galois

Developing Tools for Formal Specification and Verification

Ryan Scott
AmeriHac

February 2026

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Way-too brief history of Haskell use at Galois

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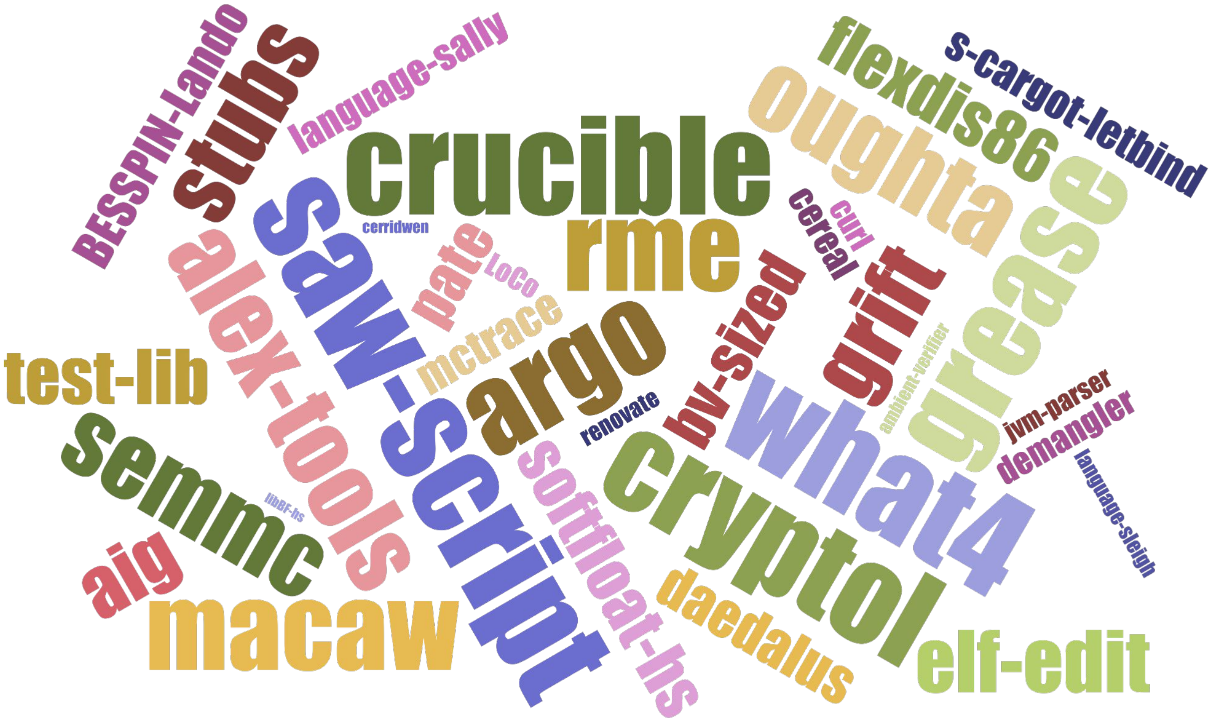
Way-too brief history of Haskell use at Galois

- We have been using Haskell since company's founding (1999).
- Cryptol (one of our first major tools) first publicly released in 2008, later released as open-source in 2014.
- Many formal verification tools and libraries, including SAW (2012), Crucible (2013), and What4 (2013), are written in Haskell.

Galois uses Haskell in *many* projects



Formal Specification and Verification

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- **Formal** specification: mathematically rigorous design techniques (logic, type systems, etc.)

- **Formal verification**: mathematically proving that a system’s implementation conforms to its specification

Formal Specification

Specifying program behavior using Cryptol

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pairOfBitvectors : ([8], [16])
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pairOfBitvectors : ([8], [16])
pairOfBitvectors = (255, 65535)

flipAllBits : [8] -> [8]
flipAllBits bits = map complement bits
```

Executing Cryptol specifications

Executing Cryptol specifications

