Microsoft Research

Each year Microsoft Research hosts hundreds of influential speakers from around the world including leading scientists, renowned experts in technology, book authors, and leading academics, and makes videos of these lectures freely available.

Project Everest
theory meets reality

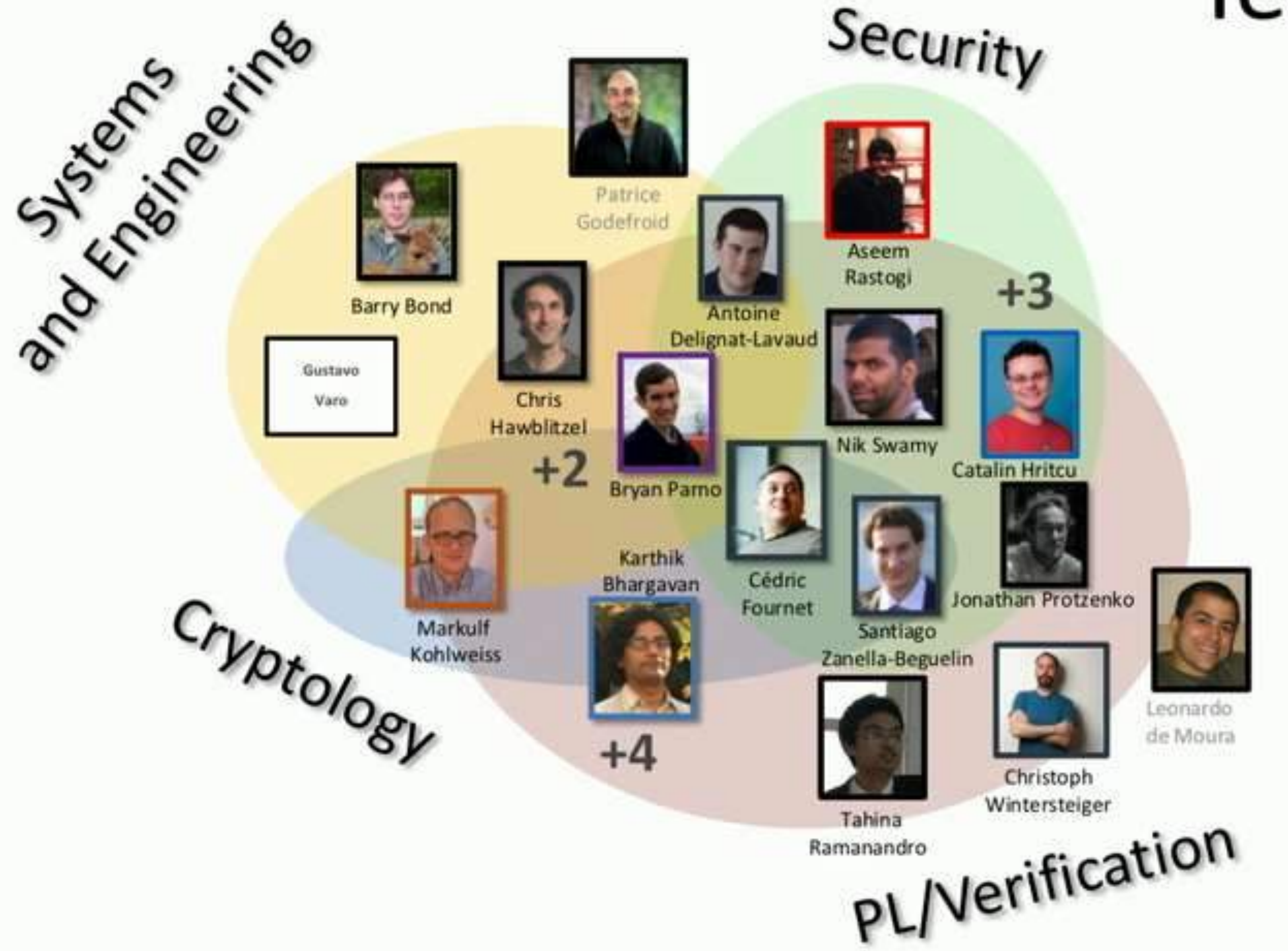
Jonathan Protzenko

Microsoft Research

Project Everest

INRIA Paris
MSR Redmond, Cambridge, Bangalore
CMU

Team Members



Cambridge

Bangalore

Redmond

Paris (INRIA)

Pittsburgh (CMU)

Edinburgh

Everest:
Deploying Verified-Secure Implementations in the HTTPS Ecosystem


CIAO
TRATTORIA - PIZZERIA
WINE - BAR
EVEREST
Scaffolding Inc.
1150 LONGWOOD AVE. BRONX, NY 10474
(718) 328-1004
EXP 08 24 18
PAYLESS SIGNS
212.912.3456
Ciao Vineria Con Cucina

1. Verification challenges in the HTTPS ecosystem
2. A formalized toolchain for delivering C and ASM code
3. Tooling support for programmer productivity
4. Stories from the “real world”

① Challenges in the HTTPS ecosystem

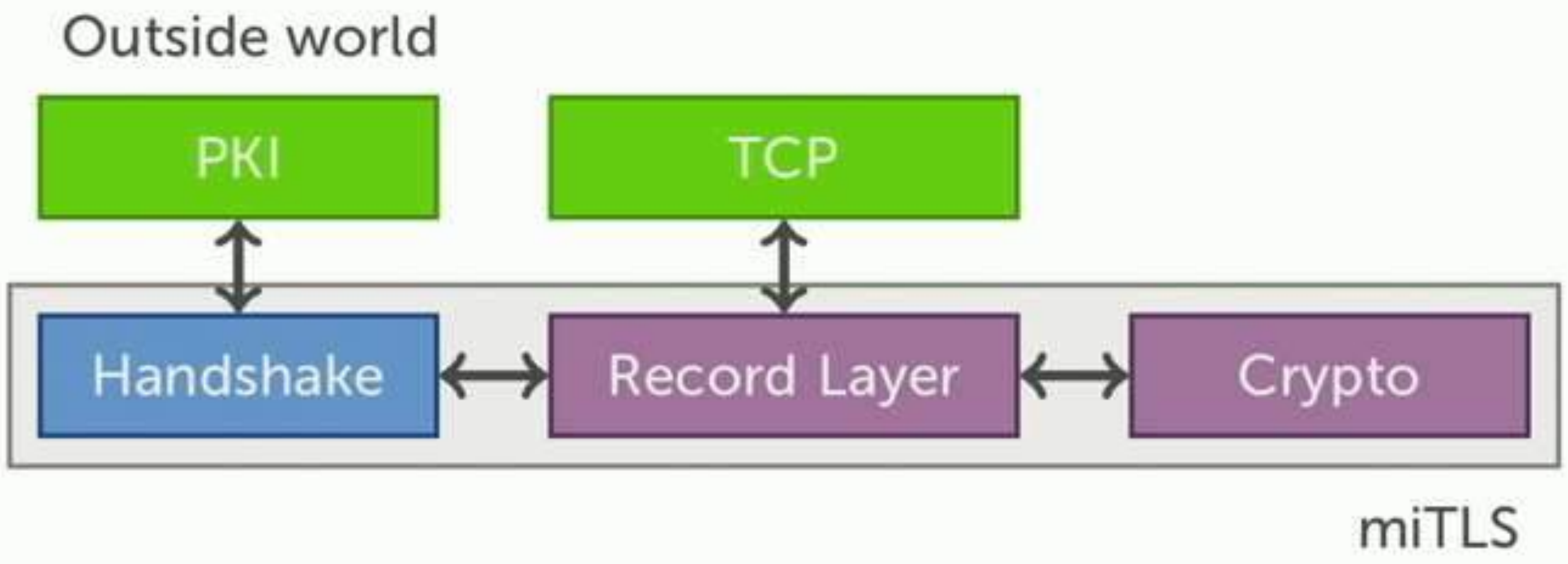
What is there to verify?

