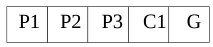
Formal Methods in Software Development
Resume of the 25/11/2020 lesson

Igor Melatti and Ivano Salvo

1 SPIN Verification Algorithm (PAN): Optimizations

- States compression
- *Byte masking*
  - similar to Murphi bit compression
  - in PAN, the current state vector `now` is essentially a concatenation of C structures, each representing a processes
  - byte masking works by aligning each of such structures to each byte, instead of each 4 bytes (word) as it would be by default with C compiler
  - this is really simple, PAN does this by default (to disable it, you have to compile PAN with `-DNOCOMP`)
  - not very effective
- Collapse compression
  - not present in Murphi, as it is closely related to processes; requires compilation of PAN with `-DCOLLAPSE`
  - it exploits the Promela models structure
  - the idea is to separately storing:
    * processes state (program counter + local variables)
      · each process separated from the others, but if you compile PAN with `-DJOININPROCS` then they will be put together
    * channels state
      · all together, but you could store them separately by compling PAN with `-DSEPQS`
    * global variables values
  - for each of such fragments, an index is generated



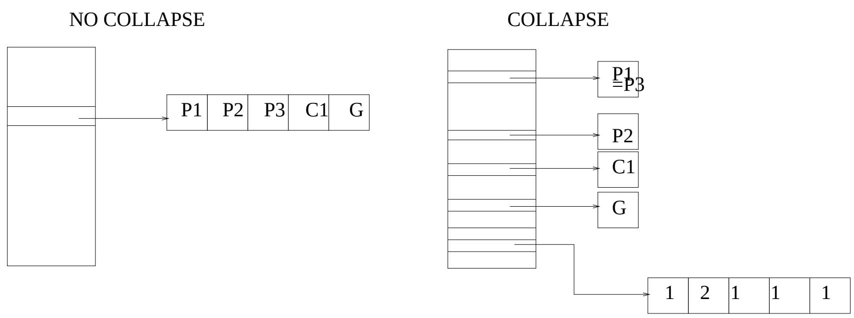


Figure 1: Collapse example, assuming P1 and P3 are an instance of the same proctype and are at the same program counter

- finally, a PAN (complete) state is stored as a vector of indices, which tells how the fragments above must be combined to obtain the complete state
- of course, this works well if there are many combinations of few fragments
  - e.g., this may happen if there are n instances of the same proctype
- in order to check if a (complete) state is already visited or not, PAN does the following
  1. split s in fragments
     - there will be $p + q + g$ fragments
     - note that $p = 1$ with `-DJOINPROCS`, $q = 1$ by default unless `-DSEPQS`, and $g = 1$ (global variables are always together)
  2. for each fragment f, PAN checks if f is in the hash table
  3. if not, the state is of course not already visited; a new unique identifier for f is generated and stored together with f
     - simply a counter: the i-th generated fragment (within the same fragment category) has identifier $i - 1$
  4. otherwise, the unique identifier is returned
  5. finally, s is stored as the list of unique identifiers previously collected (see Fig. 1)

- Hash compaction

- as in Murphi
- compile PAN with `-DHC`n for n-bytes signatures; default is 2 bytes

- Minimized Automaton
  - kind of hybrid technique between explicit and implicit model checking
  - that is, it is explicit model checking with some ideas from implicit one
  - with this technique, *no hash table is required*
  - it is replaced by a minimized automaton which recognizes visited states
  - of course, states are viewed as sequences of bits
  - in fact, you can always write the set of visited states as a regular expression on their single bits
    - at the worst, as an OR of visited states, each of whom is the AND of its bits
    - this would probably result in a memory occupation which is higher that the standard hash table
    - however, usually this worst case does not occur, and a reduction in the RAM requirements is achieved by simplifying the regular expression with the recognizing automaton, using standard formal language techniques
  - hence, if the regular expression is "regular" enough, the minimized automaton requires less RAM than the hash table
  - generally speaking, in order to perform explicit model checking, the following operations must be allowed:
    1. return 1 if a given state s has already been visited, and 0 otherwise
    2. insert a new state in the old set of visited states, and return the new set of visited states
  - this was straightforward with the hash table
  - with the automaton, operation 1 is still straightforward, operation 2 is not
    - it is necessary to modify the current automaton, by adding and/or deleting nodes and/or edges
  - to this aim, SPIN uses an ad-hoc structure representing a *limited* regular expression (recall that states are finite) and implementing sufficiently well operations 1 and 2
  - that is, a deterministic automaton with k levels is used, being k the maximum length of a state representation

    * such an automaton does not have cycles
  - see `spin_minaut.pdf`
  - the minimized automaton may be well combined with collapse compression
  - in this case, an hash table is brought back, but only to contain states fragments
  - identifiers vectors are stored with the minimized automaton

