HACL*
High-Assurance Cryptographic Library

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HACL*: a verified C crypto library

- A growing library of verified crypto algorithms
  - AEAD: Chacha20-Poly1305, AES-GCM
  - Hashes: SHA2, SHA3, Blake2
  - HMAC and HKDF
  - ECC: Curve25519, Ed25519, P256
  - High-level APIs: Box and HPKE

    coming soon: generic bignum library, RSAPSS, FFDHE
- Developed as a collaboration between the **Prosecco** team at **INRIA Paris**, **Microsoft Research**, and **Carnegie Mellon University**

HACL*: a verified C crypto library

- Implemented and verified in F* and compiled to C
  - **Memory safety** proved in the C memory model
  - **Secret independence** ("constant-time") enforced by typing
  - **Functional correctness** against a mathematical spec written in F*
- Generates readable, portable, standalone C code
  - Performance comparable to hand-written C crypto libraries
  - Used in Mozilla Firefox, WireGuard VPN, Tezos Blockchain, etc

Writing Verified Crypto Code

CRYPTO STANDARD
(IETF/NIST)

Obsoleted by: 8439 INFORMATIONAL
Errata Exist

Internet Research Task Force (IRTF)	Y. Nir
Request for Comments: 7539	Check Point
Category: Informational	A. Langley
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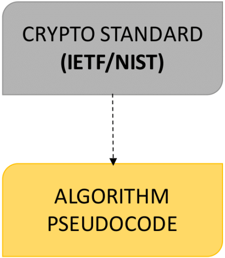
ChaCha20 and Poly1305 for IETF Protocols

Abstract

This document defines the ChaCha20 stream cipher as well as the use of the Poly1305 authenticator, both as stand-alone algorithms and as a "combined mode", or Authenticated Encryption with Associated Data (AEAD) algorithm.

This document does not introduce any new crypto, but is meant to serve as a stable reference and an implementation guide. It is a product of the Crypto Forum Research Group (CFRG).

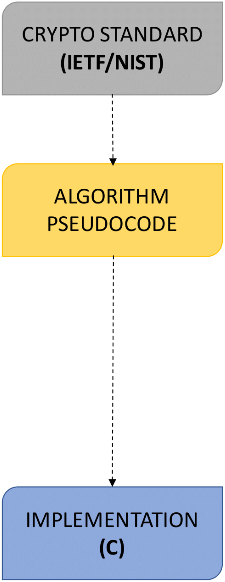
Writing Verified Crypto Code



2.5.1. The Poly1305 Algorithms in Pseudocode

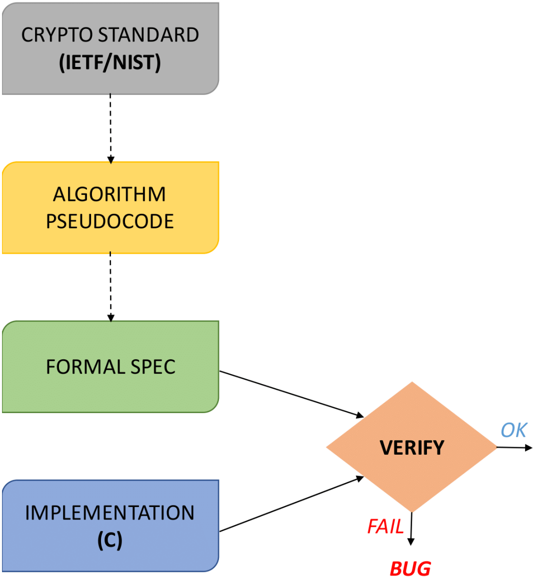
```
clamp(r): r &= 0x0ffffffc0ffffffc0ffffffc0fffffff
poly1305_mac(msg, key):
   r = (le_bytes_to_num(key[0..15])
   clamp(r)
   s = le_num(key[16..31])
   accumulator = 0
   p = (1<<130)-5
   for i=1 upto ceil(msg length in bytes / 16)
      n = le_bytes_to_num(msg[((i-1)*16)..(i*16)] | [0x01])
      a += n
      a = (r * a) % p
      end
   a += s
   return num_to_16_le_bytes(a)
   end
```

