High-Assurance High-Speed Cryptography Implementations in Jasmin

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2022-07-07, Cyber in Nancy

Cryptography Implementations

High-level specification of protocols

Implementation

Hardware-level security

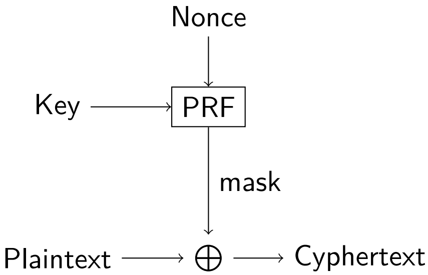
Example: symmetric encryption scheme

- k : key
- n : nonce
- m : plain-text message
- c : cyphertext

c := Enc(k, n, m)

m' := Dec(k, n, c)

Example: symmetric encryption from a PRF



$$\mathsf{Enc}(k, n, m) = m \oplus f(k, n)$$
$$\mathsf{Dec}(k, n, c) = c \oplus f(k, n)$$

Requirements

Requirements

- Efficiency
- Correctness
- Safety
- Confidentiality
  - against a PPT adversary (**cryptographic** security)
  - even in presence of side-channels (**implementation** security)

Efficiency

- CPU cycles matter
- This can be assessed experimentally (through measurements)
- No *formal* efficiency in this lecture

Correctness

Knowing the secret key allows to recover the plaintext:

$$Dec(k, n, Enc(k, n, m)) = m$$

Classical functional verification

Relies on the (formal) **semantics** of the programming language.

Safety

Running the program:

- terminates
- does not crash (division by zero...)
- does not access arrays out of bounds, uninitialized variables
- i.e., has a properly defined behavior

Programs are usually not safe. Only under some **precondition**.

Cryptographic security (IND$-CPA)

Game IND$-CPA-Real$_{\mathcal{A}}$( )

$k \twoheadleftarrow K$

$b \twoheadleftarrow \mathcal{A}^{\mathsf{RealEnc}(\cdot,\cdot)}(\,)$

Return b

proc RealEnc(n, m)

Return Enc(k, n, m)

Game IND$-CPA-Ideal$_{\mathcal{A}}$( )

$b \twoheadleftarrow \mathcal{A}^{\mathsf{IdealEnc}(\cdot,\cdot)}(\,)$

Return b

proc IdealEnc(n, m)

$c \twoheadleftarrow C$

Return c

Security requires the following advantage measure to be small

$$|\Pr[\,\text{IND\$-CPA-Real}_{\mathcal{A}}(\,) \Rightarrow \text{true}\,] - \Pr[\,\text{IND\$-CPA-Ideal}_{\mathcal{A}}(\,) \Rightarrow \text{true}\,]|$$

- Can be done using relational verification of probabilistic programs (e.g., using the EasyCrypt proof assistant).
- Not covered in this lecture.

Implementation security

An adversary can observe some effects of the program execution beyond its result:

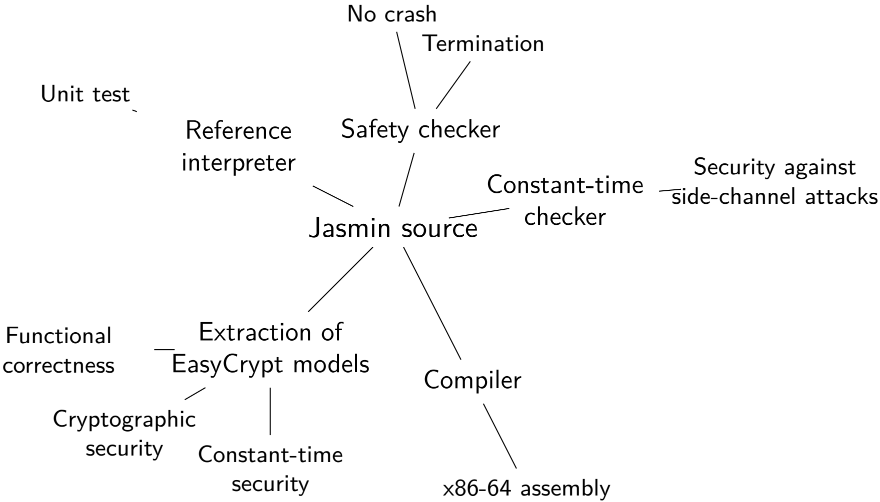
- execution time
- electromagnetic emissions
- noise
- effect on the branch predictor
- effect on the memory cache

Can any sensitive information be learned by means of these side-channels?