```
Cryptol> flipAllBits 0
255

Cryptol> flipAllBits 255
0

Cryptol> flipAllBits 127
128
```

Proving properties about Cryptol specifications

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```
Cryptol> :prove \(x : [8]) ->
    flipAllBits (flipAllBits x) == x
Q.E.D.
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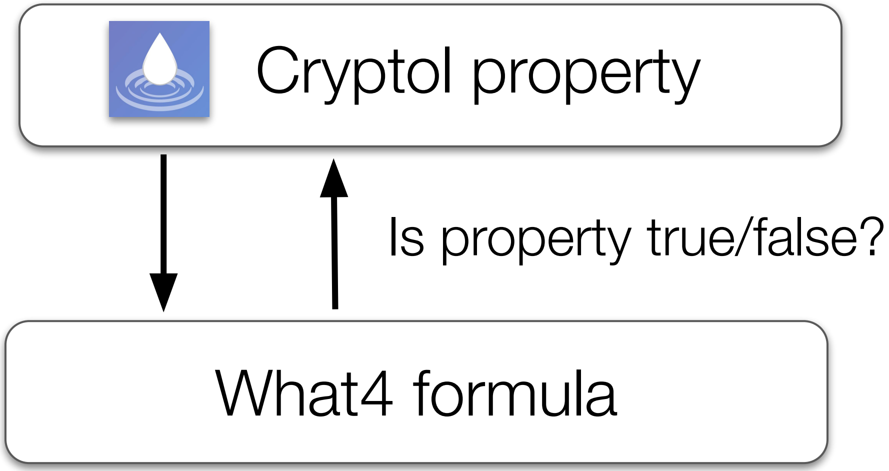
Counterexample
(\(x : [8]) -> flipAllBits x == x) 0x00 = False
```

Talking to SMT solvers using What4

- To prove Cryptol properties, we translate Cryptol code into an intermediate language called What4



Talking to SMT solvers using What4

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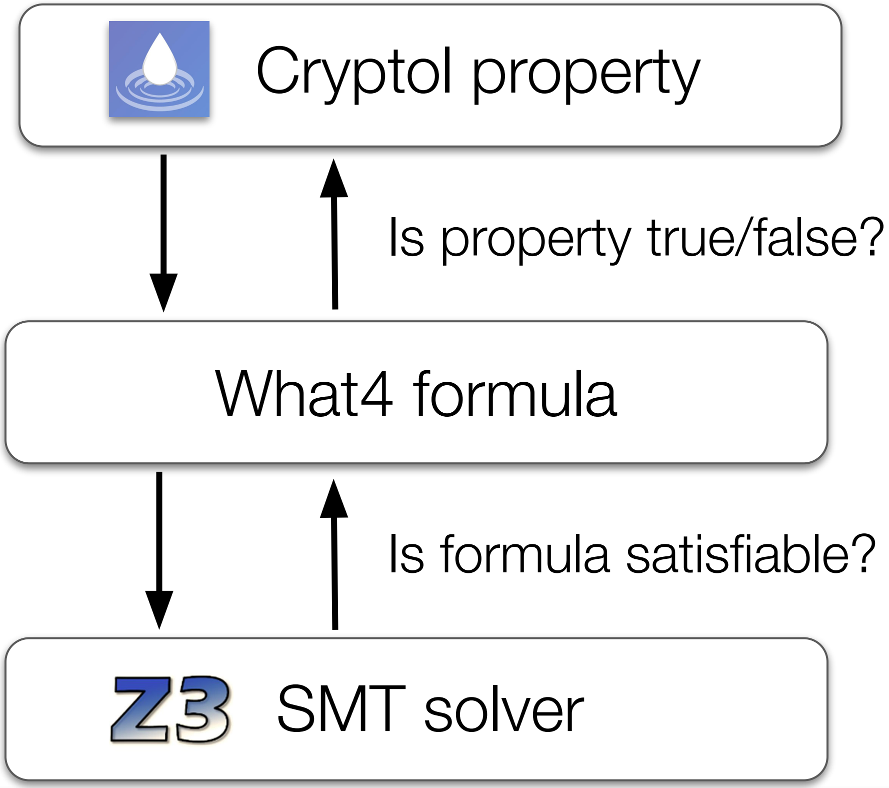
- What4 can easily be compiled into formulas that SMT solvers (e.g., Z3) can check for satisfiability



Design choice: *how* to talk to SMT solvers

Two competing options for how to communicate with SMT solvers:

1. Invoke SMT solver binaries as subprocesses (using Haskell's `process` library)
2. Use SMT solvers' C APIs (via Haskell's FFI)

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What4 picks option (1).

