Software Testing and Validation

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Corso di Laurea in Informatica

The SPIN Model Checker

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Acronyms

- Murphi stands for nothing, though it is probable that it reminds Murphi's Laws
  - "if something may fail, it will fail", i.e., $\mathbf{EF}p \to \mathbf{AF}p$
- SPIN stands for Simple Promela INterpreter
- Promela is the SPIN input language
  - Murphi input language does not have a proper name
- Promela stands for PROcess MEta LAnguage
  - as we will see, it is actually based on Operating Systems-like processes
- Also see slides at `https://spinroot.com/spin/Doc/SpinTutorial.pdf`
  - some as reused here

Structure of a Promela Model

- We recall that Murphi input language is based on:
  - global variables with finite types
    - base types are integer subranges and enumerations
    - higher types are arrays and structures
  - function and procedures
  - guarded rules and starting states (*dynamics*)
    - may call functions and procedures, in an *atomic* way
    - Pascal-like syntax: := for assignments, = for equality checks...
  - invariants

Structure of a Promela Model

- Promela instead has:
  - global variables with finite types
    - base types are integer types of the C language
    - enumerations are very limited
    - arrays and records
    - channels!
  - processes behaviour (*dynamics*)
    - possibly with arguments and local variables
  - properties to be checked:
    - assertions
    - deadlocks
    - "neverclaim" describing a BA
    - a separate tool may translate an LTL formula in the corresponding BA

Structure of a Promela Model

Variables and Types (1)

- Five different (integer) basic types.
- Arrays
- Records (structs)
- Type conflicts are detected at runtime.
- Default initial value of basic variables (local and global) is 0.

Basic types

```
bit    turn=1;      [0..1]
bool   flag;        [0..1]
byte   counter;     [0..255]
short  s;           [-2^16-1.. 2^16 –1]
int    msg;         [-2^32-1.. 2^32 –1]
```

Arrays

```
byte a[27];
bit  flags[4];
```

array indicing start at 0

Typedef (records)

```
typedef Record {
  short f1;
  byte  f2;
}
Record rr;
rr.f1 = ..
```

variable declaration

Structure of a Promela Model

- Mainly C-like syntax: = for assignments, == for equality checks...
  - with some exceptions: `if`, `while`, message exchange
- No start states: there is only one starting state
  - an "empty" state, we will see how it is defined
- Thus, if you need multiple starting states, you will have to explicitly model this in Promela
  - having the "empty" state non-deterministically going in the desired starting states
- Assertions are conceptually the same as invariants

Processes in Promela

- Dynamics in Promela is defined through *processes*
- You may define many different codes for your processes: `proctype`
- You may instantiate many times each proctype
  - each instantiation of a proctype is a process
- Each process is either active (i.e., running) from the starting state, or it is explicitly started by some other process
- Though Promela proctypes may seem procedures, they are not!
  - running a process is not like calling a function
  - it is rather like `fork`ing a new process, which executes the given code concurrently with the "calling" one

Peterson Protocol in Promela

```
bool turn, flag[2];
byte ncrit;

active [2] proctype user()
{
 assert(_pid == 0 || _pid == 1);
again:
 flag[_pid] = 1;
 turn = _pid;
 (flag[1 - _pid] == 0 || turn == 1 - _pid);
 ncrit++;
 assert(ncrit == 1); /* critical section */
 ncrit--;
 flag[_pid] = 0;
 goto again
}
```

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Peterson Protocol in Promela

- In this case, the starting state has:
  - two running processes, both ready to execute their first statement (i.e., the `assert`)
  - `turn, flag, ncrit` are all set to zero
    - both entries for `flag`
- A special local variable `_pid` is available for all processes
  - similar to Operating Systems PID
  - n instantiations of a proctype will have `_pid` going from 0 to $n-1$
  - read-only
- The often-deprecated `goto` statement is heavily used in Promela models
  - C-like labels also may have special meanings
  - the same holds for the `break` statement

Non-Determinism in Promela: Part I

- In the Peterson model above, there does not seem to be any non-determinism
- Instead, in each state there are two possible successors
  - one obtained executing the (current statement in) the first process
  - the other one obtained executing the second process
- Generally speaking, if in a state there are n active processes, then there are n successors
  - actually, they may be less, because of blocked statements
  - or more, because of the other source of non-determinism
- SPIN checks that properties hold for *all possible interleavings* between processes
  - using OS-like parlance, the model must be correct regardless of the scheduler

Blocked and Executable Statements

- Proctypes are sequences of *statements*
- Statements may be either *blocked* or *executable*
  - again, it resembles OS blocking primitives, such as those on semaphores or on message exchange
- If a statement is blocked, then the corresponding process cannot be selected for execution
- For each type of statement, we will say when it is blocked and when it is executable

Blocked and Executable Statements

- The following statements are always executable: assignments, `goto`, `break`, `skip`, `assert`, `printf`
  - `return` does not exist
  - `break` must be inside a cycle
  - `skip` does "nothing", useful in some cases
  - `assert` takes an expression e as argument: if e is false, the verification is aborted and the error is reported
  - `printf` is only used in debugging the model itself (simulation mode)

Blocked and Executable Statements

- Expressions may be used as statements
  - in Peterson protocol:
    `(flag[1 - _pid] == 0 || turn == 1 - _pid);`
- An expression *e* used as a statement is executable iff *e* is evaluated to true in the current state
  - *e* is always of some integer type
  - as usual in C, *e* is true if $e \neq 0$, and false otherwise
  - in OS parlance, we are implementing busy waiting
  - *e* is equivalent to `while (!e) /* do nothing */`

Peterson Protocol in Promela

```
bool turn, flag[2];
byte ncrit;

active [2] proctype user()
{
 assert(_pid == 0 || _pid == 1);
again:
 flag[_pid] = 1;
 turn = _pid;
 (flag[1 - _pid] == 0 || turn == 1 - _pid);
 ncrit++;
 assert(ncrit == 1); /* critical section */
 ncrit--;
 flag[_pid] = 0;
 goto again
}
```

