F* and Meta-F*

Formal Verification, Language Extensibility, and Proof automation

Nik Swamy
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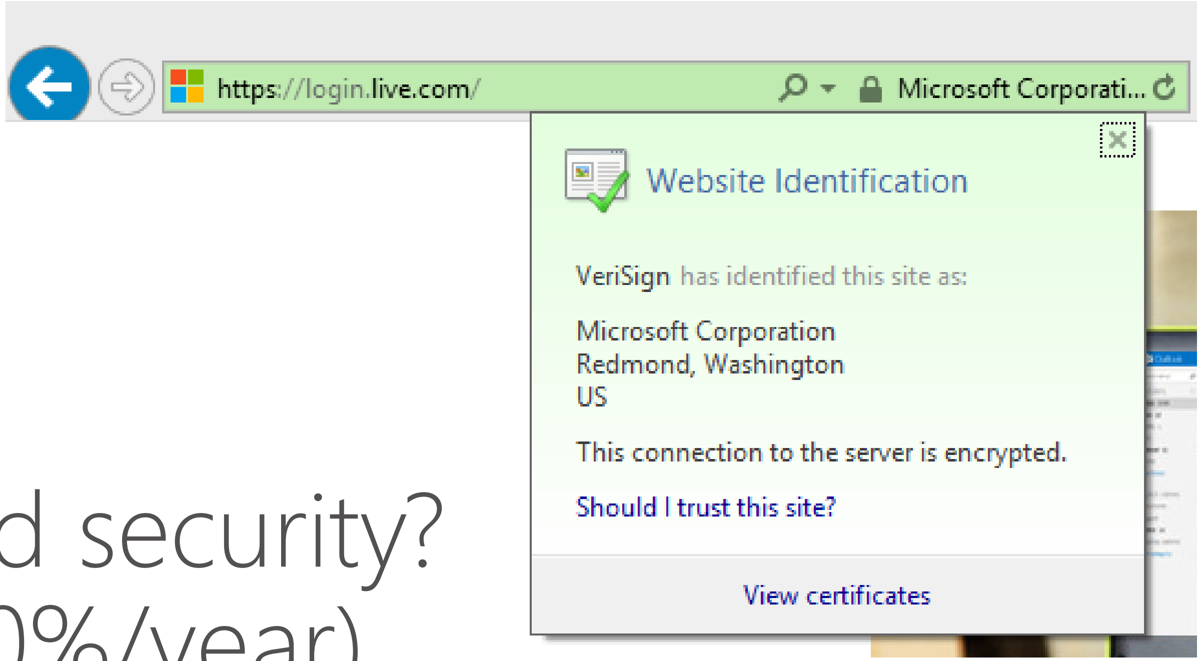
As applied in Project Everest

Microsoft Research
Inria INVENTEURS DU MONDE NUMÉRIQUE
Carnegie Mellon University
Microsoft Research - Inria JOINT CENTRE

https://fstar-lang.github.io
https://project-everest.github.io/

TLS: Transport Layer Security



- Most widely deployed security?
  ½ Internet traffic (+40%/year)
- Web, cloud, email, VoIP, 802.1x, VPNs, …

TLS: Transport Layer Security

Goal: A secure channel

20 years of attacks & fixes

- Buffer overflows
- Incorrect state machines
- Lax certificate parsing
- Weak or poorly implemented crypto
- Side channels
- Informal security goals
- Dangerous APIs
- Flawed standards

Mainstream implementations

OpenSSL, SChannel, NSS, …

The Washington Post

The Switch

'FREAK' flaw undermines security for Apple and Google users, researchers discover

As long as the adversary does not control the long-term credentials of the client and server, it cannot

- Inject forged data into the stream (authenticity)
- Distinguish the data stream from random bytes (confidentiality)

TLS 1.3: a new hope

Much discussions

IETF, Google, Mozilla, Microsoft, CDNs, cryptographers, network engineers, …

Much improvements

- Modern design
- Fewer roundtrips
- Stronger security

New implementations required for all

- An early implementer and verified too!
- Find & fix flaws before it's too late

Network Working Group
Internet-Draft
Obsoletes: 5077, 5246, 5746 (if approved)
Updates: 4492 (if approved)
Intended status: Standards Track
Expires: September 23, 2016

E. Rescorla
RTFM, Inc.
March 22, 2016

The Transport Layer Security (TLS) Protocol Version 1.3

Table of Contents

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RFC 8446: Aug 2018

Including many of our proposals

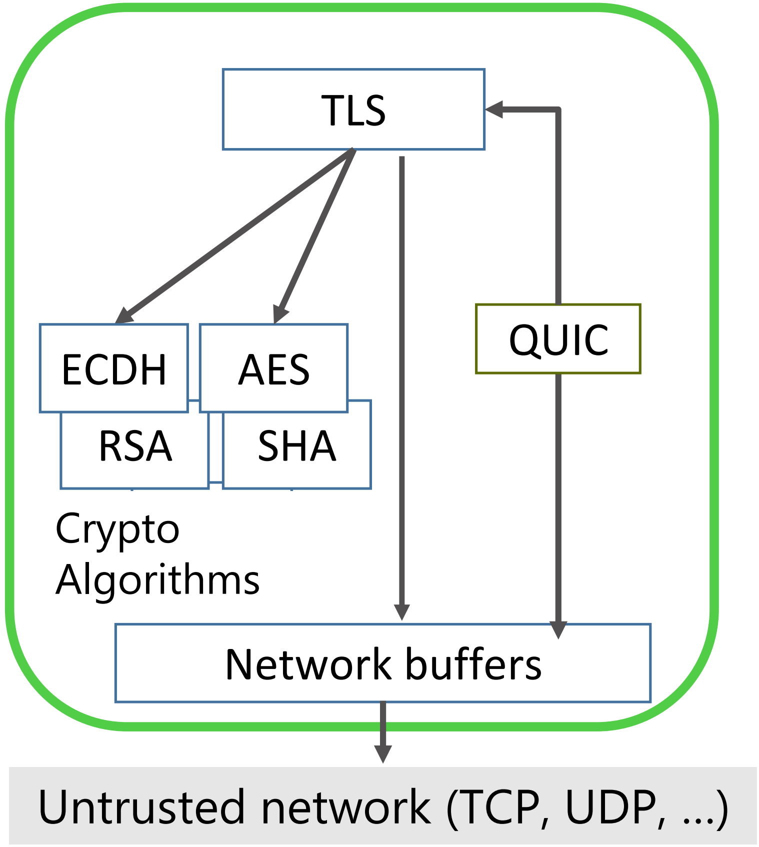
#4	log-based key separation extended session hashes (fixing attacks we found on 1.2)
#11	stream terminators (eventually fixing an attack)
#14	downgrade resilience
#15	session ticket format
#17	simplified key schedule pre-shared-key 0RTT
#18	PSK binding (fixing an attack)

