Continuous Verification of Critical Software

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Agenda

SAW Basics (Session A: 1:30 – 3:00)

- Installation and configuration
- How to think about verification
- Basic overview of SAW
- More general use of SAW

Advanced Use and CI (Session B: 3:30 – 5:00)

- Compositional verification
- Advanced proof techniques
- Build integration and CI
- Examples from s2n

Installing SAW

- Option 1: manual installation
  - LLVM + Clang: http://releases.llvm.org/download.html (most versions work, including those from Xcode)
  - Yices: http://yices.csl.sri.com/ (most tested with v2.6.0)
  - Z3: https://github.com/Z3Prover/z3/releases/tag/z3-4.7.1
  - SAW: https://saw.galois.com/builds/nightly/ (tested with 2018-08-26)
- Option 2: Docker container
  - `docker pull atomb/secdev18-saw`
  - `docker run --rm -it atomb/secdev18-saw`
- Also, check out examples and slides
  - git clone https://github.com/atomb/secdev18-saw

What is SAW?

- A tool to construct models of program behavior
  - Works with **C (LLVM)**, Java (JVM), and others in progress
  - Supports high-level specifications in the **Cryptol** language
- Models can then be proved to have certain properties
  - Equivalence with specifications
  - Guarantees to return certain values
- Proofs generally done using automated reasoning tools
  - Uses symbolic execution plus SAT/SMT
  - Similar level of effort to testing
  - Automatically repeatable once configured; great for CI

Thinking About Verification

Property Based Testing

- Rather than testing individual cases, state general properties
- For example, this function should always return a non-zero value:

```
int add_commutes(uint32_t x, uint32_t y) {
    return x + y == y + x;
}
```

- Then can test those properties on specific values
  - Manually selected
  - Randomly generated
- The QuickCheck approach is a common implementation of this paradigm

XOR Swap Example

- Say we're using the XOR-based trick for swapping values:

```
void swap_xor(uint32_t *x, uint32_t *y) {
  *x = *x ^ *y;
  *y = *x ^ *y;
  *x = *x ^ *y;
}
```

- Focus on values, since that's where the tricky parts are
    - Pointers used just so it can be a separate function

(See `xor-swap.c`.)

A Specification for Swapping

```c
void swap_direct(uint32_t *x, uint32_t *y) {
  uint32_t tmp;
  tmp = *y;
  *y = *x;
  *x = tmp;
}

int swap_correct(uint32_t x, uint32_t y) {
  uint32_t x1 = x, x2 = x, y1 = y, y2 = y;
  swap_xor(&x1, &y1);
  swap_direct(&x2, &y2);
  return (x1 == x2 && y1 == y2);
}
```

Manual Swap Testing

```
int main() {
  assert(swap_correct(0, 0));
  assert(swap_correct(0, 1));
  assert(swap_correct(32, 76));
  assert(swap_correct(0, 0xFFFFFFFF));
  assert(swap_correct(0xFFFFFFFF, 0xFFFFFFFF));
  return 0;
}
```

- Advantages
  - Ensures that you will always test important values
  - Carefully chosen tests can cover many important cases quickly
- Disadvantages
  - May miss classes of inputs that you didn't think of
  - Hard to get high coverage of a large input space

Random Swap Testing

```
int main() {
  for(int idx = 0; i < 100; i++) {
    uint32_t x = rand();
    uint32_t y = rand();
    assert(swap_correct(x, y));
  }
  return 0;
}
```

- Advantages
  - Better theoretical coverage of input space
  - Number of tests limited only by available processing power
- Disadvantages
  - May miss important inputs that are easy to identify by hand
  - Non-deterministic: different runs may have different results

