High-Assurance and High-Speed Cryptographic Implementations Using the Jasmin Language

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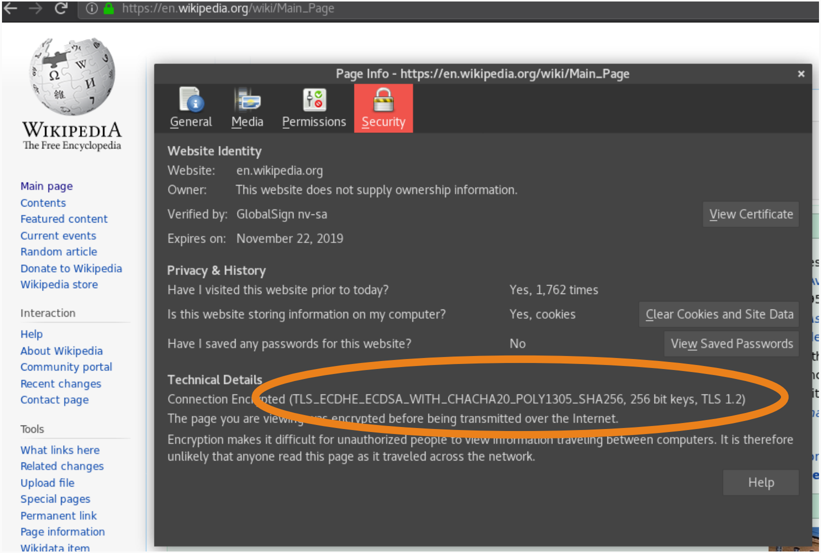
Context



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Technical Details

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Context

Cryptographic Libraries

Developing cryptographic libraries is hard, as the code must be:

- **efficient:** pervasive usage, on large amount of data.
- **functionally correct:** the specification must be respected.
- **protected against side-channel attacks:** constant-time implementation.

Context

Side-Channel Attacks

Exploit **auxilliary information** to break a cryptographic primitive.

Context

Side-Channel Attacks

Exploit **auxilliary information** to break a cryptographic primitive.

Constant-Time Programming

- Countermeasure against **timing** and **cache** attacks.
- **Control-flow** and **memory accesses** should not depend on **secret** data.
- Crypto implementations without this property are vulnerable.

Difficulties

Constraints

- Efficiency: **low-level** operations and **vectorized** instructions.
- Functional Correctness: **readable** code, with **high-level abstractions**.
- Side-Channel Attacks Protection: **control** over the executed code.

Gap Between Source and Assembly

Source

- **High-level** abstractions.
- **Readable** code.

Gap Between Source and Assembly

Source

- **High-level** abstractions.
- **Readable** code.

Source is not Security/Efficiency Friendly

- Trust compiler (GCC or Clang).
- Certified compilers are less efficient (CompCert).
- Optimizing can break side channel resistance.

Preservation of Constant-Timeness?

Before

```
int cmove(int x, int y, bool b) {
  return x + (y-x) * b;
}
```

Preservation of Constant-Timeness?

Before

```
int cmove(int x, int y, bool b) {
  return x + (y-x) ∗ b;
}
```

After

```
int cmove(int x, int y, bool b) {
  if (b) {
    return y;
  } else {
    return x;
  }
}
```

Gap Between Source and Assembly

Assembly

- **Efficient** code.
- **Control** over the program execution.

Gap Between Source and Assembly

Assembly

- **Efficient** code.
- **Control** over the program execution.

Assembly is not Programmer/Verifier Friendly

- The code is obfuscated.
- More error prone.
- Harder to prove/analyze.

Jasmin: High Assurance Cryptographic Implementations

Fast and Formally Verified Assembly Code

- **Source language**: assembly in the head with formal semantics $\Longrightarrow$ programmer & verification friendly
- **Compiler**: predictable & formally verified (in Coq) $\Longrightarrow$ programmer has control and no compiler security bug
- **Verification tool-chain**:
  - Functional correctness.
  - Side-channel resistance (constant-time).
  - Safety.

