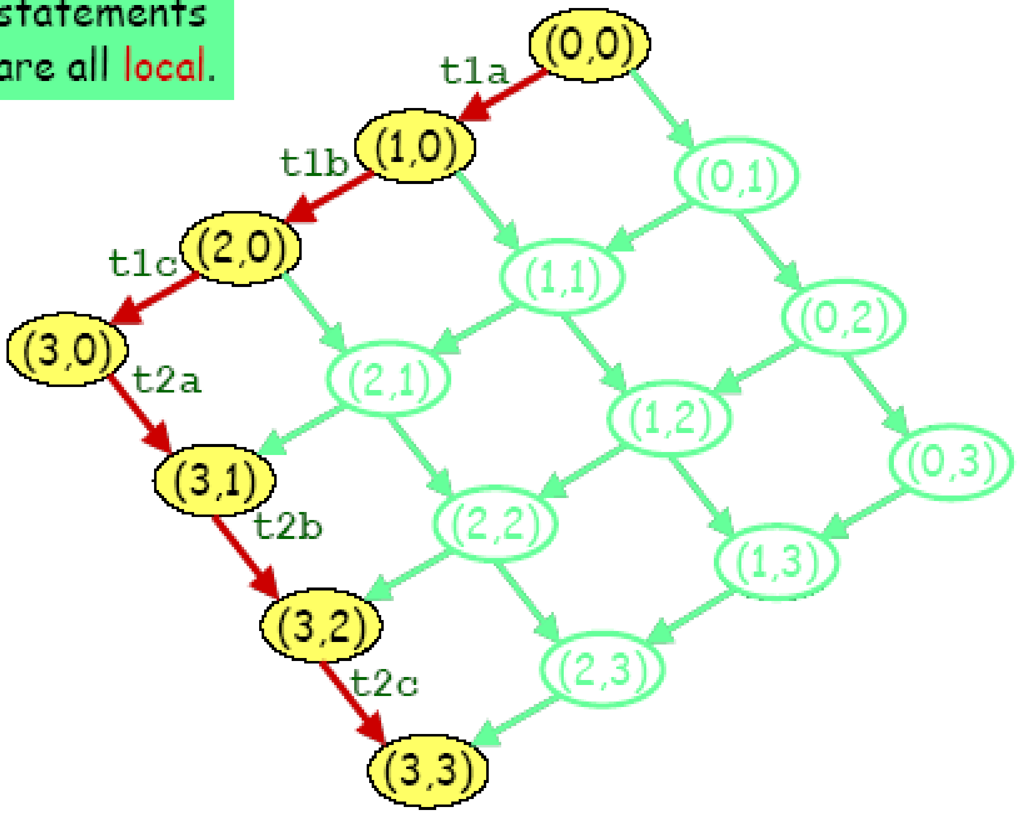
- Idea: if in some global state, a process P can execute only actions updating local variables, always do these actions first (so they will not be interleaved!)

- We can also do the same with actions that :
  - receive from a queue, from which no other process receives
  - send to a queue, to which no other process sends

# Reduction Algorithms

- Partial Order Reduction

Suppose the statements of P1 and P2 are all local.