Translating Programs to Pure Functions

- Pure function: equal arguments go to equal results
- $\lambda x.\ x + 1$ takes an argument x, and returns $x + 1$
- Translation achieved in SAW using a technique called symbolic execution
  - Think: an interpreter with expressions in place of values
  - Every variable's value at the end is an expression representing all possible values it might take
- `swap_direct`: $\lambda(x, y).\ (y, x)$
- `swap_xor`: $\lambda(x, y).\ (x \oplus y \oplus x \oplus y \oplus y, x \oplus y \oplus y)$
  - but $x \oplus x \equiv 0$, $x \oplus 0 \equiv x$, and $x \oplus y \equiv y \oplus x$

SAT and SMT Solvers

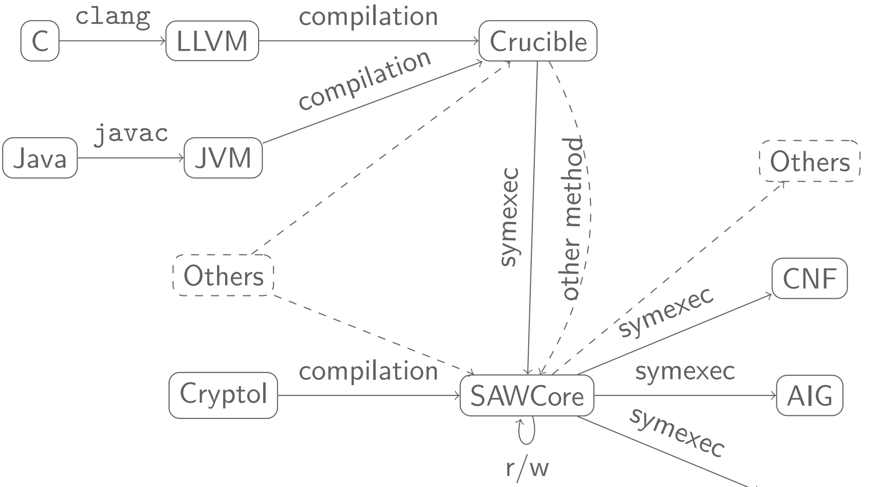
- Automated provers for mathematical theorems
  - Such as: $\forall x, y.\ (x \oplus y \oplus x \oplus y \oplus y, x \oplus y \oplus y) \equiv (y, x)$
- SAT = Boolean SATisfiability. Can encode:
  - Fixed-size bit vectors (even multiplication, but slowly)
  - Arrays of fixed sizes
  - Conditionals
- SMT = Satisfiability Modulo Theories. Adds things like:
  - Linear arithmetic on integers
  - Arrays of arbitrary size
  - Uninterpreted functions

Automated Verification vs. Testing

- Advantages
  - Ensures that you will test all possible input values
  - Sometimes faster than testing
- Disadvantages
  - Practical for a smaller class of programs than testing
  - Sometimes much slower than testing

Basics of SAW

The Components of SAW



Generating LLVM Bitcode for SAW

- SAW supports C through LLVM
- The Clang compiler translates C source to LLVM “bitcode”
- Basic use, to produce `file.bc`:

```
clang -c -emit-llvm file.c
```

- Use `llvm-link` to combine bitcode files
- For large, complex projects, `wllvm` is convenient. For example:

```
CC=wllvm CXX=wllvm++ ./configure && make
```

- Get `wllvm` here:
  https://github.com/travitch/whole-program-llvm

SAWScript

- Language used to control behavior of SAW
- Not a general-purpose language
  - Basic mechanism for combining built-in functions
- Statically typed with Haskell-style `do` notation
- The `Term` type represents SAWCore models
- Uses special quoting, between `{{` and `}}`, for Cryptol expressions
- Any value in scope with type `Term` is visible in Cryptol

Verifying Swap Correctness

```
// Load the bitcode file generated by Clang
m <- llvm_load_module "swap-correct.bc";

// Extract a formal model of `swap_correct`
model <- llvm_extract m "swap_correct" llvm_pure;

// Use the ABC prover to show it always returns non-zero
thm <- prove_print abc {{ \x y -> model x y != 0 }};
```

(In `swap_harness.saw`)

