Secure compilation from F* to C

using the KreMLin compiler

K. Bharghavan, C. Hritcu, J-K. Zinzindohoué
`INRIA`

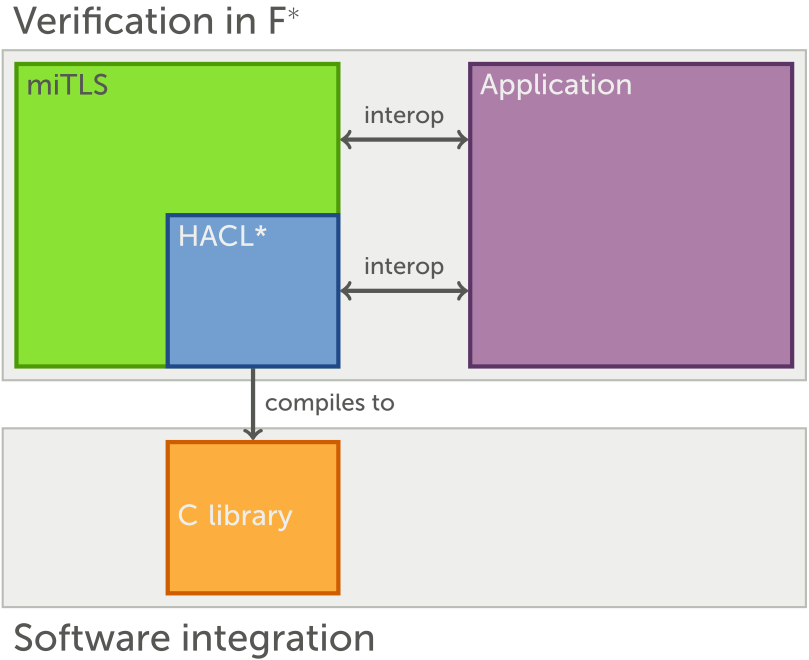
P. Wang
`MIT`

A. Delignat-Lavaud, C. Fournet, J. Protzenko,
T. Ramananandro, A. Rastogi, N. Swamy, S. Zanella-Beguelin
`Microsoft`

Everest:

Deploying Verified-Secure Implementations in the HTTPS Ecosystem

An overview of our approach


Verification in F*
miTLS
HACL*
interop
Application
interop
compiles to
C library
Software integration

High-level whole-stack proofs

We want a very expressive language for:

- side-channel resistance proofs,
- memory safety,
- cryptographic security,
- functional correctness.

We use F*.

High-level whole-stack proofs

We want a very expressive language for:

- side-channel resistance proofs,
- memory safety,
- cryptographic security,
- functional correctness.

We use F*.

Low-level software

We want to go to C.

- Go where the software is.
- Piecewise release of software components (e.g. HACL*).
- Progressive replacement, not wholesale switch (incremental).

High-level verification for low-level code

This our motto: we shallowly embed C in F*.

Low-level memory model + low-level libraries = compilation scheme to C.

The code is low-level, but the verification is not.

We call the low-level subset of F* is Low*.

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

Typically, F* extracts to OCaml.

With the C backend, we have explicit control over performance:

- no implicit allocations,
- manual, stack-based memory management,
- buffers, loops, structures.

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

Our low-level, stack-based memory model.

```
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))

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))
```

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

High-level verification for low-level code (4)

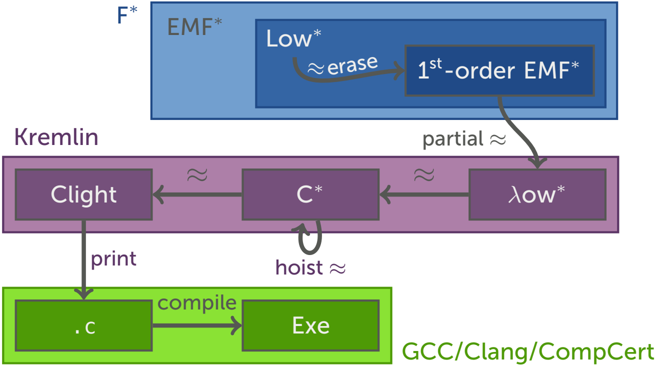
Our low-level, sequence-based buffer model.

```
noeq private type _buffer (a:Type) =
  | MkBuffer: max_length:UInt32.t
    -> content:reference (s:seq a{Seq.length s == v max_length})
    -> idx:UInt32.t
    -> length:UInt32.t{v idx + v length <= v max_length}
    -> _buffer a

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]`**.

Our toolchain



Disclaimer: these steps are currently hand-written proofs.

A function in HACL*, original F* code