Implementations in Jasmin

TLS 1.3 components : ChaCha20, Poly1305, Curve25519.

The Jasmin Language

Initialization of ChaCha20 State

```
inline fn init(reg u64 key nonce, reg u32 counter) → stack u32[16] {
  inline int i;
  stack u32[16] st;
  reg u32[8] k;
  reg u32[3] n;

  st[0] = 0x61707865;
  st[1] = 0x3320646e;
  st[2] = 0x79622d32;
  st[3] = 0x6b206574;

  for i=0 to 8 {
    k[i] = (u32)[key + 4*i];
    st[4+i] = k[i];
  }

  st[12] = counter;

  for i=0 to 3 {
    n[i] = (u32)[nonce + 4*i];
    st[13+i] = n[i];
  }

  return st;
}
```

Zero-Cost Abstractions

- Variable names.
- Arrays.
- Loops.
- Inline functions.

User Control: Loop Unrolling

```
for i=0 to 15 {
  k[i] = st[i];
}
```

```
while(i < 15) {
  k[i] = st[i];  i += 1;
}
```

For Loops

- Fully unrolled.
- The value of the counter is propagated.
- The source code still readable and compact.

While Loops

- Untouched.

User Control: Register or Stack

- Jasmin has three kinds of variables:
  - register variables (reg).
  - stack variables (stack).
  - global variables (global).
- Arrays can be register arrays or stack arrays.
- Spilling is done manually (by the user).

```
inline fn sum_states(reg u32[16] k, stack u32 k15, stack u32[16] st) → reg u32[16], stack u32
{
  inline int i;
  stack u32 k14;

  for i=0 to 15 {
    k[i] += st[i];
  }

  k14    = k[14];   k[15]  = k15;     // Spilling
  k[15] += st[15];
  k15    = k[15];   k[14]  = k14;     // Spilling

  return k, k15;
}
```

User Control: Instruction-Set

- Direct memory access.

```
reg u64 output, plain;

for i=0 to 12 {
  k[i] = (u32)[plain + 4*i];
  (u32)[output + 4*i] = k[i]; }
```

- The carry flag is an ordinary boolean variable.

```
reg u64[3] h;
reg bool cf0 cf1;
reg u64 h2rx4 h2r;

h2r       += h2rx4;
cf0, h[0] += h2r;
cf1, h[1] += 0 + cf0;
_  , h[2] += 0 + cf1;
```

User Control : Instruction-Set

- Most assembly instructions are available.

```
of, cf ,sf, pf, zf, z = x86_ADC(x, y, cf);

of, cf, x = x86_ROL_32(x, bits);
```

- Vectorized instructions (SIMD).

```
k[0] +8u32= k[1];  // vectorized addition of 8 32-bits words;

k[1] = x86_VPSHUFD_256(k[1], (4u2)[0,3,2,1]);
```

The Jasmin Compiler

The Compiler

Goals And Features

- Predictability and control of generated assembly.
- Preserves semantics (machine-checked in Coq).
- Preserves side-channel resistance

Compilation

Passes and Optimizations

- For loop unrolling.
- Function inlining.
- Constant-propagation.
- Sharing of stack variables.
- Register array expansion.
- Lowering.
- Register allocation.
- Linearisation.
- Assembly generation.

Semantic Preservation

Compilation Theorem (Coq)

$$\begin{aligned}&\forall p, p'.\ \mathrm{compile}(p) = \mathrm{ok}(p') \Rightarrow\\ &\forall v_a, m, v_r, m'.\mathrm{enough\text{-}stack\text{-}space}(p', m) \Rightarrow\\ &v_a, m \Downarrow^{p} v_r, m' \ \Rightarrow\ v_a, m \Downarrow^{p'} v_r, m'\end{aligned}$$

Remarks

- The compiler uses validation.
- We may need some extra memory space for p':

$$\mathrm{enough\text{-}stack\text{-}space}(p', m)$$

- If p is not safe, i.e. $v_a, m \Downarrow^{p} \perp$, then we have no guarantees.