Writing Verified Crypto Code




```
void Poly1305_Update(POLY1305 *ctx, const unsigned char *inp, size_t len)
{
#ifdef POLY1305_ASM
    /*
     * As documented, poly1305_blocks is never called with input
     * longer than single block and padbit argument set to 0. This
     * property is fluently used in assembly modules to optimize
     * padbit handling on loop boundary.
     */
    poly1305_blocks_f poly1305_blocks_p = ctx->func.blocks;
#endif
    size_t rem, num;

    if ((num = ctx->num)) {
        rem = POLY1305_BLOCK_SIZE - num;
        if (len >= rem) {
            memcpy(ctx->data + num, inp, rem);
            poly1305_blocks(ctx->opaque, ctx->data, POLY1305_BLOCK_SIZE, 1);
            inp += rem;
            len -= rem;
        } else {
            /* Still not enough data to process a block. */
            memcpy(ctx->data + num, inp, len);
            ctx->num = num + len;
            return;
        }
    }

    rem = len % POLY1305_BLOCK_SIZE;
    len -= rem;

    if (len >= POLY1305_BLOCK_SIZE) {
        poly1305_blocks(ctx->opaque, inp, len, 1);
        inp += len;
    }

    if (rem)
        memcpy(ctx->data, inp, rem);

    ctx->num = rem;
}
```

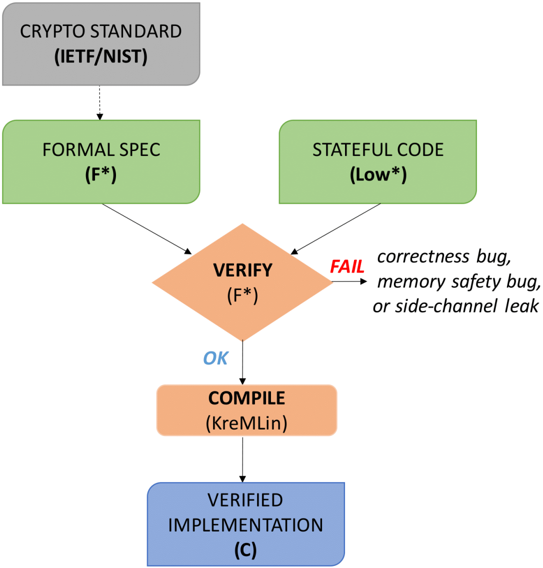
Writing Verified Crypto Code



Verification Guaranties:

1. *functional correctness*
2. *memory safety*
3. *secret independence*

HACL* programming and verification workflow



Agenda

How to write a formally verified implementation of cryptographic algorithms in F⋆?

- Example: Poly1305
- Field operations
  - Unsaturated and saturated bignum representations
  - Modulo-specific optimizations
- Polynomial evaluation
- Demo
  - F⋆ specification
  - Low⋆ implementation
- Do you want to give it a try? ☺

Poly1305

- a one-time MAC[1] function
- takes a 32-byte *key* and a *message* of arbitrary length and produces a 16-byte *tag*
- standardized as IETF RFC 7539 "ChaCha20 and Poly1305 for IETF Protocols" in 2015
- designed by Bernstein in 2005

[1] Message Authentication Code (MAC)

Poly1305

How to compute a 16-byte tag?

- split a 32-byte *key* into two 128-bit integers r and s, where r should be clamped
- split an input *message* into 16-byte blocks encoded to the field elements $m_1, \ldots, m_n$
- evaluate the following polynomial over $\mathbb{F}_p$, where $p = 2^{130} - 5$

  $acc = m_1 \times r^n + m_2 \times r^{n-1} + \ldots + m_n \times r \bmod p$

  in practice, Horner's method is used:

  $acc = (\ldots((0 + m_1) \times r + m_2) \times r + \ldots + m_n) \times r \bmod p$
- finally, compute

  $tag = acc + s \bmod 2^{128}$

Poly1305

How to compute a 16-byte tag?

