Trustworthy Runtime Verification via Bisimulation (Experience Report)

Ryan Scott, Galois, Inc.
Mike Dodds, Galois, Inc.
Ivan Perez, KBR @ NASA Ames Research Center
Alwyn Goodloe, NASA Langley Research Center
Robert Dockins, Amazon

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Our secret: building on off-the-shelf formal methods, tools and libraries.

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We reduce the key steps of a bisimulation proof to a set of goals that can be discharged with an SMT solver.

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CopilotVerifier can verify all of the programs in the Copilot test suite, including an implementation of the *Well-Clear Violation* algorithm used in unmanned aircraft.

Copilot: a framework for writing monitors using runtime verification

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Originally developed by Galois and National Institute of Aerospace in 2010.

Copilot example

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fibs = [1, 1] ++ (fibs + drop 1 fibs)
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Copilot-C99

```c
int fibs[2] = {1, 1};
size_t fibs_idx = 0;

bool even_guard(void) {
  return (fibs[fibs_idx % 2] % 2) == 0;
}

void step(void) {
  if (even_guard()) {
    even(fibs[fibs_idx % 2]);
  }
  ...
  fibs[idx] = fibs_gen();
  fibs_idx = (fibs_idx + 1) % 2;
}
```

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≈?

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}
```

How do we know that Copilot-generated C code is *trustworthy*?

Option A: Audit the code by hand

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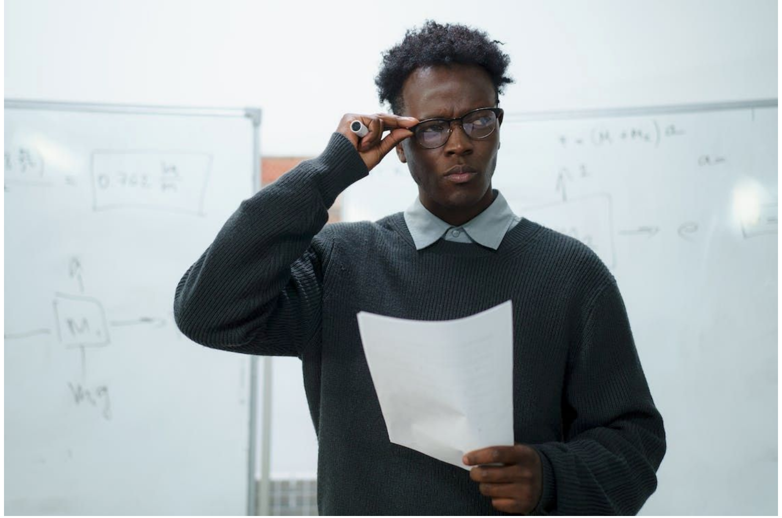
…but this is error-prone.



Free-to-use photo by cottonbro studio from Pexels