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Design choice: when *not* to use Haskell

Cryptol and What4 both depend on an external C library (LibBF) to handle arbitrary-precision floating-point arithmetic.

Why:

- It's a very mature library: not many updates required
- It's a very small library: easy to ship in a self-contained Haskell package without users needing to install external C libraries

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- What4 is written in a very different style of Haskell (lots of GADTs, type families, fancy type system features, etc.)
- Written with the goal of making SMT formulas type-correct by construction

Cryptol Haskell code

What4 Haskell code

Cryptol Haskell code

```
data Type
  = TCon !TCon ![Type]
  | TVar TVar
  | TUser !Name ![Type] !Type
  | TRec !(RecordMap Ident Type)
  | TNominal !NominalType ![Type]
```

What4 Haskell code

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```

What4 Haskell code

```haskell
data BaseTypeRepr (bt :: BaseType) :: Type where
   BaseBoolRepr :: BaseTypeRepr BaseBoolType
   BaseIntegerRepr :: BaseTypeRepr BaseIntegerType
   BaseRealRepr :: BaseTypeRepr BaseRealType
   BaseBVRepr ::
     (1 <= w) =>
     !(NatRepr w) ->
     BaseTypeRepr (BaseBVType w)
   BaseFloatRepr ::
     !(FloatPrecisionRepr fpp) ->
     BaseTypeRepr (BaseFloatType fpp)
   …
```

HFCS

HFCS (Haskell fancy code spectrum)

Simple
(Haskell2010)

Fancy
(many language extensions)

HFCS (Haskell fancy code spectrum)

Formal Reasoning

The challenge

How do we take popular imperative programming languages (C, Rust, Java, etc.) and reason about them *formally*?

Crucible

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- *Symbolic*: keeps program inputs abstract, enabling reasoning about multiple paths through a program simultaneously.

- *Execution*: interprets (simulates) a program, producing mathematical representations (What4) of the program as output.

Typical Crucible workload

Imperative program

```
uint32_t f(uint32_t a[2], uint64_t idx) {
  return a[idx];
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Program output

```
\(a : Vector Bv32) (idx : Bv64) ->
    arrayIndex a idx
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Crucible

What4

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\(a : Vector Bv32) (idx : Bv64) ->
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Side conditions

```
0 <= idx && idx < 2
```

Crucible’s flavor of Haskell

Crucible’s Haskell style is largely inspired by What4 (lots of GADTs)

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Simulating C using Crucible

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- Crucible has an LLVM backend (Crucible-LLVM) that symbolically executes the LLVM code.

- This means that we have to be able to ingest arbitrary LLVM code, which imposes some technical challenges.

Design choice: interfacing with LLVM in Haskell

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- Pros: offloads the task off to LLVM itself.
- Cons: vastly complicates the packaging story (LLVM is a large dependency), and LLVM libraries for Haskell aren’t very well maintained.

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We chose this option and wrote our own library.

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We picked option (3).

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- We then parse the JSON code into Crucible and symbolically execute it.

