HOL-Boogie — An Interactive Prover-Backend for the Verifying C Compiler

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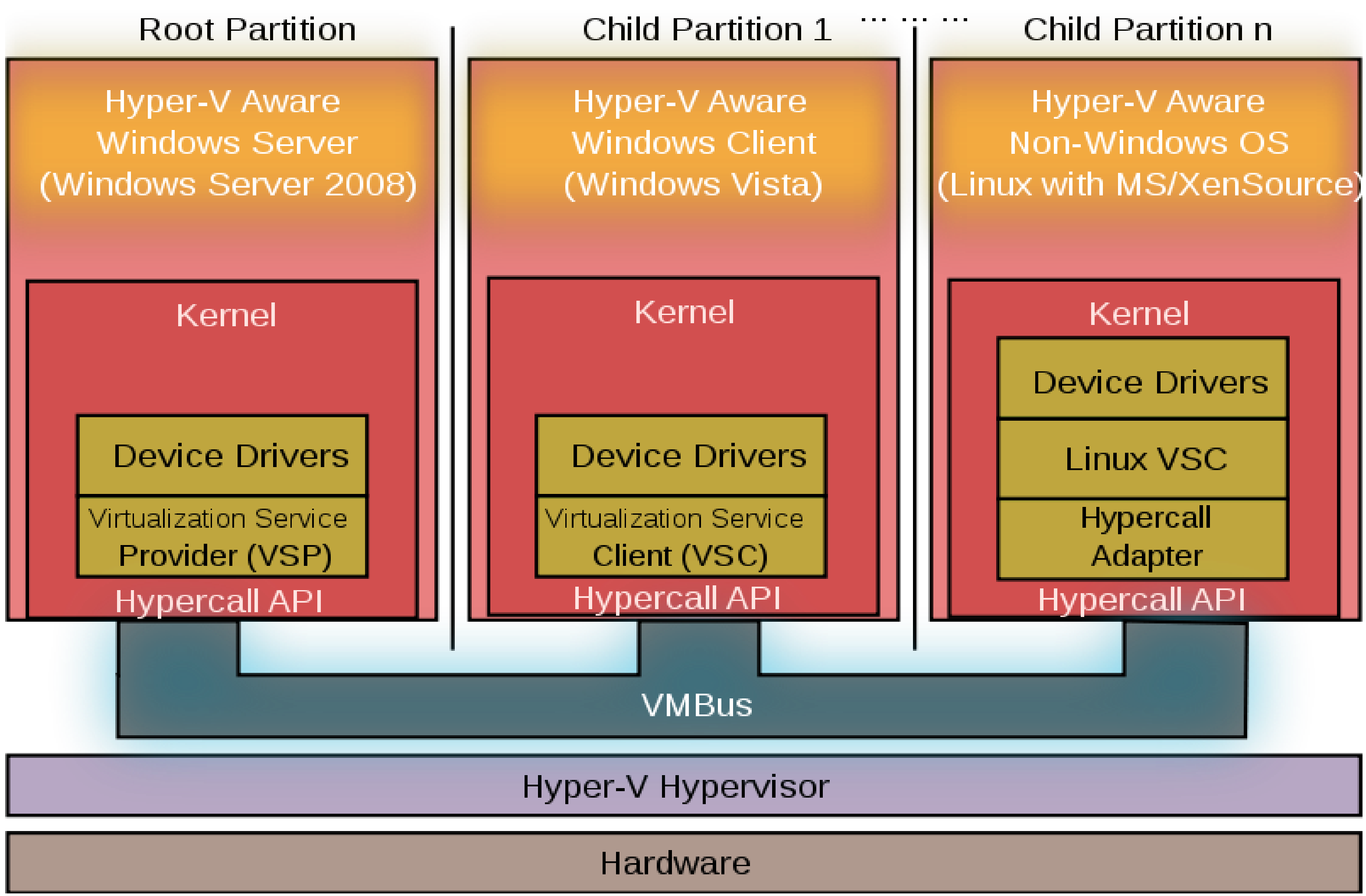
With help by: Wolfram Schulte, Rustan Leino,
Mike Barnett, Jan Smuts, Herman Venter, Michal Moskal, …

Context (1)

- The VeriSoft Xt Project
  - started 2007, 24 mio € budget, 3 years, ca. 100 men-year work.
  - several larger verification sub-projects
    - Avionics, Car-Electronics
    - Pike-OS Kernel (a real-time OS)
    - Microsofts Hyper-V (a virtualization OS)

Context (2)

- Microsofts Hyper-V (a virtualization OS)



Context (3)

- What is the Hyper-V Hypervisor ?
  - an operating system
    - manages processes (“guests”,“partitions”),
    - memory,
    - events and IPC's
    - (but no real devices, that
      is handled by the root partition)

Context (4)

- What is special with Hyper-V?
  - in contrast to a standard OS,
    which emulates linear ("logical") memory
    for its processes, it emulates
    physical memory

    i.e. an MMU

    for its guests (using X86 - V Chipset)

Context (5)

- The Hyper-V Verification Project
  - Motivation:
    Tremendously complex, difficult to test.
  - Relatively small:
    50000 line of code in ANSII C (X86 - V)
    and Assembler
  - There have been formal models of processors
    and virtual machines for a while
    (INTEL's X86 (Forte), AMD's X86 (ACL 2)
    JVM (Isabelle/HOL), VAMP (Isabelle/HOL), ...)