Blocked and Executable Statements

- The `run` statement may be used to create a new process
  - there is a limit to the number of active processes N
  - `run` is executable iff the number of currently active processes is less than N
- Other ways to have processes:
  - declare a proctype as `active [`n`]`
    - active since the start state
    - n is the number of instances to be run, may be skipped if $n = 1$
  - name a proctype as `init`
    - again, active since the start state
- There must be either active proctypes or the `init` proctype in every Promela model

Processes (3)

- Process are created using the **run** statement (which returns the process id).
- Processes can be created at any point in the execution (within any process).
- Processes start executing after the **run** statement.
- Processes can also be created by adding **active** in front of the **proctype** declaration.

```
proctype Foo(byte x) {
   ...
}

init {
  int pid2 = run Foo(2);
  run Foo(27);
}

active[3] proctype Bar() {
   ...
}
```

number of procs. (opt.)

parameters will be initialised to 0

Peterson Protocol in Promela

```
bool turn, flag[2];
byte ncrit;

proctype user()
{
/* ... as before */
}

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

Atomic Statements

- Each single statement is *atomic*
  - other processes must wait for an executable single statement completion
  - this differs from OS-like processes: if `n` is shared and `n++` is executed, race conditions may arise
  - because `n++` must be viewed as a sequence of assembly statements
  - not in Promela
- It is sometimes desirable to declare a sequence of statements $s_1, \ldots, s_n$ as atomic: `atomic` $\{s_1, \ldots, s_n\}$

Peterson Protocol in Promela

```
bool turn, flag[2];
byte ncrit;

proctype user()
{
/* ... as before */
}

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

Atomic Statements

- An atomic block like `atomic` $\{s_1, \ldots, s_n\}$ may be executable or blocked as well
- The rule is simple: `atomic` $\{s_1, \ldots, s_n\}$ is executable iff s_1 is executable
- What happens if s_i is blocked for some $i > 1$?
- The process loses the atomicity, it becomes blocked and other active processes will have to be executed
- This is the only case in which a statement is initially executable and then becomes blocked
- When s_i is executable again, and the "scheduler" selects the process, the rest of the atomic section is executed atomically again
  - unless a new s_j is blocked with $j > i$...

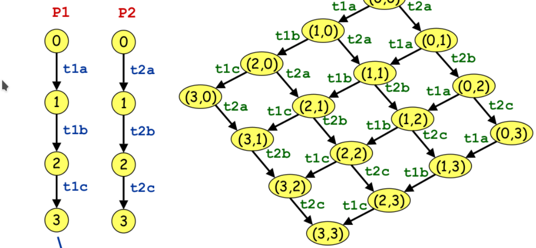
Atomic Statements

- Another way of specifying atomic blocks is `d_step` $\{s_1, \ldots, s_n\}$
- Again, executable iff s_1 is executable, but:
  - it is a (runtime) error if s_i is blocked with $i > 1$
  - each s_i must be deterministic
  - all statements seen till now are deterministic, we will see non-deterministic ones later
- Thanks to these restrictions, `d_step` is more efficient than `atomic`
  - intermediate states need not to be generated, as they cannot block and then resume

Atomic Statements

```
proctype P1() { t1a; t1b; t1c }
proctype P2() { t2a; t2b; t2c }
init { run P1(); run P2() }
```

No atomicity



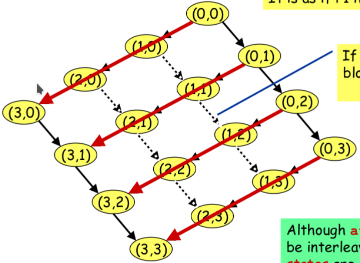
Not completely correct as each process has an implicit end-transition…

Atomic Statements

```
proctype P1() { atomic {t1a; t1b; t1c} }
proctype P2() { t2a; t2b; t2c }
init { run P1(); run P2() }
```

atomic

It is as if P1 has only one transition...



If one of P1's transitions blocks, these transitions may get executed

Although atomic clauses cannot be interleaved, the intermediate states are still constructed.

Blocked and Executable Statements

- The `timeout` statement may be used to avoid deadlocks
  - that is, states where all processes only have blocked statements
- In fact, `timeout` is an expression
  - it becomes true (and thus, as a statement, executable) iff we are in a deadlock, in the sense described above
- Used as an escape in some cases

Blocked and Executable Statements

- The `if` statement has a somewhat surprising syntax

  `if`

  `::` e_1 `->` $s_{11}; \dots; s_{1n_1}$

  $\vdots$

  `::` e_m `->` $s_{m1}; \dots; s_{mn_m}$

  `fi`

  - inspired by Dijkstra guarded command language
  - it is executable if there exists i s.t. e_i is executable
    - typically e_i are expressions, thus when e_i are true
  - as a special expression, `else` is true (executable) iff all e_i are false (blocked)
    - thus, an `if` with an `else` is always executable
  - if all e_i are blocked, then the `if` statement is blocked
  - `;` may be used instead of `->`, which is actually syntactic sugar

Blocked and Executable Statements

- The `while` statement does not exist in Promela
- Instead, we have

  do

  :: e_1 -> $s_{11}; \ldots ; s_{1n_1}$

  $\vdots$

  :: e_m -> $s_{m1}; \ldots ; s_{mn_m}$

  od

  - as for the `if`, it is executable if there exists i s.t. e_i is executable
  - if all e_i are blocked, then the `do` statement is blocked
  - of course, `if` is executed only once, while `do` is executed forever
  - more precisely: once, for some i, $s_{i1}; \ldots ; s_{in_i}$ is executed, the whole `do` is evaluated again
  - to exit from a `do`, a `break` is necessary
  - or some other escape, such as `goto` or `unless`: see later

Non-Determinism in Promela: Part II

- There are two sources of non-determinism in Promela:
  - inter-process, as a process may non-deterministically be chosen among all the currently active non-blocked processes
    - a non-blocked process is a process which current statement is executable
  - intra-process: using `if` or `do`
- In fact, if $E = \{e_{i_1}, \ldots, e_{i_k} \mid e_{i_j} \text{ is executable}\}$ is such that $|E| > 1$, there will non-deterministically be $|E|$ successors
  - of course, for the current process only
  - other processes may have a current `if` or `do` as well

Non-Determinism in Promela: Part II

if-statement (2)

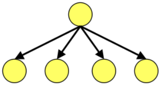
```
if
:: (n % 2 != 0) -> n=1
:: (n >= 0)     -> n=n-2
:: (n % 3 == 0) -> n=3
:: else         -> skip
fi
```

- The **else** guard becomes executable if none of the other guards is executable.

give n a random value

```
if
:: skip -> n=0
:: skip -> n=1
:: skip -> n=2
:: skip -> n=3
fi
```

non-deterministic branching



skips are redundant, because assignments are themselves always executable...