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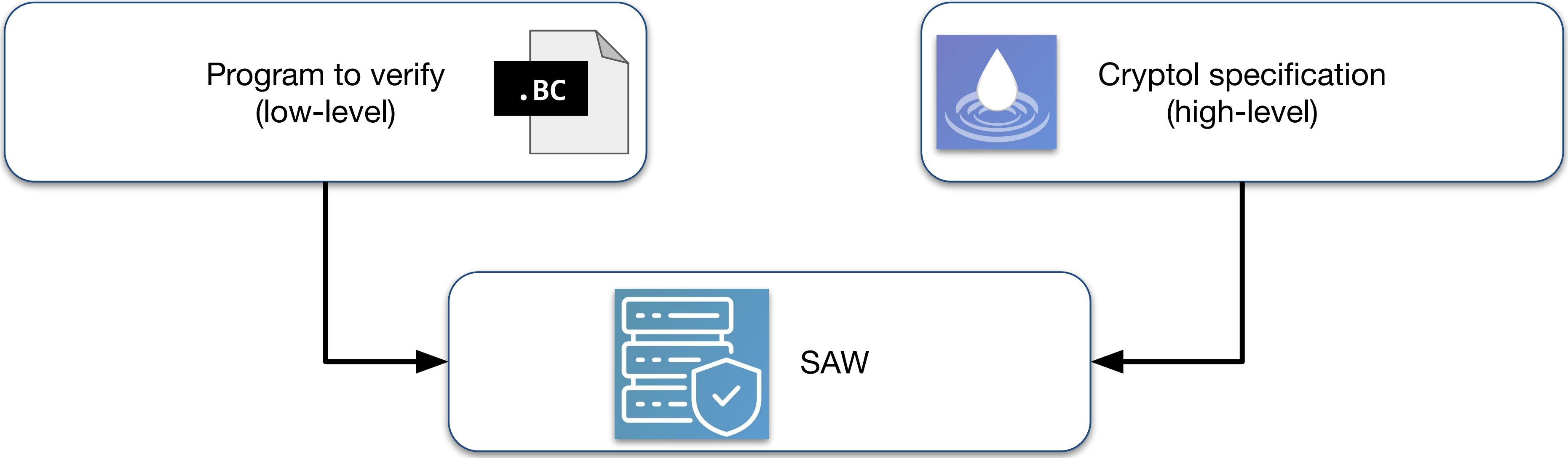
- Unlike with LLVM, where maintenance revolves around supporting new bitcode features, maintaining MIR support revolves around keeping a compiler plugin up to date.

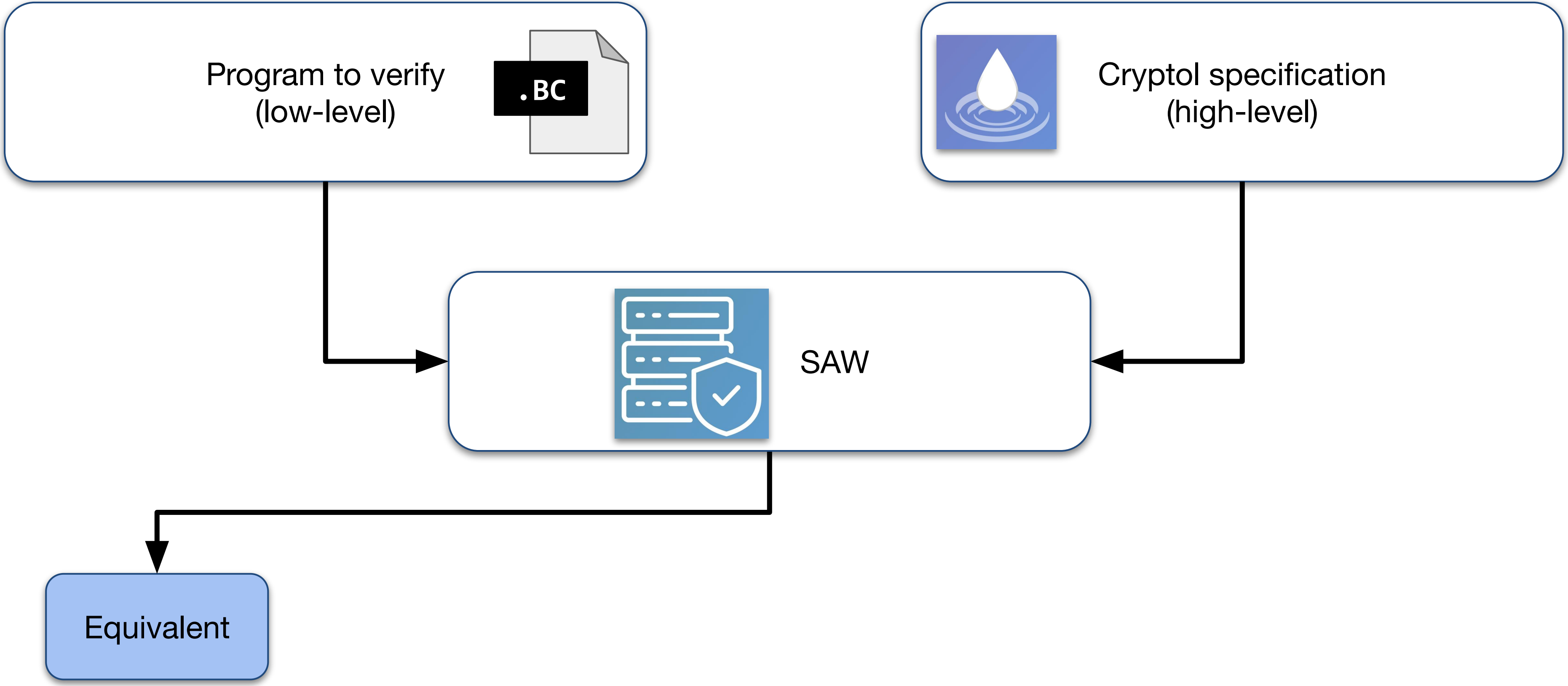
- We generally like to maintain Haskell code for ingesting other languages, but maintaining code in other languages (e.g., Rust) can also work.