Functional Correctness

Functional Correctness

Methodology

- We start from a **readable reference implementation**:
  - Using a mathematical specification (e.g. in $\mathbb{Z}/p\mathbb{Z}$).
  - Or a simple imperative specifications.
- We gradually transform the **reference implem.** into an **optimized implem.**:
  - We prove that each transformation **preserves functional correctness** by equivalence (game-hoping).
- We prove additional properties of the final implementation:
  - **Constant-time** by program equivalence.
  - **Safety** by static analysis.

Functional Correctness

Gradual Transformation

We perform functional correctness proofs by game hopping:

$$c_{\mathrm{ref}} \sim c_1 \sim \ldots \sim c_n \sim c_{\mathrm{opt}}$$

EasyCrypt

- Jasmin programs are translated into EasyCrypt programs.
- EasyCrypt model for Jasmin (memory model + instructions).
- Equivalences are proved in EasyCrypt.

Functional Correctness

Relational Hoare Logic

A judgment $\{P\}\ c_1 \sim c_2\ \{Q\}$ is valid if:

$$(m_1, m_2) \in P \;\Rightarrow\; m_1 \Downarrow^{c_1} m_1' \;\Rightarrow\; m_2 \Downarrow^{c_2} m_2' \;\Rightarrow\; (m_1', m_2') \in Q$$

Relational Hoare Logic is provided in EasyCrypt.

Example

- c_1 is the reference implementation (the specification)
- c_2 is the optimized implementation

$$\{\mathrm{args}\langle m_1\rangle = \mathrm{args}\langle m_2\rangle\}\ c_1 \sim c_2\ \{\mathrm{res}\langle m_1\rangle = \mathrm{res}\langle m_2\rangle\}$$

Example: ChaCha20

Stream cipher that iterates a *body* on all the blocks of a message.

Reference

```
while (i < len) {
  chacha_body;
  i += 1;
}
```

Loop tiling

```
while (i + 4 ≤ len) {
  chacha_body;
  chacha_body;
  chacha_body;
  chacha_body;
  i += 4;
}
chacha_end
```

Scheduling

```
while (i + 4 ≤ len) {
  chacha_body4_swapped;
  i += 4;
}
chacha_end
```

Vectorization

```
while (i + 4 ≤ len) {
  chacha_body4_vectorized;
  i += 4;
}
chacha_end
```

Safety

Safety

Definition

A program p is safe under precondition ϕ if and only if:

$$\forall (v, m) \in \phi.\ v, m \not\Downarrow^{p} \bot$$

Why do we Need Safety?

- If p is safe, its execution never crashes.
- The compilation theorem gives no guarantees if p is not safe.
- Jasmin semantics in Easycrypt assumes that p is safe.

Safety

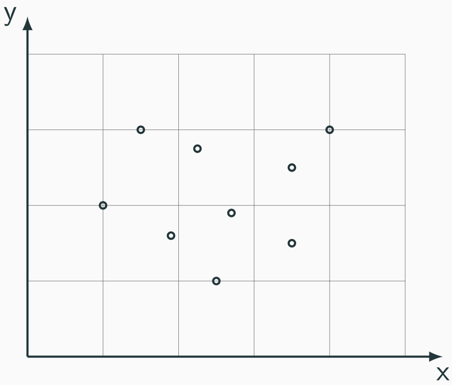
Properties to Check

- Division by zero.
- Variable and array initialization.
- Out-of-bound array access.
- Termination.
- Valid memory access.

Jasmin

Safety is checked automatically by **static analysis**.