Other Promela

unless

`{ <stats> } unless { guard; <stats> }`

– Statements in *<stats>* are executed until the first statement (*guard*) in the escape sequence becomes executable.
– resembles exception handling in languages like Java
– *Example:*

```
proctype MicroProcessor() {
  {
    ...
    /* execute normal instructions */
  }
  unless { port ? INTERRUPT; ... }
}
```

Other Promela

macros – cpp preprocessor

- Promela uses **cpp**, the C preprocessor to preprocess Promela models. This is useful to define:
  - constants
    ```
    #define MAX 4
    ```
  - macros
    ```
    #define RESET_ARRAY(a) \
        d_step { a[0]=0; a[1]=0; a[2]=0; a[3]=0; }
    ```
  - conditional Promela model fragments
    ```
    #define LOSSY 1
    …
    #ifdef LOSSY
    active proctype Daemon() { /* steal messages */ }
    #endif
    ```

All cpp commands start with a hash: #define, #ifdef, #include, etc.

Other Promela

inline - poor man's procedures

- Promela also has its own macro-expansion feature using the `inline`-construct.

```
inline init_array(a) {
  d_step {
    i=0;
    do
    :: i<N  -> a[i] = 0; i++
    :: else -> break
    od;
    i=0;
  }
}
```

Should be declared somewhere else (probably as a local variable).

Be sure to reset temporary variables.

- error messages are more useful than when using `#define`
- cannot be used as expression
- all variables should be declared somewhere else

Inter-Process Communication

- Two processes may communicate using shared memory
  - that is, using global variables
  - one writes and the other reads
- If synchronization is required, busy waiting must be used
  - that is, read only after writing

```
byte x;

active [2] proctype user()
{
  byte y;
  if
  :: _pid == 0 -> x = 1
  :: _pid == 1 -> y = x;
  fi;
  ...
}
```

What if I want `y = x` to happen only after `x = 1`?

Inter-Process Communication

```
byte x;
bit b = 0;
active [2] proctype user()
{
  byte y;
  if
  :: _pid == 0 -> atomic{b = 1; x = 1}
  :: _pid == 1 -> atomic{b == 1; y = x;}
  fi;
  ...
}
```

Inter-Process Communication: Channels

- Fortunately, Promela offers a simple way to handle communication: FIFO channels
  - similar to OS message exchange via mailbox
- To declare a channel, the `chan` data type can be used
  - the modeler must specify both the size of the channel and the type of the messages to be exchanged
- Messages may be tuples
  - their types must be enclosed in brackets

Inter-Process Communication: Channels

Communication (2)

- Communication between processes is via channels:
  - message passing
  - rendez-vous synchronisation (handshake)
- Both are defined as channels:

also called: queue or buffer

```
chan <name> = [<dim>] of {<t1>,<t2>, ... <tn>};
```

name of the channel

type of the elements that will be transmitted over the channel

number of elements in the channel
dim==0 is special case: rendez-vous

```
chan c       = [1] of {bit};
chan toR     = [2] of {mtype, bit};
chan line[2] = [1] of {mtype, Record};
```

array of channels

Inter-Process Communication: Channels

- To send a message in a channel: `channel!value1,...value`n
  - executable iff `channel` has size $m > 0$ and contains at most $m - 1$ messages
  - each message has size n...
- To receive a message in a channel: `channel?x1,...,x`n
  - if all `x`i are variables, the first still undelivered message in `channel` is stored in each `x`i, breaking down the tuple
  - executable iff the channel is not empty
  - if all `x`i are constant values, the first still undelivered message in `channel` is compared to the values `x`i, breaking down the tuple
  - executable iff the first message in the channel matches the given values
  - in this case, the message is removed from the channel
  - variables and constants may be mixed

Inter-Process Communication: Rendez-Vous Channels

- It is sometimes desirable to also have blocking send
  - that is, if there is not some other process receiving on the channel, the send must block
  - reading is always blocking, if there is not something to be received
- This may be achieved using *rendez-vous* channel
- Defined using 0 as the channel size
- Both the sending and the reading process will block, till when some other process perform the dual operation
- Then, both of them go on to the following statement
  - only case in which two separate statement of two different process are executed at the same time

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Dijkstra Protocol in Promela

```
#define p  0
#define v  1
chan sema = [0] of { bit }; /* rendez-vous */

proctype dijkstra()
{    byte count = 1; /* local variable */
     do
     :: (count == 1) -> sema!p; count = 0
     /* send 0 and blocks, unless some other
        proc is already blocked in reception */
     :: (count == 0) -> sema?v; count = 1
     /* receive 1, same as above */
     od
}
```

Dijkstra Protocol in Promela

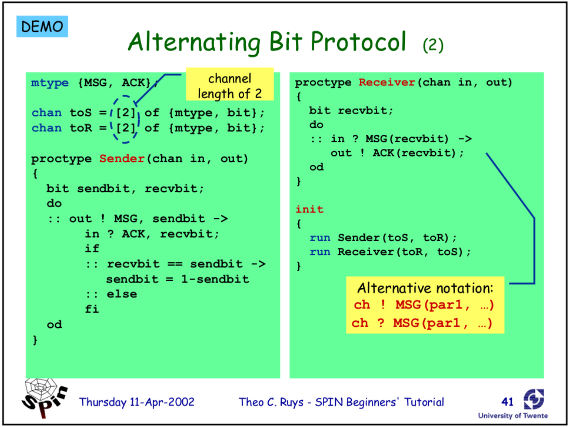
```
proctype user()
{    do
     :: sema?p;
        /*      critical section */
        sema!v;
        /* non-critical section */
     od
}

init
{    run dijkstra();
     run user(); run user(); run user()
}
```

Inter-Process Communication: Rendez-Vous Channels

- To every message, the sender adds a bit.
- The receiver acknowledges each message by sending the received bit back.
- To receiver only excepts messages with a bit that it excepted to receive.
- If the sender is sure that the receiver has correctly received the previous message, it sends a new message and it alternates the accompanying bit.