Context (6)

- The Hyper-V Verification Project
  - Target: Correctness Proof. Prove that

    an emulated X86 processor
    (running one one core of X86-V)

    behaves like

    a standard X86 processor (modulo time).

Context (6)

- The Hyper-V Verification Project

obviously, a lot of new verification technology is needed.

Motivation (1)

- Automated Theorem Proving (ATP) has found its "Killer-Application": Static Program-Analysis
  - SAL-Annotations in MS Vista and MS Word !
  - Boogie: Data-Invariant Checking

- Interactive Theorem Proving (ITP): No Killer-App in sight (people still hate to see proofs ...), but
  - Verifications of complex algorithms, or even mathematically challenging theorems, is S-o-t-A.
  - Lots of Technology exists to get calculi right and to get provers safely work together.

Motivation(2)

- Boogie:

  ... is a program-oriented specification method aiming at "deeper" algorithmic verification (as, e.g., SAL).

  ... offers an extremely attractive
  "Analyze&Fix" cycle.

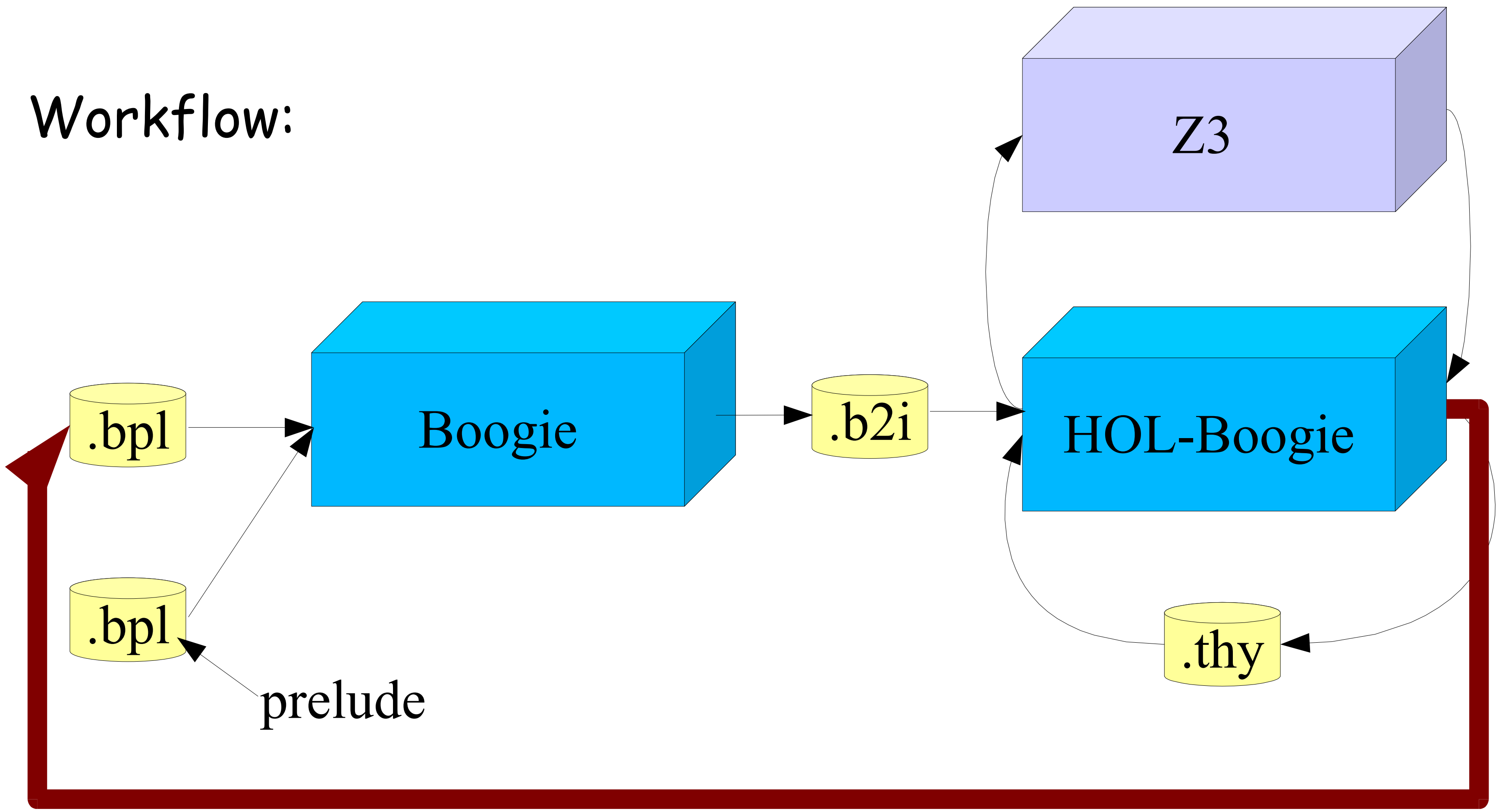
  Still, failures of proof attempts can be difficult to understand: Is it the prover? The program? The spec?