Mentioning many formal models of the protocol, including our verified implementation of the record layer

Project Everest

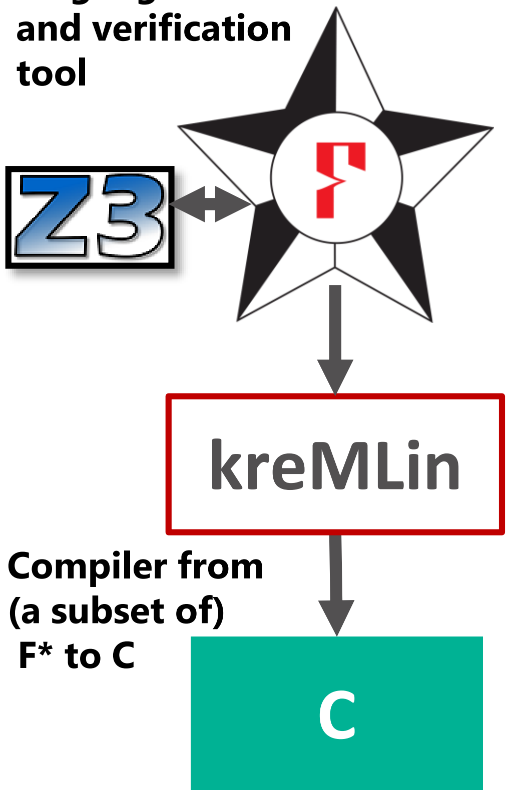
Verified Secure Components in the TLS Ecosystem

- Strong verified security
- Widespread deployment
- Trustworthy, usable tools
- Growing expertise in high-assurance software development
- Open source



Verification Tools and Methodology

F*: A general purpose programming language and verification tool



Compiler from (a subset of) F* to C

Math spec in F*

`poly1305_mac` computes a polynomial in GF(2^{130}-5), storing the result in `tag`, and not modifying anything else

```
val poly1305_mac: tag:nbytes 16 →
                  len:u32 →
                  msg:nbytes len{disjoint tag msg} →
                  key:nbytes 32 {disjoint msg key ∧ disjoint tag key} →
                     ST unit
      (requires (λ h → msg ∈ h ∧ key ∈ h ∧ tag ∈ h))
      (ensures (λ h0 _ h1 →
          let r=Spec.clamp h0.[sub key 0 16] in
          let s=h0.[sub key 16 16] in
          modifies {tag} h0 h1 ∧
          h1.[tag] == Spec.mac_1305 (encode_bytes h0.[msg]) r s))
```

Efficient C implementation

Verification imposes no runtime performance overhead

```
void
poly1305_mac(uint8_t *tag, uint32_t len, uint8_t *msg, uint8_t *key)
{
    uint64_t tmp [10] = { 0 };
    uint64_t *acc = tmp
    uint64_t *r = tmp + (uint32_t)5;
    uint8_t s[16] = { 0 };
    Crypto_Symmetric_Poly1305_poly1305_init(r, s, key);
    Crypto_Symmetric_Poly1305_poly1305_process(msg, len, acc, r);
    Crypto_Symmetric_Poly1305_poly1305_finish(tag, acc, s);
}
```

Proof strategy (simplified)

= Trusted

= Verified

Security spec

Protocol security proofs

Protocol specs

Implementation

Crypto assumptions

Secure authenticated channel

Definition 3.4.1 Let $F\colon \mathcal{K} \times D \to R$ be a family of functions, and let A be an algorithm that takes an oracle and returns a bit. We consider two games as described in Fig. 3.1. The *prf-advantage* of A is defined as

$$\mathbf{Adv}_F^{\mathrm{prf}}(A) = \Pr\left[\mathrm{Real}_F^A \Rightarrow 1\right] - \Pr\left[\mathrm{Rand}_R^A \Rightarrow 1\right]$$

```
Network Working Group                                        E. Rescorla
Internet-Draft                                                RTFM, Inc.
Obsoletes: 3268, 4346, 4366, 5246, 5077                    July 08, 2015
             (if approved)
Updates: 4492 (if approved)
Intended status: Standards Track
Expires: January 9, 2016


        The Transport Layer Security (TLS) Protocol Version 1.3
                         draft-ietf-tls-tls13-07

Abstract

   This document specifies Version 1.3 of the Transport Layer Security
   (TLS) protocol.  The TLS protocol provides communications security
   over the Internet.  The protocol allows client/server applications to
   communicate in a way that is designed to prevent eavesdropping,
   tampering, or message forgery.

Status of This Memo

   This Internet-Draft is submitted in full conformance with the
   provisions of BCP 78 and BCP 79.

   Internet-Drafts are working documents of the Internet Engineering
   Task Force (IETF).  Note that other groups may also distribute
   working documents as Internet-Drafts.  The list of current Internet-
   Drafts is at http://datatracker.ietf.org/drafts/current/.

   Internet-Drafts are draft documents valid for a maximum of six months
   and may be updated, replaced, or obsoleted by other documents at any
   time.  It is inappropriate to use Internet-Drafts as reference
```

AES is a pseudo-random function

What do we verify?

Safety

Memory- and type-safety. Mitigates buffer overruns, dangling pointers, code injections.

Functional correctness

Our fast implementations behave precisely as our simpler specifications.

Secrecy

Access to secrets, including crypto keys and private app data is restricted according to design.

Cryptographic security

We bound the probability that an attacker may break any secrecy or integrity properties

Everest in Action, so far

Production deployments of Everest Verified Cryptography

WinQUIC: Delivered Everest TLS 1.3 and crypto stack to Windows Networking, in the latest Windows developer previews

Mozilla NSS runs Everest verified crypto for several core algorithms

Everest verified crypto in the Linux kernel via WireGuard secure VPN

So what is this F* thing anyway?

