Formally Verified *Cryptographic Web Applications* in *WebAssembly*

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The Web beyond the Web

The Web environment has become the choice target for deploying applications.

Think: websites, desktop apps (Electron), server apps (node.js), browser addons...

How about security-sensitive applications, such as: password managers, secure messengers?

Life is hard for secure web apps

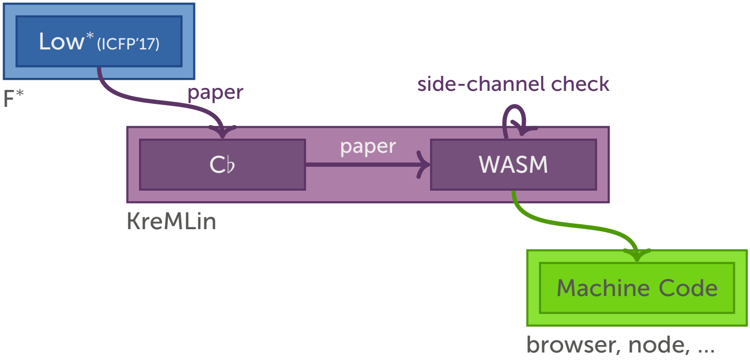
Application developers are at a loss for secure toolchains targeting the Web runtime.

- custom cryptographic schemes
- ad-hoc protocols
- unverifiable app logic
- hostile target environment (JavaScript).

(Larger) Claim: the JavaScript toolchain is inadequate for Web-based security-sensitive applications.

An F* to WASM toolchain

We formalize a verified pipeline from Low* to WASM and implement it in the KreMLin compiler.



This work's contributions

- A generic toolchain (formalization and implementation) to compile F* programs to WebAssembly
- The HACL* verified cryptographic library compiled to WebAssembly
- A formally verified implementation of Signal, in WebAssembly
    - Verified for functional correctness, memory safety, side-channel resistance and protocol security
    - No performance penalty; same API; ready to integrate

Our running example: Signal

- Signal powers WhatsApp, Messenger, Skype, Signal
  This means over 1 billion users
- Allows communicating asynchronously (trend)
- Relies on server with limited trust
- Generally trust-on-first-use

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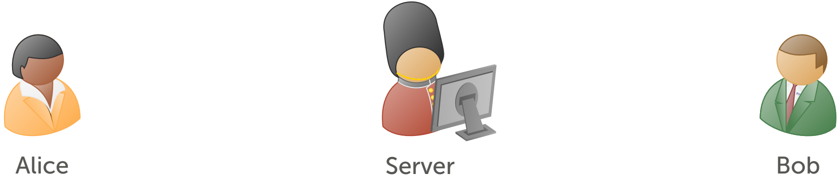
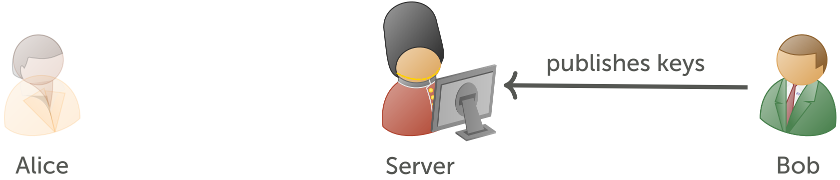
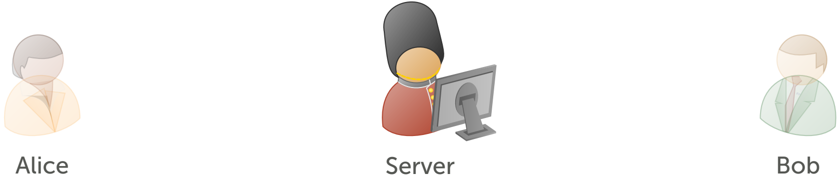
- Generally trust-on-first-use

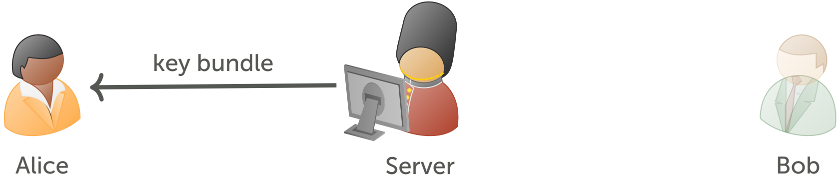
Let's start by a quick overview of the protocol.