Everest: Expedition for a VERified Secure Transport

- A verified secure HTTPS ecosystem: this is huge
- Just focusing on TLS and QUIC and their dependencies
- But first, some background on TLS

HTTPS: the TLS protocol

TLS stands for *transport layer security*.



Two different kinds of beasts:

- the protocol layer
- the record layer

HTTPS: the QUIC protocol

Based on UDP instead of TCP.

Two goals: latency and multiplexing.

Re-uses the handshake from TLS 1.3 (0RTT) but then does its own thing for the stream data.

Why is it hard? (The crypto)

Implement efficient arithmetic over large numbers (bignums).

- Optimized bitwise operations
- Each bignum has its own optimized representation (reuse)
- Difficult to exhaustively test

Goal: functional correctness (implies memory safety) + side-channel resistance.

Why is it hard? (Poly1305 example)

These heavily optimized C implementations have bugs.

Why is it hard? (Poly1305 example)

have bugs.

```
OpenSSL Security Advisory [10 Nov 2016]
========================================

ChaCha20/Poly1305 heap-buffer-overflow (CVE-2016-7054)
======================================================

Severity: High

TLS connections us
attack by corrupti
issue is not consi
```

[openssl-dev] [openssl.org #4482] Wrong results with Poly1305 functions

Hanno Boeck via RT rt at
Fri Mar 25 12:10:32 UTC

- Previous message: [o
  when using "no-asm
- Next message: [open
- **Messages sorted by:**

```
Attached is a sample code
Poly1305 functions of ope

These produce wrong resul
the other three also on 6
```

[openssl-dev] [openssl.org #4439] poly1305-x86.pl produces incorrect output

David Benjamin via RT rt at openssl.org
Thu Mar 17 21:22:26 UTC 2016

- Previous message: [openssl-dev] [openssl-users] Removing some systems
- Next message: [openssl-dev] [openssl.org #4439] poly1305-x86.pl produces incorrect output
- **Messages sorted by:** [date] [thread] [subject] [author]

```
Hi folks,

You know the drill. See the attached poly1305_test2.c.

$ OPENSSL_ia32cap=0 ./poly1305_test2
PASS
$ ./poly1305_test2
Poly1305 test failed.
got:      2637408fe03086ea73f971e3425e2820
expected: 2637408fe13086ea73f971e3425e2820

I believe this affects both the SSE2 and AVX2 code. It does seem to be
dependent on this input pattern.

This was found because a run of our SSL tests happened to find a
problematic input. I've trimmed it down to the first block where they
disagree.

I'm probably going to write something to generate random inputs and stress
all your other poly1305 codepaths against a reference
recommend doing the same in your own test ness, to
```

Why is it hard (record layer)

Provide a safe cryptographic functionality by combining primitive blocks. Example: AEAD.

- Multiplex between different algorithms (AES-GCM, Chacha-Poly).
- Safely combine the cryptographic primitives.
- Reason about integrity, authenticity, confidentiality.

Goal: cryptographic strength + side-channel resistance.

Why is it hard (the handshake)

Provide a correct state machine that manages keys properly.

- Need for speed: 0-RTT and 0.5-RTT
- Multiple ways to derive keys (PSK, forward secrecy, rekeying)
- Handle choice of algorithms, versions (1.2 *vs.* 1.3)

Goal: cryptographic security.

Why is it hard (the handshake)

Parse messages following the RFC.

- Parsers are notoriously error-prone.
- Need to interop, but hard to exhaust all the code-paths.
- RFC informal.

Goal: memory safety ("if it interops, it interops").

Why is it hard (QUIC)

Implement retransmission, windows, error correction, out-of-order frames, etc.

- Low-level systems programming
- Data structures: “inline” doubly-linked lists with ugly C macros
- Concurrency with different streams
- Interaction with the rest of the OS
- Risk of integer overflow

Goal: memory safety

In short...

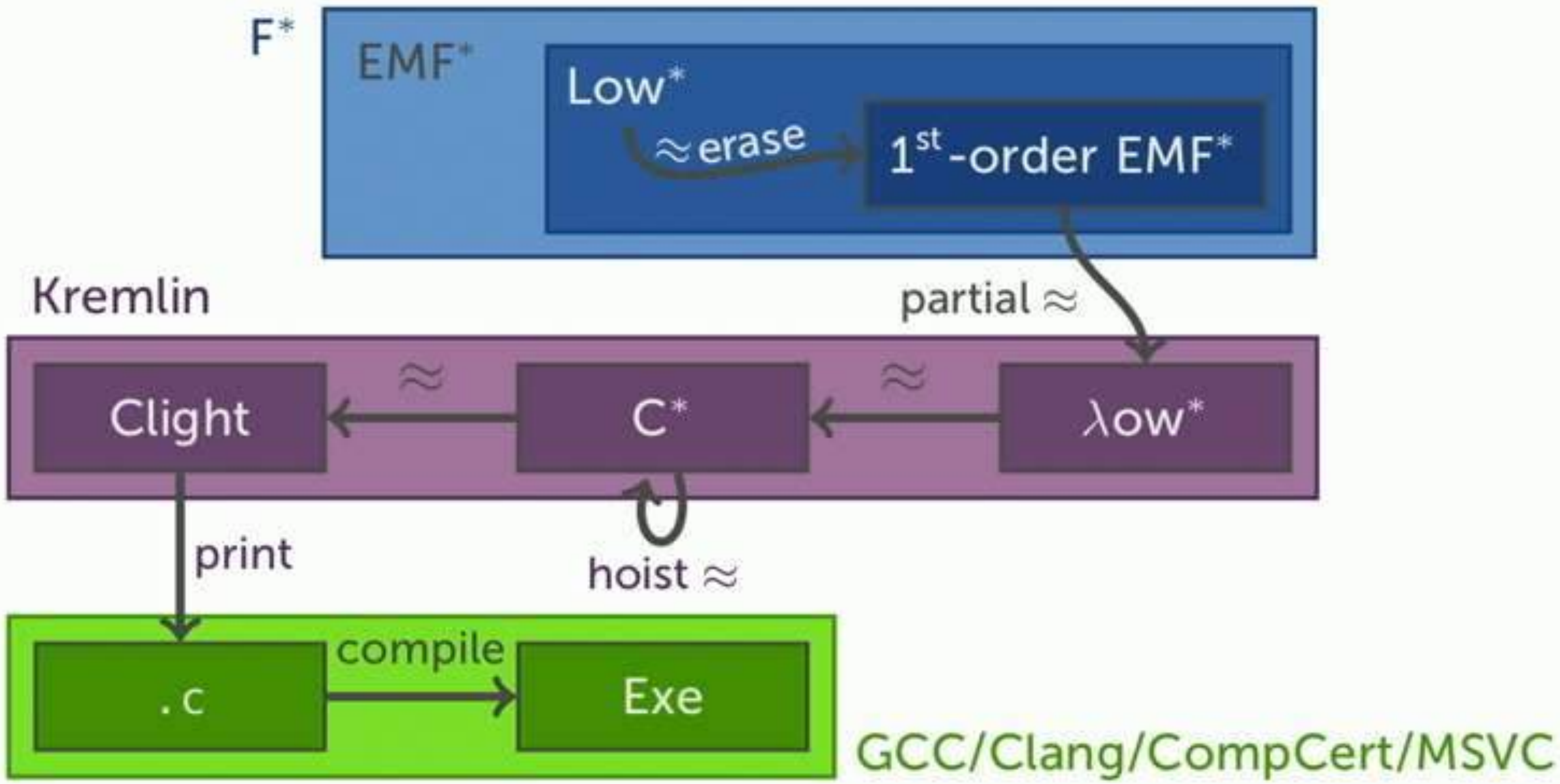
Many different types of guarantees. The HTTPS ecosystem really is a minefield.