Example Encryption Scheme in Jasmin

Look at nbaesenc.jazz

The Jasmin tool-box



Executable semantics

In program p, calling function f with arguments $\vec{a}$ from initial memory m terminates in final memory m' and returns values $\vec{r}$:

$$f : (\vec{a}, m) \Downarrow_p (\vec{r}, m')$$

This is the definition of the program *behaviors* (formalized in Coq).

All proofs are made relative to this definition.

We gain *trust* by using it (execute & verify programs, verify static analyses, verify program transformations, . . .)

Safety: jasminc -checksafety ...

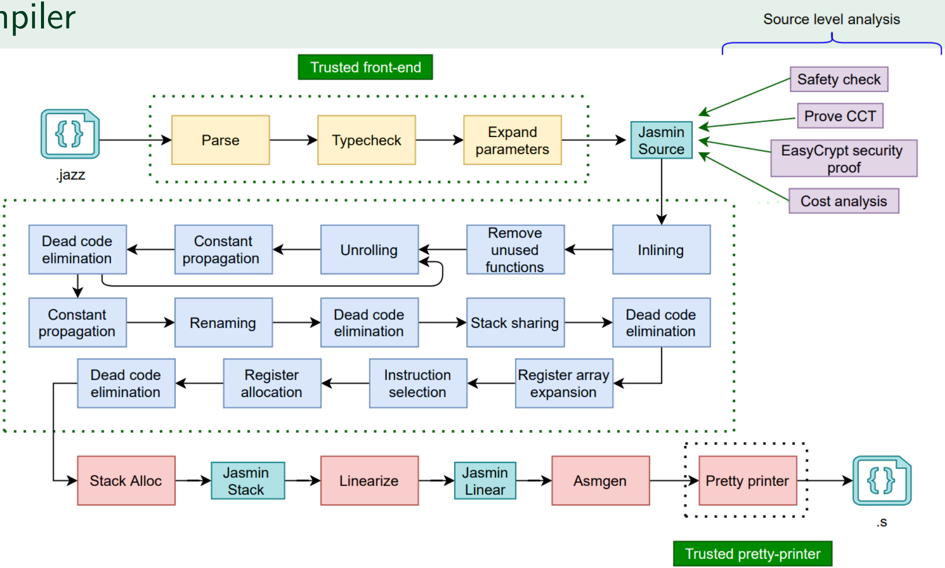
- Programs are usually **not** safe
  - Restrictions on the initial state
- Returns a sufficient pre-condition for safety (a predicate)
- Overapproximation because of undecidability
- The design of the programming language encourages the use high-level features that make safety verification doable automatically

When the safety checker infers precondition P (for a function f in program p), then for all initial state satisfying this precondition, there exists a corresponding final state:

$$\forall \vec{a}\ m, P(\vec{a}, m) \implies \exists \vec{r}\ m', f : (\vec{a}, m) \Downarrow_p (\vec{r}, m')$$

No formal proof of this property.

Compiler


Source level analysis
Trusted front-end
Safety check
Prove CCT
EasyCrypt security proof
Cost analysis
.jazz
Parse
Typecheck
Expand parameters
Jasmin Source
Dead code elimination
Constant propagation
Unrolling
Remove unused functions
Inlining
Constant propagation
Renaming
Dead code elimination
Stack sharing
Dead code elimination
Dead code elimination
Register allocation
Instruction selection
Register array expansion
Stack Alloc
Jasmin Stack
Linearize
Jasmin Linear
Asmgen
Pretty printer
.s
Trusted pretty-printer

Compiler correctness

Forward simulation

If the compilation of source program S succeeds and produces target program T,
if from the initial state i, S terminates with final result r,
then from the same initial state i, T also terminates with final result r.

Overlooked details

- Initial states may not be the same
  - Global data must be in the target memory
  - The "stack pointer" (RSP) must point to a valid region of memory
- The target stack must be large enough
  - i.e., the compiler does not enforce the absence of "stack overflow"

Preservation of functional properties

Compiler correctness implies

If a property holds for all source behaviors,
then it holds for all target behaviors.

When the source program is a *function* (deterministic, terminating)

Then the target program is the *same* function.

- Cryptographic primitives are usually functions
- even PRNGs!

Probabilities

When a function consumes random data

Reasoning about the *distribution* of the results in terms of the distribution of the inputs can be done at the source level.

Probabilistic properties of functions are preserved (example: IND$-CPA)

Given a secret key, an adversary cannot distinguish (with non-negligible probability) the encryption function from random sampling
This property is independent of the implementation.