A programming language
A proof assistant
A program verification tool

Two camps of program verification tools

Interactive proof assistants			Semi-automated verifiers of imperative programs	
Coq,	CompCert,	*air*	Dafny,	Verve,
Isabelle,	seL4,		FramaC,	IronClad,
Agda,	Bedrock,		Why3	miTLS
Lean, PVS, …	4 colors	*gap*		Vale

- **In the left corner**: Very expressive dependently-typed logics, but only purely functional programming
- **In the right**: effectful programming, SMT-based automation, but only first-order logic

F*: Bridging the gap

- Functional programming language with effects
  - Like OCaml, Haskell, F#, …
  - Compiles to OCaml or F#
  - A subset of F* compiled to C (with manual control over memory management)
- With an expressive core dependent type theory
  - Like Coq, Agda, Lean, …
- Semi-automated verification using SMT
  - Like Dafny, Vcc, Liquid Haskell, …
- In-language extensibility and proof automation using metaprograms

A first taste

- Write ML-like code

```
let rec factorial n =
  if n = 0 then 1
  else n * factorial (n - 1)
```

- Give it a specification, claiming that `factorial` is a total function from non-negative to positive integers.

```
val factorial: n:int{n >= 0} -> Tot (i:int{i >= 1})
```

- Ask F* to check it

```
fstar factorial.fst
Verified module: Factorial
All verification conditions discharged successfully
```

```
fstar factorial.fst
Verified module: Factorial
All verification conditions discharged successfully
```

F* builds a typing derivation of the form:

$$\Gamma_{\text{prelude}} \vdash \texttt{let factorial n = e} : t \Leftarrow \phi$$

- In a context Γ_{prelude} including definitions of F* primitives
- The program `let factorial n = e` has type t, given the validity of a logical formula ϕ
- ϕ is passed to Z3 (an automated theorem prover/SMT solver) to check for validity
- If the check succeds, then, from the metatheory of F*, the program is safe at type t

Beyond Pure Code

Effects

- Programmers model effects with monads
  - `st a = s -> a * s`
- F* derives a WP calculus for use with that monad
  - Also known as *Dijkstra* monads
  - `st_post a = a * s -> prop`
  - `st_pre = s -> prop`
  - `wp_st a = st_post a -> st_pre`
- And a computation type for effectful terms
  - Computations indexed by their own WPs: `STATE a (wp : wp_st a)`

Effectful programs with Hoare-style Specifications

```
let invert (r:ref int)
  : STExn unit
    (requires fun h0 -> True)
    (ensures fun h0 v h1 -> no_exn v ==> h0.[r] <> 0 /\ h1.[r] = 1 / h0.[r])
 =
    let x = !r in
    if x = 0 then
      raise Division_by_zero
    else r :=  1 / x
```

Effectful programs with Hoare-style Specifications

```
let invert (r:ref int)
  : STExn unit
    (requires fun h0 -> h0.[r] <> 0)
    (ensures fun h0 v h1 -> no_exn v /\ h1.[r] = 1 / h0.[r])
 =
    let x = !r in
    if x = 0 then
      raise Division_by_zero
    else r :=  1 / x
```

Exploiting Expressiveness & Extensibility

Low*: A subset of F* that compiles to C

- Embed within F* a CompCert C-like memory model
  - Low*: An effect for stateful programs manipulating a C-like memory model
  - Programs in the Low* effect are extracted to C by KreMLin, F*'s C backend

- Separate memory region for heaps and stacks
  - A region is a heterogeneous partial map
  - `region = addr -> option (a:Type & a)`

- With libraries modeling mutable arrays, pointers, structs, unions

Low* to C

And to support compilation to C, in nearly 1-1 correspondence, for auditability of our generated code

Designed to allow manipulating a C-like view of memory

Low* COMPILED C

```
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 → modifies_1 output m0 m1)) =
    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 ()
```

Erased specification

Stack allocation

Pointer arithmetic

```
let encrypt (#i:id) (e:writer i) (ad:bytes) (l:plainLen) (p:plain i l)
  : ST (cipher i l)
      (requires (λ h0 →
        l ≤ max_TLSPlaintext_fragment_length ∧
        sel h0 (ctr e.counter) < max_ctr))
      (ensures  (λ h0 c h1 →
        modifies [e.log_region] h0 h1 ∧
        h1 `HS.contains` (ctr e.counter) ∧
        sel h1 (ctr e.counter) == sel h0 (ctr e.counter) + 1 ∧
        (authId i ⟹
         let log = ilog e.log in
         let ent = Entry l c p in
         let n = Seq.length (sel h0 log) in
         h1 `HS.contains` log ∧
         witnessed (at_least n ent log) ∧
         sel h1 log == snoc (sel h0 log) ent))) =
  let h0 = get() in
  let ctr = ctr e.counter in
  HST.recall ctr; //lemma
  let text = if safeId i then create_ l 0z else repr i l p in
  let n = !ctr in
  lemma_repr_bytes_values n; //lemma
  let nb = bytes_of_int (AEAD.noncelen i) n in
  let iv = AEAD.create_nonce e.aead nb in
  lemma_repr_bytes_values (length text); //lemma
  let c = AEAD.encrypt e.aead iv ad text in
  if authId i then
    begin
    let ilog = ilog e.log in
    HST.recall ilog; //lemma
    let ictr: ideal_ctr e.region i ilog = e.counter in
    testify_seqn ictr;
    write_at_end ilog (Entry l c p);
    HST.recall ictr; //lemma
    increment_seqn ictr;
    HST.recall ictr //lemma
    end
  else
    ctr := n + 1;
  c
```

Dependently typed specs in the style of Hoare Type Theory / Coq

Dafny-ish proofs mostly automated by SMT, with a few well-chosen user-supplied lemmas

But SMT-based proofs can go awry

- E.g., when using theories like non-linear arithmetic

```
let lemma_carry_limb_unrolled (a0 a1 a2:nat) : Lemma
    (requires ⊤)
    (ensures (a0 % p44 + p44 * ((a1 + a0 / p44) % p44) + p88 * (a2 + ((a1 + a0 / p44) / p44))
             = a0 + p44 * a1 + p88 * a2)) =
  let open FStar.Math.Lemmas in
  let z = a0 % p44 + p44 * ((a1 + a0 / p44) % p44) + p88 * (a2 + ((a1 + a0 / p44) / p44)) in
  distributivity_add_right p88 a2 ((a1 + a0 / p44) / p44); (* argh! *)
  pow2_plus 44 44;
  lemma_div_mod (a1 + a0 / p44) p44;
  distributivity_add_right p44 ((a1 + a0 / p44) % p44) (p44 * ((a1 + a0 / p44) / p44)); (* argh! *)
  assert (p44 * ((a1 + a0 / p44) % p44) + p88 * ((a1 + a0 / p44) / p44) = p44 * (a1 + a0 / p44) );
  distributivity_add_right p44 a1 (a0 / p44); (* argh! *)
  lemma_div_mod a0 p44
```