Status:

- crypto: verified (some algorithms)
- record layer: verified
- handshake: in progress
- parser: nearing completion
- QUIC: scheduled
- PKI: on the horizon

② A formalized toolchain

With a diagram



Disclaimer: these steps are supported by hand-written proofs.

The design of Low*

High-level verification for low-level code

For code, the programmer:

- opts in the Low* effect to model the C stack and heap;
- uses low-level libraries for arrays and structs;
- leverages combinator libraries to get C loops;
- meta-programs first-order code;
- relies on data types sparingly.

For proofs and specs, the programmer:

- can use all of F*,
- prove memory safety, correctness, crypto games, relying on
- erasure to yield a first-order program.

Motto: the code is low-level but the verification is not.

A sample cryptographic operation: Poly1305

Poly1305 is a message authentication code.

$$MAC(k, m, \vec{w}) = m + \sum_{i=1}^{|\vec{w}|} w_i \times k^i$$

It authenticates the data $\vec{w}$ by:

- encoding it as a polynomial in the prime field $2^{130} - 5$
- evaluating it at a random point k (first part of the key)
- masking the result with m (second part of the key)

A sample cryptographic operation: Poly1305

Poly1305 is a message authentication code.

$$MAC(k, m, \vec{w}) = m + \sum_{i=1}^{|\vec{w}|} w_i \times k^i$$

A typical 64-bit arithmetic implementation:

- represents elements of the prime field ($p = 2^{130} - 5$) using three *limbs* holding 42 + 44 + 44 bits in 64-bit registers
- uses $(a \times 2^{130} + b)\%p = (a + 4a + b)\%p$ for reductions
- unfolds the loop

Specifying, programming and verifying Poly1305

Spec.Poly1305.fst

```
module Spec.Poly1305

let prime = pow2 130 - 5
type elem = e:ℤ{e ≥ 0 ∧ e < prime}
let fadd (e1:elem) (e2:elem) = (e1 + e2) % prime
let fmul (e1:elem) (e2:elem) = (e1 × e2) % prime

(* Specification code *)
let encode (w:word) =
  (pow2 (8 × length w)) `fadd` (little_endian w)

let rec poly (txt:text) (r:e:elem) : Tot elem (decreases (length txt)) =
  if length txt = 0 then zero
  else
    let a = poly (Seq.tail txt) r in
    let n = encode (Seq.head txt) in
    (n `fadd` a) `fmul` r
```

```
-:**-  Spec.Poly1305.fst   All (2,0)    Git-master  (F✪ company)
Auto-saving...done
```

Hacl.Impl.Poly1305_64.fst

File Edit Options Buffers Tools F★ Help

memory safety

math spec

code

proof

```
[@"substitute"]
val poly1305_last_pass_:
  acc:felem →
  Stack unit
    (requires (λ h → live h acc ∧ bounds (as_seq h acc) p44 p44 p42))
    (ensures (λ h0 _ h1 → live h0 acc ∧ bounds (as_seq h0 acc) p44 p44 p42
      ∧ live h1 acc ∧ bounds (as_seq h1 acc) p44 p44 p42
      ∧ modifies_1 acc h0 h1
      ∧ as_seq h1 acc == Hacl.Spec.Poly1305_64.poly1305_last_pass_spec_ (as_seq h0 acc)))

[@"substitute"]
let poly1305_last_pass_ acc =
  let a0 = acc.(0ul) in
  let a1 = acc.(1ul) in
  let a2 = acc.(2ul) in
  let open Hacl.Bignum.Limb in
  let mask0 = gte_mask a0 Hacl.Spec.Poly1305_64.p44m5 in
  let mask1 = eq_mask a1 Hacl.Spec.Poly1305_64.p44m1 in
  let mask2 = eq_mask a2 Hacl.Spec.Poly1305_64.p42m1 in
  let mask = mask0 &^ mask1 &^ mask2 in
  UInt.logand_lemma_1 (v mask0); UInt.logand_lemma_1 (v mask1); UInt.logand_lemma_1 (v mask2);
  UInt.logand_lemma_2 (v mask0); UInt.logand_lemma_2 (v mask1); UInt.logand_lemma_2 (v mask2);
  UInt.logand_associative (v mask0) (v mask1) (v mask2);
  cut (v mask = UInt.ones 64 ⟹ (v a0 ≥ pow2 44 - 5 ∧ v a1 = pow2 44 - 1 ∧ v a2 = pow2 42 - 1));
  UInt.logand_lemma_1 (v Hacl.Spec.Poly1305_64.p44m5); UInt.logand_lemma_1 (v Hacl.Spec.Poly1305_64.p44m1);
  UInt.logand_lemma_1 (v Hacl.Spec.Poly1305_64.p42m1); UInt.logand_lemma_2 (v Hacl.Spec.Poly1305_64.p44m5);
  UInt.logand_lemma_2 (v Hacl.Spec.Poly1305_64.p44m1); UInt.logand_lemma_2 (v Hacl.Spec.Poly1305_64.p42m1);
  let a0' = a0 -^ (Hacl.Spec.Poly1305_64.p44m5 &^ mask) in
  let a1' = a1 -^ (Hacl.Spec.Poly1305_64.p44m1 &^ mask) in
  let a2' = a2 -^ (Hacl.Spec.Poly1305_64.p42m1 &^ mask) in
  upd_3 acc a0' a1' a2'
```

-:**- Hacl.Impl.Poly1305_64.fst 55% L394 Git-master (F★ FlyC- company ElDoc Wrap)

