Automatically Finding Auxiliary Parameterized Invariants

We will now consider a method for finding inductive assertions for BDS's.
Automatic Generation of Auxiliary Invariants

Goal. Compute Auxiliary Inductive Assertion of the form $\forall i : \psi(i)$

1. Let $reach := \Theta \diamond \rho^*$ be the assertion characterizing all the reachable states of system $S(N_0)$, for $N_0 = H + 3$.

E.g. (MUTEX): Since $H = 1$, $N_0 = 4$.

$$reach := (x + \left( \sum_{i=1}^{4} (\pi[i] \in \{2, 3\}) \right) = 1)$$

2. Let $\psi_1$ be the assertion obtained from $reach$ by projecting away all the references to variables subscripted by indices other than 1.

E.g.: (MUTEX) $\psi_1 : \pi[1] \in \{2, 3\} \rightarrow (x = 0)$.

3. Let $\psi(i)$ be the assertion obtained from $\psi_1$ by generalizing 1 into $i$. The candidate for inductive assertion is $\forall i : \psi(i)$.

E.g.: (MUTEX) $\psi(i) : \pi[i] \in \{2, 3\} \rightarrow (x = 0)$.

Unfortunately, $\forall i : \psi(i)$ is not inductive over MUTEX (2) $\Rightarrow$ algorithm is not guaranteed to produce inductive assertions.
Compute Auxiliary Assertion of the form \( \varphi : \forall i : \psi(i) \)

1. Let \( reach := \Theta \diamond \rho^* \) be the assertion characterizing all the reachable states of system \( S(N_0) \).

2. Let \( \rho_g \) be the transition (abstraction) relation, which contains for each finite-domain variable \( x \), the conjunct \( x' = x \).

3. For each \( i \in 1..N_0 \), let \( \rho_{[1\mapsto i]} \) be the transition relation which contains, for each index variable \( k : 1..N \) the conjunct \( (k' = i) \equiv (k = 1) \), and for each array variable \( y : \text{array}[1..N] \) of boolean the conjunct \( y'[i] = y[1] \).

4. Let \( \psi(i) = reach \diamond (\rho_g \land \rho_{[1\mapsto i]}) \) be the assertion obtained from \( reach \) by preserving all the global variables, and porting all the properties of index 1 to index \( i \).

We take \( \varphi : \bigwedge_{i=1}^{N_0} \psi(i) \)

Since assertion \( \varphi \) is computed internally and immediately consumed, the user never gets to see it. This is why we refer to this method as

Verification by invisible invariants.
Example: MUTEX with 1-Index Assertion

In file `mutex5_inv1_pf` we place:

```pascal
Func abs(reach, f, t);
  Local trans := (next(y) = y) &
                  (next(P[t].loc) = P[f].loc);
  Return succ(trans, reach);
End -- Func abs(reach, f, t);
```

