Survey of Verified Cryptography

CSCI-762 / Tom Arnold

Verified Cryptography

- Using tools to apply cryptography and prove that the implementation is correct
- Assuming the algorithms and protocols are secure, there are still many challenges in implementing them
  - Memory Safety
  - Functional Correctness
  - Side Channel Resistance

Memory Safety

- High performance code usually written in memory unsafe languages (C/C++).
- Vulnerabilities can allow attacker can access arbitrary memory.
  - OpenSSL Heartbleed - Heartbeat request returning uninitialized memory to client, allowing client (slow) read access to memory to hunt for private keys and other secrets
- Managed languages like Java solve this but have worse performance, complex implementation, unusable for embedded/legacy code bases

Functional Correctness

- Specification usually given as IETF (Internet Task Force) RFC document
  - Turn spec into code, does it still match spec?
  - Optimize code, does it still match spec?
- Exhaustive test suite not trivial
  - Property based testing
  - Proof assistants

Side-channel Resistance

- Attacker can determine information by observing runtime, CPU usage, power usage, etc
- Can be caused by optimizations in code, e.g. shortcut multiplication when operand is zero
- Can be caused by arch level (CPU/memory) optimizations like branch prediction and cache
- Secret independence - Don’t allow optimizations/ shortcuts based on secret values

FStar (F*) Programming Language

- ML-based programming language from INRIA and Microsoft Research
- Features: refinement types, dependent types, proof assistant
  - Pre-post conditions on functions that the compiler can use to prove the code is correct
- Compiles to OCaml/F#
  - Low* dialect compiles to C
- High level verification for low-level code

Low*

- Executable specifications (proofs) written in high-level F*, operations written in Low* dialect
  - No recursive data structures, no dynamic allocation, bounded heaps (region based memory management)
- Low* compiled to C for inclusion in other software or manual verification
- Use the powerful type system to enforce memory safety and secret independence in generated code

Implementation

- Implement algorithm in high-level F* code
  - This is the executable specification
  - No fancy stuff here, stay close to RFC
- Implement algorithm in low-level F* code
  - Optimizations happen here, e.g. vectorization
- Low-level implementation linked to specification through post-conditions

Refinement/Dependent Types

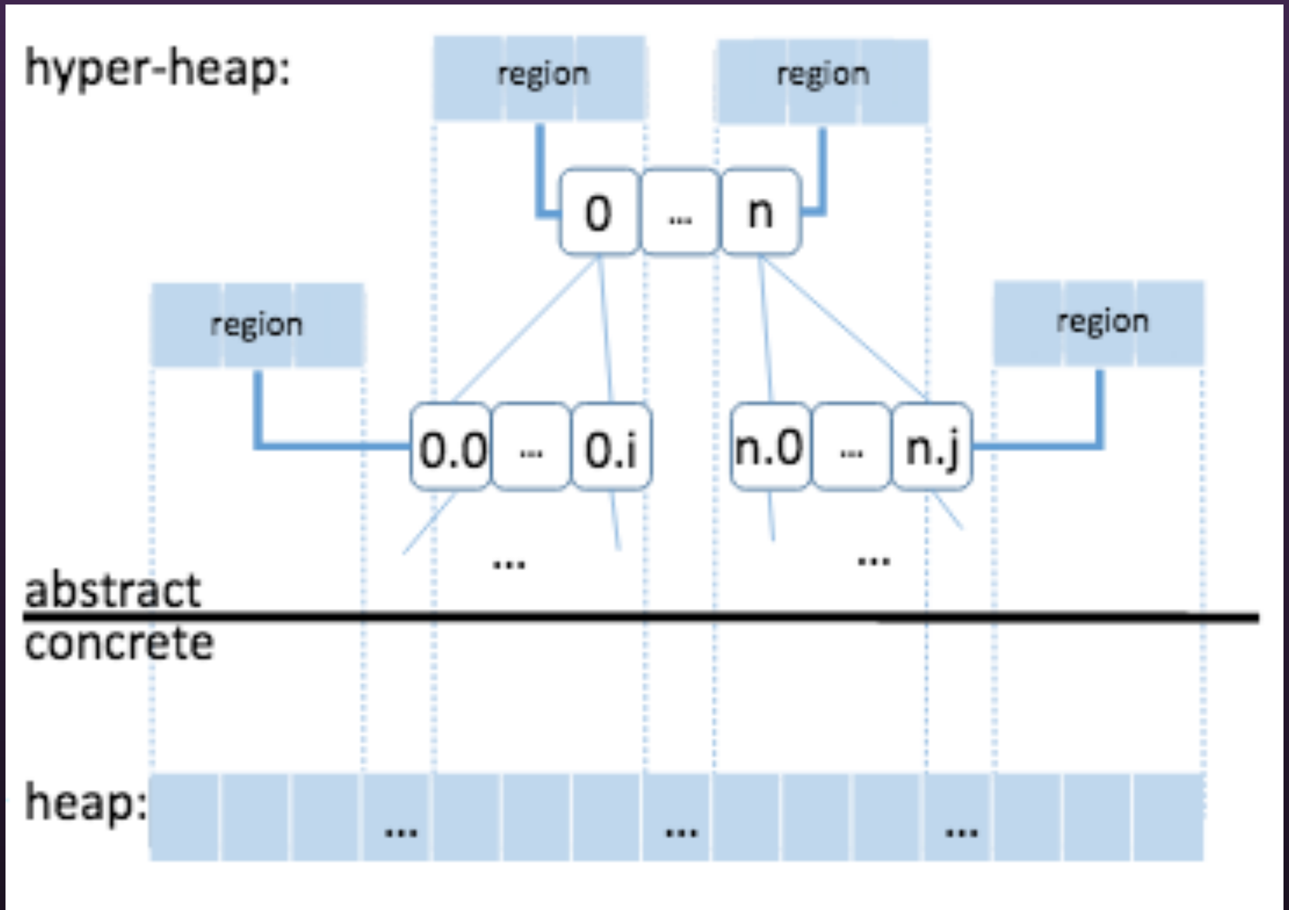
- Adding constraints to a type, e.g.
  - x: uint32 - x is unsigned 32bit int
  - x: uint32 { 1 <= x <= 10 } - x is unsigned 32bit int between 1 and 10
- The constraints can be relative to other types, e.g. length < 10 and buffer size = length
- Checks performed at <u>compile</u> time

```
val p = 2^130 − 5 (* the prime order of the field *)
type elem = n:nat {n < p} (* abstract field element *)
let x +@ y : Tot elem = (x + y) % p (* field addition *)
let x *@ y : Tot elem = (x * y) % p (* field multiplication *)
```