- split an input *message* into 16-byte blocks encoded to the field elements $m_1, \ldots, m_n$
- evaluate the following polynomial over $\mathbb{F}_p$, where $p = 2^{130} - 5$

$$acc = (\ldots((0 + m_1) \times r + m_2) \times r + \ldots + m_n) \times r \bmod p$$

Bignum operations over $\mathbb{F}_{2^{130}-5}$

```
let prime = pow2 130 − 5
let felem = x:nat{x < prime}
let zero : felem = 0
let one : felem = 1

let fadd (x:felem) (y:felem) : felem = (x + y) % prime
let fmul (x:felem) (y:felem) : felem = (x ∗ y) % prime

let blocksize = 16
let block = lbytes blocksize
let block_last (len:nat{len < blocksize}) = lbytes len

val encode_block: b:block → felem
val encode_last: len:nat{len < blocksize} → b:block_last len → felem
```

Polynomial evaluation

$$acc = (\ldots((acc0 + m_1) \times r + m_2) \times r + \ldots + m_n) \times r \bmod p,$$
where $+$ is fadd and $\times$ is fmul

```
let poly_update1 (r:felem) (b:block) (acc:felem) : felem =
  (acc `fadd` encode_block b) `fmul` r

let poly_update_last (r:felem) len (b:block_last len) (acc:felem) : felem =
  if len = 0 then acc else (acc `fadd` encode_last len b) `fmul` r

let poly_update (msg:bytes) (acc0:felem) (r:felem) : felem =
  repeat_blocks #uint8 #felem #felem blocksize msg
    (poly_update1 r)
    (poly_update_last r)
  acc0
```

F⋆ specification

- F⋆ specification:
  `https://github.com/aseemr/Indocrypt-VerifiedCrypto-Tutorials/blob/main/FStar/exercises/lowstar/example-poly/Spec.Poly.fst`
- For simplicity, we ignore the last block if it is partial

F⋆ specification

- F⋆ specification:

  `https://github.com/aseemr/Indocrypt-VerifiedCrypto-Tutorials/blob/main/FStar/exercises/lowstar/example-poly/Spec.Poly.fst`
- For simplicity, we ignore the last block if it is partial
- Are we ready for the Low⋆ implementation?
- Not yet, since we are dealing with 130-bit integers!

Representing large integers

- Any number can be represented as $a = (a_n\ a_{n-1}\ \ldots\ a_0)_r$, where r is called **radix** or **base**
- evaluation function as_nat $a = \sum_{i=0}^{n} a_i \cdot r^i$

r	numeral systems
2	binary
8	octal
10	decimal
16	hexadecimal
...	

r	unsigned machine integers
2^8	uint8
2^{16}	uint16
2^{32}	uint32
2^{64}	uint64
...	

- if $0 \leq a_i < r$
  - \+ such a representation is unique
  - − some arithmetic operations may require to handle carries
- if a_i might be $\geq r$
  - \+ we can postpone carry propagation!
  - a is in a *reduced* form if $0 \leq a_i < r$

Bignum operations over $\mathbb{F}_{2^{130}-5}$

- Let's stick with radix-2^{26} representation of a field element
- as_nat $a = \sum_{i=0}^{4} a_i \cdot 2^{26 \cdot i}$
- bignum addition

  as_nat a + as_nat b ==
  $\sum_{i=0}^{4} a_i \cdot r^i + \sum_{i=0}^{4} b_i \cdot r^i ==$
  $\sum_{i=0}^{4} (a_i + b_i) \cdot r^i ==$
  as_nat (a ‘fadd‘ b)
- multiplication by a scalar

  as_nat $a \cdot b_i$ ==
  $\left(\sum_{i=0}^{4} a_i \cdot r^i\right) \cdot b_i ==$
  $\sum_{i=0}^{4} (a_i \cdot b_i) \cdot r^i ==$
  as_nat (a ‘smul‘ b_i)