Forced to write very detailed proof terms when SMT fails

And can be at a low level of abstraction

- Lots of boilerplate to define parsers/formatters and prove them mutually inverse

emacs@NSWAMY-SURFBK

File Edit Options Buffers Tools Help

```
let cipherSuiteBytes cs =
    match cs with
    | UnknownCipherSuite b1 b2 → twobytes (b1,b2)
    | NullCipherSuite                                 → twobytes ( 0x00z, 0x00z )

    | CipherSuite13 AES128_GCM        SHA256          → twobytes ( 0x13z, 0x01z )
    | CipherSuite13 AES256_GCM        SHA384          → twobytes ( 0x13z, 0x02z )
    | CipherSuite13 CHACHA20_POLY1305 SHA256          → twobytes ( 0x13z, 0x03z )
    | CipherSuite13 AES128_CCM        SHA256          → twobytes ( 0x13z, 0x04z )
    | CipherSuite13 AES128_CCM8       SHA256          → twobytes ( 0x13z, 0x05z )

    | CipherSuite Kex_RSA None (MACOnly MD5)          → twobytes ( 0x00z, 0x01z )
    | CipherSuite Kex_RSA None (MACOnly SHA1)         → twobytes ( 0x00z, 0x02z )
    | CipherSuite Kex_RSA None (MACOnly SHA256)       → twobytes ( 0x00z, 0x3Bz )
    | CipherSuite Kex_RSA None(MtE (Stream RC4_128) MD5)  → twobytes ( 0x00z, 0x04z )
    | CipherSuite Kex_RSA None(MtE (Stream RC4_128) SHA1) → twobytes ( 0x00z, 0x05z )

    | CipherSuite Kex_RSA None(MtE (Block TDES_EDE_CBC) SHA1)  → twobytes ( 0x00z, 0x0Az )
    | CipherSuite Kex_RSA None(MtE (Block AES128_CBC) SHA1)   → twobytes ( 0x00z, 0x2Fz )
    | CipherSuite Kex_RSA None(MtE (Block AES256_CBC) SHA1)   → twobytes ( 0x00z, 0x35z )
    | CipherSuite Kex_RSA None(MtE (Block AES128_CBC) SHA256) → twobytes ( 0x00z, 0x3Cz )
    | CipherSuite Kex_RSA None(MtE (Block AES256_CBC) SHA256) → twobytes ( 0x00z, 0x3Dz )

    (****************************************************************************)
    | CipherSuite Kex_DH (Some DSA)     (MtE (Block TDES_EDE_CBC) SHA1)  → twobytes ( 0x00z, 0x0Dz )
    | CipherSuite Kex_DH (Some RSASIG)  (MtE (Block TDES_EDE_CBC) SHA1)  → twobytes ( 0x00z, 0x10z )
    | CipherSuite Kex_DHE (Some DSA)    (MtE (Block TDES_EDE_CBC) SHA1)  → twobytes ( 0x00z, 0x13z )
    | CipherSuite Kex_DHE (Some RSASIG) (MtE (Block TDES_EDE_CBC) SHA1)  → twobytes ( 0x00z, 0x16z )

    | CipherSuite Kex_DH (Some DSA)     (MtE (Block AES128_CBC) SHA1)    → twobytes ( 0x00z, 0x30z )
    | CipherSuite Kex_DH (Some RSASIG)  (MtE (Block AES128_CBC) SHA1)    → twobytes ( 0x00z, 0x31z )
```

1**- p1.fst Top L18 (Fundamental -2)

```
let parseCipherSuite b =
  match b.[0ul], b.[1ul] with
  | ( 0x00z, 0x00z ) → Correct(NullCipherSuite)

  | ( 0x13z, 0x01z ) → Correct (CipherSuite13 AES128_GCM SHA256)
  | ( 0x13z, 0x02z ) → Correct (CipherSuite13 AES256_GCM SHA384)
  | ( 0x13z, 0x03z ) → Correct (CipherSuite13 CHACHA20_POLY1305 SHA256)
  | ( 0x13z, 0x04z ) → Correct (CipherSuite13 AES128_CCM SHA256)
  | ( 0x13z, 0x05z ) → Correct (CipherSuite13 AES128_CCM8 SHA256)

  | ( 0x00z, 0x01z ) → Correct(CipherSuite Kex_RSA None (MACOnly MD5))
  | ( 0x00z, 0x02z ) → Correct(CipherSuite Kex_RSA None (MACOnly SHA1))
  | ( 0x00z, 0x3Bz ) → Correct(CipherSuite Kex_RSA None (MACOnly SHA256))
  | ( 0x00z, 0x04z ) → Correct(CipherSuite Kex_RSA None (MtE (Stream RC4_128) MD5))
  | ( 0x00z, 0x05z ) → Correct(CipherSuite Kex_RSA None (MtE (Stream RC4_128) SHA1))

  | ( 0x00z, 0x0Az ) → Correct(CipherSuite Kex_RSA None (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x2Fz ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES128_CBC) SHA1))
  | ( 0x00z, 0x35z ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES256_CBC) SHA1))
  | ( 0x00z, 0x3Cz ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES128_CBC) SHA256))
  | ( 0x00z, 0x3Dz ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES256_CBC) SHA256))

  (****************************************************************************)
  | ( 0x00z, 0x0Dz ) → Correct(CipherSuite Kex_DH (Some DSA) (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x10z ) → Correct(CipherSuite Kex_DH (Some RSASIG) (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x13z ) → Correct(CipherSuite Kex_DHE (Some DSA) (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x16z ) → Correct(CipherSuite Kex_DHE (Some RSASIG) (MtE (Block TDES_EDE_CBC) SHA1))

  | ( 0x00z, 0x30z ) → Correct(CipherSuite Kex_DH (Some DSA) (MtE (Block AES128_CBC) SHA1))
  | ( 0x00z, 0x31z ) → Correct(CipherSuite Kex_DH (Some RSASIG) (MtE (Block AES128_CBC) SHA1))
  | ( 0x00z, 0x32z ) → Correct(CipherSuite Kex_DHE (Some DSA) (MtE (Block AES128_CBC) SHA1))
```

1**- p1.fst 52% L139 (Fundamental -2)

```
let inverse_cipherSuite (x:cipherSuite)
    : Lemma
      (requires (¬ (UnknownCipherSuite? x)))
      (ensures (let y = cipherSuiteBytes x in
                Some? y ⟹ parseCipherSuite (Some?.v y) = Correct x))
    = ...
```

```
let inverse_cipherSuite' (x:lbytes 2)
    : Lemma
      (ensures (let y = parseCipherSuite x in
                Correct? y /\ not (UnknownCipherSuite? (Correct?._0 y)) ==>
                Some? (cipherSuiteBytes (Correct?._0 y)) /\
                x == Some?.v (cipherSuiteBytes (Correct?._0 y)))) =

    ...
```

Domain-specific languages, ad hoc proof automation, extensibility

Allow programmers to:

- Customize how programs are typechecked, producing domain-specific VCs
- Metaprogram programs and their proofs
- Define their own equivalence preserving program transformations
- …