Inter-Process Communication: Channels

https://en.wikipedia.org/wiki/Alternating_bit_protocol



Promela: Other

- Each statement may have a label (e.g. `again` in Peterson's protocol)
- If the label begins with "end", then it is a valid end-state
- An end-state is valid if it has an "end" label or if it consists of the closing brackets of a process
- Any other state from which it is not possible to execute a transition triggers a verification error, claiming a *deadlock* has been found
- If the label begins with "accept", then it is an accepting state
  - typically inside some neverclaim representing a BA of some LTL formula

From Promela to Kripke Structures

- We define the Kripke structure $\mathcal{S} = \langle S, I, R, L \rangle$ corresponding to a given Promela model
  - $S = D_1 \times \ldots \times D_n \times \{1, \ldots, M_1\} \times \ldots \times \{1, \ldots, M_k\}$
    - here we are assuming n (flattened) local and global variables, including channels
    - we also assume there are k running processes, with process i having M_i statements inside it
    - this is due to the fact that *program counters* must be stored for each running process
    - so we can single out the exact statement to be executed in each process, being on some current state
    - if a D_i corresponds to `short` or `int`, then it has 2^{16} or 2^{32} values on a typical 64-bit architecture, as it is in C
    - a channel is essentially an array of structures

From Promela to Kripke Structures

- This state space is *dynamic*, as it contains the *currently running* processes
  - new processes may be added at any time by a `run` statement
  - thus, the state space cannot be defined *in advance* as it is with Murphi
  - this could only be possible when only `active` proctypes are used, without `run` commands
  - however, local variables may be defined at any point inside proctypes, thus it is not possible even in that case
- Thus, state space grows: as new processes run and new local variables are reached
- ... and shrinks: as some process terminate

From Promela to Kripke Structures

- $I = \{s_0\}$ where s_0 contains only processes defined as `active` and all global variables are zero
  - all program counters are at the beginning, local variables still does not exist
- Intuitively, $R(s, s')$ holds iff there is a running process p in s and an executable statement t at the current program counter of p s.t. t, when executed, leads from s to s'
  - if t is the beginning of an atomic sequence, then the whole atomic sequence must be executed
  - till the first blocking statement of the sequence
  - if t is a send on a rendez-vous channel c, and there is another current statement t' in another process p' s.t. t' is a receive on c, both t and t' have to be executed when leading from s to s'
- L is similar to Murphi, i.e., equations between (global and local) variables and values; however, also program counters must be considered

SPIN Simulation

Almost equal to Murphi one

```
void Make_a_run(NFSS 𝒩)
{
 let 𝒩 = ⟨S, {s₀}, Post⟩;
 s_curr = s₀;
 if (some assertion fail in s_curr))
  return with error message;
 while (1) { /* loop forever */
  if (Post(s_curr) = ∅)
   return with deadlock message;
  s_next = pick_a_state(Post(s_curr));
  if (some assertion fail in s_curr))
   return with error message;
  s_curr = s_next;
 }
}
```

SPIN Verification

- Able to answer to the following questions:
  - is there a deadlock (invalid end state)?
  - are there reachable assertions which fail (safety)?
  - is a given LTL formula (safety or liveness) ok in the current system?
  - is a given neverclaim (safety or liveness) ok in the current system?
- It is possible to specify some side behaviours:
  - is sending to a full channel blocking, or the message is dropped without blocking?
- It may report unreachable code
  - Promela statements in the model which are never executed

SPIN Verification

- Similar to Murphi:
  1. the SPIN compiler (`SrcXXX/spin -a`) is invoked on `model.prm` and outputs 5 files:
     - `pan.c`, `pan.h`, `pan.m`, `pan.b`, `pan.t` (unless there are errors...)
  2. the 5 files given above are compiled with a C compiler
     - it is sufficient to compile `pan.c`, which includes all other files
     - in this way, an executable file `model` is obtained
  3. just execute `model`
     - option `--help` gives an overview of all possible options

SPIN Verification of LTL Formulas

- The former is ok for assertion or deadlock checks
- If you also have an LTL formula
  1. the SPIN compiler (`SrcXXX/spin -F`) is invoked on `model.ltl` and outputs a neverclaim on the standard output
     - `model.ltl` must be a text file with only 1 line
     - file extensions does not matter
     - syntax for the formula: **G** is `[]`, **F** is `<>`, **U** is `U`
     - atomic propositions must be identifiers
  2. append the neverclaim to the promela file
  3. define the identifiers used as atomic proposition by `#defines` in the promela file
  4. go on as before

PAN: Protocol ANalyzer

- `pan.[ch]` is the fixed part of the verifier, it implements a DFS (also BFS starting from some later version, but less efficient), it also includes the other files
- `pan.t` creates a table with an entry for each statement in the source Promela model
  - for each statement, the corresponding values to execute the forward and backward in `pan.[bm]` are stored
  - this is needed for simulations and counterexamples

PAN: Protocol ANalyzer

- `pan.m` is the part of the verifier which depends on the Promela model: it contains a C `switch` statement implementing the transition relation
  - very similar to Murphi `Code` implementing a rule body
  - given the current state, given a running process index i and the program counter p inside that process, it performs on `now` the modifications demanded by the Promela statement at line i of process p, so obtaining the next state
  - the current state is saved in a memory buffer called `now` which is very similar to the Murphi's `workingstate`
  - actually, a second index j is needed in the case the current statement is non-deterministic

PAN: Protocol ANalyzer

- `pan.b`: the same of `pan.m`, but *backwards*!
  - actually, `pan.m` does not surprise and it is not conceptually difficult to understand and implement
  - implementing the same backwards is not straightforward, but SPIN does it!
  - essentially, all Promela instruction may be reversed, and the code to reverse them is in `pan.b`
  - PAN maintains old values for all variables in the state (i.e., values are saved before overwriting due to new assignments)
  - thanks to the fact that the visit is a DFS (SPIN is optimized for DFS), it is only needed to maintain the *last* values, thus a stack for each variable is used for this purpose