- PAN also efficiently implements the DFS stack through the *stack cycling* technique

  - the DFS stack is only accessed *sequentially*; no random access
  - thus, it is ok to store the stack on disk
  - a finite-length M portion is kept in RAM, holding the currently needed stack
  - that is, once push and pop operations require to access to a stack portion which is outside RAM, that part is fetched from a file on disk
  - the block taken from the file has size $\frac{M}{2}$, in order to avoid going back and forth on the disk due to sequences pop-push-pop-push...
  - see Figure 2, and suppose pushes are towards the top (from 0 to $M-1$), whilest pops are towards the bottom
  - if a push over $k-1$ is made, more memory is required, and such (clean) memory is fetched from the file
  - in order to do this, the part labelled b is stored in some file zone (e.g., that highlighted with an asterisk in Figure 2)
  - then, b may be overwritten by copying a in it
  - of course, also the file is kept as a stack, thus further memory requirements are fulfilled by copying right after b
  - on the other end, now a is free, and push may be executed starting from $\frac{k}{2}$
  - for pops, the idea is symmetric; this time, fetching a disk zone does not bring a cleared memory buffer, but a part of stack which was stored in the disk previously (as a consequence of former too many pushes)
  - of course, PAN first copies b into a (this overwrites a, why is this fine?) and the overwrites b (again, why is this fine?) using a block from the file

- All this techniques allow to save memory, when storing the same set of visited states

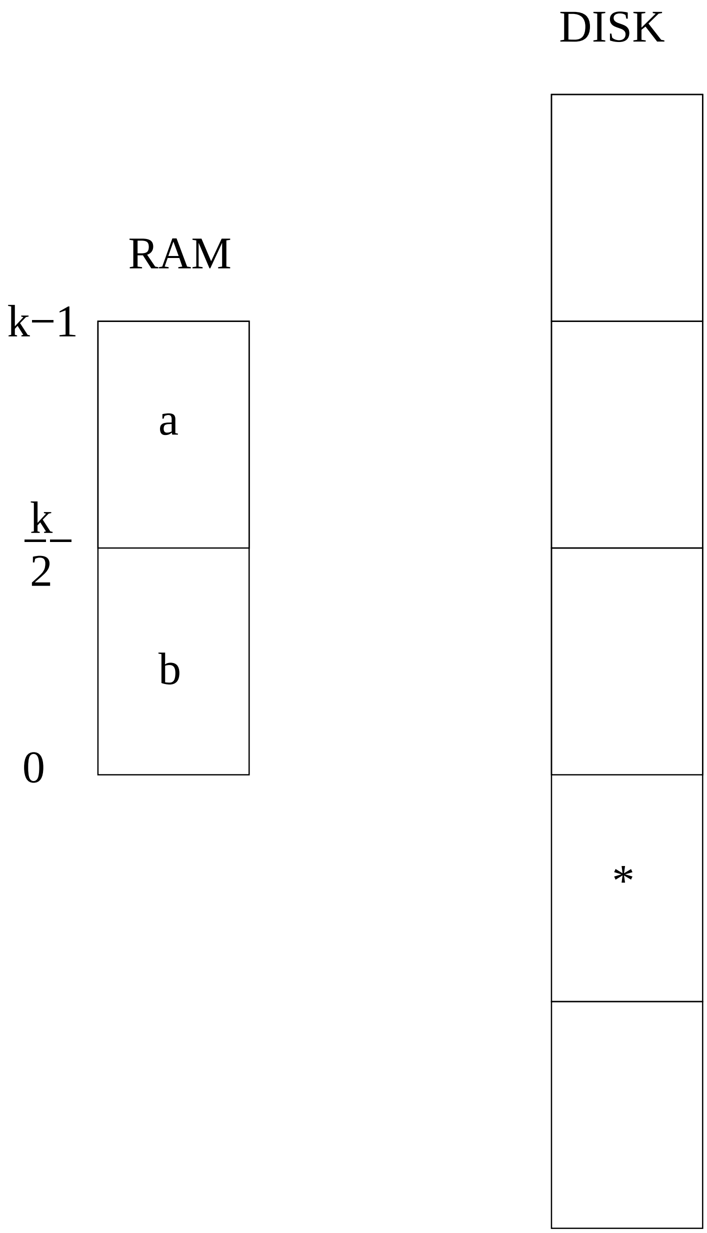


Figure 2: Stack cycling

- It is difficult to tell which method is good for a given Promela model; you can only go for trial and errors
  - i.e., if a method exhaust all available RAM, you try with the following one
- SPIN and PAN also implement a strategy which reduces the number of visited states themselves: the *partial order reduction* (POR)
  - similar to Murphi symmetry reduction, in the sense that the goal is the same
  - however, in Murphi symmetry reduction the modeler is aware of such technique (some variables types such as `multiset` have to be used)
  - in SPIN, POR is applied to nearly all Promela models automatically, with very few execptions
  - the idea for POR is that not all possible interleavings of currently running processes in Promela have to be considered in order to verify the given property
  - this allows to lower down the number of states to be visited
  - some conditions which guarantee actions independence are in `spin_por.pdf`, pages 2 and 3
  - note that recently (2019) a paper was published showing that there are cases in which POR and on-the-fly model checking do not give the correct answer
  - POR is always active in PAN, unless you compile with `-DNOREDUCE`
    * in some cases it is not applicable, e.g., when both fairness and synchronous channels are used