Plan of the Talk

- Scenario I: HOL-Boogie as Interactive Prover of Boogie VC's, with an "Analyse&Fix" based on ITP. (%70)
- Challenges and Answers for ITP in a static program analysis application (%20)
- Scenario II: HOL-Boogie in C Verification (%10)

Scenario I

- Workflow:



Scenario I

- The Problem: Dijkstra's Shortest Path Algorithm
  Data:

```
type Vertex;
const Graph: [Vertex, Vertex] int;
const AllVertices: [Vertex] bool;
axiom (forall x: Vertex :: AllVertices[x]);
axiom (forall x: Vertex, y: Vertex:: x != y ==> 0 <Graph[x,y]);
axiom (forall x: Vertex, y: Vertex:: x == y ==> Graph[x,y] == 0);
const Infinity: int;
axiom 0 < Infinity;
var Shortest: [Vertex, Vertex] int;
```

Scenario I

- The Problem: Dijkstra's Shortest Path Algorithm
  Toplevel-Specification:

```
procedure Dijkstra();
modifies Shortest
ensures (forall x:Vertex::AllVertices[x]==>Shortest[x,x] == 0);
ensures (forall x: Vertex, y: Vertex, z: Vertex ::
        AllVertices[x] && AllVertices[y] && AllVertices[z] ==>
          Shortest[x,z] <= Shortest[x,y] + Graph[y,z]);
ensures (forall x: Vertex, z: Vertex ::
        AllVertices[x] && AllVertices[z] ==>
            Shortest[x,z] <= Graph[x,z]);

. . .
```

Scenario I

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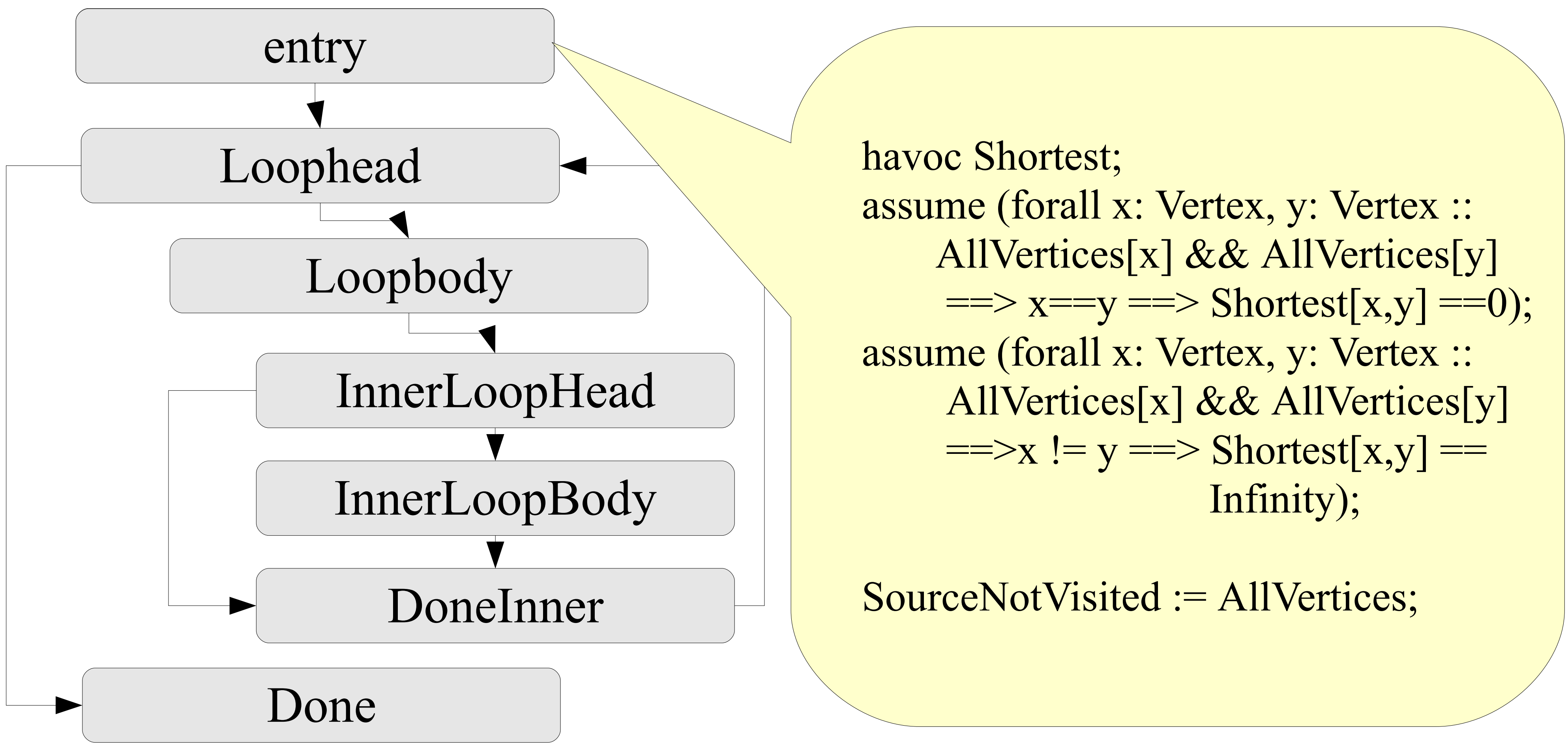
Scenario I

- The Problem: Dijkstra's Shortest Path Algorithm Implementation:



Scenario I

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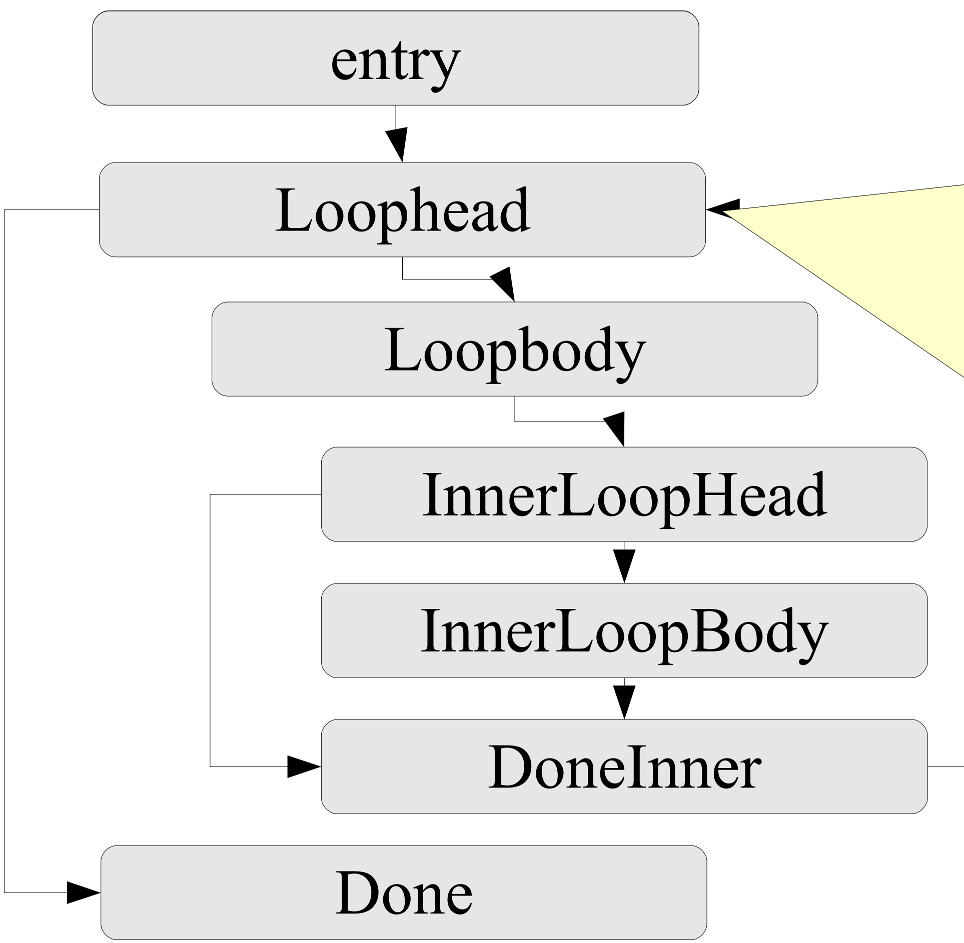


```
assert (forall x: Vertex ::
    SourceNotVisited[x] ==> AllVertices[x]);

assert (forall x: Vertex :: AllVertices[x] ==>
              Shortest[x,x] == 0);
assert (forall x: Vertex, y: Vertex, z: Vertex ::
    AllVertices[x] && AllVertices[y] ....  ==>
          SourceNotVisited[x] ||
          Shortest[x,z] <=
          Shortest[x,y] + Graph[y,z]);
  ...
```

Scenario I

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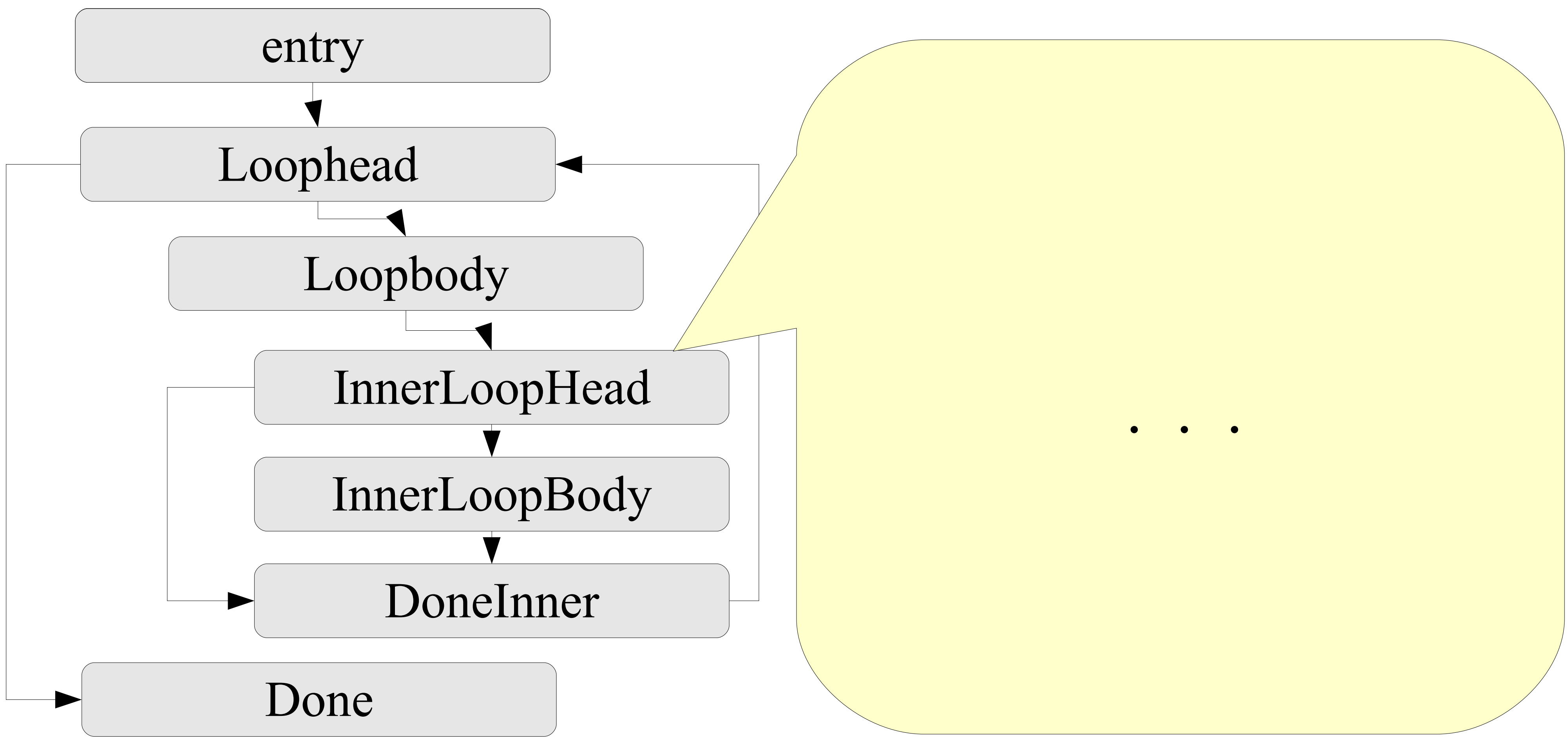