Bignum operations over $\mathbb{F}_{2^{130}-5}$

- multiplication by a scalar and then bignum addition

  $$\text{as\_nat } a \cdot b_i + \text{as\_nat } c ==$$
  $$\left(\sum_{i=0}^{4} a_i \cdot r^i\right) \cdot b_i + \sum_{i=0}^{4} c_i \cdot r^i ==$$
  $$\sum_{i=0}^{4}(a_i \cdot b_i + c_i) \cdot r^i ==$$
  $$\text{as\_nat } ((a \text{ `sfmul` } b_i) \text{ `fadd` } c_i)$$

- bignum multiplcation

  $$\text{as\_nat } a \cdot \text{as\_nat } b ==$$
  $$\text{as\_nat } a \cdot \left(\sum_{i=0}^{4} b_i \cdot r^i\right) ==$$
  $$\text{as\_nat } a \cdot b_0 + \text{as\_nat } a \cdot (b_1 \cdot r) + \text{as\_nat } a \cdot (b_2 \cdot r^2) +$$
  $$\text{as\_nat } a \cdot (b_3 \cdot r^3) + \text{as\_nat } a \cdot (b_4 \cdot r^4) ==$$

  $\ldots$

Bignum operations over $\mathbb{F}_{2^{130}-5}$

- we have such a nice property for modular reduction:
  $2^{130} \bmod p = 5$ or $r^5 \bmod p = 5$
- $\text{as\_nat}\ a \cdot r \bmod p ==$
  $\text{as\_nat}\ (a_4\ a_3\ a_2\ a_1\ a_0)_r \cdot r \bmod p ==$
  $(a_0 \cdot p + a_1 \cdot p^2 + a_2 \cdot p^3 + a_3 \cdot p^4 + a_4 \cdot r^5) \bmod p ==$
  $(a_0 \cdot p + a_1 \cdot p^2 + a_2 \cdot p^3 + a_3 \cdot p^4 + a_4 \cdot 5) \bmod p ==$
  $\text{as\_nat}\ (a_3\ a_2\ a_1\ a_0\ (5 \cdot a_4))_r \bmod p$
- modular bignum multiplication
  $(\text{as\_nat}\ a \cdot \text{as\_nat}\ b) \bmod p ==$
  $(\text{as\_nat}\ a \cdot b_0 + \text{as\_nat}\ a \cdot (b_1 \cdot r) + \cdots) \bmod p$
  $(\text{as\_nat}\ a \cdot b_0 + \text{as\_nat}\ (a_3\ a_2\ a_1\ a_0\ (5 \cdot a_4))_r \cdot b_1 + \cdots) \bmod p$

Bignum operations over $\mathbb{F}_{2^{130}-5}$

So far so good? In the real world, our coefficients are bounded with $2^{machine\ word\ size}$. So we need to make sure that all our computations won't "overflow"

- bignum addition

  $$\text{as\_nat}\ a + \text{as\_nat}\ b ==$$
  $$\sum_{i=0}^{4} a_i \cdot r^i + \sum_{i=0}^{4} b_i \cdot r^i ==$$
  $$\sum_{i=0}^{4} (a_i + b_i) \cdot r^i == \{a_i + b_i < 2^{bits\ t}\}$$
  $$\text{as\_nat}\ (a \text{ `fadd` } b)$$

- multiplication by a scalar

  $$\text{as\_nat}\ a \cdot b_i ==$$
  $$\left(\sum_{i=0}^{4} a_i \cdot r^i\right) \cdot b_i ==$$
  $$\sum_{i=0}^{4} (a_i \cdot b_i) \cdot r^i == \{a_i \cdot b_i < 2^{bits\ t}\}$$
  $$\text{as\_nat}\ (a \text{ `smul` } b_i)$$