Abstract Interpretation: Abstract Values



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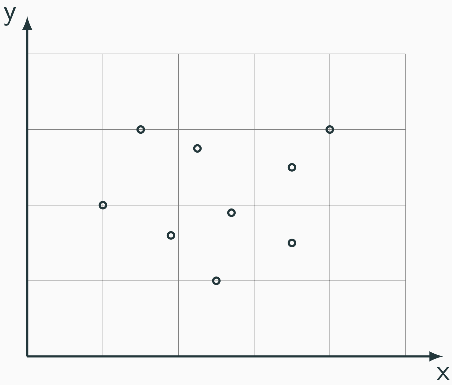

Soundness

$X^\sharp$ over-approximates X if and only if $X \subseteq \gamma(X^\sharp)$

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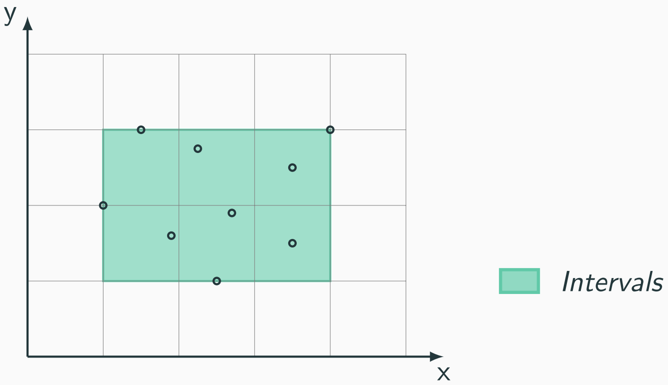

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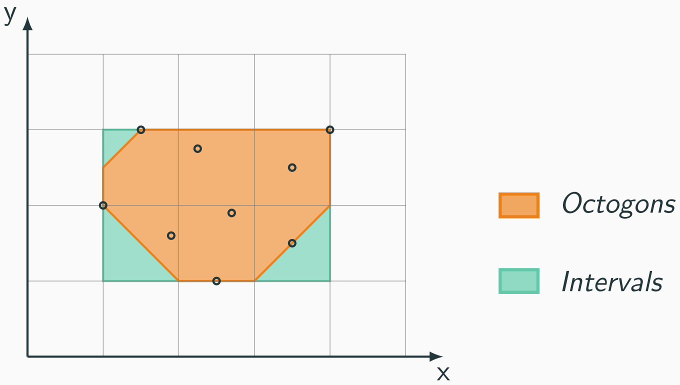

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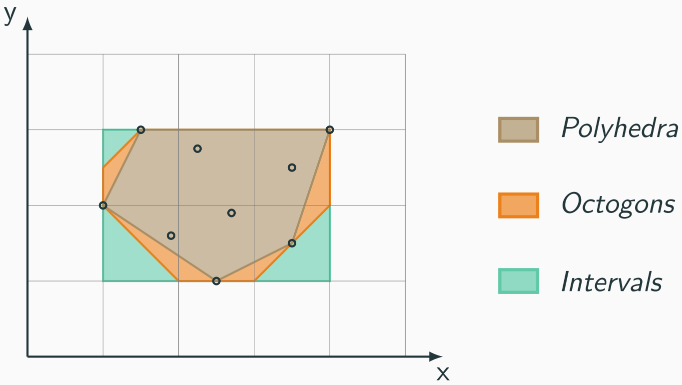

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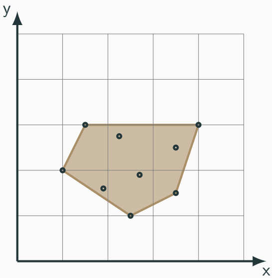
Abstract Interpretation: Abstract Transformers

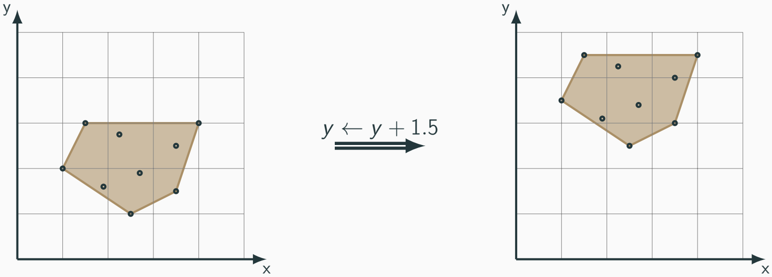


Soundness

$f^\sharp$ over-approximates f if and only if:

$$\forall X^\sharp.\ f \circ \gamma(X^\sharp) \subseteq \gamma \circ f^\sharp(X^\sharp)$$