Scenario I

- Verification with HOL-Boogie (Attempt I)

  Generating .b2i-file:

  /cygdrive/c/boogie/Binaries/Boogie /prover:isabelle Dijkstra.bpl

  and *get* it under /cygdrive/c/Dijkstra.1.b2i.

  And then start Isabelle under ProofGeneral:

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Scenario I

- Verification with HOL-Boogie (Attempt I)

  Attempt 1 stuck at:

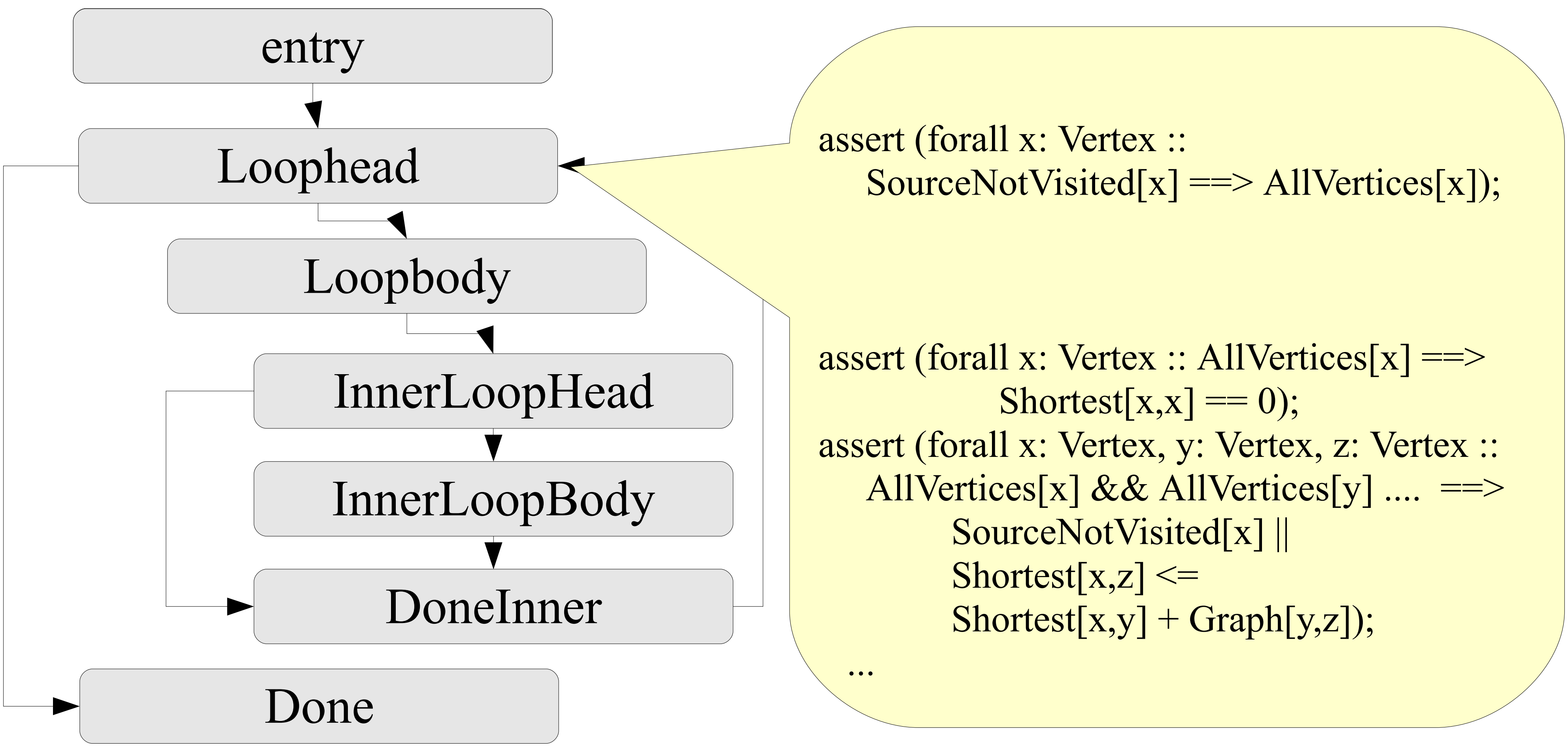
  [| ... ;
  ... ;
  |] ⇒ $0 \leqq Shortest@3(x,y) + Graph(y,z)$

  The Problem occurs when establishing the entry-condition from DoneInner to Loophead.