FFS Example

```
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;
}

uint32_t ffs_imp(uint32_t i) {
  char n = 1;
  if (!(i & 0xffff)) { n += 16; i >>= 16; }
  if (!(i & 0x00ff)) { n +=  8; i >>=  8; }
  if (!(i & 0x000f)) { n +=  4; i >>=  4; }
  if (!(i & 0x0003)) { n +=  2; i >>=  2; }
  return (i) ? (n+((i+1) & 0x01)) : 0;
}
```

Manual FFS Testing

```
int ffs_imp_correct(uint32_t x) {
  return ffs_imp(x) == ffs_ref(x);
}

int main() {
  assert(ffs_imp_correct(0x00000000));
  assert(ffs_imp_correct(0x00000001));
  assert(ffs_imp_correct(0x80000000));
  assert(ffs_imp_correct(0x80000001));
  assert(ffs_imp_correct(0xF0000000));
  assert(ffs_imp_correct(0x0000000F));
  assert(ffs_imp_correct(0xFFFFFFFF));
  return 0;
}
```

Random FFS Testing

- Same pros and cons as for the swap example

```
int main() {
  for(int idx = 0; i < 100; i++) {
    uint32_t x = rand();
    assert(ffs_imp_correct(x));
  }
  return 0;
}
```

- Even exhaustive testing possible in this case
    - But not for 64-bit inputs

Verifying FFS Harness

```
m <- llvm_load_module "ffs.bc";

imp_correct <- llvm_extract m "ffs_imp_correct" llvm_pure;
bug_correct <- llvm_extract m "ffs_bug_correct" llvm_pure;

set_base 16;
print "Proving ffs_imp_correct always returns true...";
prove_print abc {{ \x -> imp_correct x == 1 }};
print "Failing to prove ffs_bug_correct returns true...";
prove_print abc {{ \x -> bug_correct x == 1 }};
```

(In `ffs_harness.saw`)

Verifying FFS Without Wrapper

```
m <- llvm_load_module "ffs.bc";
print "Extracting functional models...";
ref <- llvm_extract m "ffs_ref" llvm_pure;
imp <- llvm_extract m "ffs_imp" llvm_pure;
print "Comparing reference and implementation...";
// The === operator compares functions directly
r <- time (prove abc {{ ref === imp }});
print r;
```

(In `ffs_eq.saw`)

Exercises: FFS

1. Port the FFS code to use `uint64_t`
   - Translate both reference and implementation
   - Try to prove equivalence (and don't worry if you fail)
2. Try to break the FFS code, in obvious and subtle ways
   - Can you make it do the wrong thing and not be caught?
3. Try to discover the "haystack" bug in `ffs_bug`
   - Use random testing (`ffs_bug_fail.saw`)
     - Increase the number of tests and see how long it takes
     - Try a similar case with `uint64_t`
   - Use `ffs_bug.saw` to find it with a SAT solver

More Complex Verification

General Verification Structure

- Verifications in SAW consist of three phases
  - Initialize a (symbolic!) starting state
  - Run the target code (symbolically) in that state
  - Check that the final state is correct (using automated provers)
- For LLVM, encapsulated in `crucible_llvm_verify`
  - The `llvm_extract` command just simplifies a common case
- When running the target code, we can sometimes use previously-proven facts about code it calls (or assumed facts about external code)

Using crucible_llvm_verify

```
m <- llvm_load_module "foo.bc";
let foo_spec = do {
    // Set up the initial state

    crucible_execute_func [/* some argument */];

    // Check the final state
};
crucible_llvm_verify m "foo" [] true foo_spec abc;
```

- Introduce symbolic variables with `crucible_fresh_var`
- Specify heap layout with `crucible_alloc`, `crucible_points_to`
- All work before or after `crucible_execute_func`, with different meanings