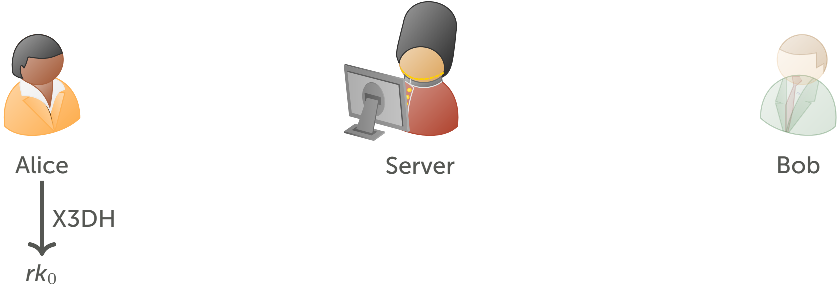

Alice
Server
Bob

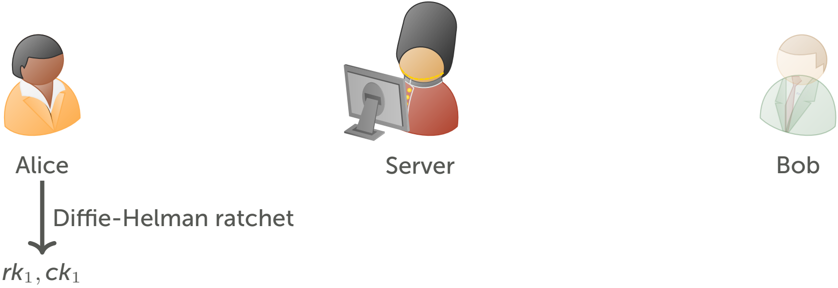


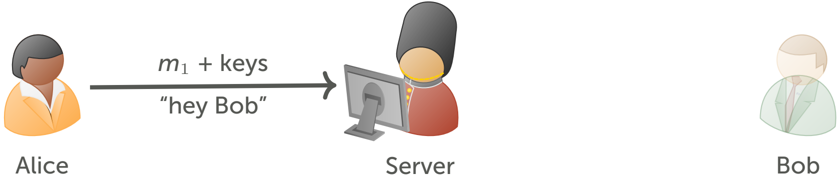
publishes keys
Alice
Server
Bob


Alice
Server
Bob

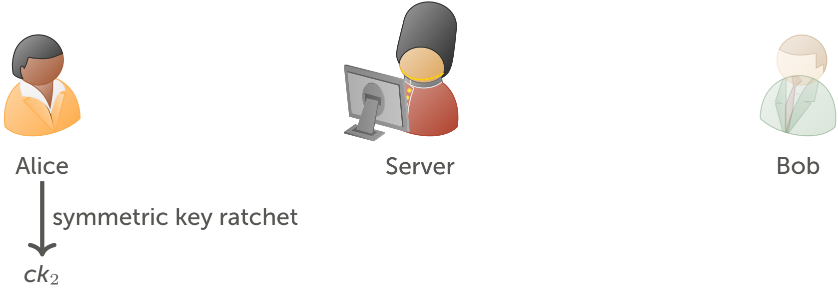

key bundle
Alice
Server
Bob

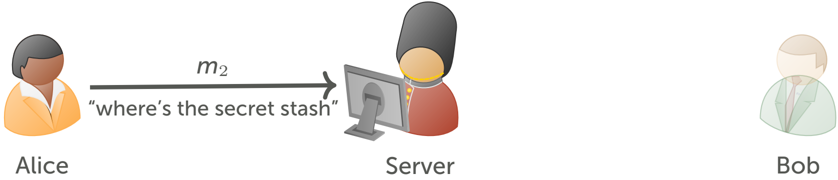

Alice
Server
Bob
X3DH
rk_0


Alice