```
#include<stdio.h> #include<string.h>
main(){char*O,l[999]="'`acgo\177~|xp .
-\OR^8)NJ6%K4O+A2M(*OID57$3G1FBL";
while(O=fgets(l+45,954,stdin)){*l=O[
strlen(O)[O-1]=0,strspn(O,l+11)];
while(*O)switch((*l&&isalnum(*O))-!*l)
{case-1:{char*I=(O+=strspn(O,l+12)
+1)-2,O=34;while(*I&3&&(O=(O-16<<1)+
*I---'-')<80);putchar(O&93?*I
&8||!( I=memchr( l , O , 44 ) ) ?'?':
I-l+47:32); break; case 1: ;}*l=
(*O&31)[l-15+(*O>61)*32];while(putchar
(45+*l%2),(*l=*l+32>>1)>35); case 0:
putchar((++O ,32));}putchar(10);}}
```

Option B: Formally verify the Copilot compiler

Option B: Formally verify the Copilot compiler

…but this would require more time and budget than we had.

$$\forall C, \forall i, compile(C)(i) = semantics(C)(i)$$

Option C: Translation validation

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This is a weaker result than full compiler verification, but one that is more readily adaptable to existing compilers.

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CopilotVerifier overview

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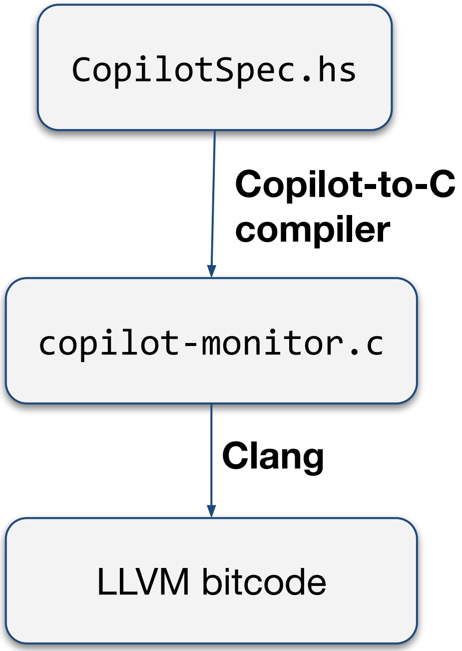
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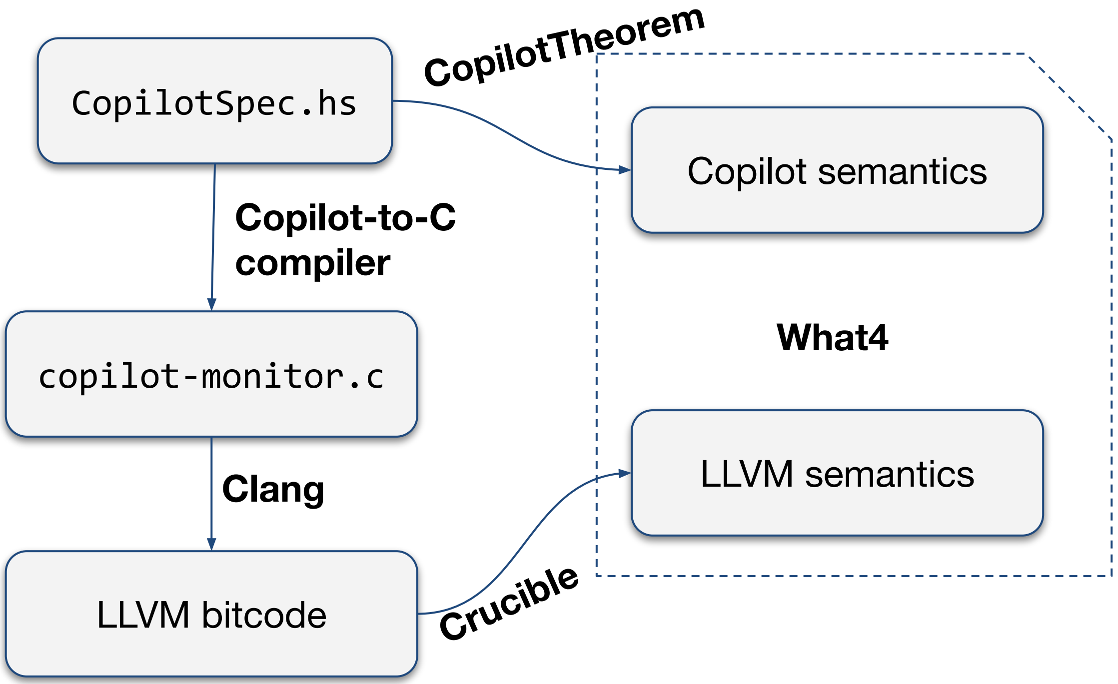
Copilot-to-C compiler
copilot-monitor.c
Clang
LLVM bitcode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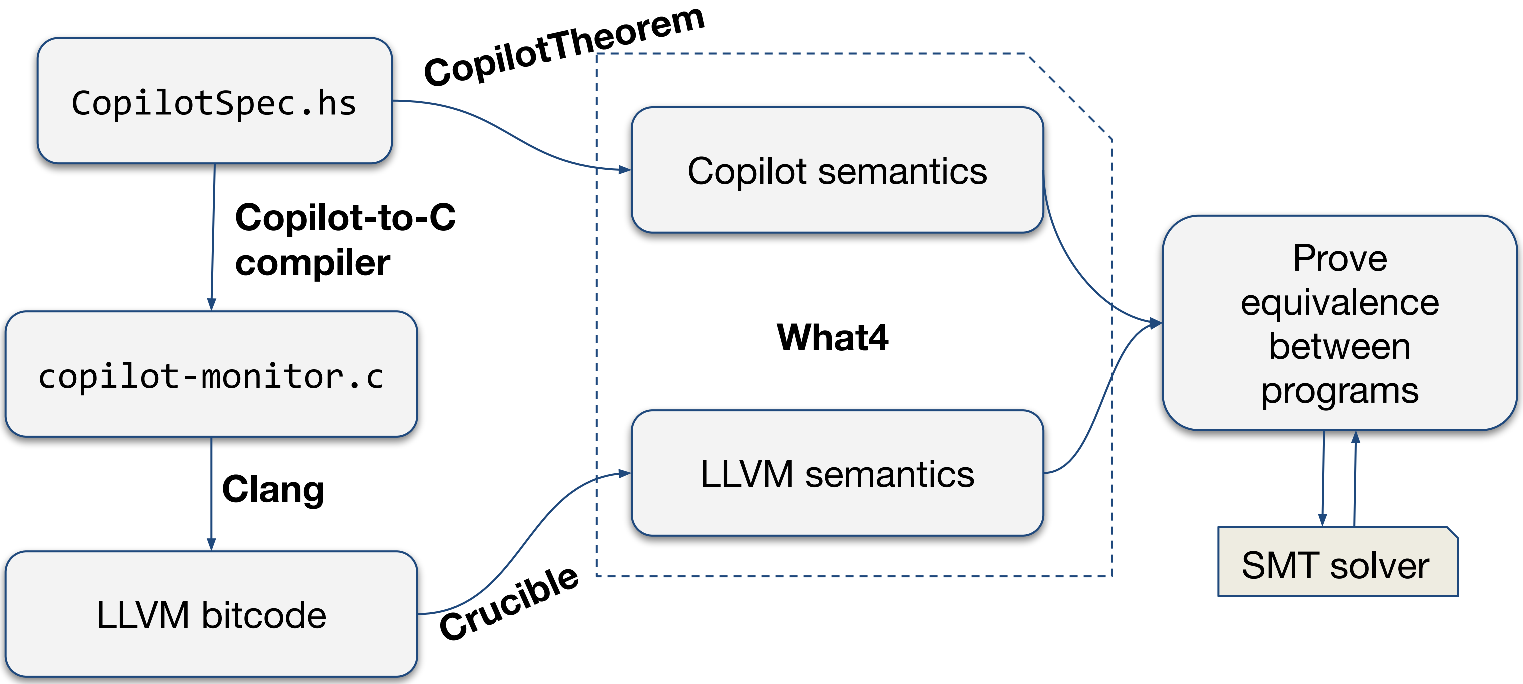