Poly1305_64.c

File Edit Options Buffers Tools C Help

```c
static void Hacl_Impl_Poly1305_64_poly1305_last_pass(uint64_t *acc)
{
  Hacl_Bignum_Fproduct_carry_limb_(acc);
  Hacl_Bignum_Modulo_carry_top(acc);
  uint64_t a0 = acc[0];
  uint64_t a10 = acc[1];
  uint64_t a20 = acc[2];
  uint64_t a0_ = a0 & (uint64_t )0xfffffffffff;
  uint64_t r0 = a0 >> (uint32_t )44;
  uint64_t a1_ = (a10 + r0) & (uint64_t )0xfffffffffff;
  uint64_t r1 = (a10 + r0) >> (uint32_t )44;
  uint64_t a2_ = a20 + r1;
  acc[0] = a0_;
  acc[1] = a1_;
  acc[2] = a2_;
  Hacl_Bignum_Modulo_carry_top(acc);
  uint64_t i0 = acc[0];
  uint64_t i1 = acc[1];
  uint64_t i0_ = i0 & (((uint64_t )1 << (uint32_t )44) - (uint64_t )1);
  uint64_t i1_ = i1 + (i0 >> (uint32_t )44);
  acc[0] = i0_;
  acc[1] = i1_;
  uint64_t a00 = acc[0];
  uint64_t a1 = acc[1];
  uint64_t a2 = acc[2];
  uint64_t mask0 = FStar_UInt64_gte_mask(a00, (uint64_t )0xffffffffffb);
  uint64_t mask1 = FStar_UInt64_eq_mask(a1, (uint64_t )0xfffffffffff);
  uint64_t mask2 = FStar_UInt64_eq_mask(a2, (uint64_t )0x3ffffffffff);
  uint64_t mask = mask0 & mask1 & mask2;
  uint64_t a0_0 = a00 - ((uint64_t )0xffffffffffb & mask);
  uint64_t a1_0 = a1 - ((uint64_t )0xfffffffffff & mask);
  uint64_t a2_0 = a2 - ((uint64_t )0x3ffffffffff & mask);
  acc[0] = a0_0;
  acc[1] = a1_0;
  acc[2] = a2_0;
}
```

-:**- Poly1305_64.c 49% L272 Git-master (C/l company A

Insights about our formalization

High-level verification for low-level code (2)

Our low-level, stack-based memory model.

```
effect Stack (a:Type) (pre:st_pre) (post: (mem -> Tot (st_post a))) =
  STATE a (fun (p:st_post a) (h:mem) ->
    pre h /\ (∀ a h1.
      (pre h /\ post h a h1 /\ equal_domains h h1) ==> p a h1))

let equal_domains (m0:mem) (m1:mem) =
  m0.tip = m1.tip
  /\ Set.equal (Map.domain m0.h) (Map.domain m1.h)
  /\ (forall r. Map.contains m0.h r ==>
    Heap.equal_dom (Map.sel m0.h r) (Map.sel m1.h r))
```

Preserves the layout of the stack and doesn't allocate in any caller frame.

High-level verification for low-level code (2)

Our low-level, stack-based memory model.

```
effect Stack (a:T                                    post a))) =
  STATE a (fun (p
    pre h /\ (∀ a h1.
      (pre h /\ post h a h1 /\ equal_domains h h1) ==> p a h1))
```

preservation of the stack structure

```
let equal_domains (m0:mem) (m1:mem) =
  m0.tip = m1.tip
  /\ Set.equal (Map.domain m0.h) (Map.domain m1.h)
  /\ (forall r. Map.contains m0.h r ==>
    Heap.equal_dom (Map.sel m0.h r) (Map.sel m1.h r))
```

Preserves the layout of the stack and doesn't allocate in any caller frame.

High-level verification for low-level code (2)

Our low-level, stack-based memory model.

```
effect Stack (a:Type) (pre:st_pre) (post: (mem -> Tot (st_post a))) =
  STATE a (fun (p:st_post a) (h:mem) ->
    pre h /\ (∀ a h1.
      (pre h /\ post h a h1 /\ equal_domains h h1) ==> p a h1))

let equal_domains (m0:mem) (m1:mem) =
  m0.tip = m1.tip
  /\ Set.equal (Map.domain m0.h) (Map.domain m1.h)
  /\ (for                              =>
    Heap.                              Map.sel m1.h r))
```

the tip remains the same

Preserves the layout of the stack and doesn't allocate in any caller frame.

High-level verification for low-level code (3)

Our low-level, sequence-based buffer model.

```
val index: #a:Type -> b:buffer a -> n:UInt32.t{v n < length b} ->
  Stack a
    (requires (fun h -> live h b))
    (ensures (fun h0 z h1 -> live h0 b /\ h1 == h0
      /\ z == Seq.index (as_seq h0 b) (v n)))
let index #a b n =
  let s = !b.content in
  Seq.index s (v b.idx + v n)
```

We swap this F* model with a low-level implementation.
`buffer int` becomes **`int*`** and **`index b i`** becomes **`b[i]`**.

High-level verification for low-level code (3)

Our low-level, sequence-based buf

spatial
safety

```
val index: #a:Type -> b:buffer a -> n:UInt32.t{v n < length b} ->
  Stack a
    (requires (fun h -> live h b))
    (ensures (fun h0 z h1 -> live h0 b /\ h1 == h0
      /\ z == Seq.index (as_seq h0 b) (v n)))
let index #a b n =
  let s = !b.content in
  Seq.index s (v b.idx + v n)
```

We swap this F* model with a low-level implementation.
buffer int becomes **int*** and **index b i** becomes **b[i]**.

High-level verification for low-level code (3)

Our low-level, sequence-based buffer model.

```
val index: #a:Type -> b:buffer a -> n:UInt32.t{v n < length b} ->
  Stack a
    (requires (fun h -> live h b))
    (ensures (fun h0 z h1 -> live h0 b /\ h1 == h0
      /\ z == Seq.index (as_seq h0 b) (v n)))
let index #a b n =
  let s = !b.content in
  Seq.index s (v b.idx + v n)
```

temporal safety

We swap this F* model with a low-level implementation.
`buffer int` becomes **`int*`** and **`index b i`** becomes **`b[i]`**.

Side-channel resistance

What are we protecting against

- We want to guard against some memory and timing side-channels
- Our secret data is at an abstract type
- By using abstraction, we can control what operations we allow on secret data

Abstraction to the rescue

Our module for secret integers exposes a handful of audited, carefully-crafted functions that we trust have secret-independent traces.

```
(* limbs only ghostly revealed as numbers *)
val v : limb -> Ghost nat

val eq_mask: x:limb -> y:limb ->
  Tot (z:limb{if v x <> v y then v z = 0 else v z = pow2 26 - 1})
```

By construction, the programmer cannot use a `limb` for branching or array accesses.

What we show

We model trace events as part of our reduction.

$$\ell ::= \cdot \mid \mathsf{read}(b, n, \overrightarrow{f}) \mid \mathsf{write}(b, n, \overrightarrow{f}) \mid \mathsf{brT} \mid \mathsf{brF} \mid \ell_1, \ell_2$$

Note: this does not rule out ALL side channels!

The KreMLin tool

A compiler from F* to *readable* C

The KreMLin facts:

- about 14,000 lines of OCaml
- carefully engineered to generate readable C code
- essential for integration into existing software.