Server
Bob
Diffie-Helman ratchet
rk_1, ck_1

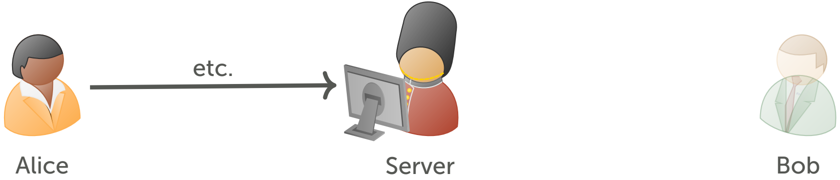


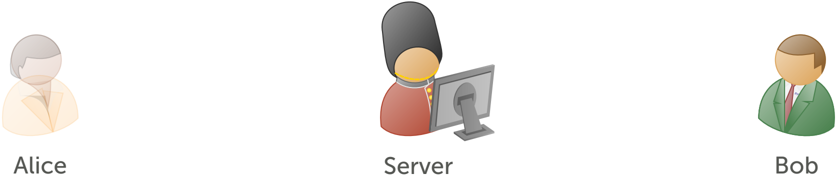
m_1 + keys
"hey Bob"
Alice
Server
Bob

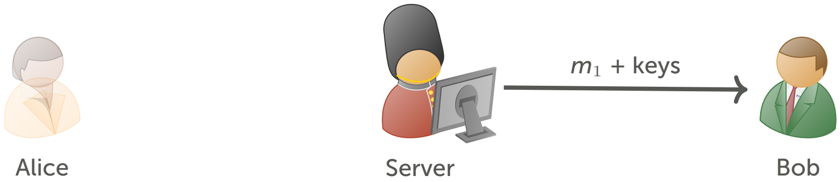

Alice
Server
Bob
symmetric key ratchet
ck_2



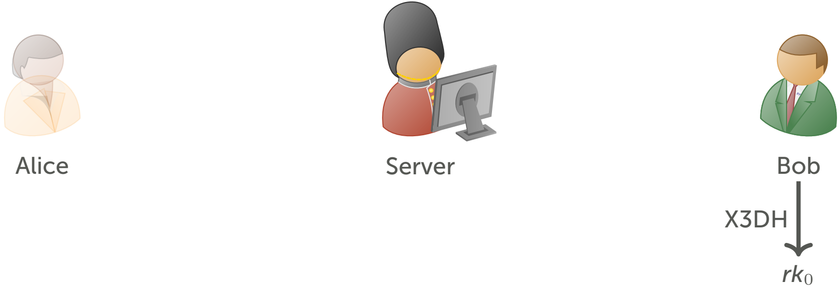
m_2
"where's the secret stash"
Alice
Server
Bob