PAN: Protocol ANalyzer

- On-the-fly exploration: as in Murphi, the RAM contains only the part of the graph which has been explored till now
  - only the states, no transitions between them
- Hash table for the visited states
  - Murphi uses open addressing, here the hash table is handled with collision lists
  - in order to speed up visited states check, such lists are ordered (i.e., each new state is inserted in order)
- Iterative DFS (recursive one is inefficient)
  - with `goto`s and global variables!
  - DFS stack is explicitly handled in a lighter and more efficient way

Standard Recursive DFS

```
HashTable Visited = ∅;

DFS(graph G = (V, E), node v)
{
  Visited := Visited ∪ v;
  foreach v′ ∈ V t.c. (v, v′) ∈ E {
    if (v′ ∉ Visited)
      DFS(G, v′);
  }
}
```

Iterative DFS Easy Version

```
DFS(graph G = (V, E))
{
  s := init;
  push(s, 1);
  while (stack ≠ ∅) {
    (s, i) := top();
    increment i on the top of the stack;
    if (s ∉ Visited) {
      Visited := Visited ∪ s;
      let S' = {s' | (s, s') ∈ E};
      if (|S'| >= i) {
        s := i-th element in S';
        push(s, 1);
      }
      else pop();
    }
    else pop();
} }
```

Iterative DFS

```
DFS(graph G = (V, E))
{
  s := init; i := 1; depth := 0;
  push(s, 1);
Down:
  if (s ∈ Visited)
    goto Up;
  Visited := Visited ∪ s;
  let S' = {s' | (s, s') ∈ E};
  if (|S'| >= i) {
    s := i-th element in S';
    increment i on the top of the stack;
    push(s, 1);
    depth := depth + 1;
    goto Down;
  }
```

Iterative DFS

```
Up:
  (s, i) := pop();
  depth := depth - 1;
  if (depth > 0)
    goto Down;
}
```

DFS in PAN

```
DFS(NFSS 𝒩)
{
  let 𝒩 = (S, I, Post);
  now := init; depth := 0;
Down:
  if (now ∈ Visited)
    goto Up;
  Visited := Visited ∪ now;
  foreach p s.t. p is a running process in now {
    foreach opt s.t. opt is enabled at p.pc {
      now := apply(now, p, opt);
/* no need of incrementing opt on the top of the
stack: when popping, it will be done by the
foreach on opt... */
      push(p, opt);
      depth := depth + 1;
      goto Down;
```

```
Up:
      (p, opt) := pop();
      depth := depth - 1;
      now := undo(now, p, opt);
  } }
  if (depth > 0)
    goto Down;
}
```

PAN: Just Two Indexes!

- The stack does *not* store states
- Instead, each stack entry stores a pair $\langle p, o \rangle$ of indices (integers)
  - p is a process pid
  - o identifies a statement at the current program counter of p
  - (recall that there may be non-determinism inside each process...)
  - so it is 8 bytes, whilst the current state may easily require some kB
- We now detail the rational behind this choice

PAN: Just Two Indexes!

- There is just one initial state
- Let $\langle p_0, o_0 \rangle$ be the first (from the bottom) pair on the stack; it univocally identifies a statement $istr_0$ to be executed
- By applying $istr_0$ to s_0 we obtain a state s_1 (formally, $s_1 = \text{apply}(s_0, p_0, o_0)$)
- Analoguously, $s_2 = \text{apply}(s_1, p_1, o_1)$ if $\langle p_1, o_1 \rangle$ is the second pair on the stack
- Thus, a stack $\langle \langle p_0, o_0 \rangle, \ldots, \langle p_d, o_d \rangle \rangle$ univocally identifies a state s_d, obtained by chaining the executions due to pairs $\langle p_i, o_i \rangle$
- Formally, $\forall 1 \leq i \leq d \; s_i = \text{apply}(s_{i-1}, p_{i-1}, o_{i-1})$

PAN: Just Two Indexes!

- Moreover, SPIN is able to define the *undo* function, with the same parameters of the apply function
  - of course, apply is defined in `pan.m`, undo in `pan.b`
  - undo needs a stack of values for each variable, as explained above
  - however, it tries to minimise such stacks usage; e.g., if a `c = c + 2` statement must be undone, then it is sufficient to execute `c = c - 2`
  - for direct assigments (e.g., `c = 4`), the apply function puts the preceding values of `v` in the stack of `v` before overwriting it with 4
  - undo will pop the value from the stack of `v` and put it back in `v`
  - this works because the whole visit is a DFS

PAN: Just Two Indexes!

- Finally, recall we have a global fixed structure `now` implementing the current state
  - same as Murphi's `workingstate`
- Summing up, given what we said:
  - no need of pushing a whole state s in the DFS stack: SPIN pushes the pair $\langle p, o \rangle$ which generates s if applied to the current state
  - no need of popping a state s: SPIN pops the pair $\langle p, o \rangle$ which generates s if undone on the current state

PAN: Details

- `ch13.pdf` adds some more details
- Atomic sequences handling:
  - if we are inside an atomic sequence, SPIN must take care that only the current process can execute
  - this is done by setting `From = To = II` (line 44), which forces the `for` loop in line 24 to oly select the current process
  - normal behaviour is reprised at line 46
  - a state may be searched and possibly inserted in the hash table (line 13) only if we are not in an atomic sequence

PAN: Details

- `ch13.pdf` adds some more details
- `timeout` handling:
    - it is a Promela boolean expression, which is true iff the whole system deadlocks (all processes must execute non-executable statements)
    - thus, when the double `for` at lines 24 and 28 is finished without any statement being executable (thus, `n` is still 0) and this is not a valid end state, PAN tries to perform the whole computation again with `timeout` set to 1
    - linea 46 reprises the normal non-`timeout` behaviour

PAN: Details

- `ch13.pdf` adds some more details
- Apply ed undo are implemented in `pan.m` (included at line 30) and `pan.b` (line 54)
  - if a statement cannot be executed, `pan.m` performs a C `continue` statement, which forces `for` in line 28 to go on with next iteration
  - otherwise, a `goto P999` is executed
  - instead, `pan.b` executes `goto R999`
- Finally, recall that, for LTL verification, a nested DFS is used