Design:

- relies on the same Letouzey-style erasure from F*
- one internal AST with several compilation passes
- abstract C grammar + pretty-printer
- small amounts of hand-written C code (host functions)

So far, about 120k lines of C generated.

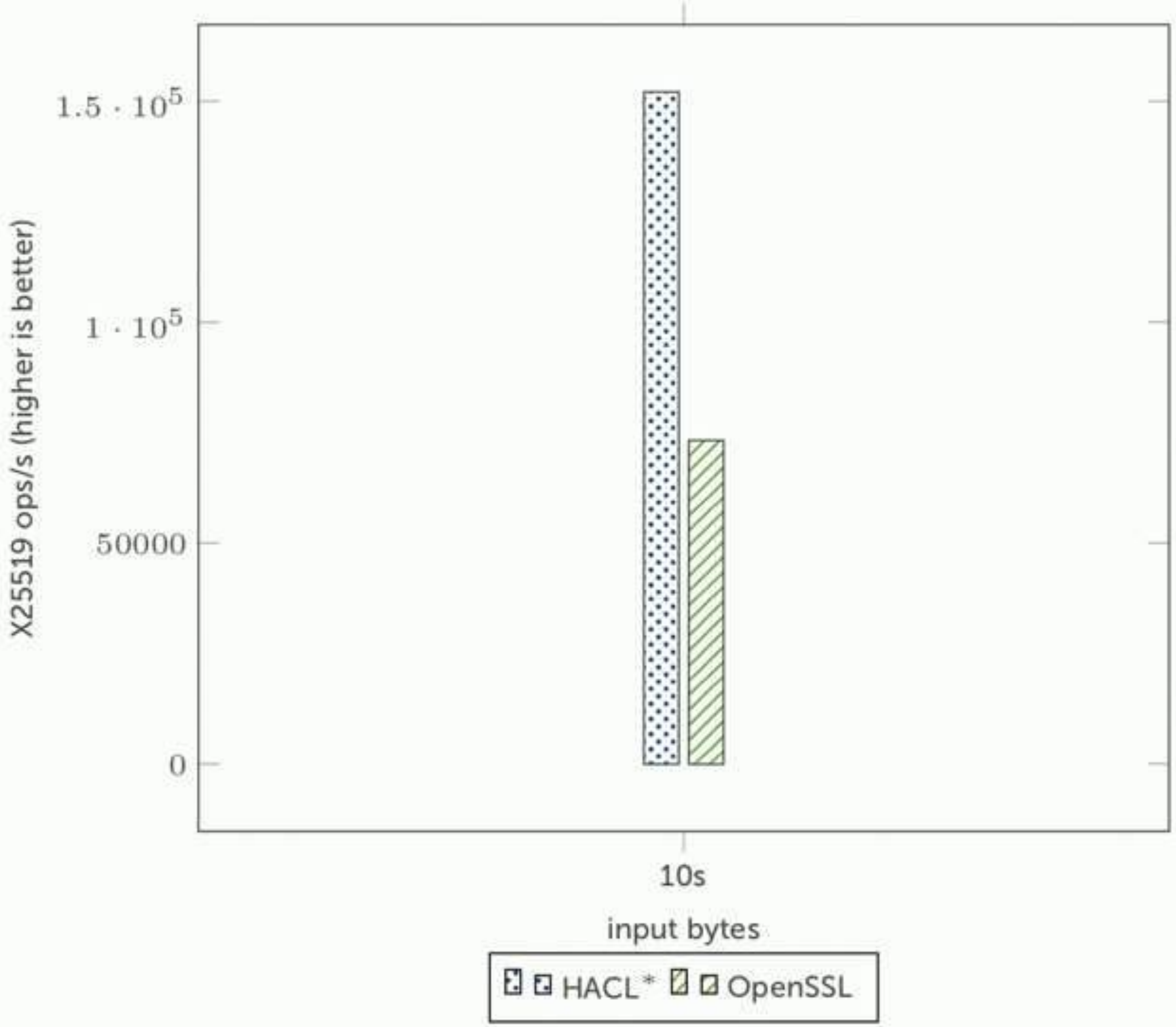
Evaluation

A word on HACL*

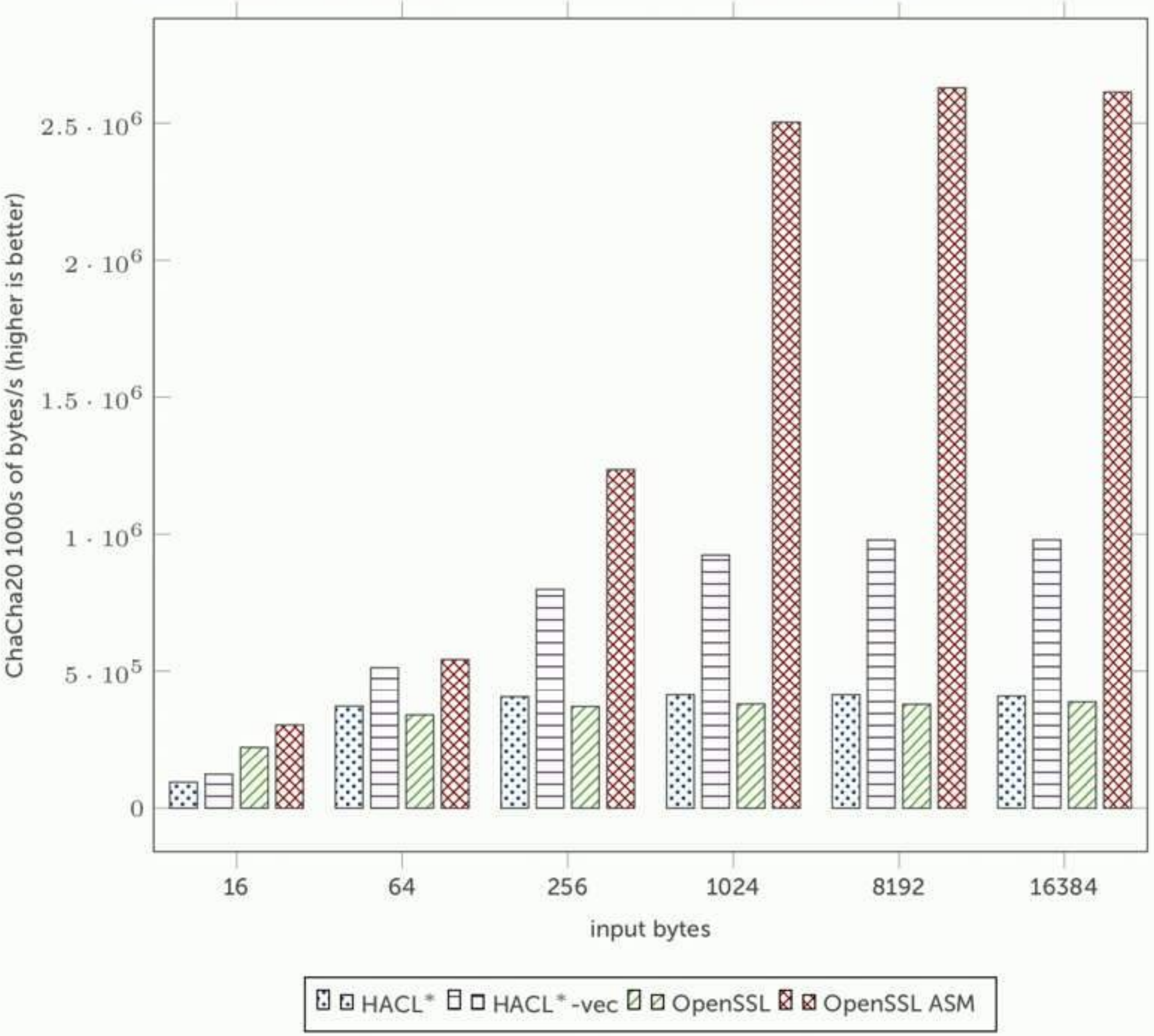
Our crypto algorithms library. Available standalone, as an OpenSSL engine, or via the NaCl API.