- Solution: Strengthen the Invariants to $0 \leqq Shortest(x,y)$

Scenario I

- The Problem: Dijkstra's Shortest Path Algorithm Implementation:



Scenario I

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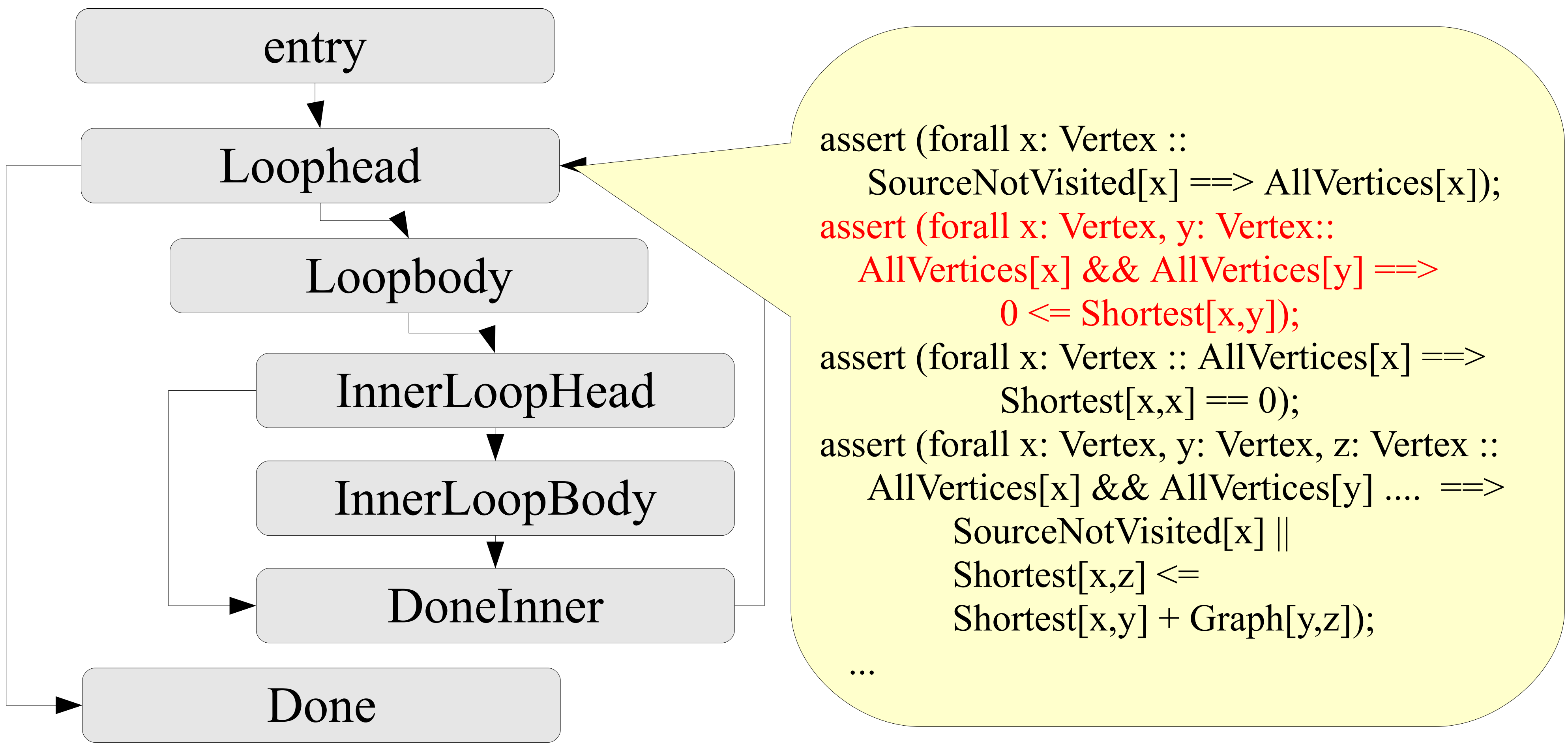