Verifying XOR Swap Without Wrapper

```
m <- llvm_load_module "xor-swap.bc";
// void swap_xor(uint32_t *x, uint32_t *y);
let swap_spec = do {
    x <- crucible_fresh_var "x" (llvm_int 32);
    y <- crucible_fresh_var "y" (llvm_int 32);
    xp <- crucible_alloc (llvm_int 32);
    yp <- crucible_alloc (llvm_int 32);
    crucible_points_to xp (crucible_term x);
    crucible_points_to yp (crucible_term y);
    crucible_execute_func [xp, yp];
    crucible_points_to xp (crucible_term y);
    crucible_points_to yp (crucible_term x);
};
crucible_llvm_verify m "swap_xor" [] true swap_spec abc;
```

(In `swap.saw`, comparing all versions)

Simplifying the XOR Swap specification

```
m <- llvm_load_module "xor-swap.bc";
let ptr_to_fresh nm ty = do {
    x <- crucible_fresh_var nm ty;
    p <- crucible_alloc ty;
    crucible_points_to p (crucible_term x);
    return (x, p);
};
let swap_spec = do {
    (x, xp) <- ptr_to_fresh "x" (llvm_int 32);
    (y, yp) <- ptr_to_fresh "y" (llvm_int 32);
    crucible_execute_func [xp, yp];
    crucible_points_to xp (crucible_term y);
    crucible_points_to yp (crucible_term x);
};
crucible_llvm_verify m "swap_xor" [] true swap_spec abc;
```

Exercises: Code with Pointers

1. Try to break the XOR-based swapping in some way and run the proof
   - Use `swap.saw` or `swap_harness.saw`
2. Write a buggy version and use SAW to find inputs for which it's correct
   - These would be bad test cases!
3. Write a script to prove the FFS test harness using `crucible_llvm_verify`
   - You'll need `crucible_return {{ 1 : [32] }}` and `crucible_term`
   - You won't need `crucible_alloc` or `crucible_points_to`

Composition

Review: SAW Basics

- SAW executes functions symbolically to translate them into pure functions
- Symbolic state must be configured before execution
  - Similar to writing a test harness
  - Need to allocate memory, indicate symbolic values
- After execution, SAT and SMT solvers can prove properties of result state
- Use `crucible_fresh_var` to create symbolic values
  - The name is just for debugging
- Use `crucible_execute_func` to specify arguments, division between pre and post state

Review: Pointers

- Use crucible_alloc to specify that allocated memory exists
- Use crucible_points_to to specify where values are stored in the heap

```
let ptr_to_fresh nm ty = do {
    x <- crucible_fresh_var nm ty;
    p <- crucible_alloc ty;
    crucible_points_to p (crucible_term x);
    return (x, p);
};
```

Composition: Verifying Salsa20 (C code)

```
uint32_t rotl(uint32_t value, int shift) {
  return (value << shift) | (value >> (32 - shift));
}

void s20_quarterround(uint32_t *y0, uint32_t *y1,
                      uint32_t *y2, uint32_t *y3) {
  *y1 = *y1 ^ rotl(*y0 + *y3, 7);
  // ... and three more
}

void s20_rowround(uint32_t y[static 16]) {
  s20_quarterround(&y[0], &y[1], &y[2], &y[3]);
  // ... and three more
}
```

Composition: Specifying Salsa20 (SAW code)

```
let quarterround_setup : CrucibleSetup () = do {
  (p0, y0) <- ptr_to_fresh "y0" i32;
  // ... and three more
  crucible_execute_func [p0, p1, p2, p3];
  let zs = {{ quarterround [y0,y1,y2,y3] }};
  crucible_points_to p0 (crucible_term {{ zs@0 }});
  // ... and three more
};

let rowround_setup = do {
  (y, p) <- ptr_to_fresh "y" (llvm_array 16 i32);
  crucible_execute_func [p];
  crucible_points_to p (crucible_term {{ rowround y }});
};
```

Composition: Verifying Salsa20 (SAW code)

```
m <- llvm_load_module "salsa20.bc";
let verify f ovs spec =
  crucible_llvm_verify m f ovs true spec abc;
qr <- verify "s20_quarterround" []   quarterround_setup;
rr <- verify "s20_rowround"     [qr] rowround_setup;
```