- Implements Chacha20, Salsa20, Curve25519, X25519, Poly1305, SHA-2, HMAC
- 7000 lines of C code
- 23,000 lines of F* code
- Performance is comparable to existing C code (not ASM)
- Some bits are in the Firefox web browser!

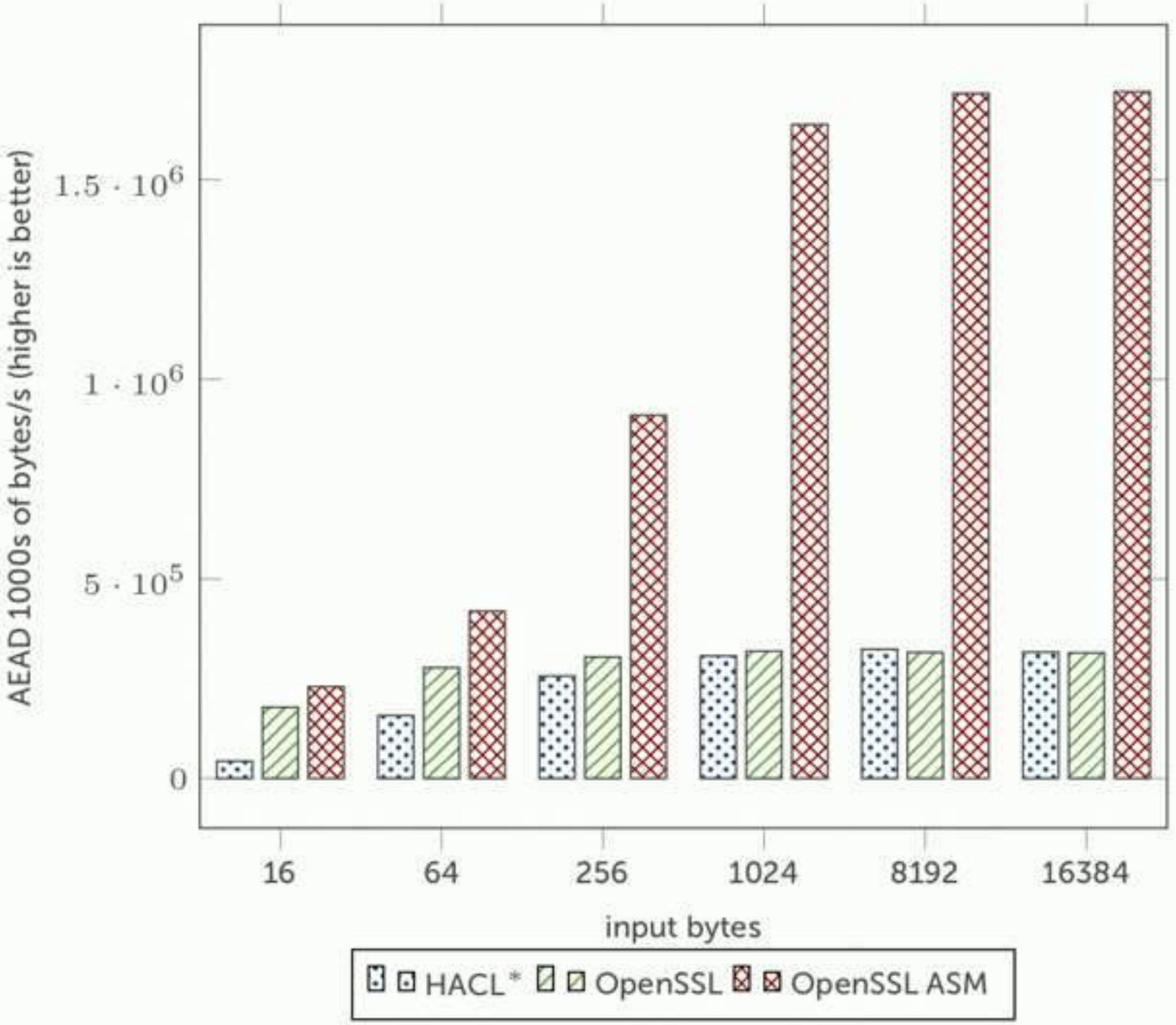
Jean-Karim Zinzindohoué, Karthikeyan Bhargavan, Jonathan Protzenko, Benjamin Beurdouche
HACL*: A Verified Modern Cryptographic Library
CCS'17



1.5 · 10^5
1 · 10^5
50000
0
X25519 ops/s (higher is better)
10s
input bytes
HACL*
OpenSSL



