Proving Functional Correctness with the Software Analysis Workbench

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What is SAW?

• SAW = Software Analysis Workbench
  – Software: many languages
  – Analysis: many types of analysis, focused on functionality
  – Workbench: flexible interface, supporting many goals

• What separates it from other systems?
  – One view: compiler :: imperative code → functional code
  – Captures all functional behavior, simplifying later if necessary
  – Uses efficient internal representations tuned to equivalence checking
  – Strong bit vector reasoning support
  – Focus on practicality over novelty

• Open source (BSD3) and available now
Current Capabilities

- Imperative to functional translation for programs that:
  - Have only *bounded* iteration
  - Have *size-bounded* inputs, outputs, and heap use
- Supports JVM, LLVM, and Cryptol (a DSL designed for cryptography)
- Translation to SAT or SMT to do things such as:
  - Prove two implementations *equivalent* (useful for *regression* verification)
  - Prove *relations* between inputs and outputs
  - Find *inputs* that lead to outputs with given properties
- Concrete execution and random testing
- User-guided rewriting
Example: Find First Set

```c
uint32_t ffs_ref(uint32_t word) {
    if (!word) return 0;
    for (int c = 0, i = 0; c < 32; c++)
        if (((1 << i++) & word) != 0)
            return i;
    return 0;
}
```

```c
uint32_t ffs_imp(uint32_t i) {
    char n = 0;
    if (!(i & 0xffff)) { n += 1; i >>= 16; }
    if (!(i & 0xff00)) { n += 8; i >>= 8; }
    if (!(i & 0x0f00)) { n += 16; i >>= 8; }
    if (!(i & 0x000f)) { n += 32; i >>= 4; }
    return (i) ? (n + ((i + 1) & 0x1)) : n;
}
```

- Reference implementation
- Easy to understand
- Inefficient

- Optimized implementation
- Hard to understand
- Faster
- Identical functionality
Demo of FFS Verification
Verification of HMAC in s2n

• Amazon’s open source implementation of TLS
• Verified C implementation of HMAC against Cryptol spec
  – ~15 LOC in Cryptol (high-level spec)
  – ~300 LOC in C (from official s2n repository)
  – ~400 LOC of script (all plumbing; likely smaller in the future)
• Proofs for various fixed message sizes
• Proof integrated into Travis build, running on every commit
  – Build and standard test: ~3-25 minutes
  – Proof for each hash algorithm: ~4-7 minutes
• Related: proof of OpenSSL's HMAC using VST (Coq)
  – Beringer, Petcher, Ye, Appel (2015)
  – SAW proof is more automated, less foundational
Demo of HMAC Integration
What Kinds of Code Work Well?

- Termination is guaranteed after a fixed number of iterations
  - SAW unrolls loops and recursion
- Inputs and outputs are fixed size (specific number of bits)
  - Pointers can exist, but layout needs to be known
- Code consists of pure computation
  - Any I/O or non-local control flow needs to be axiomatized
- A specification exists
  - Either a complete functional spec or a property
- You care about precise details of computations (bit-level reasoning)
  - Other tools more efficient for, e.g., proving memory safety
- Domains such as cryptography, serialization, signal processing
Summary

• SAW is a powerful tool for precise and flexible software analysis
  – Especially focused on equivalence checking
  – Supports automated reasoning with SAT/SMT
  – Uses Cryptol for high-level specifications
  – Can verify implementations in JVM, LLVM

• Focused on finite programs for now, with plans for generalization

• Many real-world case studies, mostly from cryptography
  – HMAC from s2n
  – BSM parser for V2V
  – AES from OpenSSL
  – Many others

• Available now as open source: https://saw.galois.com
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Resources

• Cryptol
  – Web: https://cryptol.net
  – GitHub: https://github.com/GaloisInc/cryptol

• SAW
  – Web: https://saw.galois.com
  – GitHub: https://github.com/GaloisInc/saw-script

• HMAC verification