Formal Verification
(matching programs with specifications)

Verifying code against specs using SAW

SAW (Software Analysis Workbench) is a tool for formally verifying properties of imperative code (using Crucible) against high-level Cryptol specifications.


Program to verify
(low-level)
.BC
Cryptol specification
(high-level)
SAW


Program to verify
(low-level)
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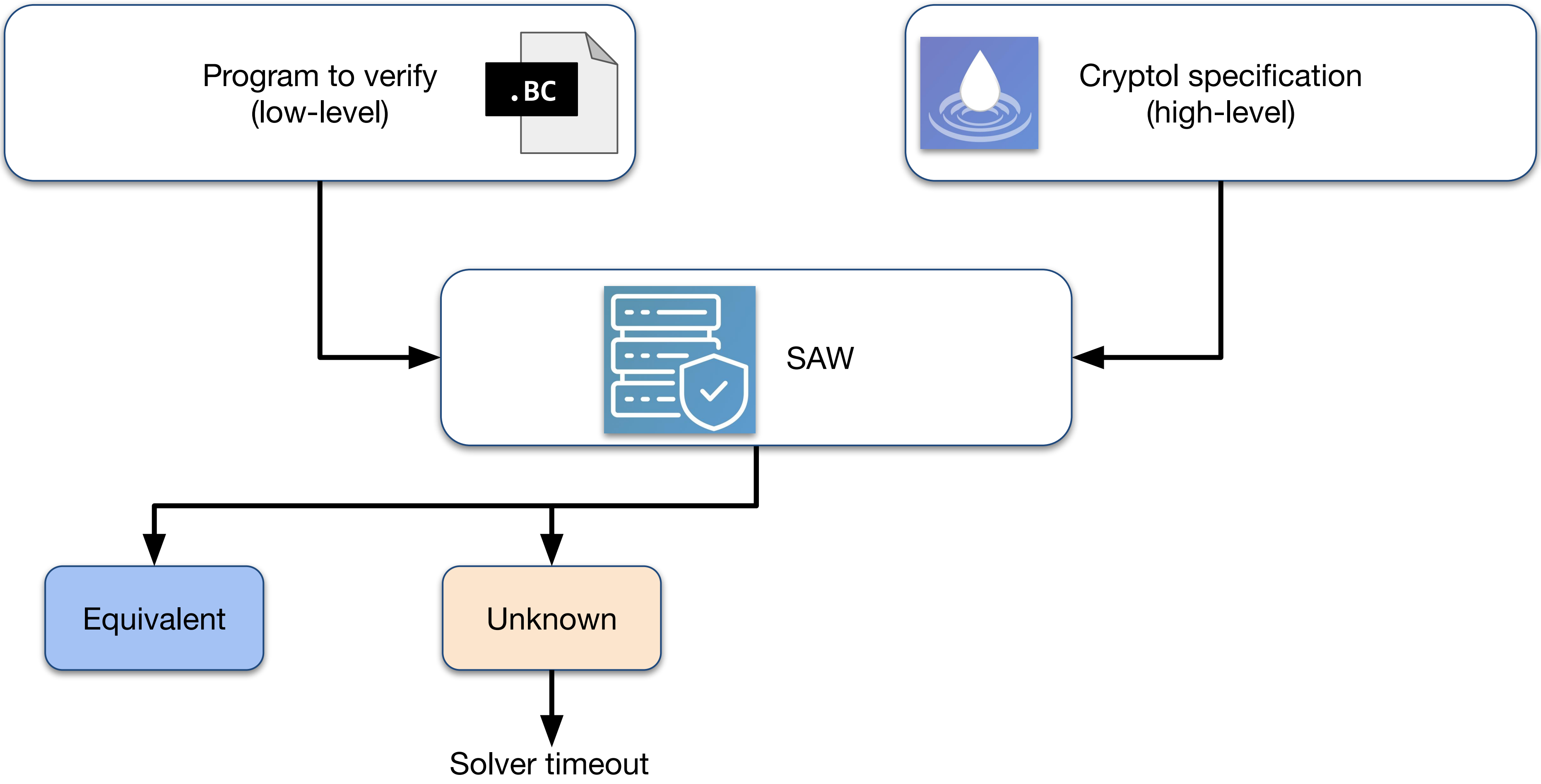
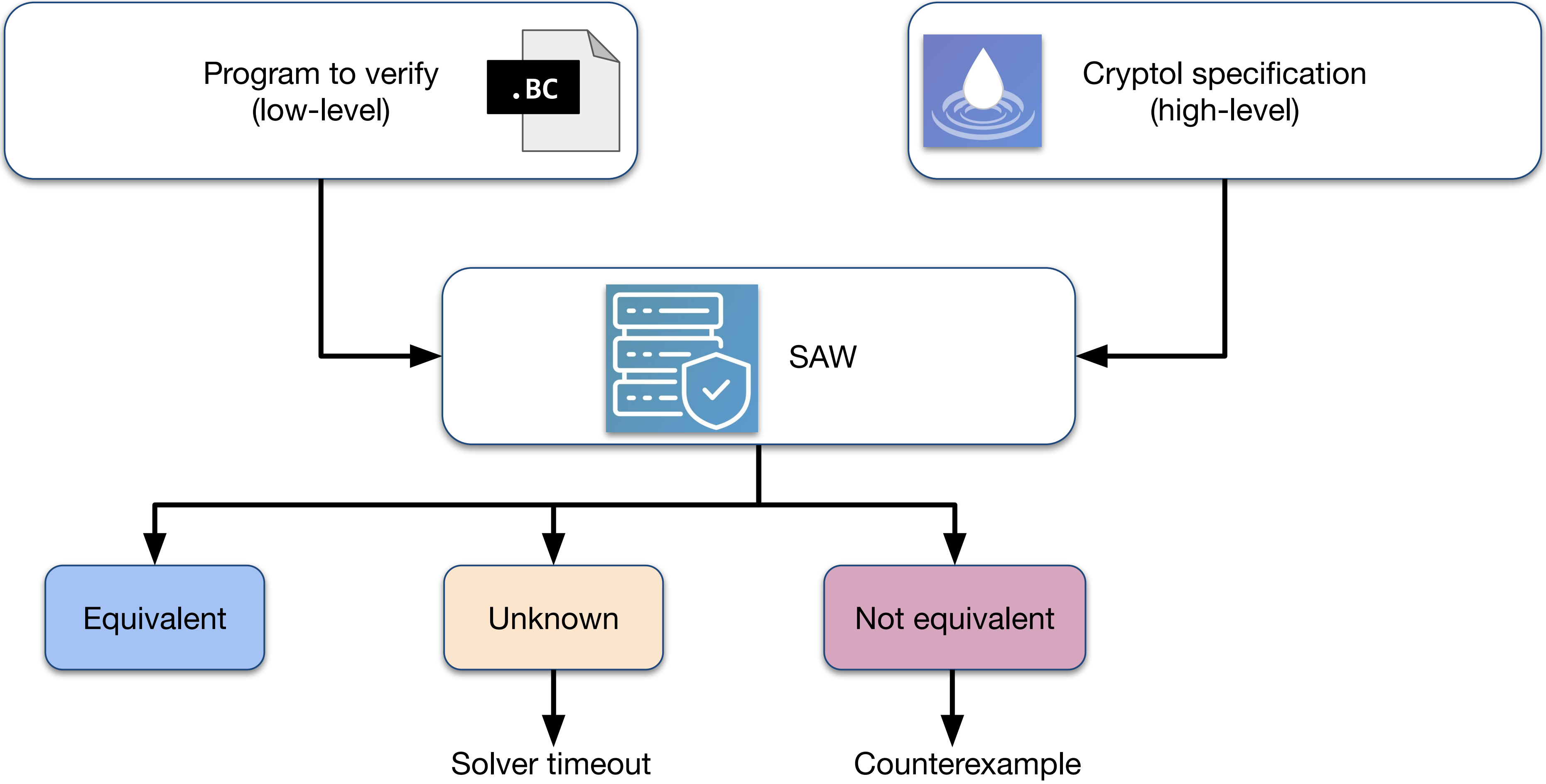
Equivalent