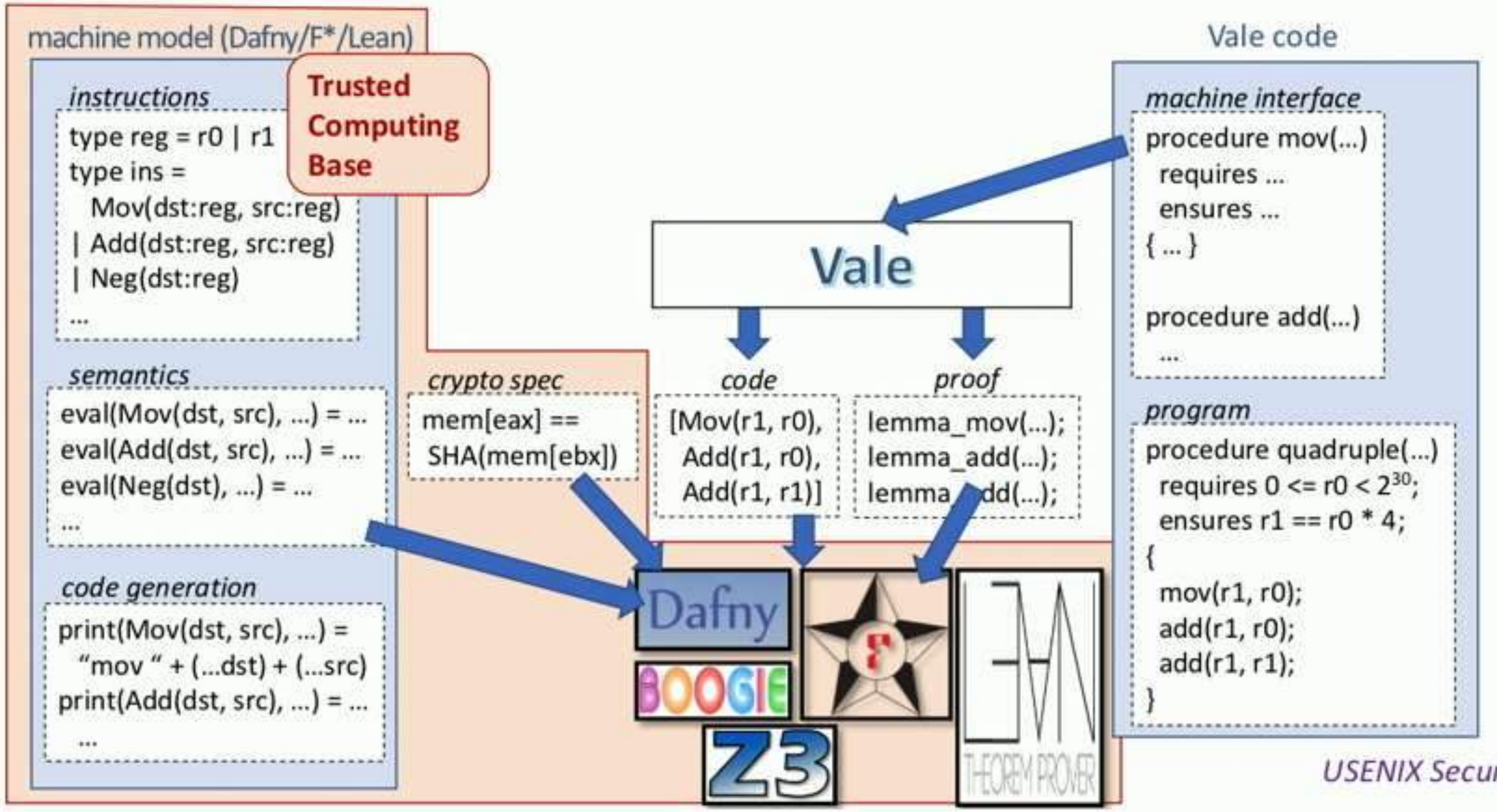
ChaCha20 1000s of bytes/s (higher is better)
0
$5 \cdot 10^5$
$1 \cdot 10^6$
$1.5 \cdot 10^6$
$2 \cdot 10^6$
$2.5 \cdot 10^6$
16
64
256
1024
8192
16384
input bytes
HACL*
HACL*-vec
OpenSSL
OpenSSL ASM



AEAD 1000s of bytes/s (higher is better)
$1.5 \cdot 10^6$
$1 \cdot 10^6$
$5 \cdot 10^5$
0
16
64
256
1024
8192
16384
input bytes
HACL*
OpenSSL
OpenSSL ASM

Vale

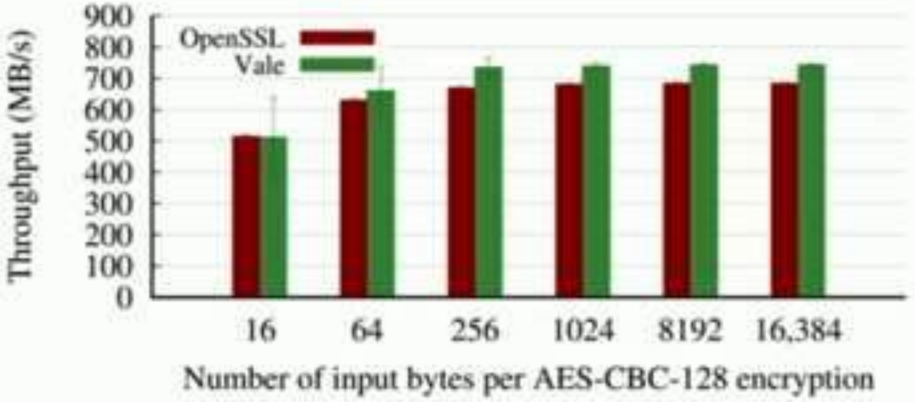
Vale: extensible, assembly language verification

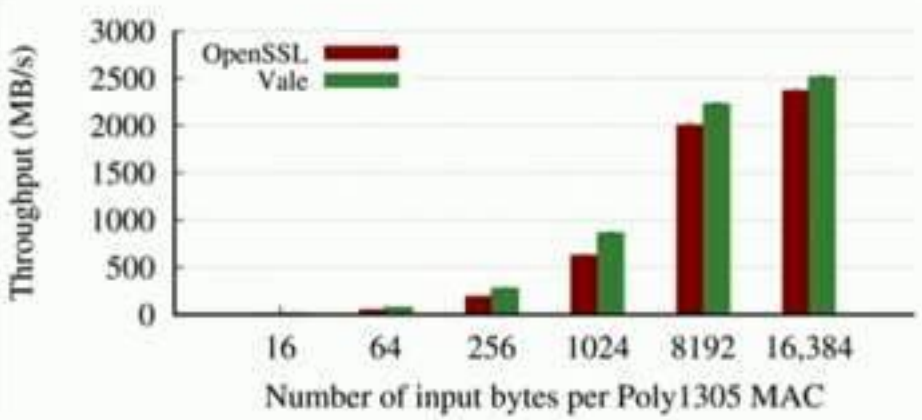


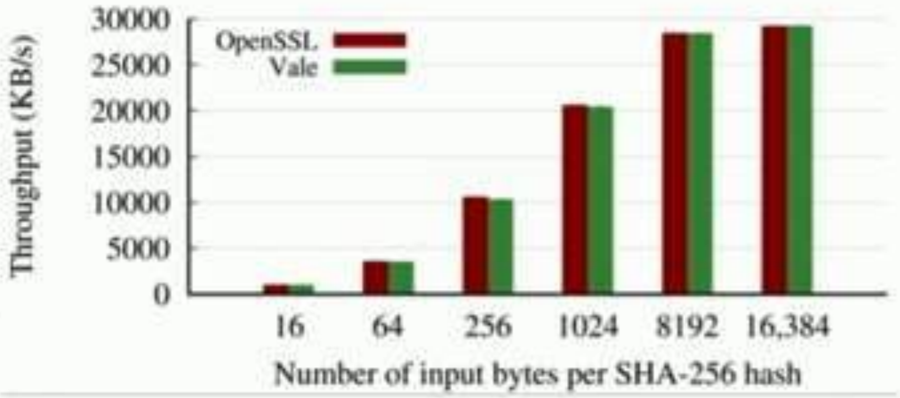
USENIX Security 2017

Crypto performance: OpenSSL vs. Vale

- AES: OpenSSL with SIMD, AES-NI
- Poly1305 and SHA-256: OpenSSL non-SIMD assembly language
  - Same assembly code for OpenSSL, Vale







③ Tooling support

Cryptography: a (too) good example

- Crystal clear math spec
- Trivial allocation patterns
- The code is naturally low-level

A driver that informed the design and implementation of Low*.