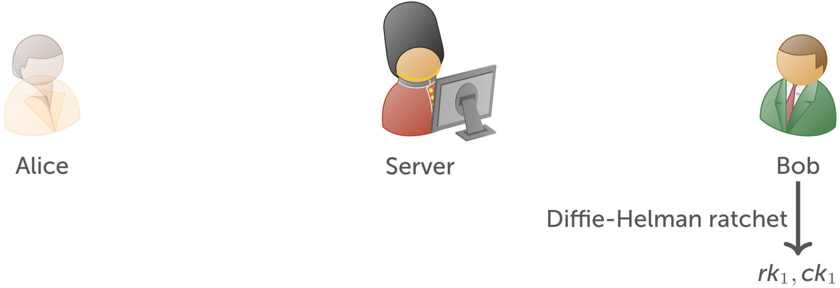

etc.
Alice
Server
Bob

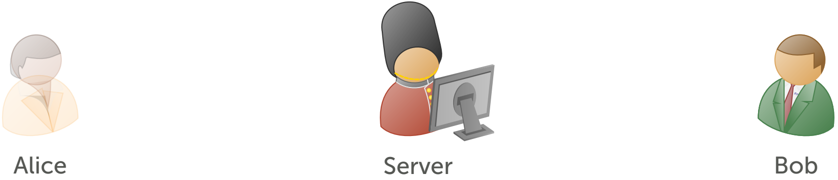

Alice
Server
Bob



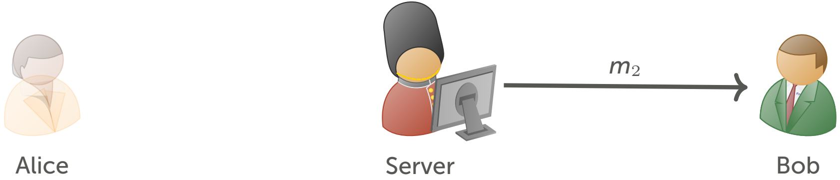
Alice
Server
m_1 + keys
Bob

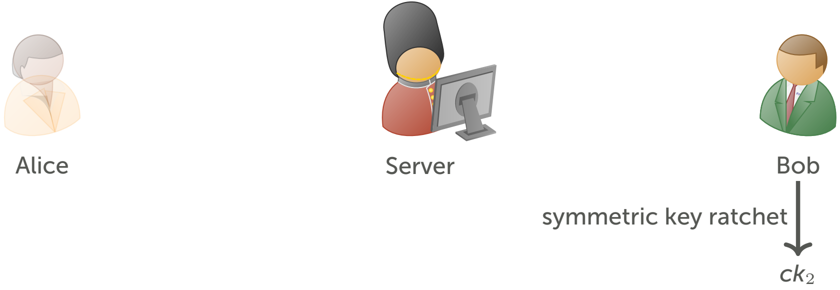

Alice
Server
Bob
X3DH
rk_0


Alice
Server
Bob
Diffie-Helman ratchet
rk_1, ck_1



$m_1 =$ “hey Bob”


m_2
Alice
Server
Bob



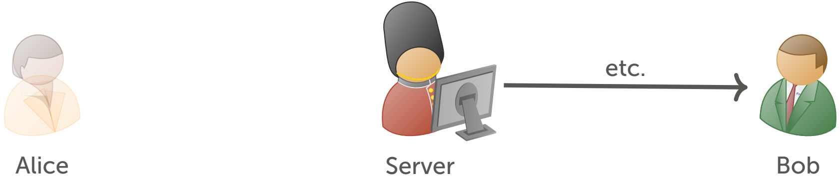
Alice
Server
Bob
symmetric key ratchet
ck_2

Alice

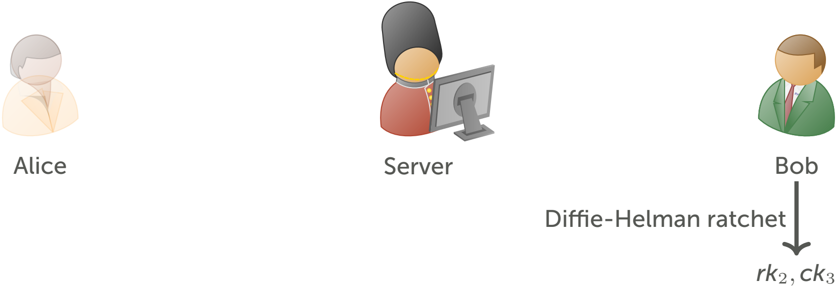
Server

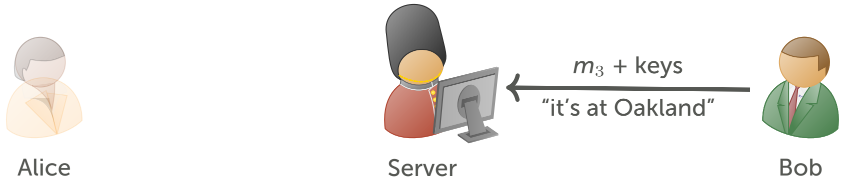
Bob

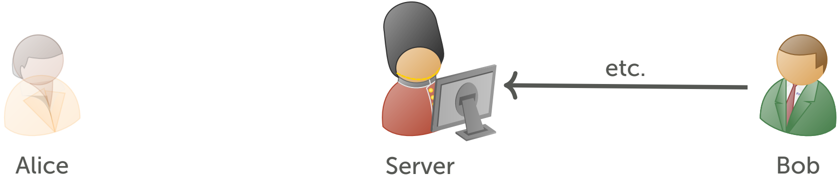
$m_2 =$ "where's the secret stash"