Abstract Interpretation: Abstract Transformers



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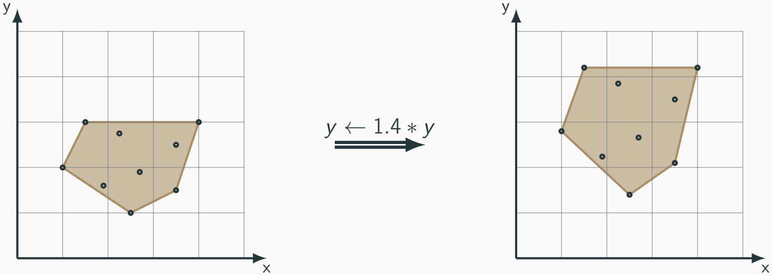

$$\xRightarrow{y \leftarrow 1.4 * y}$$

Soundness

f$^\sharp$ over-approximates f if and only if:

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Safety

Features of the Language

Jasmin is a simple language for static analysis:

- No recursion.
- Arrays size are statically known.
- No dynamic memory allocation.

Example

```
fn load(reg u64 in, reg u64 len) {
 inline int i;
 reg u8 tmp;

 tmp = 0;
 while (len >= 16) {
  for i = 0 to 16 {
   tmp = (u8)[in + i]; }
  in += 16;
  len -= 16; }

 for i = 0 to 16 {
  if i < len {
   tmp = (u8)[in + i]; }}

 return tmp;
}
```

Example

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  return tmp;
}
```

Memory Calling Contract

$$\text{valid-mem}_{\text{load}}(\text{in}_0, \text{len}_0) = [\text{in}_0; \text{in}_0 + \text{len}_0]$$

Static Analysis

Variables in the Abstract Domain

Let $\mathcal{P}$ be a set of pointers. To a variable $x \in \mathcal{V}$, we associate:

- $x \in \mathcal{V}^\sharp$: its abstract value.
- $x_0 \in \mathcal{V}^\sharp$: its abstract initial value.
- $\mathrm{pt}_x \subseteq \mathcal{P}$: points-to information.
- $\mathrm{offset}_x \in \mathcal{V}^\sharp$: its abstract offset.

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- $\mathrm{pt}_x \subseteq \mathcal{P}$: points-to information.
- $\mathrm{offset}_x \in \mathcal{V}^\sharp$: its abstract offset.

Moreover, for every $\mathrm{p} \in \mathcal{P}$, we have:

- $\mathrm{mem}_\mathrm{p} \in \mathcal{V}^\sharp$: memory accesses at p (plus an offset).

Static Analysis

Concretization Function

We decompose x into a base pointer p and an offset offset_x:

$$\gamma(\mathsf{pt}_x = \{\mathsf{p}\} \wedge \mathsf{offset}_x = \mathcal{S}^\sharp) = x \mapsto \{\mathsf{p} + o \mid o \in \gamma(\mathcal{S}^\sharp)\}$$

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Example

- $\gamma(\mathsf{pt}_x = \{\mathsf{p}\} \wedge \mathsf{offset}_x = [32; 63]) = x \mapsto [\mathsf{p} + 32; \mathsf{p} + 63]$

Static Analysis

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Example

- $\gamma(\mathsf{pt}_x = \{\mathsf{p}\} \wedge \mathsf{offset}_x = [32; 63]) = x \mapsto [\mathsf{p} + 32; \mathsf{p} + 63]$
- Abstract transformer:
  - $\mathcal{S}^\sharp$: $\mathsf{pt}_x = \{\mathsf{p}\} \wedge \mathsf{offset}_x = [32; 63]$
    $y \leftarrow x + 16$
  - $\mathcal{S}'^\sharp$: $\mathsf{pt}_y = \{\mathsf{p}\} \wedge \mathsf{offset}_y = [48; 79]$

Static Analysis

Remark

- In $y \leftarrow x + z$, we can either use x or z as a base pointer.
- In practice, it is never a problem (assembly coding style).

Static Analysis

Memory Calling Contract

Let f be a procedure with pointers $\mathcal{P}$. If:

$$[\![\mathsf{f}]\!]^\sharp(\mathcal{S}^\sharp_{\mathsf{init}}) \doteq \bigwedge_{\mathsf{p}\in\mathcal{P}} \mathsf{mem}_{\mathsf{p}} = \mathcal{S}^\sharp_{\mathsf{p}} \wedge \ldots$$

Then for every $\mathcal{S}_{\mathsf{init}} \subseteq \gamma(\mathcal{S}^\sharp_{\mathsf{init}})$:

$$\mathsf{valid\text{-}mem}_{\mathsf{f}}(\mathcal{S}_{\mathsf{init}}) \subseteq \bigcup_{\mathsf{p}\in\mathcal{P}} \gamma(\mathcal{S}^\sharp_{\mathsf{p}})$$

Static Analysis

Example

- $\mathcal{S}^\sharp \;:\; \mathrm{pt}_x = \{\mathrm{p}\} \wedge \mathrm{mem}_{\mathrm{p}} = [0;127] \wedge \mathrm{offset}_x = [128;128+16]$

  $\mathrm{tmp} \leftarrow (\mathrm{u8})[x+16]$

- $\mathcal{S}'^\sharp \;:\; \mathrm{mem}_{\mathrm{p}} = [0;127] \cup^\sharp [128;128+32] = [0;160]$

Example