But! ...beyond cryptography

- Allocation patterns are more complex
- The code is naturally higher-level
- Surprise: people actually do not want to write C in F*
- Strong push for more tooling support

A point in the design space

Reality	moving beyond the paper formalization
Tension	the tooling is not verified
Claim	priority ordering: high-risk source, lower risk tooling

Productivity/scaling vs. Verified toolchain

Tooling support: killing abstraction

Abstraction	= good for verification
No Abstraction	= good for compilation

- At the module level (`-bundle`)
- At the function level (`inline_for_extraction`)

This triggers enough compiler optimizations to fulfill the original promise.

Tooling support: data types

Or: "programmer productivity".

- Tuples, inductives (tagged unions) are supported
- Four (!) different compilation schemes
- Use at your own risk (MSVC! CompCert! x86 ABI!)
- Requires:
  - monomorphization
  - implementation in KreMLin of recursive equality predicates
  - mutual recursion; forward declarations

Tooling support: misc

- Type abbreviations
- C loops (syntactic closures for bodies)
- Removal of **uu___**
- Optimal visibility
- Removal of unused function and data types arguments
- Passing structures by reference

Tooling support: conclusion

so... none of this is rocket science

but... it's a slippery slope

idea have a mode that disables cosmetic optimizations to do differential testing.

There is a constant tension (e.g. tail-rec).

There is hope: all the bugs found so far were either in the formalization, in unverified, glue code, or in the compiler.

④ Two stories about the real world

1. Firefox
2. Windows Kernel mode

Firefox (1): the code

- These people actually read our code
- Stringent coding standards
  - parentheses
  - unused variables
  - unused parameters
- Cosmetic (indentation, no clang-format)
- More fundamentally: no recursion and no **`uint128`** support (cross-platform)
- Still need to implement const support ($\neq$ our formalization)

Firefox (2): the infrastructure

- They used a Docker VM to put the toolchain under CI
- No one can modify the code directly
- One student at INRIA supports them
- Minimize the hand-written glue code (`FStar.h` and `kremlib.h`)

Kernel mode (1): why?

- Lower latency (usermode/kernelmode transitions) + connection management in-kernel
- Pooling of connections to the same domain
- Better security (keys in OS memory)
- Primitive IO API support
- Makes it available to other drivers

Kernel mode (2): MSVC

The first problem was the Microsoft Compiler (MSVC)

- VS2017 has decent C11 support
- No **`uint128`** type
- No variable-length arrays
- Arbitrary nested struct depth
- Unpredictable tail-calls and struct passing optimizations

Kernel mode (3): all the other things

A lof of things were not captured by our formalization.

- excessive stack consumption: limit is **12k** in kernel mode (value structs, lack of tail-calls)
- abuse of recursion: byte-by-byte copy is great for verification but...
- need to offer C-like APIs: some amount of glue code

Stack overflows are not good...

Kernel mode (4): misc

- No C runtime means different APIs
- Logging APIs
- Symbol collisions
- MSVC compiler bug
- C standard library bug

⑤ Conclusion

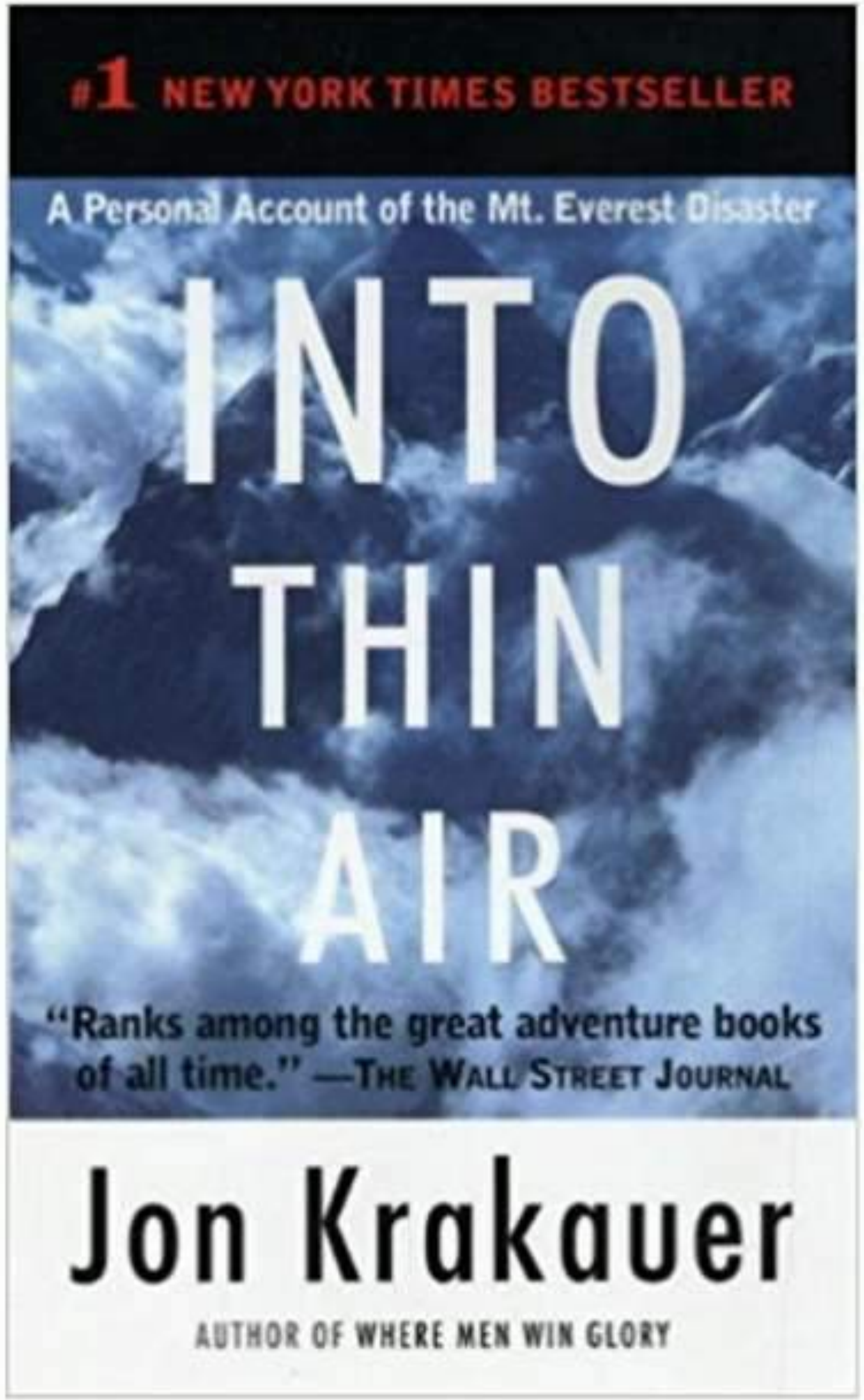
In hindsight

- The paper is only half the work
- Prioritize verification effort
- Nothing beats good CI and testing
- Tooling matters

Your future plans

It's all on GitHub!

- `https://www.github.com/FStarLang/FStar`
- `https://www.github.com/project-everest/vale`
- `https://www.github.com/FStarLang/kremlin`
- `https://www.github.com/mitls/mitls-fstar`
- `https://www.github.com/mitls/hacl-star`
- `https://www.github.com/project-everest/everest`



Thanks.
Questions?