Scenario I

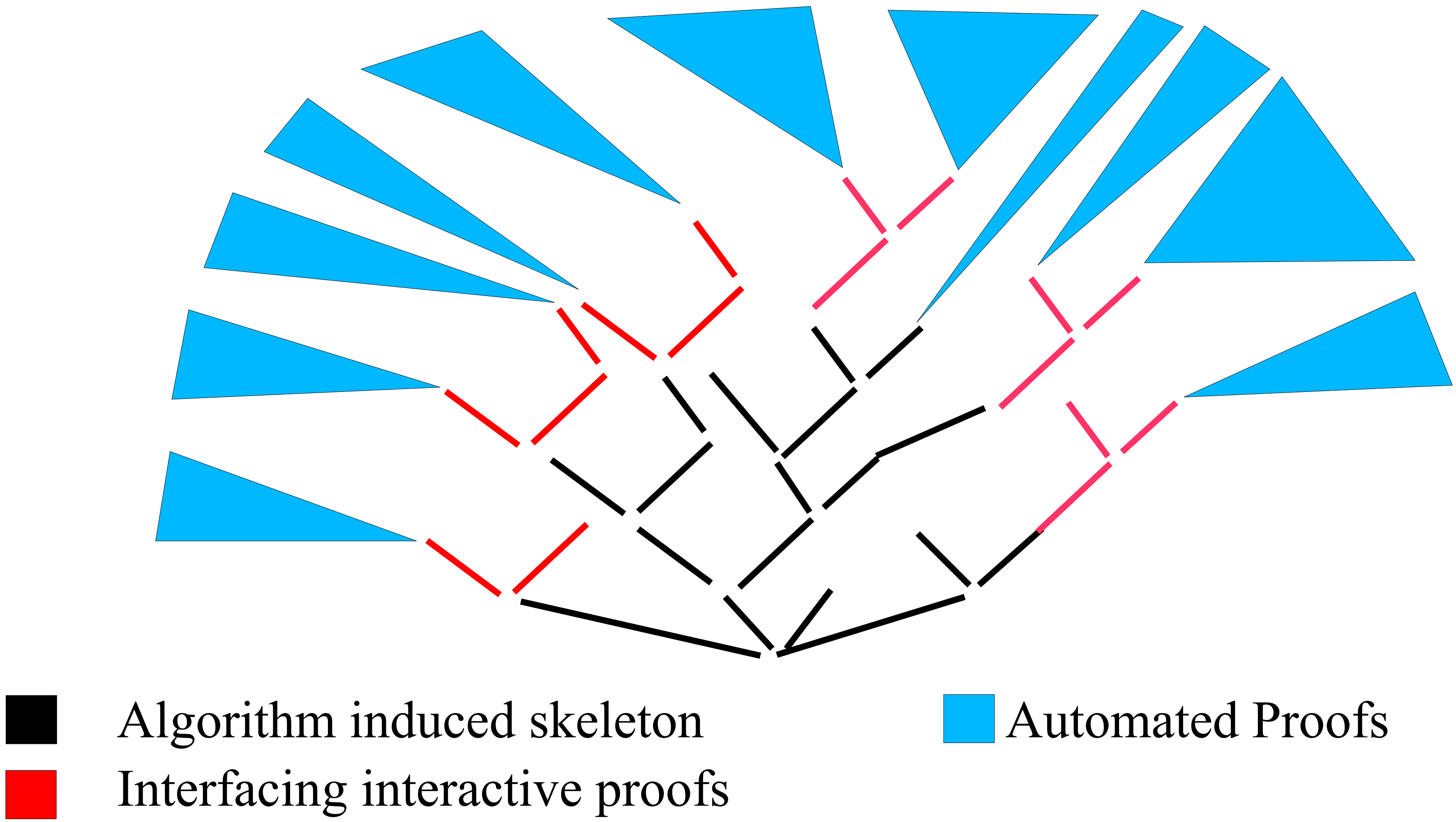
- Results I:
  - Attempt II (with strengthened Invariant) succeeds
  - Proof takes 5 min. in interactive mode.
  - Proof deliberately low-level; anyone with medium expertise in ITP should be able to do this!
  - Z3 does still not find the proof.
  - Proof development took 1,5 working days
  - An alternative “classic” ATP verification by improvement of DijkstraN was abandoned by [Leino&al] after 1,5 days.

Challenges: ITP for PA

- Techniques specific to ITP in Program Analysis
  - Tactics taking the structure of wp-generated formulas into acount
  - Positional and Structural Labelling Techniques
  - Integration of SMT solvers
  - Integration of techniques to make prover instrumentations transparent through different provers ...

Scenario I : Tactics

- Observation of wp-generated formulas:
  Why? ... The "skeleton" is a deterministic proof.



Scenario I : Labelling

- Positional labels "this assertion is from line 55 ..."

  block_at Line_25_Col_3 True
  assert_at Line_55_Col_4 (...)

  (Technique described in Leino, Millstein, and Saxe: *Generating error traces from verificationcondition counterexamples*. SCP, 55-1-3, 2005)

- Structural Labels "this assertion holds at entry of loop *A*"

  ...

  (not much used so far, but better for repeated

  Analyse&Fix.)

Scenario I: Instrumentation

- *Any prover has a life of its own.*
  Rules must be massaged and instrumented to tell
  an automated prover HOW a ruleset has to be used.