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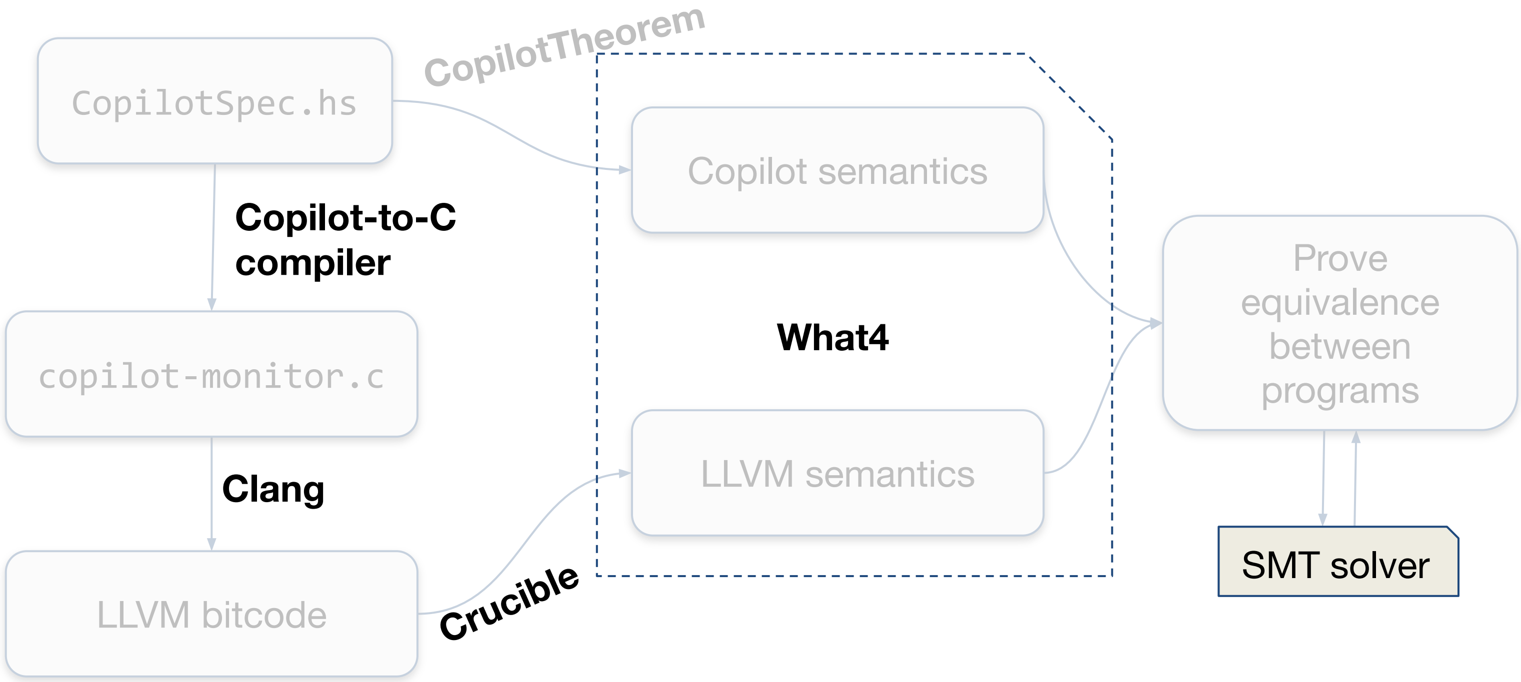
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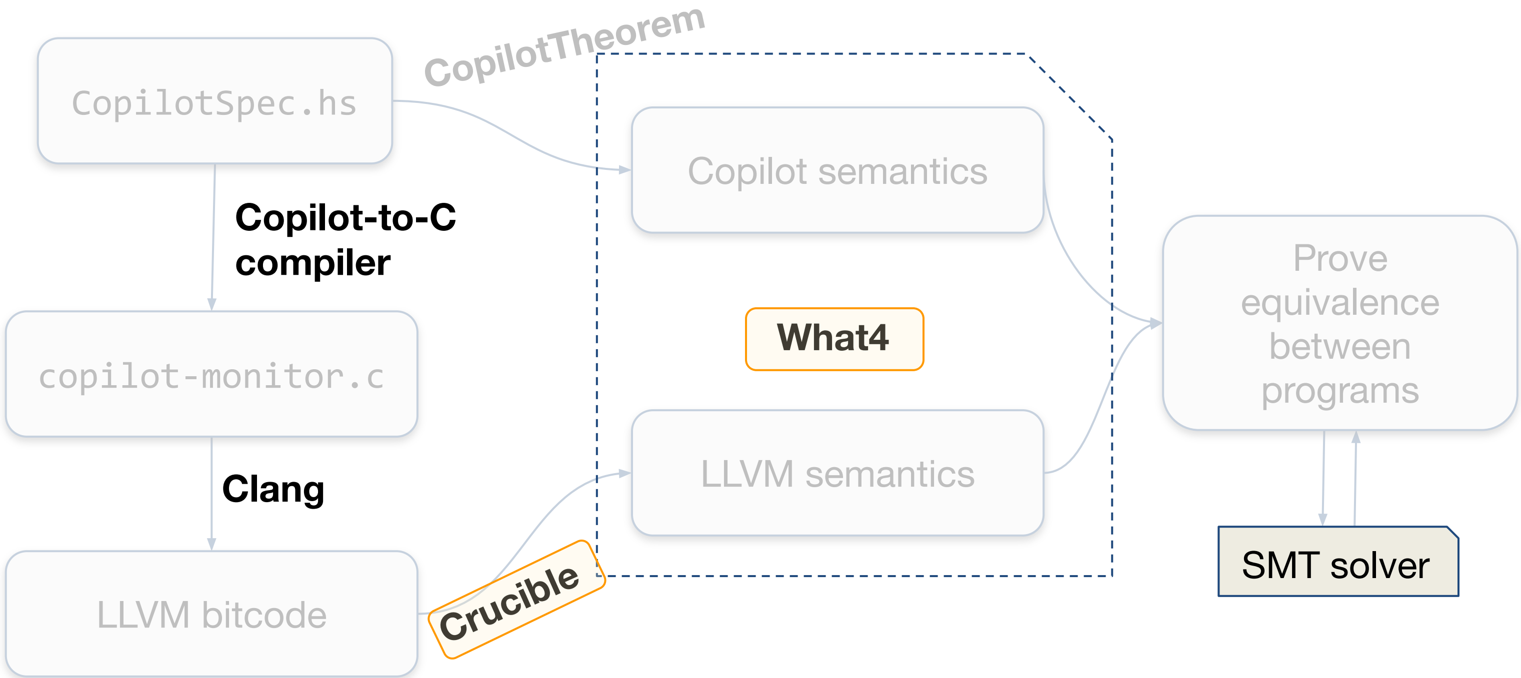

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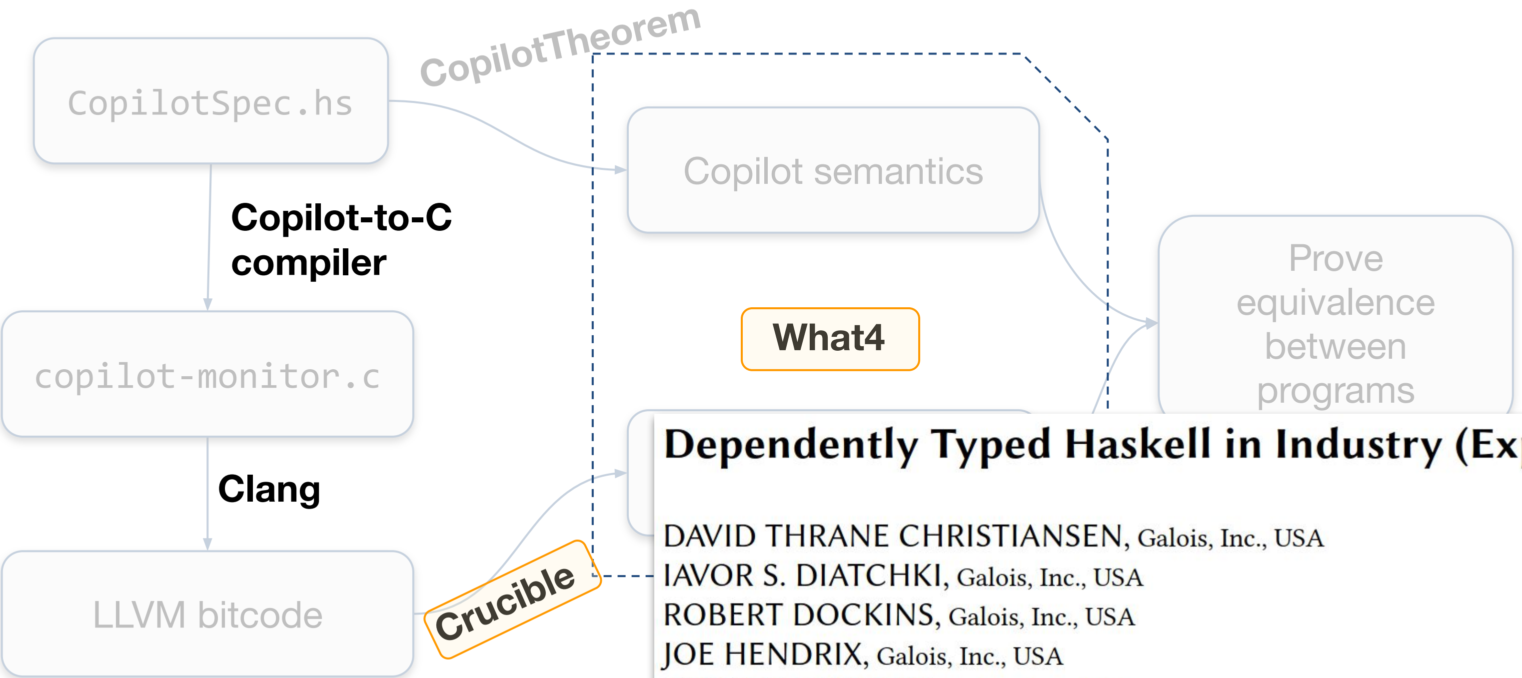
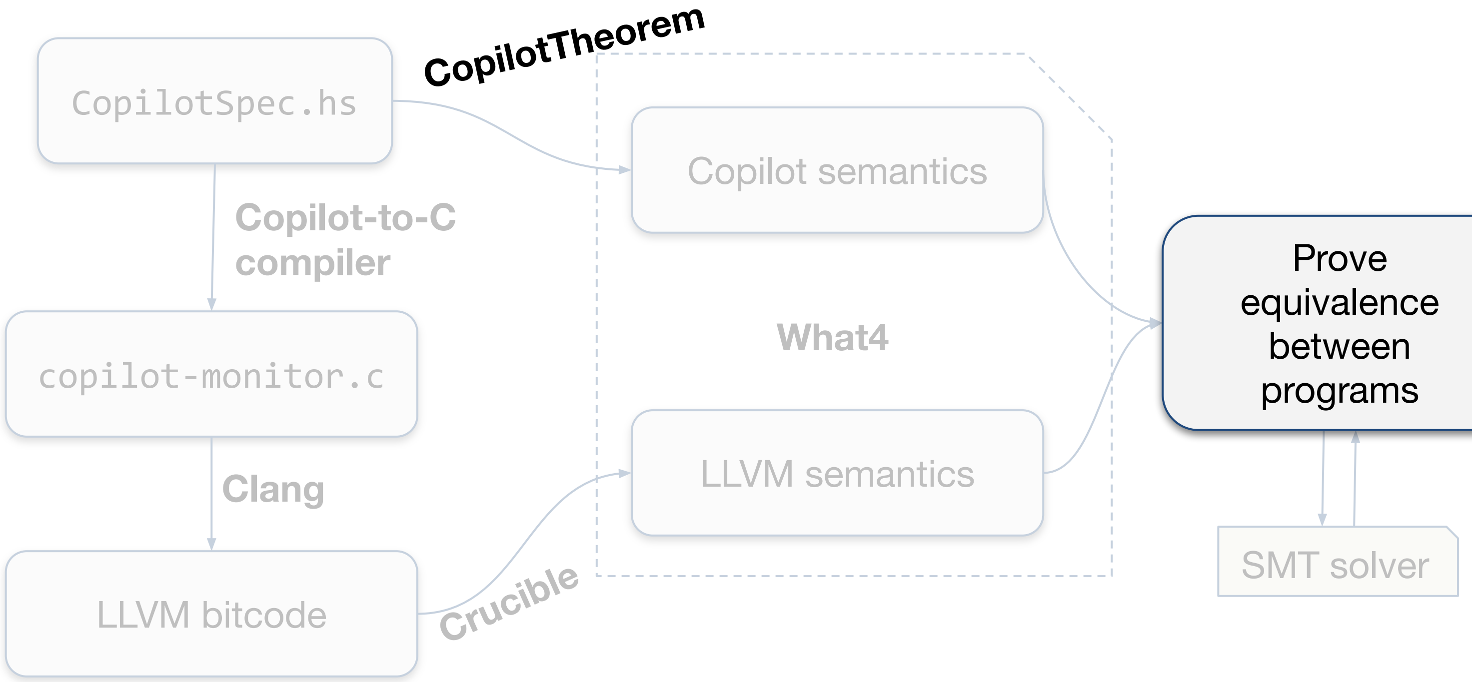


Dependently Typed Haskell in Industry (Experience Report)

DAVID THRANE CHRISTIANSEN, Galois, Inc., USA
IAVOR S. DIATCHKI, Galois, Inc., USA
ROBERT DOCKINS, Galois, Inc., USA
JOE HENDRIX, Galois, Inc., USA
TRISTAN RAVITCH, Galois, Inc., USA

Recent versions of the Haskell compiler GHC have a number of advanced features that allow many idioms from dependently typed programming to be encoded. We describe our experiences using this "dependently typed Haskell" to construct a performance-critical library that is a key component in a number of verification tools. We have discovered that it can be done, and it brings significant value, but also at a high cost. In this experience report, we describe the ways in which programming at the edge of what is expressible in Haskell's type system has brought us value, the difficulties that it has imposed, and some of the ways we coped with the difficulties.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Proving programs equivalent via bisimulation

We want to prove that a Copilot stream program and its corresponding C program are *extensionally equal*, i.e., at every time step:

- The same set of trigger functions are called in both programs with the same arguments
- The stream program crashes if and only if the C program crashes

Proving programs equivalent via bisimulation

We prove extensional equality by:

1. Representing each program as a labelled transition system (LTS)

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1. Representing each program as a labelled transition system (LTS)
2. Generating verification conditions to show the two LTSs are extensionally equal at a given time step

Goal 1: even trigger fires in both programs