- Pass results of prior verification into later verification
- Can have multiple previously-verified facts about one function
  - For example, different array sizes
  - Used only for the top level of Salsa20

Sidebar: Array Sizes and Looping

- With the current version of SAW, programs must be finite
  - SAT-based proofs need to know how many bits are involved
  - Inputs need to have fixed sizes
  - All pointers must point to data of known size
  - All loops need to execute a bounded number of times
- But Salsa20 can operate on any input size
  - So we prove it correct separately for several possible sizes
  - Our original version had a bug because of this!
- Future SAW versions are likely to relax these restrictions

Exercises: Composition

1. Compare the timing of the monolithic and compositional proofs
   - When checking multiple sizes, how does it compare?
   - How many sizes before composition becomes better?
2. Try to break the code and see what happens
   - First try a leaf function
   - Then try the top-level function
3. Can you break it so that one size succeeds but another fails?

Additional SAW Details

Built-in Prover Tradeoffs

- SAW supports many back-end provers
  - `abc`: good for very bit-level things (and linked in)
  - `yices`: good for compositional bit vector problems
  - `z3`: good for integer problems
- Others are available, but less frequently useful
  - I usually use `yices`

Offline Provers

- It's also possible to write theorems to files and prove later
  - `write_cnf` and `offline_cnf` support standard SAT solvers
  - `write_aig` and `offline_aig` support AIG-based solvers (like ABC as an external program)
  - `write_smtlib2` and `offline_smtlib2` support SMT solvers (like Yices and Z3 as external programs)
- The tactic versions (`offline_*`) always succeed, with a warning
- See `write_cnf.saw`

Unfolding and Simplification

```
sawscript> let {{ f x y = (x : [8]) + y }}
sawscript> {{ f }}
f

sawscript> let t = unfold_term ["f"] {{ f }}
sawscript> t
let { x@1 = Prelude.Vec 8 Prelude.Bool }
 in \(x :: x@1) -> \(y :: x@1) ->
    Cryptol.ecPlus x@1
      (Cryptol.PArithSeqBool (Cryptol.TCNum 8)) x   y

sawscript> rewrite (cryptol_ss ()) t
let { x@1 = Prelude.Vec 8 Prelude.Bool }
 in \(x :: x@1) -> \(y :: x@1) -> Prelude.bvAdd 8 x y
```

(See `unfold.saw`.)

Uninterpreted Functions

```
let {{ f x y = (x : [8]) + y }};
let {{ g x y = 2 * (f x y) }};
let {{ h x y = (f x y) + (f x y) }};
let {{ prop x y = g x y == h x y }};
let {{ prop2 x y = h x y == 2*x + 2*y }};

print "Proving prop fully unfolded:";
prove_print yices {{ prop }};
print "Proving prop with f uninterpreted:";
prove_print (unint_yices ["f"]) {{ prop }};
print "Proving prop2 fully unfolded:";
prove_print yices {{ prop2 }};
print "Proving prop2 with f uninterpreted (should fail):";
prove_print (unint_yices ["f"]) {{ prop2 }};
```

(See `unint.saw`.)

Rewriting

```
let {{
    f x y = (x : [8]) + y
    g x y = (y : [8]) + x
    h x y = (f x y) + (g x y)
}};
f_eq_g <- prove_print abc {{ \x y -> f x y == g x y }};
print f_eq_g;
```

```
t1 <- unfold_term ["h"] {{ \x y -> h x y == 2*(f x y) }};
print_term t1;
```

```
t2 <- rewrite (addsimp f_eq_g empty_ss) t1;
print_term t2;
```

```
prove_print (unint_yices ["g"]) t2;
```

(See `rewrite.saw`.)

Proof Scripts

- Commands like `prove` and `crucible_llvm_verify` use proof scripts
- Instead of just a prover, can have tactics in a `do` block
- Show current goal with `print_goal`
- Term manipulation
  - `unfold_term` becomes `unfolding`
  - `rewrite` becomes `simplify`
- Finishing proofs
  - Skip proof with `assume_unsat`
  - Match `True` with `trivial`
  - Invoke prover (`abc`, `yices`, `z3`, etc.)