```
[@ ”c_inline”]
val chacha20_block:
  log:log_t ->
  stream_block:uint8_p{length stream_block = 64} ->
  st:state{disjoint st stream_block} ->
  ctr:UInt32.t ->
  Stack log_t
    (requires (fun h -> live h stream_block /\ invariant log h st))
    (ensures  (fun h0 updated_log h1 -> live h1 stream_block /\ invariant log h0 st
      /\ invariant updated_log h1 st /\ modifies_2 stream_block st h0 h1
      /\ (let block = reveal_sbytes (as_seq h1 stream_block) in
         match Ghost.reveal log, Ghost.reveal updated_log with
         | MkLog k n, MkLog k’ n’ ->
             block == chacha20_block k n (U32.v ctr) /\ k == k’ /\ n == n’)))
[@ ”c_inline”]
let chacha20_block log stream_block st ctr =
  push_frame();
  let h_0 = ST.get() in
  let st’ = Buffer.create (uint32_to_sint32 0ul) 16ul in
  let log’ = chacha20_core log st’ st ctr in
  uint32s_to_le_bytes stream_block st’ 16ul;
  let h = ST.get() in
  cut (reveal_sbytes (as_seq h stream_block) == chacha20_block (Ghost.reveal log’).k (Ghost.reveal log’).n (
  cut (modifies_3_2 stream_block st h_0 h);
  pop_frame();
  Ghost.elift1 (fun l -> match l with | MkLog k n -> MkLog k n) log’
```

A function in HACL*, extracted C code

```
inline static void
Hacl_Impl_Chacha20_chacha20_block(uint8_t *stream_block,
  uint32_t *st,
  uint32_t ctr)
{
  uint32_t st_[16] = { 0 };
  Hacl_Impl_Chacha20_chacha20_core(st_, st, ctr);
  Hacl_Lib_LoadStore32_uint32s_to_le_bytes(stream_block,
    st_,
    (uint32_t )16);
  return;
}
```

Applications of our methodology

- HACL*, our high-assurance crypto library
    - as a standalone library
    - within an OpenSSL engine (speed / benchmark)
    - as a NaCl alternative (**`LD_PRELOAD`**)
- miTLS, our TLS library in F* (WIP)
    - as an alternate SSL backend for curl
    - a fork of Nginx
- low-level parsers (e.g. ASN.1) (WIP)

Applications of our methodology

Demo!

- HACL*, our high-assurance crypto library
  - as a standalone library
  - within an OpenSSL engine (speed / benchmark)
  - as a NaCl alternative (**`LD_PRELOAD`**)
- miTLS, our TLS library in F* (WIP)
  - as an alternate SSL backend for curl
  - a fork of Nginx
- low-level parsers (e.g. ASN.1) (WIP)

Preservation of correctness and side-channel resistance

Removal of ghost code (1)

- `Ghost` is an F* effect
- Used only for proofs, i.e. specifications ("contagious")
- $\boxed{\text{ABSOLUTELY}}$ does not fit in Low*
- Removed via a logical relations argument

Removal of erased (2)

- `erased a` is a computationally-irrelevant value
- unlike `Ghost`, can be used within code
- used for the `log` of operations, say, in Chacha
- the value can be used in specifications via:
  `val reveal: #a -> erased a -> GTot a`

All erased values, being irrelevant, can be compiled to `()` (ML).
We remove them via a whole-program analysis.

From monadic to effectful semantics (3)

Explicitly-monadic F* (POPL'17) can be translated to a primitive state semantics.

Danel Ahman, Cătălin Hriţcu, Guido Martínez, Gordon Plotkin, Jonathan Protzenko, Aseem Rastogi, Nikhil Swamy.
Dijkstra Monads for Free
POPL'17

From the user-facing Low* to λow* (4)

A series of (unproven) transformations for programmer convenience.

- going from an expression language to a statement language
- compilation of pattern-matching
- structures by value
- etc.

These are performed by the KreMLin tool.

The core lambda-calculus: λow^*

$$
\begin{array}{rl}
\tau ::= & \mathsf{int} \mid \mathsf{unit} \mid \{\overrightarrow{f = \tau}\} \mid \mathsf{buf}\ \tau \mid \alpha \\
v ::= & x \mid n \mid () \mid \{\overrightarrow{f = v}\} \mid (b, n, \overrightarrow{f}) \\
e ::= & \mathsf{let}\ x : \tau = \mathsf{readbuf}\ e_1\ e_2\ \mathsf{in}\ e \mid \mathsf{let}\ \_ = \mathsf{writebuf}\ e_1\ e_2\ e_3\ \mathsf{in}\ e \\
\mid & \mathsf{let}\ x = \mathsf{newbuf}\ n\ (e_1 : \tau)\ \mathsf{in}\ e_2 \mid \mathsf{subbuf}\ e_1\ e_2 \\
\mid & \mathsf{let}\ x : \tau = \mathsf{readstruct}\ e_1\ \mathsf{in}\ e \mid \mathsf{let}\ \_ = \mathsf{writestruct}\ e_1\ e_2\ \mathsf{in}\ e \\
\mid & \mathsf{let}\ x = \mathsf{newstruct}\ (e_1 : \tau)\ \mathsf{in}\ e_2 \mid e_1 \triangleright f \\
\mid & \mathsf{withframe}\ e \mid \mathsf{pop}\ e \mid \mathsf{if}\ e_1\ \mathsf{then}\ e_2\ \mathsf{else}\ e_3 \\
\mid & \mathsf{let}\ x : \tau = d\ e_1\ \mathsf{in}\ e_2 \mid \mathsf{let}\ x : \tau = e_1\ \mathsf{in}\ e_2 \mid \{\overrightarrow{f = e}\} \mid e.f \mid v \\
P ::= & \cdot \mid \mathsf{let}\ d = \lambda y : \tau_1.\ e : \tau_2, P
\end{array}
$$

About λow^*:

- a type system without progress
- in a simulation with the original F* program
- standard substitutive semantics.

The judgements of λow^*

Typing judgement:

$$\Gamma_P; \Sigma; \Gamma \vdash e : \tau$$

where:

- Γ_P is the set of global program definitions
- Σ is the store typing
- Γ is the local context

The judgements of λow* (2)

Reduction semantics:

$$P \vdash (H, e) \xrightarrow{\ell} (H', e')$$

where:

- ℓ is the set of trace events
- H is the stack of frames

Let's talk about traces!

The judgements of λow* (2)

Reduction semantics:

$$P \vdash (H, e) \xrightarrow{\ell} (H', e')$$

where:

- ℓ is the set of trace events
- H is the stack of frames

Let's talk about traces!

Traces in λow^*

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

We record:

- memory accesses, reads and writes
- branching

Traces in λow^*: the secret library

We assume a trusted module that operates on secrets, whose traces are secret-independent.