Bignum operations over $\mathbb{F}_{2^{130}-5}$

So far so good? In the real world, our coefficients are bounded with $2^{machine\ word\ size}$. So we need to make sure that all our computations won't "overflow"

- multiplication by a scalar and then bignum addition

  $\text{as\_nat } a \cdot b_i + \text{as\_nat } c ==$
  $\left(\sum_{i=0}^{4} a_i \cdot r^i\right) \cdot b_i + \sum_{i=0}^{4} c_i \cdot r^i ==$
  $\sum_{i=0}^{4}(a_i \cdot b_i + c_i) \cdot r^i == \{a_i \cdot b_i + c_i < 2^{bits\ t}\}$
  $\text{as\_nat } ((a \text{ `sfmul` } b_i) \text{ `fadd` } c_i)$

- bignum multiplcation

  $\text{as\_nat } a \cdot \text{as\_nat } b ==$
  $\text{as\_nat } a \cdot \left(\sum_{i=0}^{4} b_i \cdot r^i\right) ==$
  $\text{as\_nat } a \cdot b_0 + \text{as\_nat } a \cdot (b_1 \cdot r) + \text{as\_nat } a \cdot (b_2 \cdot r^2) +$
  $\text{as\_nat } a \cdot (b_3 \cdot r^3) + \text{as\_nat } a \cdot (b_4 \cdot r^4) ==$
  ... really?

Definition of machine integer base types in HACL*

```
type inttype =
  | U1 | U8 | U16 | U32 | U64 | U128 | S8 | S16 | S32 | S64 | S128
type secrecy_level =
  | SEC | PUB
val sec_int_t: inttype → Type0 (* secret machine integers *)
let pub_int_t (t:inttype) = (* public machine integers *)
  match t with
  | U1 → n:UInt8.t{UInt8.v n < 2}
  | U8 → UInt8.t
  | U16 → UInt16.t
  | U32 → UInt32.t
  | ...
let int_t (t:inttype) (l:secrecy_level) =
  match l with
  | PUB → pub_int_t t
  | SEC → sec_int_t t

val add_mod: #t:inttype{unsigned t} → #l:secrecy_level
  → int_t t l → int_t t l → int_t t l
```

Representation an element of $\mathbb{F}_{2^{130}-5}$ in F*

- radix-2^{26} representation

```
let felem5 = (uint64 & uint64 & uint64 & uint64 & uint64)
let as_nat5 (f:felem5) : GTot nat =
  let (s0, s1, s2, s3, s4) = f in
  v s0 + v s1 * pow26 + v s2 * pow52 + v s3 * pow78 + v s4 * pow104
```

Representation an element of $\mathbb{F}_{2^{130}-5}$ in F*

- radix-2^{26} representation

```
let felem5 = (uint64 & uint64 & uint64 & uint64 & uint64)
let as_nat5 (f:felem5) : GTot nat =
  let (s0, s1, s2, s3, s4) = f in
  v s0 + v s1 * pow26 + v s2 * pow52 + v s3 * pow78 + v s4 * pow104
```

- f is in a *reduced* form if felem_fits5 f (1, 1, 1, 1, 1) holds

```
let scale32 = s:nat{s ≤ 64}
let nat5 = (nat & nat & nat & nat & nat)
let scale32_5 = x:nat5{let (x1,x2,x3,x4,x5) = x in
                        x1 ≤ 64 ∧ x2 ≤ 64 ∧ x3 ≤ 64 ∧ x4 ≤ 64 ∧ x5 ≤ 64}
let felem_fits1 (x:uint64) (m:scale32) =
  uint_v x ≤ m * max26
let felem_fits5 (f:felem5) (m:scale32_5) =
  let (x1,x2,x3,x4,x5) = f in
  let (m1,m2,m3,m4,m5) = m in
  felem_fits1 x1 m1 ∧ felem_fits1 x2 m2 ∧
  felem_fits1 x3 m3 ∧ felem_fits1 x4 m4 ∧
  felem_fits1 x5 m5
```