To compute_invis;
  Let reach := reachable(1);
  Let phi := 1;
  For (i in 1...N)
    Let phi := phi & abs(reach, 1, i);
  End -- For (i in 1...N)
End -- compute_invis;
```
To calc_exc;
  Let exc := 1;
  For (i in 1...N)
    For (j in i+1...N)
      Let exc := exc & ((P[i].loc notin 3) | (P[j].loc notin 3));
    End -- For (j in i+1...N)
  End -- For (i in 1...N)
End -- calc_exc;

calc_exc;
compute_invis;
Print "\nCheck mutual exclusion\n";
Call inv(exc,phi,1);

Computed assertion fails to be inductive (Premise 2 fails).
Compute Auxiliary Assertion of the form $\forall i \neq j : \psi(i, j)$

1. Let $reach := \Theta \diamond \rho^*$ be the assertion characterizing all the reachable states of system $S(N_0)$.

2. Let $\rho_g$ be the transition (abstraction) relation, which contains for each finite-domain variable $x$, the conjunct $x' = x$.

3. For each $i \in 1..N_0$, let $\rho_{[1 \mapsto i]}$ be the transition relation which contains, for each index variable $k : 1..N$ the conjunct $(k' = i) \equiv (k = 1)$, and for each array variable $y : array[1..N]$ of boolean the conjunct $y'[i] = y[1]$. Similarly define $\rho_{[2 \mapsto j]}$

4. Let $\psi(i, j) = reach \diamond (\rho_g \land \rho_{[1 \mapsto i]} \land \rho_{[2 \mapsto j]})$ be the assertion obtained from $reach$ by preserving all the global variables, and porting all the properties of indices 1, 2 to index $i, j$, respectively.

We take

$$\varphi : \bigwedge_{i=1}^{N_0} \bigwedge_{j=i+1}^{N_0} \psi(i, j)$$
Applying the Algorithm to MUTEX

Consider MUTEX with $N_0 = 3$.

\[ \text{reach} : \left( \sum_{i=1}^{4} (\pi[i] \in \{2, 3\}) \right) + x = 1 \]

\[ \psi_{1,2} : \begin{cases} \pi[1] \in \{2, 3\} \rightarrow (x = 0) \land \pi[2] \in \{0, 1\} \\ \pi[2] \in \{2, 3\} \rightarrow (x = 0) \land \pi[1] \in \{0, 1\} \end{cases} \]

\[ \psi(i, j) : \begin{cases} \pi[i] \in \{2, 3\} \rightarrow (x = 0) \land \pi[i] \in \{0, 1\} \\ \pi[j] \in \{2, 3\} \rightarrow (x = 0) \land \pi[j] \in \{0, 1\} \end{cases} \]

$\forall i \neq j : \psi(i, j)$ is an inductive assertion over MUTEX (5), and, therefore, over all MUTEX ($N$). It also implies the property of mutual exclusion:

$\forall i \neq j : \neg(\pi[i] = 2 \land \pi[j] = 2)$
In TLV

In file `mutex5_inv2.pf` we modify function `abs` and `compute_invis` as follows:

```
Func abs(reach,f1,f2,t1,t2);
    Local trans := (next(y) = y) &
        (next(P[t1].loc) = P[f1].loc) &
        (next(P[t2].loc) = P[f2].loc);
    Return succ(trans,reach);
End -- Func abs(reach,f1,f2,t1,t2);
```

To `compute_invis`;

```
Let reach := reachable(1);
Let phi := 1;
For (i in 1...N)
    For (j in i+1...N)
        Let phi := phi & abs(reach,1,2,i,j);
    End -- For (j in i+1...N)
End -- For (i in 1...N)
End -- compute_invis;
```
Example: A Modified MUTEX

\[
\begin{align*}
\text{in} & \quad N : \text{natural where } N > 1 \\
\text{local} & \quad x : \text{boolean where } x = 1 \\
\text{local} & \quad last : [1..N] \\
& \quad \begin{cases}
0 : \text{loop forever do} \\
1 : \text{Non-Critical} \\
2 : \langle \text{request } x; \text{last := } h \rangle \\
3 : \text{Critical} \\
4 : \text{release } x
\end{cases}
\end{align*}
\]

\[
\prod_{h=1}^{N} P[h] ::
\]

Searching for a \( \psi(i) \) inductive assertion, we obtained the calculated invariant

\[
\varphi : \forall i : \pi[i] \in \{3, 4\} \leftrightarrow (x = 0 \land last = i)
\]

The candidate assertion \( \varphi \) is inductive and also implies the property of mutual exclusion:

\[
p : \forall i \neq j : \neg(\pi[i] = 3 \land \pi[j] = 3)
\]
In file `mutex_mod_inv1.pf` we place:

```plaintext
Func abs(reach,f,t);
  Local trans := (next(y) = y) &
                  ((next(last)=t) = (last=f)) &
                  (next(P[t].loc) = P[f].loc);
  Return succ(trans,reach);
End -- Func abs(reach,f,t);
```

This time the auxiliary assertion is inductive.
Example: Program Arbiter

Consider the following program \textsf{ARBITER}:

\[
\begin{align*}
  r, g &: \text{array}[1..N] \text{ of boolean} \quad \forall i : [1..N] : r[i] = g[i] = 0 \\
  k &: [1..N] \text{ where } k = 1 \\
  &\text{loop forever do} \\
  m_0 &: \text{if } r[k] \text{ then} \\
  m_1 &: g[k] := 1 \\
  m_2 &: \text{await } \neg r[k] \\
  m_3 &: g[k] := 0 \\
  m_4 &: k := k \oplus_N 1
\end{align*}
\]

\[\begin{array}{c}
\text{loop forever do} \\
\ell_0 &: \text{Non-Critical} \\
\ell_1 &: r[i] := 1 \\
\ell_2 &: \text{await } g[i] \\
\ell_3 &: \text{Critical} \\
\ell_4 &: r[i] := 0 \\
\ell_5 &: \text{await } \neg g[i]
\end{array}\]

for which we wish to prove

\[
p : \forall i \neq j : \neg (\text{at}\_\ell_3[i] \land \text{at}\_\ell_3[j])
\]
Verifying Arbiter by the Invisible Invariants Method

In file `arbiter.smv`, we place the following:

```plaintext
MODULE main
DEFINE
    N := 6;
VAR
    k : 1..N;
    Arb : process MA(k, N, r, g);
for (i=1; i <= N; i = i+1)

    r[i]: boolean;
    g[i]: boolean;
    Cl[i] : process MC(r[i], g[i]);
}
Id : process Idle;

MODULE Idle
```

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MODULE MA(k,N,r,g)
DEFINE rk := | for(i=1; i <= N; i = i+1){i=k ? r[i] : 0};
VAR loc : 0..4;
ASSIGN init(loc) := 0; init(k) := 1;
next(loc) := case
  loc=0 & rk : 1;
  loc=0 : 4;
  loc in {1,3,4} : (loc+1) mod 5;
  loc=2 & !rk : 3;
  1 : loc;
esac;
next(k) := loc=4 ? (k mod N)+1 : k;
for (i=1; i <= N; i = i+1){next(g[i]) := case
  i != k : g[i];
  loc=1 : 1;
  loc=3 : 0;
  1 : g[i];
esac;}

JUSTICE
  loc != 0, loc != 1, loc != 3, loc != 4, !(loc=2 & !rk)
MODULE MC(r, g)
VAR loc : 0..5;
ASSIGN
  init(loc) := 0; init(r) := 0; init(g) := 0;
  next(loc) := case
    loc in {1, 3, 4} : (loc+1) mod 6;
    loc=0       : {0, 1};
    loc=2 & g   : 3;
    loc=5 & !g  : 0;
    1           : loc;
  esac;
  next(r)  := case
    loc=1    : 1;
    loc=4    : 0;
    1        : r;
  esac;
JUSTICE
  loc != 1, !(loc=2 & g), loc != 3, loc != 4, !(loc=5 & !g)
Applying the Invisible Invariants Method

In file `arb-inv.pf`, we place:

```plaintext
Func abs(reach,f1,t1);
    Local trans := ((next(k)=t1) <-> (k=f1)) &
    (next(Arb.loc) = Arb.loc) &
    (next(g[t1]) = g[f1]) &
    (next(r[t1]) = r[f1]) &
    (next(Cl[t1].loc) = Cl[f1].loc);
    Return succ(trans,reach);
End -- Func abs(reach,f1,t1);
To compute_invis;
    Let reach := reachable(1);
    Let phi := 1;
    For (i in 1...N)
        Let phi := phi & abs(reach,1,i);
    End -- For (i in 1...N)
End -- compute_invis;
```

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To compute_prop;
    Let exc := 1;
    For (i in 1...N)
        For (j in i+1...N)
            Let exc := exc & !(Cl[i].loc=3 & Cl[j].loc=3);
        End -- For (j in i+1...N)
    End -- For (i in 1...N)
End -- compute_prop;
compute_invis;
compute_prop;
Print "\n Check mutual exclusion\n";
Call inv(exc,phi,1);