Alice
Server
etc.
Bob


Alice
Server
Bob
Diffie-Helman ratchet
rk_2, ck_3


Alice
Server
m_3 + keys
“it’s at Oakland”
Bob



Alice
Server
etc.
Bob

Signal: a recap

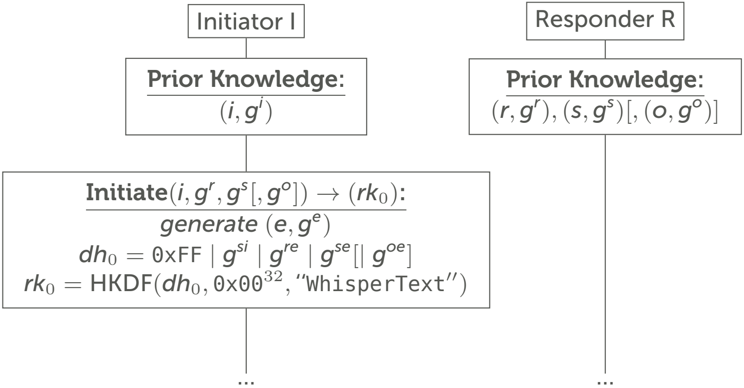
- the protocol is sophisticated
- X3DH for session initiation
- double-ratchet for asynchronous communications, forward secrecy and post-compromise security
- involves non-trivial cryptography (X25519, etc.)

`https://signal.org/docs/`

Step 1: a protocol specification

Written in ProVerif (symbolic model). Builds on previous work (Euro S&P'17).

Guarantees integrity, confidentiality, forward secrecy, post-compromise security.



Step 1: a protocol specification

Written in ProVerif (symbolic model). Builds on previous work (Euro S&P'17).

Guarantees integrity, confidentiality, forward secrecy, post-compromise security.

Initiator I

Prior Knowledge: (i, g^i)

Responder R

Prior Knowledge: $(r, g^r), (s, g^s)[, (o, g^o)]$

Initiate$(i, g^r, g^s[, g^o]) \to (rk_0)$:

generate (e, g^e)

$dh_0 = \texttt{0xFF} \mid g^{si} \mid g^{re} \mid g^{se} [\mid\mid g^{oe}]$

$rk_0 = \text{HKDF}(dh_0, \texttt{0x00}^{32}, \text{``}\texttt{WhisperText}\text{''})$

...

...

Step 2: transcribe specifications to F*

An ML-like language with support for program verification via SMT automation.

- Specifications include more detail than ProVerif (e.g. tags)
- Currently manual; hope to automate it
- Specifications extract to OCaml, for tests – not suitable for implementations!

Step 3a: implement cryptography

We use HACL* for the cryptographic primitives.

HACL* has been integrated in Firefox, WireGuard, mbedTLS, etc.

Now available on the Web!

Generally useful:

- fills the gap for custom or new primitives (not in WebCrypto or Node)
- a solution for code that needs synchronous APIs
- avoid legacy libraries (OpenSSL on Node).

Step 3b: implement Signal core

We implement all the core operations of the Signal protocol in Low*.

Low* is a low-level subset of F* that compiles to C using the KreMLin compiler.

Low* has been used by HACL*, EverCrypt, Merkle Trees, libquiccrypto.

Now a verified implementation of Signal in C and WebAssembly.

Step 4: compile Low* to WebAssembly

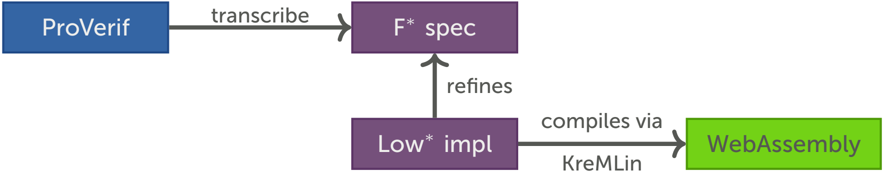
A new, safe, widely supported target for fast, portable execution. Used primarily in web runtimes but not only.

- isolation guarantees
- basic type safety relying on an operand stack and structured control flow
- more compiler support every day: LLVM, emscripten, mono, etc.

Used for video games, AutoCad, large applications...

Our ProVerif to WASM toolchain

We formalize a verified pipeline from ProVerif to WASM and extend the KreMLin compiler with a WASM backend.



A direct route from Low* to WASM

We formalize the compilation from Low* to WASM.

A simple translation (WASM is an expression language) that eliminates complexity and fits in two paper pages.

Thanks to a new intermediary language in KreMLin, the compilations rules are compact, auditable and simple.

A direct route from Low* to WASM

We implement the compilation from Low* to WASM.

The implementation is carefully audited and follows the paper rules.

- 2,400 lines of OCaml code (total: 11,000)
- does not implement any sophisticated optimization
- very regular.