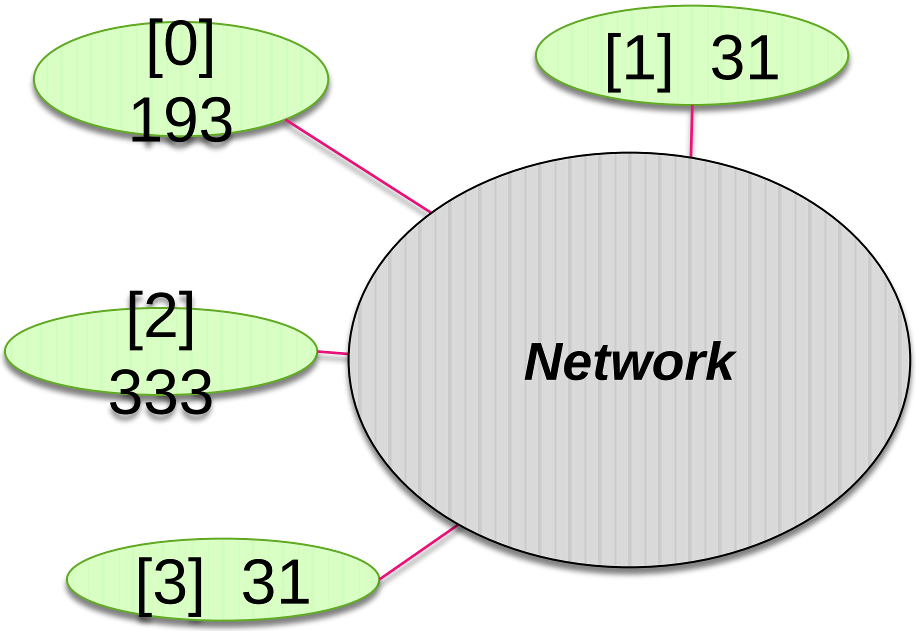


# Results on Partial Order Reduction

| Protocol | Algorithm | States | Transitions | Time(sec.) | Memory (Mb) |
|---|---|---|---|---|---|
| Best-Case | Non-Reduced | 100,001 | 450,002 | 13.2 | 4.3 |
| | Static Reduction | 47 | 47 | (<0.1) | 1.0 |
| | Dynamic Reduction | 47 | 47 | 0.1 | 1.4 |
| Worst-Case | Non-Reduced | 100,001 | 450,002 | 14.5 | 5.0 |
| | Static Reduction | 100,001 | 450,002 | 16.7 | 5.1 |
| | Dynamic Reduction | 100,001 | 450,002 | 84.5 | 5.3 |
| Tpc | Non-Reduced | 3,918,286 | 11,762,426 | 630.6 | 268.4 |
| | Static Reduction | 391,534 | 466,753 | 30.6 | 26.2 |
| | Dynamic Reduction | 267,204 | 295,395 | 131.4 | 18.9 |
| Snoopy | Non-Reduced | 91,920 | 305,460 | 14.4 | 11.5 |
| | Static Reduction | 16,279 | 23,532 | 1.7 | 3.2 |
| | Dynamic Reduction | 7,158 | 8,459 | 6.8 | 2.6 |
| Pftp | Non-Reduced | 417,321 | 1,244,865 | 73.2 | 62.3 |
| | Static Reduction | 53,244 | 67,901 | 6.8 | 9.3 |
| | Dynamic Reduction | 125,718 | 163,459 | 105.5 | 20.6 |
| Leader | Non-Reduced | 45,885 | 185,032 | 8.1 | 9.6 |
| | Static Reduction | 79 | 79 | 0.1 | 1.1 |
| | Dynamic Reduction | 79 | 79 | 0.2 | 1.4 |

*This result is from Holzmann & Peled in 1994, on a Sparc-10 workstation with 128Mbyte of RAM. (about 40 mhz; so 1 mips??)*

# Example: distributed sorting




- Idea:

*Let P(i) swap values with P(i+1).*

- Spec:

*Eventually the values will be sorted.*

# SPIN model

```
#define N 5

byte a[N] ;

proctype P(byte i) {
  byte tmp = 0 ;
  do
  :: d_step{ a[i]>a[i+1] ->
             tmp=a[i] ;
             a[i]=a[i+1] ;
             a[i+1]=tmp  ;
             tmp=0 }
  od ;
}
```

```
init {
  byte i ;
  do
  :: i<N ->
        if
        :: a[i]=0
        :: a[i]=1
        ...
        fi      ;  i++
  :: else -> break ;
  od ;
  i=0 ;
  do
  :: i< N - 1 -> run P(i)     ; i++
  :: else     -> run detect() ; break
  od
}
```

*Swap values, set tmp back to 0 to save state.*

# Expressing the spec

*Eventually the values will be sorted.*

With LTL: $\boxed{\texttt{<>[]}\ (\forall i : 0 \le i < N\text{-}1 : a[i] \le a[i+1])}$

*But SPIN does not support quantification in its Expr!*

*Introduce a global shadow var i, non-deterministically initialized to* : $0 \le i < N\text{-}1$. *Then verify this instead :*

$\texttt{<>[]}\ a[i] \le a[i+1]$

# Detecting “termination”

*New spec: we want each P(i) to know that the goal (to sort values) has been acomplished.*

```
proctype detect() {
  byte i ;
  timeout ->
   do
   :: i<N-1 -> assert (a[i]<=a[i+1])
   :: else  -> break
   od
}
```

done = true

*Extend P(i), such that when it sees “done” is true, it will terminate.*

*Unfortunately, not good enough. The above solution uses “timeout” which here serves as a mechanism to detect termination; in the actual system we now assume not to have this mechanism in the first place, and hence have to implement it ourselves.*

# Detecting “termination”

*Idea: let “detect” keep scanning the array to check if it is sorted.*

```
proctype detect() {
  byte i ;
  i=0 ;
  do
  :: i<N-1 -> if
              :: a[i]>a[i+1] ->  i=0
              :: else          ->  i++
              fi
  :: else -> done=true ; break
  od
}
```

Unfortunately, this doesn’t work perfectly. Consider this sequence of steps:

[ 4, 5, 1 ]

detect 0,1 → ok

swap 1,2

[ 4, 1, 5 ]

detect 1,2 → ok

now “detect” concludes termination!

Can you find a solution for this??