Debugging Symbolic Execution Failure

- Invalid memory reads/writes
  - Usually a result of failing to declare an input (argument, field, global)
  - Compile with -g to see where the read is happening
- Failure to terminate
  - Intrinsic non-termination in the target program?
  - Try branch satisfiability checking
  - Complex memory operations
- Check whether it's in symbolic execution or proof
  - With prover other than `abc`, check `saw` CPU use

Continuous Integration

Onward to Continuous Integration

- SAW verification configurations are manual
- But executing a script can be automated
- Scripts need to change only in a few cases
  - If the expected behavior of the code being checked changes
  - If the inputs or outputs of the code change
- So CI systems can automatically re-check many code changes
  - Changes to other parts of code
  - Changes that preserve functionality

Continuous Integration with Travis

1. Download SAW binaries
   - From https://saw.galois.com/builds/nightly
2. Download prover binaries
   - Yices from http://yices.csl.sri.com
   - Z3 from https://github.com/Z3Prover/z3/releases
3. Unpack everything and put binaries in the `PATH`
4. Build your code (maybe using `wllvm`)
5. Run `saw` on a script file
   - Caching binaries (e.g., on S3) can improve reliability

Tips and Tricks for Travis

- General procedure for binary tarballs (SAW, Yices, Z3)

```
- curl -L --retry 3 URL --output /tmp/foo.tar.gz
- tar -xzvf /tmp/foo.tar.gz
- export PATH=$PATH:$(pwd)/foo-0.1
```

- See `.travis.yml` in the repository for this talk for details
- To experiment with changes, use branches (and tell Travis to build them)
- Travis output: https://travis-ci.org/atomb/secdev18-saw

Exercises: Travis

1. Create a new repository running SAW under Travis:
   - Try the `ffs` example, or `xor-swap`
   - Get it to pass
2. Experiment with changes to the code
   - Create a branch for a change (so you can delete a series of messy commits)
   - Make a mistake, push, observe the output
   - Travis example: https://travis-ci.org/atomb/secdev18-saw/builds/435026975

Proof Maintenance

- Unchanged code easily reproved
- Modified code with identical functionality automatically reproved
- Some changes require script changes
  - Changes in types (e.g., `struct` definitions) used by function
  - Changes in number or shape of inputs or outputs
- We're working on ways to automate some changes, when possible

Proving HMAC in s2n

NIST Document

$$HMAC(k, m) = H((k_0 \oplus opad) \| H((k_0 \oplus ipad) \| m))$$

Cryptol

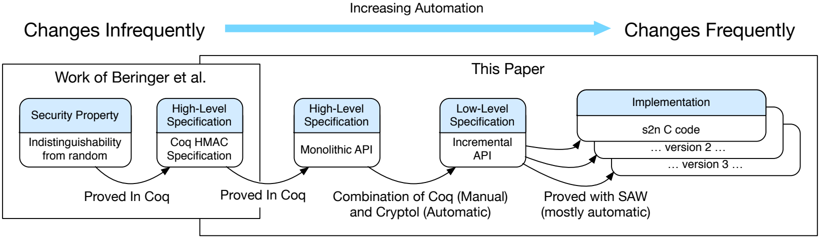
```
hmac k m = H (opad # split (H (ipad # m)))
  where
    k0 = kinit H k
    opad = [kb ^ 0x5C | kb <- k0]
    ipad = [kb ^ 0x36 | kb <- k0]
```

C and Verification

- ~200 lines of code, multiple functions
- Low-level spec corresponding to each function
- Proof between Cryptol specs in SAW (one lemma in Coq)
- One proof for each of several hash algorithms, message sizes