Program to verify
(low-level)
.BC
Cryptol specification
(high-level)
SAW
Equivalent
Unknown
Solver timeout


Program to verify
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Equivalent
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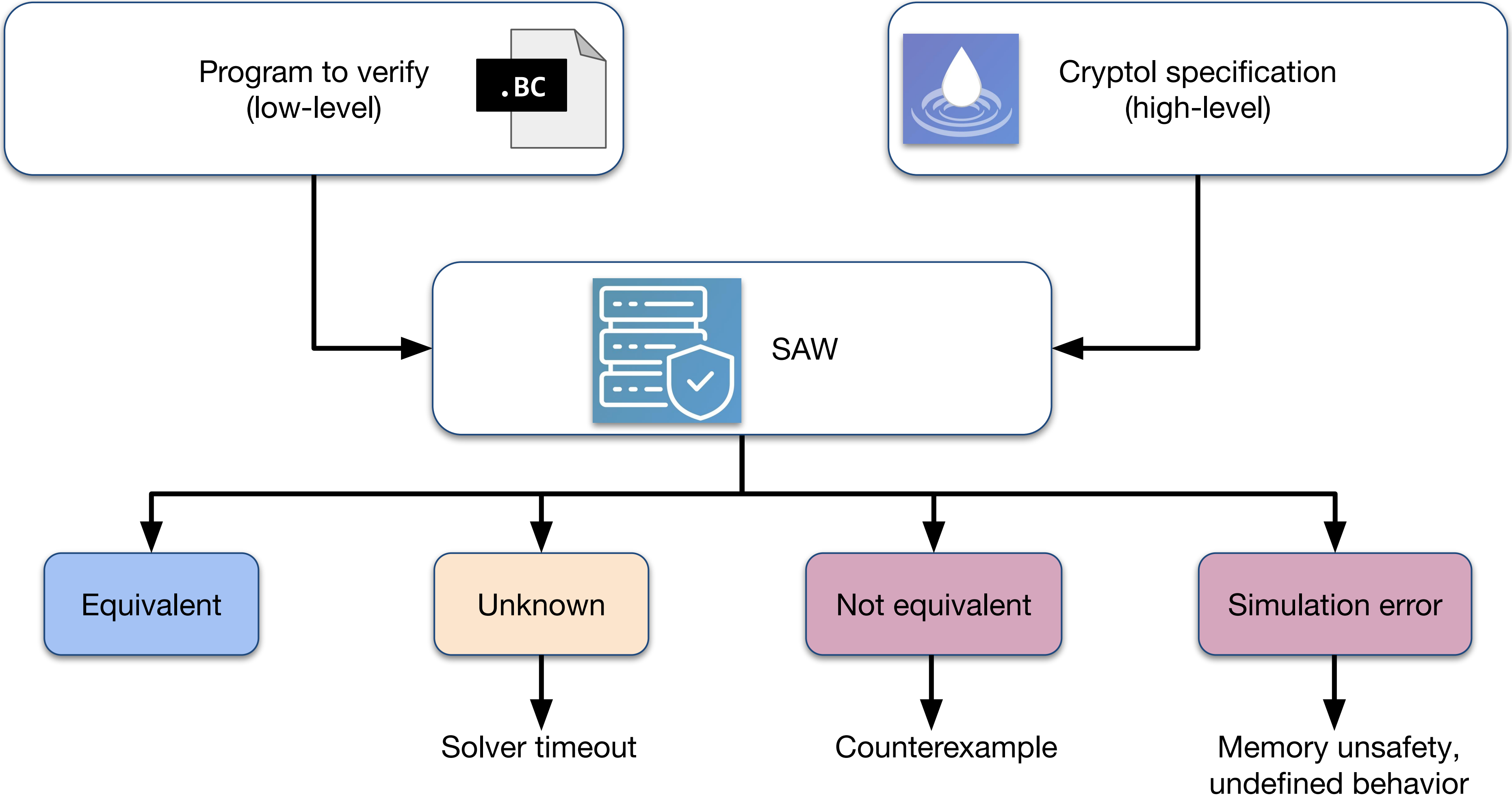
Not equivalent
Solver timeout
Counterexample