PAN: Counteracting State Space Explosion

- PAN has the same bit compression (called *byte masking*) and hash compaction techniques we described for Murphi
  - to enable hash compaction, compile `pan.c` with `-DHC`
  - byte masking is always enabled, compile with `-DNOCOMP` to disable it
    - simply align to bytes instead of 4-bytes words
  - also bitstate hashing, a precursor of hash compaction
  - stack cycling, i.e., efficiently use disk for DFS stack
- Other interesting techniques: collapse compression, minimized automaton (may be combined), partial order reduction
- First two techniques try to use less memory to represent the set of visited states so far
  - same goal of hash compaction et similia
- Last technique directly prunes the state space
  - same goal of symmetry reduction in Murphi

Collapse Compression

- Less effective than hash compaction, but exhaustive as bit compression
  - to enable it, compile `pan.c` with `-DCOLLAPSE`
- Recall the main components of a Promela model: N processes, global variables, channels
- The idea is to store in the hashtable $N+2$ state fragments, instead of a single state
  - this is the default, but you can put all processes together (`-DJOINPROCS`)
  - or separate channels with `DSEPQS`
- A further special "order fragment" is used to say which is the first fragment, the second, ... till the $(N+2)$-th fragment

Collapse Compression

- Thus, to decide if the current state is visited, first split it as described above
- If at least one fragment is not in the hashtable, the state is new
  - of course, the missing fragment(s) must be placed inside the hash table
  - for each of them, a unique identifier is generated and stored together with the fragment
  - the unique identifier is an integer with value i, if this is the i-th fragment to be generated
    - of course, only considering the current fragment typology...
  - the special order fragment contains the sequence of such identifiers

Collapse Compression

- Otherwise, also the order fragment must be checked
  - if it is found, then the state is already visited
  - otherwise, insert the new fragment order and return the state as not visited
- Very good if there are many combinations of a few state fragments
  - the order fragment is much shorter than fragments concatenation

Minimized Automaton

- Explicit model checking, borrowing ideas from symbolic model checking
- We still have the DFS as above, but as for visited states check there is not any hash table!
- It is replaced by a "minimized automaton" representing the visited states
  - here, a minimized automaton is essentially similar to those recognizing regular expressions
  - but they are limited: no cycles (it is a DAG), as there is a maximum length to the words

Minimized Automaton

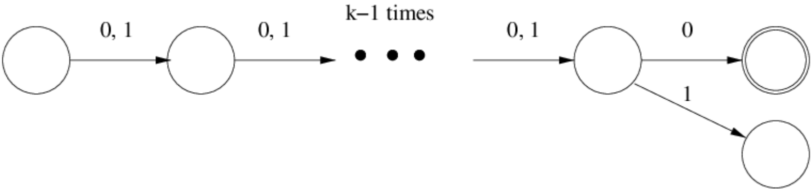
- Finite State Automaton (FSA) for regular expressions: $\mathcal{F} = \langle Q, \Sigma, \delta, q_0, F \rangle$
  - Q is the finite set of states
  - being $q_0 \in Q$ the initial state and $F \subseteq Q$ the final states
  - Σ is the alphabet (input symbols) of the regular expression
  - $\delta \subseteq Q \times \Sigma \times Q$ is the transition relation
- A word $w \in \Sigma^*$ is recognized if, starting from q_0, it ends up in a final state in F
  - $w = \sigma_1 \ldots \sigma_n$, $\langle q_0, \ldots, q_n \rangle$ is such that $(q_{i-1}, w_i, q_i) \in \delta$ for $1 \leq i \leq n$
  - w is recognized iff $q_n \in F$
- $\mathcal{L}(\mathcal{F})$ is the set of recognized words

Minimized Automaton

- A minimized automaton $\mathcal{F}$ is a special case of a FSA where:
  - $\Sigma = \{0, 1\}^8$ (input symbols are bytes)
  - $|F| = 1$
  - δ is deterministic, thus $\delta : Q \times \Sigma \to Q$
  - $\mathcal{L}(\mathcal{F})$ is the set of bit sequences representing visited states, which implies $|\mathcal{L}(\mathcal{F})| < \infty$
  - as a consequence, there are no cycles induced by δ (it is a DAG)
    - "diamonds", i.e., circuits, are still possible
    - the original definition of minimized automaton also has layers of states
    - s.t. δ goes from a state in level i to $i + 1$
- PAN incrementally constructs $\mathcal{F}$ for each unvisited state
  - keeping it minimal w.r.t. the number of states
  - several heuristics are also used, not covered here

Minimized Automaton: Why Effective?

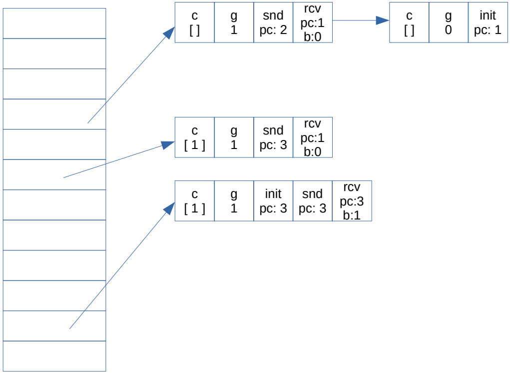
- Suppose you have a k-bytes state vector, and that the visited states are exactly those having 8 zeros in the last byte
  - thus, a visited state is represented by $[0,1]^{8(k-1)}0$
- Using an hash table, we have to store 2^{k-1} states
- Instead, using the minimized automaton:



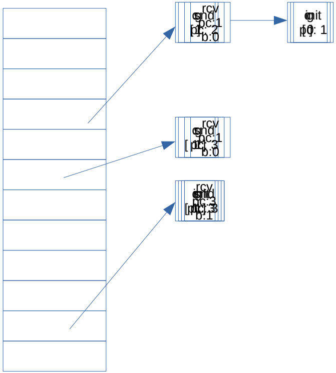
Minimized Automaton: Why Effective?