```
(* 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})
```

We trust that the **eq_mask** function has been written properly.

Secret-independence: an intuition

A type-indexed relation $v_1 \equiv_\tau v_2$ over values:

$$
\begin{gathered}
n \equiv_{\mathsf{int}} n \\
v_1 \equiv_a v_2 \\
\ldots
\end{gathered}
$$

Intuition: terms are related if they only differ on sub-terms at secret types.

Main theorem: functions, when applied to related values in related stores, have related reductions and emit the same traces.

Theorem (Secret independence)

Given

1. *A program well-typed against a secret interface,* Γ_s*, i.e,* $\Gamma_s, \Gamma_P; \Sigma; \Gamma \vdash (H, e) : \tau$*, where e is not a value.*
2. *A well-typed implementation of the* Γ_s *interface,* $\Gamma_s; \Sigma; \cdot \vdash_\Delta P_s$*, such that* P_s *is equivalent modulo secrets.*
3. *A pair* (ρ_1, ρ_2) *of well-typed (related) substitutions for* Γ*.*

There exists $\ell, \Sigma' \supseteq \Sigma, \Gamma', H', e'$ *and a pair* (ρ'_1, ρ'_2) *of well-typed substitutions for* Γ'*, such that*

1. $P_s, P \vdash (H, e)[\rho_1] \rightarrow^+_\ell (H', e')[\rho'_1]$ *if and only if,* $P_s, P \vdash (H, e)[\rho_2] \rightarrow^+_\ell (H', e')[\rho'_2]$*, and*
2. $\Gamma_s, \Gamma_P; \Sigma'; \Gamma' \vdash (H', e') : \tau$

Next step: C*, an imperative language

This our next intermediary language.

- statement language
- not substitutive semantics (stack of contexts with holes)
- expressions are pure
- deterministic

We relate λow* programs to C* programs via a simulation.

A glimpse of the reduction rules

From λow*:

$$\frac{}{P \vdash (H, \textsf{if } 0 \textsf{ then } e_1 \textsf{ else } e_2) \rightarrow_{\textsf{brF}} (H, e_2)} \textsf{LIfF}$$

From C*:

$$\frac{[\![\hat{e}]\!]_{(V)} = 0}{\hat{P} \vdash (S, V, \textsf{if } \hat{e} \textsf{ then } \overrightarrow{s_1} \textsf{ else } \overrightarrow{s_2}; \overrightarrow{s}) \rightsquigarrow_{\textsf{brF}} (S, V, \overrightarrow{s_2}; \overrightarrow{s})} \textsf{CIfF}$$

Theorem

The C* program $\hat{P}$ terminates with trace ℓ and return value v, i.e., $\hat{P} \vdash ([], V, \overrightarrow{s}; \mathit{return}\ \hat{e}) \overset{\ell,*}{\to} ([], V', \mathit{return}\ v)$ if, and only if, so does the λow* program: $P \vdash (\{\}, e[V]) \overset{\ell,*}{\to} (H', v)$; and similarly for divergence.

Next step: C^* to CompCert Clight

We encode the trace preservation using builtins that generate trace events.

Two relevant bits:

- hoisting, which changes the memory layout (abstract traces)
- struct passing, which changes the memory accesses (two passes)

Final step: Clight to assembly

Some possible approaches:

- instrument CompCert (Barthe *et al.*)
- Use Vellvm (Zdancewicz *et al.*)

Thanks. Questions?