Program to verify
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(high-level)
SAW
Equivalent
Unknown
Not equivalent
Simulation error
Solver timeout
Counterexample
Memory unsafety,
undefined behavior

SAW's flavor of Haskell

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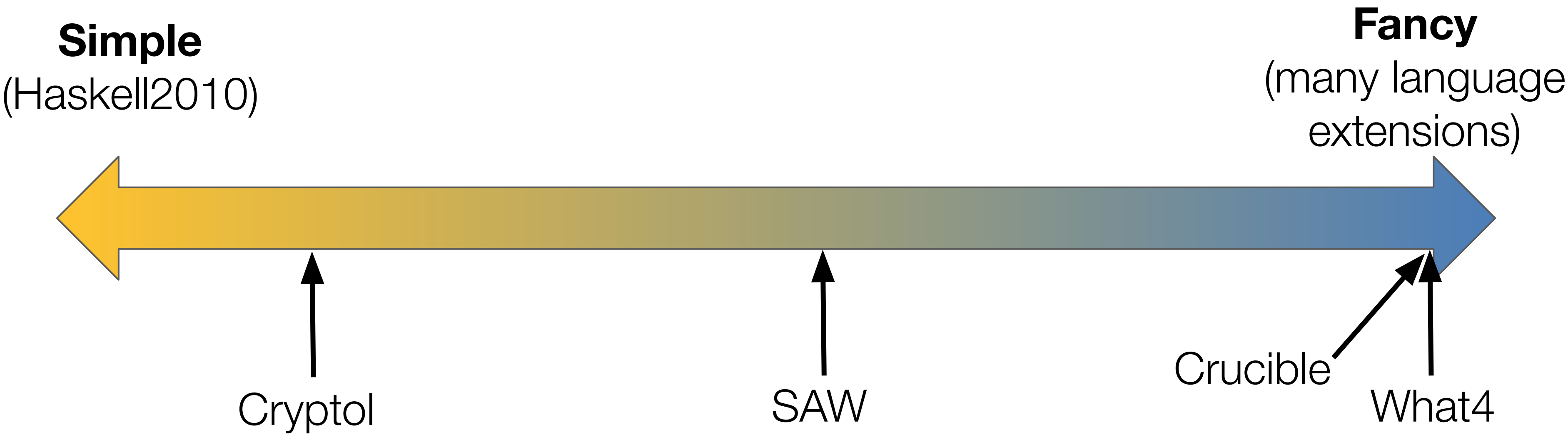
SAW's uses a mix of simple and fancy Haskell styles.



Reflections on industrial use of Haskell
(Here come the hot takes!)

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dependent types in

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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- This greatly increases our confidence about the correctness of our code, even after performing large-scale refactors.

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- Fancy Haskell code is more likely to trigger GHC bugs!

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- Code coverage (`hpc` is clunky, and achieving 100% code coverage is more difficult than it ought to be).
- Documentation: Haddock is surprisingly slow on large projects, has some unintuitive default settings.
- Minimizing GHC bugs: I wish there was something like CReduce for GHC.

Not-so-hot takes

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- Haskell is a great language for developing tooling for specification and verification!
- We aren’t afraid to use other languages in our tech stack if it makes more sense to use them.
- We err on the side of simple Haskell, but we may reach for fancy Haskell features if correctness is paramount.

Any questions?

Links to some Haskell-based tools we maintain:

`https://tools.galois.com/cryptol`

`https://tools.galois.com/saw`