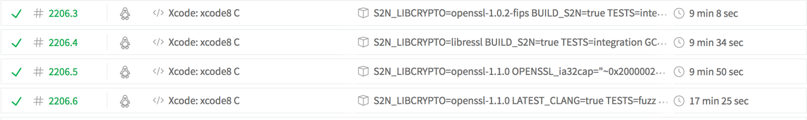
Proof Approach

- Abstract Cryptol spec derived from RFC or NIST document
- Concrete spec matching what s2n implements
    - Incremental HMAC, subset of handshake protocol
- Proof of refinement between two Cryptol specs
- Proof of equivalence between low-level Cryptol and C

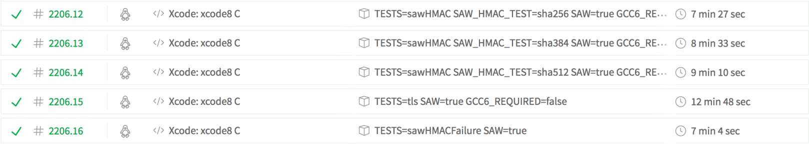


Travis for s2n

- One of many testing and analysis tasks for s2n
- Run on every commit
- Completes in about the same time as the concrete tests
- See: https://travis-ci.org/awslabs/s2n



✓	# 2206.3	</> Xcode: xcode8 C	S2N_LIBCRYPTO=openssl-1.0.2-fips BUILD_S2N=true TESTS=inte…	9 min 8 sec
✓	# 2206.4	</> Xcode: xcode8 C	S2N_LIBCRYPTO=libressl BUILD_S2N=true TESTS=integration GC…	9 min 34 sec
✓	# 2206.5	</> Xcode: xcode8 C	S2N_LIBCRYPTO=openssl-1.1.0 OPENSSL_ia32cap="~0x2000002…	9 min 50 sec
✓	# 2206.6	</> Xcode: xcode8 C	S2N_LIBCRYPTO=openssl-1.1.0 LATEST_CLANG=true TESTS=fuzz …	17 min 25 sec



✓	# 2206.12	</> Xcode: xcode8 C	TESTS=sawHMAC SAW_HMAC_TEST=sha256 SAW=true GCC6_RE…	7 min 27 sec
✓	# 2206.13	</> Xcode: xcode8 C	TESTS=sawHMAC SAW_HMAC_TEST=sha384 SAW=true GCC6_RE…	8 min 33 sec
✓	# 2206.14	</> Xcode: xcode8 C	TESTS=sawHMAC SAW_HMAC_TEST=sha512 SAW=true GCC6_RE…	9 min 10 sec
✓	# 2206.15	</> Xcode: xcode8 C	TESTS=tls SAW=true GCC6_REQUIRED=false	12 min 48 sec
✓	# 2206.16	</> Xcode: xcode8 C	TESTS=sawHMACFailure SAW=true	7 min 4 sec

Wrapping Up

More Complex Examples

- Proof of equivalence between Cryptol and Java versions of ECDSA
  - https://github.com/GaloisInc/saw-script/tree/master/examples/ecdsa
- Proof of the absence of undefined behavior or assertion failures
  - https://github.com/GaloisInc/saw-script/tree/master/examples/sv-comp
- Proof of HMAC, DRBG, and the TLS handshake in s2n
  - GitHub: https://github.com/awslabs/s2n/tree/master/tests/saw
  - CAV Paper: https://link.springer.com/chapter/10.1007/978-3-319-96142-2_26

Future of SAW

- Better support for unbounded programs
  - Data: variable-size and variable-shape heap structures
  - Control: unbounded iteration
- More flexible/powerful scripting language
  - May expose SAWScript functions as an API for other languages (Python?)
- Analysis of more languages
  - Partial support for Rust, Go, various forms of machine code

Contributors

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Continuing with SAW

- Resources
  - SAW web site: https://saw.galois.com
  - Cryptol web site: https://cryptol.net
  - SAW documentation
    - Tutorial: https://saw.galois.com/tutorial.html
    - Manual: https://saw.galois.com/manual.html
  - Cryptol documentation: https://cryptol.net/documentation.html
  - These examples and slides: https://github.com/atomb/secdev18-saw
- If this sort of thing interests you, Galois is hiring!