```
(declare-fun s0_idx () (_ BitVec 64))
(define-fun x!0 () (_ BitVec 64) (bvadd s0_idx (_ bv4 64)))
(define-fun x!1 () (_ BitVec 64) (bvurem x!0 (_ bv5 64)))
(define-fun x!2 () (_ BitVec 64) (bvmul (_ bv4 64) x!1))
...
```

Goal 2: ...

...

Goal 3: ...

...

Proving programs equivalent via bisimulation

We prove extensional equality by:

1. Representing each program as a labelled transition system (LTS)
2. Generating verification conditions to show the two LTSs are extensionally equal at a given time step
3. Check verification conditions with SMT solver

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Goal 2: ...

...

Goal 3: ...

...

More in the paper

- Handling floating-point operations (e.g., `sin`/`cos`) with SMT solvers
- How CopilotVerifier presents proof evidence for certification
  - Certification is a human-driven process, so we must produce evidence suitable for human auditors

Next steps

- Copilot has been released as Class D, open-source software at NASA

- Plan to use CopilotVerifier as part of safety cases for Class C NASA missions involving Copilot monitors

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Thank you!

Backup slides

Handling floating-point ops with SMT solvers

- CopilotVerifier treats all floating-point operations (arithmetic, `sin`/`cos`, etc.) as uninterpreted functions at the SMT level
- This works, but it is brittle: the order of floating-point operations must be the exact same in both the stream and C programs
- For instance, these two stream expressions are *not* equivalent:

```
constantF :: Float -> Stream Float
```

```
constantF (150.0 / 255.0)
```

↓

```
0.5882353f
```

```
constantF 150.0 / constantF 255.0
```

↓

```
150.0f / 255.0f
```