  - *Attributation of Signature elements:*

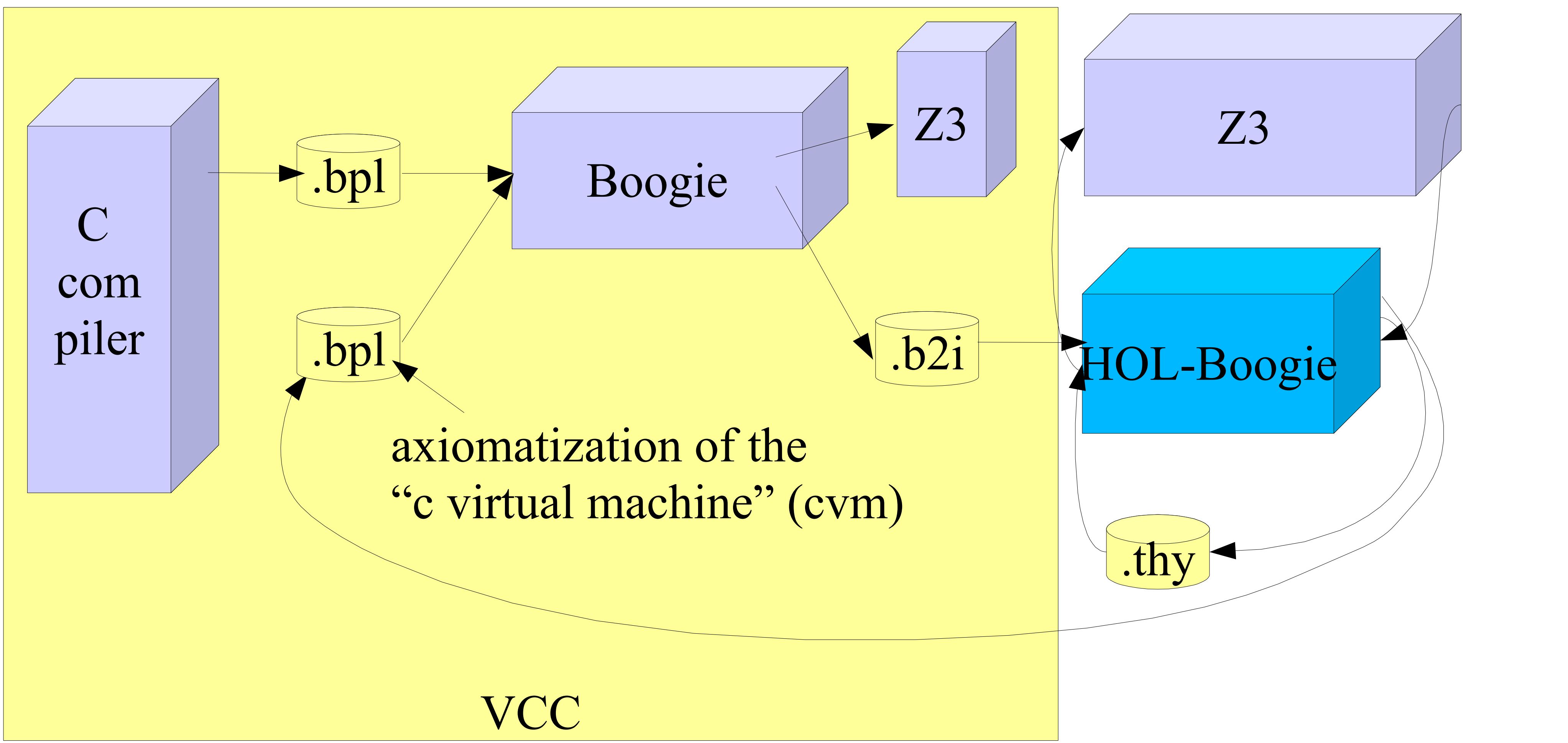
    ```
    axiom {prover:{isabelle:builtin"add_commute"}} ( ... )
    ```

  - Prover instrumentation:

    ```
    axiom {prover:{isabelle:intro!}} ( ... )
    axiom {:ignore "bvDefSem"} (forall x:int ::
    { $sign_extend.1.32($_int.to.bv32(x)[1:0]) }
        -$_bv64.to.int(1bv64) <= x && x < $_bv64.to.int(1bv64)
         ==> $sign_extend.1.32($_int.to.bv32(x)[1:0]) ==
                                      $_int.to.bv32(x));
    ```

Scenario II : Verifying C Programs

- Workflow: One further redirection step. And a complex memory/machine model.



Scenario II

- Example:

```
longint i = 0;

void incr()
requires i < maxint
ensures  i <= maxint
{
   (i++);
}
```

Scenario II

- Example:

```
const i_ptr :: ptr

procedure incr();
modifies mem
requires ($clt.u8($ld.u2(mem,i_ptr), maxint))
ensures  ($cle.u8($ld.u2(mem,i_ptr), maxint) &&
          modifiesOnly(mkSet(i_ptr)))

implementation incr(){
assumes($clt.u8($ld.u2(mem, i_ptr), maxint))

mem := $st.i8(mem, $add.i8($ld.i8(mem, i_ptr),1))

assert($cle.u8($ld.u2(mem, i_ptr), maxint) &&
       modifiesOnly(mkSet(i_ptr)))
}
```

Scenario II

- VCC or Spec# require:

  considerably large,
  axiomatic background theories on

  - memory models
  - machine operations (X86 VT)
  - specialized instrumentations on the prover side for each memory/machine model (actually, there is VCC1 and VCC2)

Scenario II

- Task:
  - HOL-Boogie as a generator of a consistent prelude, the "C-Virtual Machine".
  - Motivation: Providing a comprehensive Axiomatization of logics and its environment (State, Bitvectors, CVM)
    - for checking the consistency
    - for prover integration

Conclusion

- ITP techniques can provide an effective means to algorithmic verification in Boogie although the “Analyze&Fix”-cycle is substantially slower
- ITP techniques can provide explicit, comprehensive and consistent preludes for complex logical contexts. This helps to increase confidence into the approach.
- ITP's are still unavoidable in “real” Code-Analysis if algorithms, recursive data-structures, or deep arithmetic reasoning is involved.

⇒ Lots of Potential !!!

We proudly announce ...

- Journal Paper on the nitty-gritty details:

  Sascha Böhme, Michal Moskal, Wolfram Schulte and Burkhart Wolff: HOL-Boogie - An Interactive Prover-Backend for the Verified C Compiler. Accepted (with minor revisions) for the Journal of Automated Reasoning (JAR), Springer, 2009.

  see: http://www.lri.fr/~wolff/publications_year.html

Scenario II

- Let's do it: (it will take some time !!!)

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