- As usual in Model Checking: impossible to a priori state that a given KS will be "well" represented by a minimized automaton, or collapse compression, or whatever
  - all such techniques may be seen as "heuristics" in some sense
- For the minimized automaton, some "regularity" is needed inside the bit representation of the set of visited state
- Also note that sometimes adding a state may improve regularity, making the minimized automaton smaller
  - and of course, in some other cases, adding a state may decrease regularity and make the automaton bigger

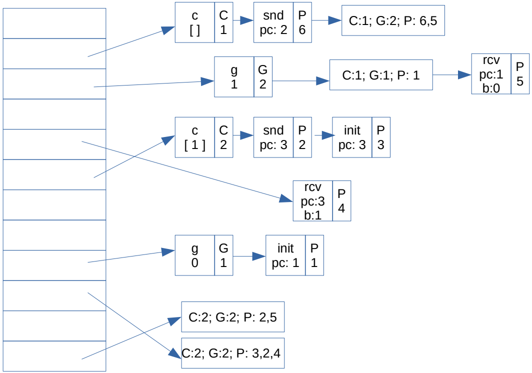
PAN Saving Memory Recap: Normal



PAN Saving Memory Recap: Hash Compaction



PAN Saving Memory Recap: Collapse



PAN Saving Memory Recap: Minimized Automaton

c	g	snd	rcv
[ ]	1	pc: 2	pc:1 b:0

0x00 01 12 210

c	g	init
[ ]	0	pc: 1

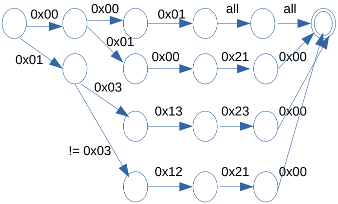
0x00 00 01

c	g	snd	rcv
[1]	1	pc: 3	pc:1 b:0

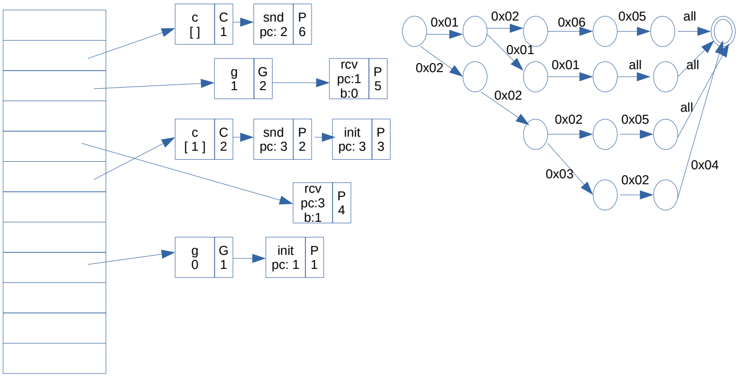
0x01 01 12 210

c	g	init	snd	rcv
[1]	1	pc: 3	pc: 3	pc:3 b:1

0x01 01 03 13 230



PAN Saving Memory Recap: Collapse + Minimized Automaton



Partial Order Reduction

- POR does not try to use less memory to save the same states: it tries to save less states
  - while retaining correctness, of course
  - some states are "useless" and need not to be explored (and saved)
  - also saves in computation time, of course
- Similar to Murphi symmetry for the goal, but different in use and algorithm
  - use: Murphi modeler must specify which parts of the model are symmetric
  - in SPIN, POR is directly applied without the modeler being aware of it
  - though it is possible to disable it

Partial Order Reduction

- There are many ways to perform POR; here, we focus on *ample sets*
- The main idea is that not all interleavings of processes must actually be expanded
  - if we have, e.g., 2 processes, for some actions it is not important if we execute P1 and then P2 or viceversa
- We need an algorithm to decide when only one interleaving can be considered, retaining verification correctness
  - such algorithm must have a low overhead
  - must also work locally (we cannot first expand all reachable states and then decide which one can be removed...)

Partial Order Reduction

- Let $\mathcal{P} = \langle Q, q_0, T \rangle$ be a *finite state program* (FSP) where:
  - Q is a finite set of states, $q_0 \in Q$ is the start state
  - T is a finite set of *operations*
    - also called *actions* or *transitions*
    - each action $t \in T$ is a partial function $t : Q \to Q \cup \{\perp\}$
    - i.e., executing t from a state q generates a new state $q' = t(q)$
    - we also define, for each action $t \in T$, the set $\mathrm{en}_t = \{q \in Q \mid t(q) \neq \perp\}$
    - furthermore, the function $\mathrm{en} : Q \to 2^T$ returns all actions enabled in a state q, i.e., $\mathrm{en}(q) = \{t \in T \mid q \in \mathrm{en}_t\}$
  - paths are sequences $\pi = r_0 \alpha_0 r_1 \ldots$
    - notation: $\pi^{(q)}(i) = r_i$, $\pi^{(a)}(i) = \alpha_i$
    - of course, $r_{i+1} = \alpha_i(r_i)$, $\alpha_{i+1} \in \mathrm{en}(r_i)$

Partial Order Reduction

- From an FSP $\mathcal{P} = \langle Q, I, T \rangle$ it is easy to generate a KS $\mathcal{S} = \langle S, J, R, L \rangle$
  - $Q = S, J = I$
  - $(s, s') \in R$ iff $\exists t \in \mathrm{en}(s): \; s' = t(s)$
  - L may be defined as needed
- Note that actions are deterministic, but the resulting KS may be non-deterministic
  - there may exists $t, t' \in T, q \in S$ s.t. $t \neq t'$, $q \in \mathrm{en}_t \cap \mathrm{en}_{t'}$ and $t(q) \neq t'(q)$
- It is easy to see that a Promela model is close to an FSP: each action is a statement
  - thus, an action is identified by a PID and a statement inside that PID
  - of course, states are defined as above from Promela to KSs
  - possible $\perp$: if the process is not at the correct PC...
  - less straightforward: if t is not executable

Partial Order Reduction: FSP vs Promela

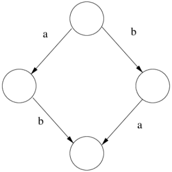
- Actually, we may see that, given an action t, we have that $q \in \mathrm{en}_t$ iff the following holds
  - let i inside process p be the Promela statement corresponding to t
  - must be a single statement, thus `do`s are replaced by `if`s with `goto`s
  - if nondeterminism is present, i is one of the nondeterministic options
  - if more processes of the same proctype are present, t is related to *one* of these processes
  - thus T is defined so as to consider the possible maximum number of processes for each proctype
  - then, q must be such that PC of p corresponds to i and i is executable