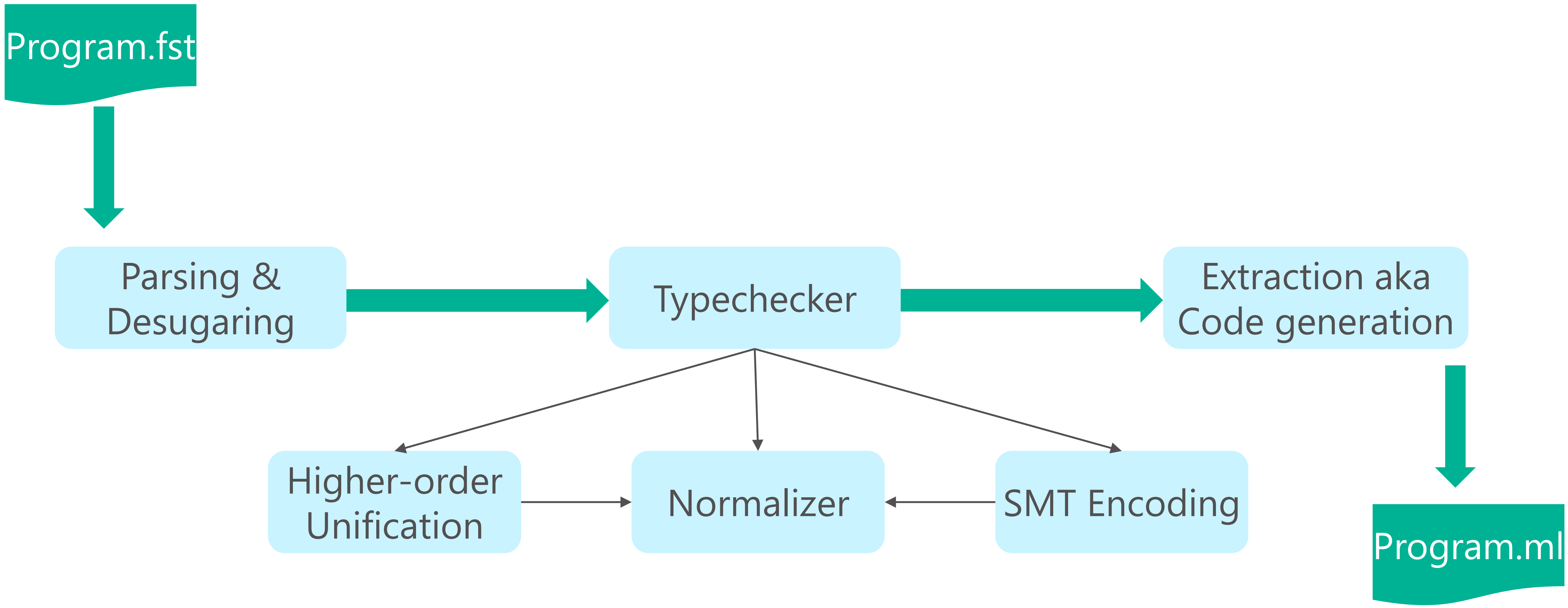
Domain-specific languages, ad hoc proof automation, extensibility

By treating the F* object language as its own metalanguage

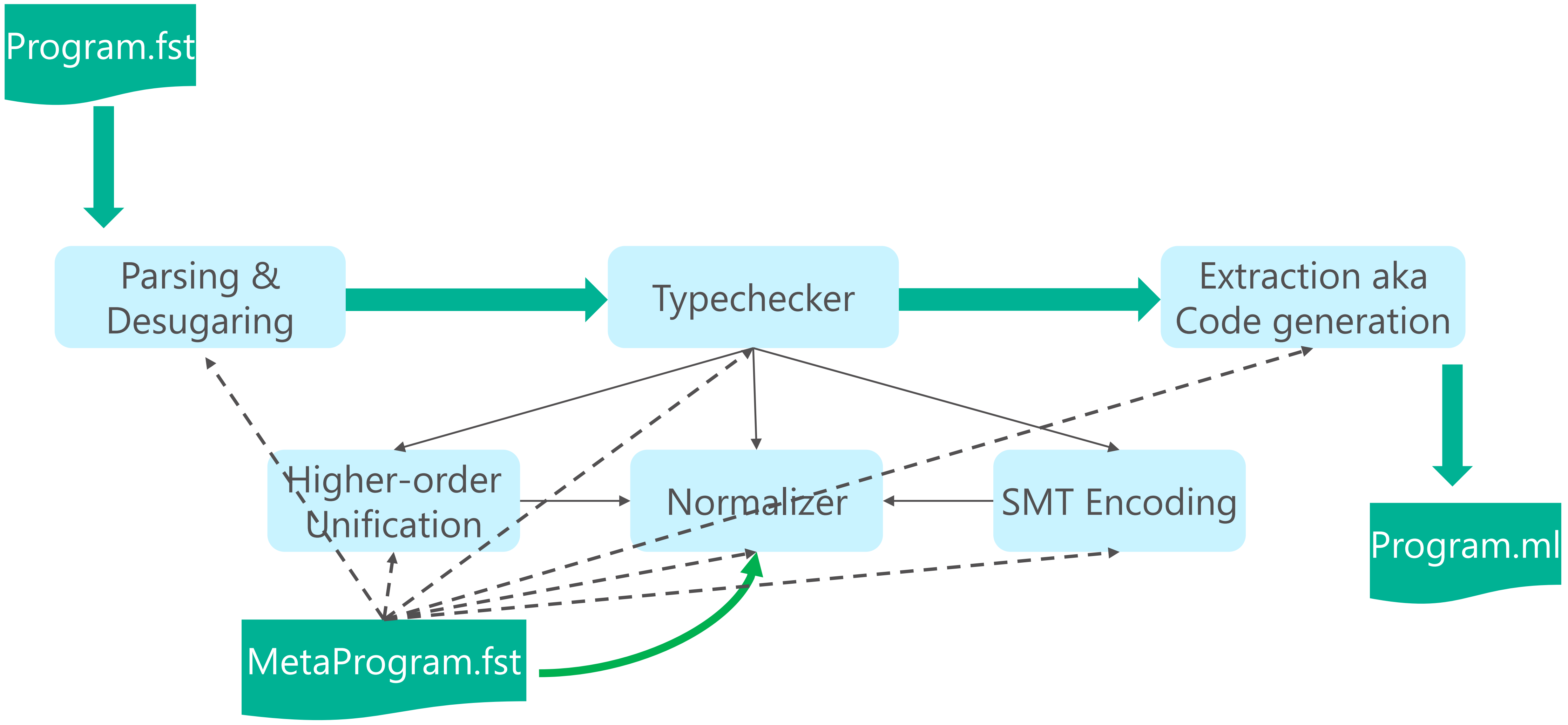
Building on *elaborator reflection* a great idea by