Consequence

A high-assurance compilation toolchain to WASM!

An indirect route from Low* to WASM

One reason we chose to implement our own toolchain...

Classic route (via Emscripten): Low* $\rightarrow$ C $\rightarrow$ WASM

- massive TCB
- no side-channel reasoning
- requires KreMLin to deal with C semantics (un-necessary transformations)

With only 2,400 extra lines of OCaml, we have greater confidence.

What we prove

Thanks to a combination of techniques, we guarantee:

- memory safety, by virtue of Low*
- functional correctness, by virtue of the specifications
- absence of "classic" side-channel leaks, by construction *and* through a dedicated check

In short, we offer a library of core building blocks of the Signal protocol.

Session and state management, policies to discard old ratchets, etc. are left to the JavaScript code (need integration with the browser).

Integration

We pass the entire testsuite. The WASM memory is behind a closure (defensive). We offer the same API.

Shuffled Signal Protocol Test Vectors as Alice

- ✓ send prekey message A 58ms
- ✓ send message B
- ✓ receive message D
- ✓ receive message C
- ✓ send message E

Standard Signal Protocol Test Vectors as Bob

- ✓ receive prekey message A 56ms
- ✓ receive prekey message B
- ✓ send message C
- ✓ send message D
- ✓ receive message E

passes: *158* failures: *0* duration: *6.09*s

Performance (1)

Step	F^*-WebAssembly	Vanilla Signal
initiate/respond	61.6 ms	74.7 ms
Diffie-Hellman ratchet	21.7 ms	35.4 ms
symmetric key ratchet	2.19 ms	3.52 ms

Our implementation is faster on many operations than the original libsignal. (Reason: an asm.js version of curve25519).

For operations involving SHA and AES-CBC, hard to beat native crypto in WebCrypto.

Performance (2)

Primitive (blocksize, rounds)	HACL* → C → WASM via Emscripten	HACL* → WASM via KreMLin
Chacha20 (4kB, 100k)	2.8 s	4.1 s
SHA2_256 (16kB, 10k)	1.8 s	3.5 s
SHA2_512 (16kB, 10k)	1.3 s	3.4 s
Poly1305_32 (16kB, 10k)	0.15 s	0.4 s
Curve25519 (1k)	0.7 s	2.5 s
Ed25519 sign (16kB, 1k)	3.0 s	10.0 s
Ed25519 verify (16kB, 1k)	3.0 s	10.0 s

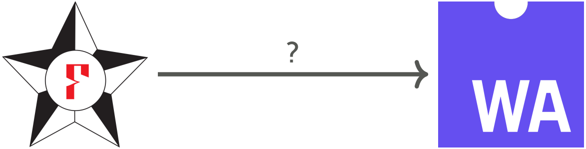
- simple compilation scheme not always optimal
- 128-bit arithmetic destroys performance, need 32-bit versions
- low hanging fruits: see chacha20.

Verified Cryptographic Web Applications in WASM

- A general pattern any application in a Web context (desktop, server or browser)
- Offers a solution for crypto libraries: new algorithms, custom schemes, absence of async, no legacy binaries
- We built software: Signal* + Web-HACL* as a side effect

Please get in touch! `https://signalstar.gforge.inria.fr/`

Ye olde backuppe slides



Emscripten Low* $\rightarrow$ C (KreMLin): OK (ICFP’17)

C $\rightarrow$ WASM (emscripten): low trust

?

Emscripten Low* → C (KreMLin): OK (ICFP'17)

C → WASM (emscripten): low trust

KreMLin Low* → WASM (KreMLin): OK (S&P'19)

```
(* Spec *)
let p = pow2 255 - 19
type elem = n:int { 0 <= n /\ n < p }
let add (x y: elem): elem = (x + y) % p

(* Implem *)
type felem = p:uint64_p { length p = 5 }

let fadd (output a b: felem):
  Stack unit
    (requires (fun h0 -> live h0 output /\
      live h0 a /\ live h0 b /\
      fadd_pre h0.[a] h0.[b])
    (ensures (fun h0 _ h1 ->
      modifies_1 output h0 h1 /\
      h1.[output] == add h0.[a] h0.[b]))
```

concise
specification

```
(* Spec *)
let p = pow2 255 - 19
type elem = n:int { 0 <= n /\ n < p }
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```

optimized
representation