https://eprint.iacr.org/2016/1178.pdf

Heap Model

- Heap divided into regions; regions can be subdivided
- Prevents memory corruption and simplifies verification
- Code works with fixed-sized buffers



https://www.fstar-lang.org/papers/mumon/paper.pdf

Stack Model

- Functions that only allocate on the stack can't leak memory
  - Memory allocated on stack freed when stack frame popped
- Functions can be annotated that they only allocate on the stack (and not heap)

Secure Integers

- Only constant time operations allowed
  - If operation time varies, could reveal information to attacker
  - Avoid common optimizations that would make operations variable-time
- Masked (bitwise) equality to prevent CPU branch prediction

HACL*

- Library of verified cryptography primitives written in F*
  - Stream ciphers: ChaCha20, Salsa20
  - Hashing: SHA-2
  - Signature: Ed25519
  - Authentication: Poly1305, HMAC-SHA-2
  - Authenticated crypto: ChaCha20-Poly1305
- Performance between OpenSSL C and ASM
- Proof-to-code ratio 2:1

Example - ChaCha20

```
let chacha20
  (len: uint32{len ≤ blocklen})
  (output: bytes{len = output.length})
  (key: keyBytes)
  (nonce: nonceBytes{disjoint [output; key; nonce]})
  (counter: uint32) : Stack unit
  (requires (λ m0 → output ∈ m0 ∧ key ∈ m0 ∧ nonce ∈ m0))
  (ensures (λ m0 _m1 → modifies₁ output m0 m1 ∧
      m1.[output] ==
      Seq.prefix len (Spec.chacha20 m0.[key] m0.[nonce]) counter))) =
    push_frame ();
    let state = Buffer.create 0ul 32ul in
    let block = Buffer.sub state 16ul 16ul in
    chacha20_init block key nonce counter;
    chacha20_update output state len;
    pop_frame ()
```

let blocklen = 64;

```
void chacha20 (
  uint32_t len,
  uint8_t *output,
  uint8_t *key,
  uint8_t *nonce,
  uint32_t counter)




{
  uint32_t state[32] = { 0 };
  uint32_t *block = state + 16;
  chacha20_init(block, key, nonce, counter);
  chacha20_update(output, state, len);
}
```

Fig. 2. A snippet from ChaCha20 in Low* (left) and its C compilation (right)

https://arxiv.org/pdf/1703.00053.pdf

Conclusions

- Open question of maintenance
  - F* is "living" language
  - How to verify changes to the generated code?
- Promising approach, automation helps produce consistent results

References

- HACL*: A Verified Modern Cryptographic Library: https://eprint.iacr.org/2017/536.pdf
- Verified Low Level Programming Embedded in F*: https://arxiv.org/pdf/1703.00053.pdf
- Implementing and Proving the TLS 1.3 Record Layer: https://eprint.iacr.org/2016/1178.pdf
- Dependent Types and Multi-monadic Effects in F*: https://www.fstar-lang.org/papers/mumon/paper.pdf