- David Christiansen and Edwin Brady (Idris)
- Leonardo de Moura (Lean)

A passive compiler pipeline



Scripting components with a metaprogram



Scripting a language implementation from within the language

Provide a API to compiler internals for F* (meta)programs to reflect and/or construct

- Syntax of terms
- Typechecking environment
- Typing derivations
- …

F* compiler runs F* metaprograms to build and typecheck other F* programs

From F* to Meta-F*, In three easy steps

1. Metaprogramming as a computational effect of *proof-state transformers*

2. Primitive operations to manipulate proof-states, using trusted compiler primitives

3. Reflecting on syntax: quotation and unquotation

Proof-state: A collection of typed holes

A hole is a missing program fragment in a context

$$\Gamma \vdash ?_0 : \tau$$

(aka a *goal*)

The proof-state is a collection of pending holes

$$\overline{\{\Gamma_i \vdash ?_i : \tau_i\}}$$

+ some internal persistent state
(e.g., unionfind graph of the unifier)

Metaprograms are proofstate transformers

```
let meta a = proofstate → Dv (either (a × proofstate) error)
```

- Uses an existing F* effect for non-termination: **Dv**
- The type of the state is an abstract type: proofstate
- error is the type of exceptions

State + Exception + Non-termination monad

Step 2

Primitive operations on proofstate

- Every typing rule (read backwards) provided as a proofstate primitive

$$\frac{\Gamma, x{:}t_1 \vdash ?_1 : t_2}{\Gamma \vdash ?_o : (x{:}t_1 \rightarrow t_2)}\ \text{[TC-Abs]} \qquad \textit{where}\ \ ?_0 \coloneqq \lambda\, x{:}\, t_1.\, ?_1$$

```
intro : unit -> Meta binder
intro ()  (Γ ⊢ ?₀ : (x:t₁ → t₂)  :: rest) =
  Inl (x, (Γ, x:t₁ ⊢ ?₁ : t₂        :: rest))
  where fresh x and ?₀ := fun (x:t₁)->?₁
intro () _ = raise (Failure "Goal is not an arrow")
```

Step 3

Reflecting on syntax

- Locally nameless abstract syntax of F* terms provided as a datatype to metaprograms

```
type term =
  | T_Var      : v:bv → term
  | T_BVar     : v:bv → term
  | T_FVar     : v:fv → term
  | T_App      : hd:term → a:argv → term
  | T_Abs      : bv:binder → body:term → term
  | T_Arrow    : bv:binder → c:comp → term
  | T_Type     : unit → term
  | T_Refine : bv:bv → ref:term → term
  | T_Const    : vconst → term
  | T_Uvar     : ℤ → ctx_uvar_and_subst → term
  | T_Let      : recf:bool → bv:bv → def:term → body:term → term
  | T_Match    : scrutinee:term → brs:(list branch) → term
  | T_AscribedT : e:term → t:term → tac:option term → term
  | T_AscribedC : e:term → c:comp → tac:option term → term
```

- Quotation: Builds the syntax of a term

  ```
  `(0 + 1) : term
  ```

- Unquotation
  - Typechecks syntax at a given type

```
val unquote: a:Type -> x:term -> Meta a
```

Putting it together

Entrypoint: Decorate an implicit with a metaprogram

```
let id : (a:Type) -> a -> a =
  _ by (
        let a = intro () in
        let x = intro () in
        hyp x
        )
```

$[\cdot \vdash \_ : (a\!: \mathrm{Type}) \to a \to a]$

$[a\!: \mathrm{Type} \vdash \_ : a \to a]$

$[a\!: \mathrm{Type}, x\!: a \vdash \_ : a]$

$[]$

And can be at a low level of abstraction

- Lots of boilerplate to define parsers/formatters and prove them mutually inverse

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```
let cipherSuiteBytes cs =
    match cs with
    | UnknownCipherSuite b1 b2 → twobytes (b1,b2)
    | NullCipherSuite                                        → twobytes ( 0x00z, 0x00z )

    | CipherSuite13 AES128_GCM        SHA256                 → twobytes ( 0x13z, 0x01z )
    | CipherSuite13 AES256_GCM        SHA384                 → twobytes ( 0x13z, 0x02z )
    | CipherSuite13 CHACHA20_POLY1305 SHA256                 → twobytes ( 0x13z, 0x03z )
    | CipherSuite13 AES128_CCM        SHA256                 → twobytes ( 0x13z, 0x04z )
    | CipherSuite13 AES128_CCM8       SHA256                 → twobytes ( 0x13z, 0x05z )

    | CipherSuite Kex_RSA None (MACOnly MD5)                 → twobytes ( 0x00z, 0x01z )
    | CipherSuite Kex_RSA None (MACOnly SHA1)                → twobytes ( 0x00z, 0x02z )
    | CipherSuite Kex_RSA None (MACOnly SHA256)              → twobytes ( 0x00z, 0x3Bz )
    | CipherSuite Kex_RSA None(MtE (Stream RC4_128) MD5)     → twobytes ( 0x00z, 0x04z )
    | CipherSuite Kex_RSA None(MtE (Stream RC4_128) SHA1)    → twobytes ( 0x00z, 0x05z )

    | CipherSuite Kex_RSA None(MtE (Block TDES_EDE_CBC) SHA1)   → twobytes ( 0x00z, 0x0Az )
    | CipherSuite Kex_RSA None(MtE (Block AES128_CBC) SHA1)    → twobytes ( 0x00z, 0x2Fz )
    | CipherSuite Kex_RSA None(MtE (Block AES256_CBC) SHA1)    → twobytes ( 0x00z, 0x35z )
    | CipherSuite Kex_RSA None(MtE (Block AES128_CBC) SHA256)  → twobytes ( 0x00z, 0x3Cz )
    | CipherSuite Kex_RSA None(MtE (Block AES256_CBC) SHA256)  → twobytes ( 0x00z, 0x3Dz )

    (***********************************************************************)
    | CipherSuite Kex_DH (Some DSA)     (MtE (Block TDES_EDE_CBC) SHA1)   → twobytes ( 0x00z, 0x0Dz )
    | CipherSuite Kex_DH (Some RSASIG)  (MtE (Block TDES_EDE_CBC) SHA1)   → twobytes ( 0x00z, 0x10z )
    | CipherSuite Kex_DHE (Some DSA)    (MtE (Block TDES_EDE_CBC) SHA1)   → twobytes ( 0x00z, 0x13z )
    | CipherSuite Kex_DHE (Some RSASIG) (MtE (Block TDES_EDE_CBC) SHA1)   → twobytes ( 0x00z, 0x16z )

    | CipherSuite Kex_DH (Some DSA)     (MtE (Block AES128_CBC) SHA1)    → twobytes ( 0x00z, 0x30z )
    | CipherSuite Kex_DH (Some RSASIG)  (MtE (Block AES128_CBC) SHA1)    → twobytes ( 0x00z, 0x31z )
```

1**- **p1.fst** Top L18 (Fundamental -2)