```
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      h1.[output] == add h0.[a] h0.[b]))
```

memory safety

```
(* Spec *)
let p = pow2 255 - 19
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let add (x y: elem): elem = (x + y) % p

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    (requires (fun h0 -> live h0 output /\
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    (ensures (fun h0 _ h1 ->
      modifies_1 output h0 h1 /\
      h1.[output] == add h0.[a] h0.[b]))
```

functional specification (erased)

```
(* Spec *)
let p = pow2 255 - 19
type elem = n:int { 0 <= n /\ n < p }
let add (x y: elem): elem = (x + y) % p

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type felem = p:uint64_p { length p = 5 }

let fadd (output a b: felem):
  Stack unit
    (requires (fun h0 -> live h0 output /\
      live h0 a /\ live h0 b /\
      fadd_pre h0.[a] h0.[b])
    (ensures (fun h0 _ h1 ->
      modifies_1 output h0 h1 /\
      h1.[output] == add h0.[a] h0.[b]))
```

...compiles to

$\textit{fadd} = \text{func}\ [\text{int32}; \text{int32}; \text{int32}] \rightarrow []$
  local $[\ell_0, \ell_1, \ell_2 : \text{int32};\ \ell_3 : \text{int32};\ \ell : \text{int32}]$.
  call get_stack; loop(
    // Push dst + 8*i on the stack
    get_local ℓ_0; get_local ℓ_3; i32.const 8; i32.binop$*$; i32.binop$+$
    // Load a + 8*i on the stack
    get_local ℓ_1; get_local ℓ_3; i32.const 8; i32.binop$*$; i32.binop$+$
    i64.load
    // Load b + 8*i on the stack (elided, same as above)
    // Add a.[i] and b.[i], store into dst.[i]
    i64.binop$+$; i64.store
    // Per the rules, return unit
    i32.const 0; drop
    // Increment i; break if i == 5
    get_local ℓ_3; i32.const 1; i32.binop$+$; tee_local ℓ_3
    i32.const 5; i32.op $=$; br_if
  ); i32.const 0
  store_local ℓ ; call set_stack; get_local ℓ

...transcribed to an F* spec ...

```
let initiate'
  (our_identity_priv_key: privkey) (* i *)
  (our_onetime_priv_key: privkey)  (* e *)
  (their_identity_pub_key: pubkey) (* g^r *)
  (their_signed_pub_key: pubkey)   (* g^s *)
  (their_onetime_pub_key: option pubkey)  (* g^o, optional *)
  : Tot (lbytes 32) =                      (* output: rk_0 *)

let dh1 = dh our_identity_priv_key their_signed_pub_key in
let dh2 = dh our_onetime_priv_key their_identity_pub_key in
let dh3 = dh our_onetime_priv_key their_signed_pub_key in
let shared_secret =
  match their_onetime_pub_key with
  | None -> ff @| dh1 @| dh2 @| dh3
  | Some their_onetime_pub_key ->
      let dh4 = dh our_onetime_priv_key their_onetime_pub_key in
      ff @| dh1 @| dh2 @| dh3 @| dh4
in
let res = hkdf1 shared_secret zz label_WhisperText in
res
```

...implemented in Low*

```
val initiate': output: lbuffer uint8 (size 32) ->
  our_identity_priv_key: privkey_p ->
  our_onetime_priv_key: privkey_p ->
  their_identity_pub_key: pubkey_p ->
  their_signed_pub_key: pubkey_p ->
  their_onetime_pub_key: pubkey_p ->
  defined_their_onetime_pub_key: bool ->
    Stack unit
      (requires (fun h -> live h output /\ ... (* more liveness *) /\
        disjoint output our_identity_priv_key /\
        ... (* more disjointness *)))
      (ensures  (fun h0 _ h1 -> modifies1 output h0 h1 /\
        (* THE IMPLEMENTATION MATCHES THE SPEC *)
        h1.[output] == Spec.Signal.Core.initiate'
        h0.[our_identity_priv_key] h0.[our_onetime_priv_key]
        h0.[their_identity_pub_key] h0.[their_signed_pub_key]
        (if defined_their_onetime_pub_key then
          Some(h0.[their_onetime_pub_key])
        else
          None)))
```