Partial Order Reduction

- Given an FSP $\mathcal{P} = \langle Q, I, T \rangle$, an *ample selector* is a function $\mathrm{amp} : Q \to 2^T$ s.t. $\mathrm{amp}(q) \subseteq \mathrm{en}(q)$
  - for a given $q \in Q$, $\mathrm{amp}(q)$ is an *ample set*
- An ample selector defines a new KS $\mathcal{S}' = \langle S, I, R', L \rangle$, where $(s, s') \in R'$ iff $\exists t \in \mathrm{amp}(s) : \; s' = t(s)$
  - of course, $R' \subseteq R$
  - from a DFS point of view, we normally expand actions in $\mathrm{en}(q)$; instead, here we expand only $\mathrm{amp}(q)$
- We want to choose a *POR-sound* amp
  - $\mathcal{S} \models \varphi$ iff $\mathcal{S}' \models \varphi$
  - we start by considering only invariants (assertions) as φ
- We want to compute $\mathrm{amp}(q)$ (almost) only looking at current state q
  - must be simple, i.e., with little overhead
  - no need to be optimal

Partial Order Reduction: Independent Actions

- Two actions $\alpha, \beta \in T$ are *independent* iff $\forall q \in \mathrm{en}_\alpha \cap \mathrm{en}_\beta.\ \alpha(q) \in \mathrm{en}_\beta \wedge \beta(q) \in \mathrm{en}_\alpha \wedge \alpha(\beta(q)) = \beta(\alpha(q))$
  - i.e., α, β can be executed in any order, obtaining the same result
  - otherwise, α, β are *dependent*, which means that $\exists q \in \mathrm{en}_\alpha \cap \mathrm{en}_\beta :\ (\alpha(q) \in \mathrm{en}_\beta \wedge \beta(q) \in \mathrm{en}_\alpha) \to \alpha(\beta(q)) \neq \beta(\alpha(q))$
  - in this case, it is both α dependent on β and viceversa
  - example 1: two actions modifying local variables only are always independent
  - example 2: two actions modifying the same global variable are nearly always dependent
    - unless $\alpha = \beta$, or the new value is however the same



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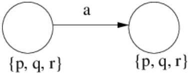
Partial Order Reduction: Invisible Actions

- An action α is *invisible* w.r.t. a labeling $L : Q \to 2^{AP}$ iff $\forall q \in \mathrm{en}_\alpha.\ L(q) = L(\alpha(q))$



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Partial Order Reduction: Conditions for amp

- Recall:
  - we are performing a DFS of the KS generated by an FSP
  - we have a current state q
  - we want to decide if we can consider $\mathrm{amp}(q) \subset \mathrm{en}(q)$ instead of $\mathrm{en}(q)$
- The first 2 conditions only look at q and its actions
  - $\forall q \in Q.\ \mathrm{en}(q) \neq \emptyset \to \mathrm{amp}(q) \neq \emptyset$
    - otherwise, we have introduced a deadlock...
  - $\forall q \in Q.\ \mathrm{amp}(q) \subset \mathrm{en}(q) \to (\forall \alpha \in \mathrm{amp}(q).\ \alpha$ is invisible$)$
    - if we cut some actions, then this must not affect the labeling
    - this also means that only invisible actions can be cut

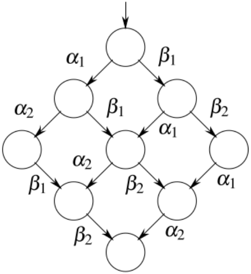
Partial Order Reduction: Conditions for amp

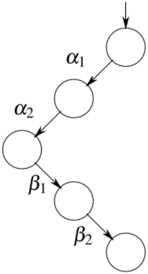
The remaining conditions also consider paths starting from q

- $\forall q \in Q, \forall \pi \in \mathrm{Path}(\mathcal{P}, q).\ (\exists i > 0, \alpha \in \mathrm{amp}(q) :\ \pi^{(a)}(i), \alpha$ are dependent) $\rightarrow \exists j < i :\ \pi^{(a)}(j) \in \mathrm{amp}(q)$
- if this is true, then either:
  - there exists an $\alpha \in \mathrm{amp}(q)$ which is the first from $\mathrm{amp}(q)$ in π
    - then, α is independent on all previous actions on π, and can be executed first
  - otherwise, there exists an $\alpha \in \mathrm{amp}(q)$ which is independent on all other actions in π
    - again, such α can be executed first

Partial Order Reduction: Conditions for amp

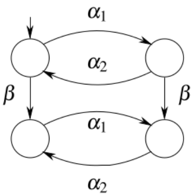
- Example till now: α_1, β_1 and α_2, β_2 are independent





Partial Order Reduction: Conditions for amp

- Essentially, POR *defers* execution of some actions
  - not executing an action at all means that a meaningful portion of the state space is omitted
- With these 3 conditions only, it may happen that an action is never expanded, due to cycles
  - in the example below, β is independent on both α_1, α_2



Partial Order Reduction: Conditions for amp

The remaining condition rules out the problem with cycles

- Consider a DFS on the reduced KS, and suppose an expanded state q is detected as already visited
- We also check if it is on the DFS stack; this implies:
  - there is a cycle
  - some part of the q sub-tree has not be explored
- Then, $\mathrm{amp}(q) = \mathrm{en}(q)$
  - i.e., q must be fully expanded

Partial Order Reduction with LTL Formulas

- It seemed that POR with ample set was ok for any *stutter-invariant* LTL formula
  - recall that a formula φ may be viewed as the set (language) of words $\mathcal{L}(\varphi)$ in AP^* which are recognized by φ
  - φ is stutter-invariant iff, for any sequence of integers $i_j \in \mathbb{N}$ and $w = p_0 p_1 \ldots \in \mathcal{L}(\varphi)$, $p_0^{i_0} p_1^{i_1} \ldots \in \mathcal{L}(\varphi)$
  - essentially, by repeating any character in the word for any number of times you still obtain a word in the language
  - if φ does not contain **X**, then it is stutter-invariant
  - viceversa does not hold
- However an error was discovered (and corrected) in 2019