```
let parseCipherSuite b =
  match b.[0ul], b.[1ul] with
  | ( 0x00z, 0x00z ) → Correct(NullCipherSuite)

  | ( 0x13z, 0x01z ) → Correct (CipherSuite13 AES128_GCM SHA256)
  | ( 0x13z, 0x02z ) → Correct (CipherSuite13 AES256_GCM SHA384)
  | ( 0x13z, 0x03z ) → Correct (CipherSuite13 CHACHA20_POLY1305 SHA256)
  | ( 0x13z, 0x04z ) → Correct (CipherSuite13 AES128_CCM SHA256)
  | ( 0x13z, 0x05z ) → Correct (CipherSuite13 AES128_CCM8 SHA256)

  | ( 0x00z, 0x01z ) → Correct(CipherSuite Kex_RSA None (MACOnly MD5))
  | ( 0x00z, 0x02z ) → Correct(CipherSuite Kex_RSA None (MACOnly SHA1))
  | ( 0x00z, 0x3Bz ) → Correct(CipherSuite Kex_RSA None (MACOnly SHA256))
  | ( 0x00z, 0x04z ) → Correct(CipherSuite Kex_RSA None (MtE (Stream RC4_128) MD5))
  | ( 0x00z, 0x05z ) → Correct(CipherSuite Kex_RSA None (MtE (Stream RC4_128) SHA1))

  | ( 0x00z, 0x0Az ) → Correct(CipherSuite Kex_RSA None (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x2Fz ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES128_CBC) SHA1))
  | ( 0x00z, 0x35z ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES256_CBC) SHA1))
  | ( 0x00z, 0x3Cz ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES128_CBC) SHA256))
  | ( 0x00z, 0x3Dz ) → Correct(CipherSuite Kex_RSA None (MtE (Block AES256_CBC) SHA256))

  (***********************************************************************)
  | ( 0x00z, 0x0Dz ) → Correct(CipherSuite Kex_DH (Some DSA) (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x10z ) → Correct(CipherSuite Kex_DH (Some RSASIG) (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x13z ) → Correct(CipherSuite Kex_DHE (Some DSA) (MtE (Block TDES_EDE_CBC) SHA1))
  | ( 0x00z, 0x16z ) → Correct(CipherSuite Kex_DHE (Some RSASIG) (MtE (Block TDES_EDE_CBC) SHA1))

  | ( 0x00z, 0x30z ) → Correct(CipherSuite Kex_DH (Some DSA) (MtE (Block AES128_CBC) SHA1))
  | ( 0x00z, 0x31z ) → Correct(CipherSuite Kex_DH (Some RSASIG) (MtE (Block AES128_CBC) SHA1))
  | ( 0x00z, 0x32z ) → Correct(CipherSuite Kex_DHE (Some DSA) (MtE (Block AES128_CBC) SHA1))
```

Remember this?

1**- **p1.fst** 52% L139 (Fundamental -2)

```
let inverse_cipherSuite (x:cipherSuite)
    : Lemma
    (requires (¬ (UnknownCipherSuite? x)))
    (ensures (let y = cipherSuiteBytes x in
              Some? y ⟹ parseCipherSuite (Some?.v y) = Correct x))
    = ...
```

```
let inverse_cipherSuite' (x:lbytes 2)
    : Lemma
    (ensures (let y = parseCipherSuite x in
              Correct? y /\ not (UnknownCipherSuite? (Correct?._0 y)) ==>
              Some? (cipherSuiteBytes (Correct?._0 y)) /\
              x == Some?.v (cipherSuiteBytes (Correct?._0 y)))) =
    ...
```

Metaprogramming mutually inverse parsers and formatters

```
type color = | Red | Blue | Green | Yellow
type pallette = nlist 18 (color × u8)
let ps : (p:parser pallette & serializer p) =
  _ by (gen_parser_serializer (`pallette))
```

Where, the types capture that parser/serializer are mutual inverses

```
let parser (t:Type) = bytes → option t
let serializer (#t:Type) (p:parser t) =
  s : (x:t → b:bytes) {
    (∀ x. p (s x) = Some x) ∧
    (∀ b. match p b with
          | Some x → s x = b
          | _ → ⊤)}
```

Putting it together

Entrypoint: Decorate an assertion with a metaprogram

```
let f (x:nat) =
  if x > 1 then
    assert (x * x > x)
      by tac;
    …
```

$$x\!: nat, h\!: (x > 1) \vdash \_ : (x * x > x)$$

- Assertions produce a goal in a context including control flow hypotheses
- Tackled by the metaprogram `tac`

SMT: Just one of F*'s tactic primitives

```
val smt: unit -> Meta unit


let f (x:nat) =
  if x > 1 then
    assert (x * x > x)
      by (smt());
    …
```

$$x\colon nat, h\colon (x > 1) \vdash \_ : \ (x * x > x)$$

- Assertions produce a goal in a context including control flow hypotheses
- Tackled by the metaprogram tac

But SMT-based proofs can go awry

- E.g., when using theories like non-linear arithmetic