Bignum addition over $\mathbb{F}_{2^{130}-5}$

```
val fadd5: f:felem5 → g:felem5 → Pure felem5
  (requires
    felem_fits5 f (2, 2, 2, 2, 2) ∧
    felem_fits5 g (1, 1, 1, 1, 1))
  (ensures λ out →
    felem_fits5 out (3, 3, 3, 3, 3) ∧
    feval5 out == fadd (feval5 f) (feval5 g))
let fadd5 (f0, f1, f2, f3, f4) (g0, g1, g2, g3, g4) =
  let o0 = f0 +! g0 in
  let o1 = f1 +! g1 in
  let o2 = f2 +! g2 in
  let o3 = f3 +! g3 in
  let o4 = f4 +! g4 in
  (o0, o1, o2, o3, o4)
```

- No need to compute modular reduction immediately

Bignum multiplication over $\mathbb{F}_{2^{130}-5}$

```
val mul5: f:felem5 → r:felem5 → r5:felem5 → Pure felem_wide5
  (requires
    felem_fits5 f (3, 3, 3, 3, 3) ∧ felem_fits5 r (1, 1, 1, 1, 1) ∧
    felem_fits5 r5 (5, 5, 5, 5, 5) ∧ r5 == precomp_r5 r)
  (ensures λ out →
    felem_wide_fits5 out (63, 51, 39, 27, 15) ∧
    feval_wide out == fmul (feval5 f) (feval5 r))
let mul5 (f0, f1, f2, f3, f4) (r0, r1, r2, r3, r4) (r50, r51, r52, r53, r54) =
  let out = smul5 f0 (r0, r1, r2, r3, r4) in
  let out = smul_add5 f1 (r54, r0, r1, r2, r3) out in
  let out = smul_add5 f2 (r53, r54, r0, r1, r2) out in
  let out = smul_add5 f3 (r52, r53, r54, r0, r1) out in
  let out = smul_add5 f4 (r51, r52, r53, r54, r0) out in
  out
```

Demo

- Low-level specification written in F⋆:

  example-poly/Hacl.Spec.Poly.fst

  example-poly/Hacl.Spec.Poly.Lemmas.fst

  example-poly/Hacl.Spec.Poly.Lemmas0.fst

- Low⋆ implementation:

  example-poly/Hacl.Impl.Poly.Field.fst

  example-poly/Hacl.Impl.Poly.fst

Exercise

Write a verified implementation of Gimli[2] in F*!

What should you first look at?

- lowstar/gimli/Spec.Gimli.fst
- lowstar/gimli/Hacl.Impl.Gimli.fst

	F*	Low*
	Lib.IntTypes.fsti	
	Lib.RawIntTypes.fsti (BREAKS secret independence)	
lib/	Lib.Sequence.fsti	Lib.Buffer.fsti
	Lib.ByteSequence.fsti	Lib.ByteBuffer.fsti
	Lib.LoopCombinators.fsti	Lib.Loops.fsti
	specs/	*code/*
chacha20	Spec.Chacha20.fst	Hacl.Impl.Chacha20.Core32.fst
		Hacl.Impl.Chacha20.fst
SHA3	Spec.SHA3.fst	Hacl.Impl.SHA3.fst

[2] Gimli: a cross-platform permutation `https://gimli.cr.yp.to/spec.html`

Conclusion

Questions?

- HACL*: `https://github.com/project-everest/hacl-star`
- F*: `https://www.fstar-lang.org`

- INRIA PROSECCO: `http://prosecco.inria.fr`
- Microsoft Project Everest: `https://project-everest.github.io`