```
fn load(reg u64 in, reg u64 len) {
  inline int i;
  reg u8 tmp;

  tmp = 0;
  while (len >= 16) {
    for i = 0 to 16 {
      tmp = (u8)[in + i]; }
    in += 16;
    len -= 16; }

  for i = 0 to 16 {
    if i < len {
      tmp = (u8)[in + i]; }}

  return tmp;
}
```

After the While Loop

$$\begin{aligned} & 0 \leq \mathsf{offset}_{\mathsf{in}}, \mathsf{len}, \mathsf{len}_0, \mathsf{mem}_{\mathsf{in}} \\ \wedge\ & \mathsf{offset}_{\mathsf{in}} + \mathsf{len} = \mathsf{len}_0 \\ \wedge\ & \mathsf{len}_0 - 15 \leq \mathsf{offset}_{\mathsf{in}} \leq \mathsf{len}_0 \\ \wedge\ & \mathsf{mem}_{\mathsf{in}} \leq \mathsf{offset}_{\mathsf{in}} \end{aligned}$$

At the End

$$0 \leq \mathsf{mem}_{\mathsf{in}} \leq \mathsf{len}_0$$

Static Analysis

The Analyzer

- Intervals + Relational domain (polyhedra).
- Basic syntactic pre-analysis.
- Disjunctive domain (using the control flow).
- Simple non-relational boolean abstractions (for bools and initialization).
- Brutal handling of function calls.

Static Analysis

Result

For Poly1305, with signature:

```
export fn poly1305_avx2(reg u64 out, reg u64 in, reg u64 len, reg u64 k)
```

We infer the ranges:

$$\begin{array}{llll} \mathrm{mem}_{\mathrm{out}}: & \mathrm{out} + [0;16[& \mathrm{mem}_{\mathrm{len}}: & \emptyset \\ \mathrm{mem}_{\mathrm{k}}\ : & \mathrm{k} + [0;32[& \mathrm{mem}_{\mathrm{in}}\ : & \mathrm{in} + [0;\mathrm{len}[\end{array}$$

Static Analysis

Caveat

We manually provide some information to the analyser:

- pointers (input) variables: k, in and out in Poly1305.
- relational (input) variables: len in Poly1305.

Conclusion

Conclusion

Contributions

A framework to build high-speed certified implementations of cryptographic primitives.

- Code is manually optimized.
- Functional correctness is obtained by game hopping.
- Safety and security against timing attacks are proved automatically.
- Efficient implementation of Poly1305, ChaCha20 and Gimli.

Conclusion

Future Works

- More TLS 1.3 primitives.
- More architectures, more general purpose language.
  - procedure calls.
  - register allocation/spilling.
- Certification for safety proofs.