2 SPIN and LTL

- How to use SPIN to verify LTL formulas
  - not very user-friendly, not even with the graphical user interface
  - it is necessary to first generate the Büchi automaton (as a *never claim*) for the desired LTL formula and then *manually* attach to the Promela file
  - a never claim is a special proctype containing the Promela description of the Büchi automaton corresponding to the *negation* of the desired LTL formula
    * SPIN will try to find a path satisfying such negation, and such a path, if it exists, will be the counterexample...

- moreover, atomic propositions in LTL formulas must be defined using `define` macros beginning with a capital letter
- may be generated also from the command line with option `-f` (requiring the actual formula, enclosed in single apexes) or `-F` (requiring the name of a file containing the actual formula, in one line only)
  * see `exp.script`; both log files contain an error!
  * this notwithstanding I am verifying a formula φ first, and then $\neg\varphi$
  * this may be happen in LTL!
  * in fact, as LTL model checking problem requires, PAN checks that *all* paths satisfy the given formula
  * among all possible paths in a Kriepke structure, there may be two paths s.t. $\pi_1 \neq \pi_2$ and $\pi_1 \models \varphi$ and $\pi_2 \not\models \varphi \equiv \pi_2 \models \neg\varphi$
  * thus:
    · $\exists \pi \; \pi \not\models \varphi$, hence $\mathcal{M} \not\models \varphi$
    · $\exists \pi \; \pi \not\models \neg\varphi$, hence $\mathcal{M} \not\models \neg\varphi$
  * of course, if $\mathcal{M} \models \varphi$, then $\mathcal{M} \not\models \neg\varphi$
  * for a visual representation see slide 3 of `timo5.pdf`
- in order to verify φ from the command line, it is necessary to generate $\neg\varphi$ and append it to the Promela description
- it is sufficient to prefix a `!` enclosing the whole φ
- using the GUI, the formula may be created with buttons, and `define`s may be not put in the file
- it is also possible to specify either the desired or the undesired behavior
- in the first case, the negation of the given formula will be generated
- in order to check the generated never claim also writes as a comment the formula used
- example: $\varphi \equiv \mathbf{G}(p \; \mathbf{U} \; q)$
- with `spin -f '!([] (p U q))'` Figure 3 is obtained
- the corresponding Büchi automaton is in Figure 4
  * the last transition in the rightmost state is automatically inserted, as it is not present in the neverclaim
  * automaton in Figure 4 encodes all possible *counterexamples* to given φ
  * in fact, if the verification finds a path satisfying a neverclaim, it returns it as a counterexample
  * in particular, all paths that eventually satisfy $\neg p \wedge \neg q$ are sent in accepting states

```
never {    /* !([] (p U q)) */
T0_init:
        if
        :: (! ((q))) -> goto accept_S4
        :: (! ((p)) && ! ((q))) -> goto accept_all
        :: (1) -> goto T0_init
        fi;
accept_S4:
        if
        :: (! ((q))) -> goto accept_S4
        :: (! ((p)) && ! ((q))) -> goto accept_all
        fi;
accept_all:
        skip
}
```

Figure 3: Neverclaim generated by SPIN for LTL formula $\varphi \equiv \mathbf{G}(p\ \mathbf{U}\ q)$

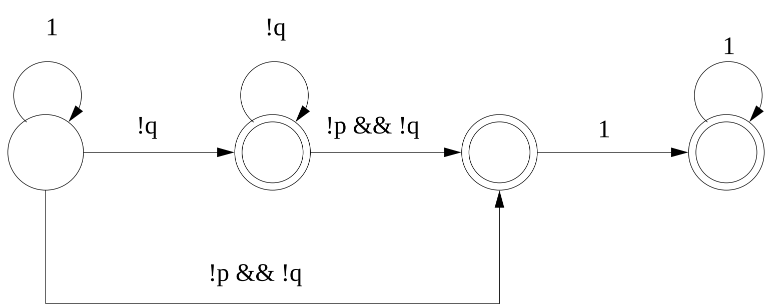


Figure 4: Büchi automaton from Figure 3