```
let lemma_carry_limb_unrolled (a0 a1 a2:nat) : Lemma
    (requires ⊤)
    (ensures (a0 % p44 + p44 * ((a1 + a0 / p44) % p44) + p88 * (a2 + ((a1 + a0 / p44) / p44))
           = a0 + p44 * a1 + p88 * a2)) =
  let open FStar.Math.Lemmas in
  let z = a0 % p44 + p44 * ((a1 + a0 / p44) % p44) + p88 * (a2 + ((a1 + a0 / p44) / p44)) in
  distributivity_add_right p88 a2 ((a1 + a0 / p44) / p44); (* argh! *)
  pow2_plus 44 44;
  lemma_div_mod (a1 + a0 / p44) p44;
  distributivity_add_right p44 ((a1 + a0 / p44) % p44) (p44 * ((a1 + a0 / p44) / p44)); (* argh! *)
  assert (p44 * ((a1 + a0 / p44) % p44) + p88 * ((a1 + a0 / p44) / p44) = p44 * (a1 + a0 / p44) );
  distributivity_add_right p44 a1 (a0 / p44); (* argh! *)
  lemma_div_mod a0 p44
```

Remember this?

Forced to write very detailed proof terms when SMT fails

SMT + Tactics for more automated, robust proofs

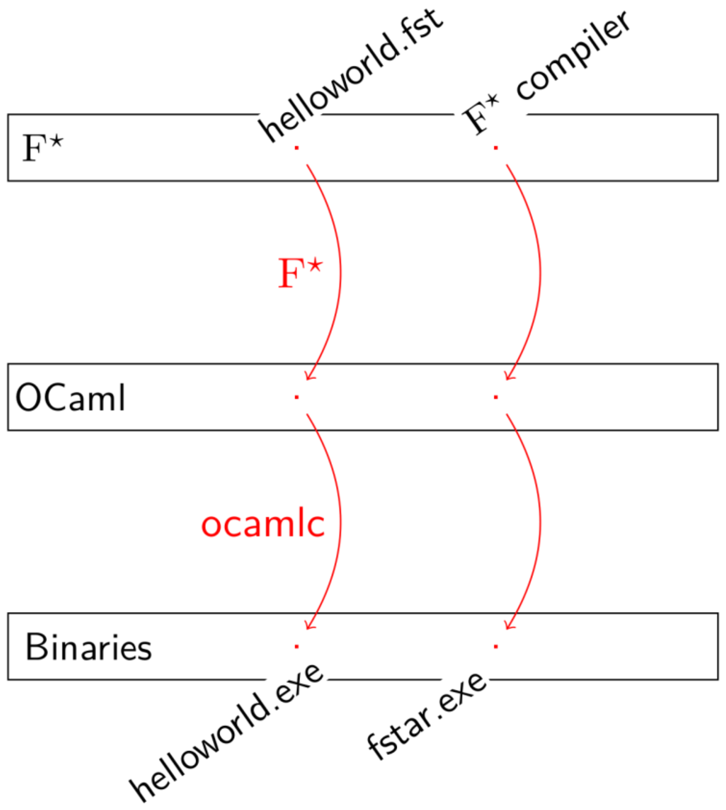
Key lemma in poly1305, a MAC algorithm,
doing multiplication in the prime field $2^{130} - 5$

```
let poly_multiply (n p r h r0 r1 h0 h1 h2 s1 d0 d1 d2 h1 h2 hh : ℤ)
    : Lemma
      (requires p > 0 ∧ r1 ≥ 0 ∧ n > 0 ∧ 4 × (n × n) == p + 5 ∧ r == r1 × n + r0 ∧
                h == h2 × (n × n) + h1 × n + h0 ∧ s1 == r1 + (r1 / 4) ∧ r1 % 4 == 0 ∧
                d0 == h0 × r0 + h1 × s1 ∧ d1 ==
                d2 == h2 × r0 ∧ hh == d2 × (n
      (ensures (h × r) % p == hh % p) =
  let r14 = r1 / 4 in
  let h_r_expand = (h2 × (n × n) + h1 × n + h0)
  let hh_expand = (h2 × r0) × (n × n) + (h0 × (
                  (5 × r14)) × n + (h0 × r0 + h
  let b = (h2 × n + h1) × r14 in
  modulo_addition_lemma hh_expand p b;
  assert (h_r_expand == hh_expand + b × (n × n
      by (canon_semiring int_csr;
          smt())
```

- A reflective metaprogram to canonicalize terms in commutative semirings
- Simplifies goal into a form that smt can then solve using linear arithmetic only
- Prior manual proof required 41 steps of explicit rewriting lemmas (!)

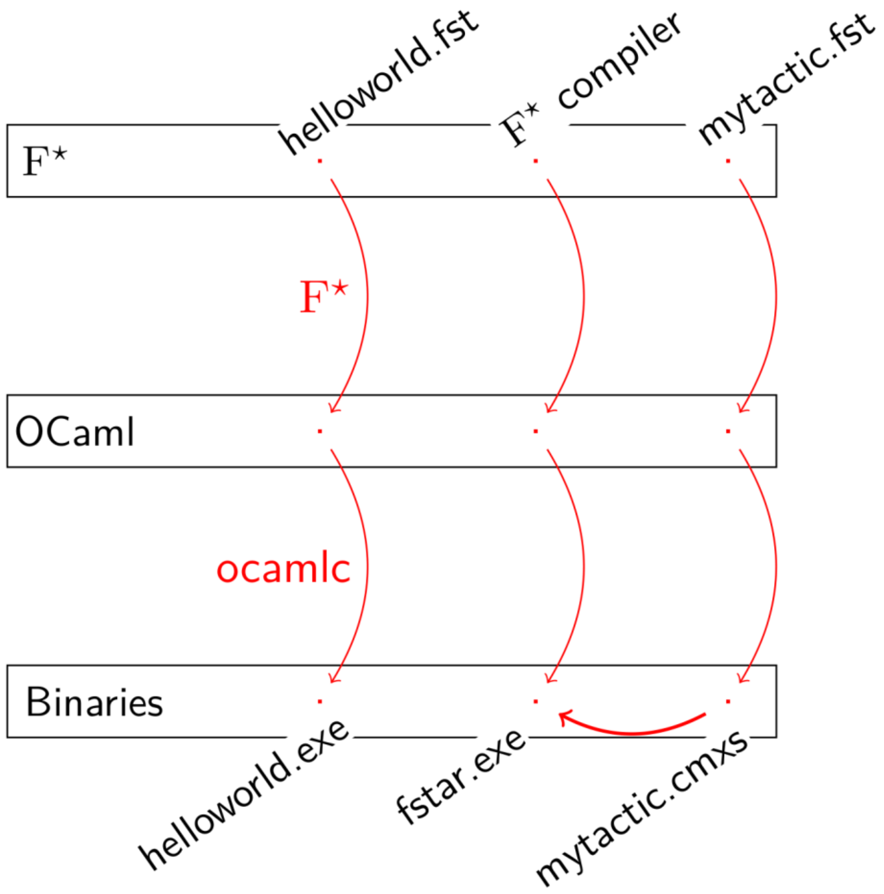
Language extension with native metaprograms

- By default, metaprograms are interpreted on F*'s normalizer
- But, F* is implemented in F* and all F* programs can be compiled to OCaml



Language extension with native metaprograms

- Typeclass resolution in F* is implemented entirely in “user-land” with a metaprogram
- As a language implementor this is great! Push language feature requests back to users
- But, F* is implemented in F* and all F* programs can be compiled to OCaml
- Metaprograms too: 10x perf



Some takeaways

- Freedom of expression
  - Tools for large-scale, full program verification need arbitrary expressive power
- Proof automation, Expressiveness, Control
  - SMT is great, but not a panacea: Eventually hit a complexity/undecidability wall
- Careful combination of tactics and SMT *improve* automation relative to either SMT or tactics alone
- Meta-F*: Self-scripting a PL implementation with reflective metaprogramming; tactics are just a special case