- Unless the adversary has access to non-functional properties of the implementation

Non-preservation

Non-deterministic programs

A *correct* compiler may not preserve distributions.
For instance, a source program that tosses a coin may be correctly compiled to the constant program that always returns *heads*.

Changing the representation of values

E.g., booleans implemented as 63-bit machine integers.

$$S : b \mapsto \neg b \qquad\qquad T : n \mapsto 1 - n$$

How to map *invalid* target values to source values?
There is no way to express at the source level the target behavior.

Non-functional properties

The theorem does not say anything about things that cannot be described by *behaviors*.

Constant-time: jasminc -checkCT ...

The compiler (always) preserves the constant-time property.

Formal (machine-checked) proof of this statement for version 21.0 of the compiler (Barthe et al. 2021).

This is a stronger property than compiler-correctness.

EasyCrypt models

Reasoning about semantics of source programs is better done in a dedicated proof assistant.

Extract an EasyCrypt model from a Jasmin source program.

For safe inputs to the Jasmin program, the EasyCrypt program computes the same outputs (as the Jasmin program).

No formal proof of this statement.

Summary

- A language
- A compiler
- Safety is a key property
- Reasoning at the source level is valid
  - about safety; functional correctness (cryptographic security); constant-time security
  - Coq proofs justify this claim

Overview of the Jasmin programming language

Look at aes.jinc.

Low-level control

Function inlining

inline fn or #inline calls

Loop unrolling

for loops: unrolled
while loops: preserved

Storage class

param, inline: compile-time use only
global, stack: memory
reg: registers

Vector (SIMD) instructions

No automatic vectorization
Convenient syntax for most operations

Intrinsic instructions & flag registers

jasminc -help-intrinsics to get the list
Flags are plain variables

Common uses of intrinsics & flags

- Initialize to zero using a XOR: #set0
- Branch on the result of an arithmetic operation
- A single comparison with more than two outcomes

See src/low-level.jazz

Quizz (see src/array.jazz)

Can we tell something about the first returned value?

```
// Defines fn f(reg u8 x y) ⟶ reg u8
require "array.jinc"

inline
fn quizz0(reg u8 x) ⟶ reg u8, reg u8 {
    reg u8 r, y;

    r = 0;
    y = f(r, x);
    return r, y;
}
```

Quizz (see src/array.jazz)

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    r = 0;
    y = f(r, x);
    return r, y;
}
```

```
// Defines fn g(stack u8[1] x, reg u8 y) ⟶ stack u8[1]
require "array.jinc"

inline
fn quizz1(reg u8 x) ⟶ stack u8[1], stack u8[1] {
    stack u8[1] r, y;

    r[0] = 0;
    y = g(r, x);
    return r, y;
}
```

Arrays: an explicit and powerful way to structure memory

Things made easier

- Modular reasoning is possible
- Sizes are explicit
  - Useful for proving safety
- Alias analysis is trivial
  - Array may overlap only when they have the same name

Caveat

Ensuring call-by-value semantics without copy is tricky (the compiler rejects programs)

Practice tomorrow

- Expand the encryption scheme to messages of 256 bits
- Prove constant-time security of small low-level programs

Constant-Time Security?

Threat: any shared component is a communication channel

Aim: protect against remote cache-based timing side-channel attacks

Attack scenarios

- A distant server takes time to answer
- Two clients of a (trusted) cloud provider
  - Processes are isolated (virtual memory, hypervisor, . . .)
- Two websites in a browser
- Two apps running on the same device

Constant-Time Programming

Adversary model aka leakage model

The adversary learns from the victim program (whose code is public):

- the sequence of executed instructions (*program counter security*)
- the sequence of accessed memory addresses
  - sometimes only the cache-line (i.e., the least significant bits are kept secret)

and also:

- (size of) operands to some operations (division, floating-point arithmetic, . . .)
- values of local variables on function return
- . . .

Protection

Ensure that the leakage is independent of secrets

Constant-time select

In order to replace a conditional expression $\mathrm{r = c\ ?\ t : f}$:

- compute operations from both branches
- chose the right result depending on the condition

Using arithmetic

$$r = (t \times m) + (f \times (1 - m))$$

Using a conditional move instruction

$\mathrm{r = f;}$
$\mathrm{r = t\ if\ c;}$

See src/ctselect.jazz

Enforcement by typing

See src/max.jazz

Security type annotations

Tell which inputs are public (and which are not).
Security types are ordered (aka two-point lattice)

Typing rules

Result of operations is not lower than the level of arguments
Array indices and branch/loop conditions must be public
Note: usually points-to analysis is hard

Access memory at secret addresses

This can become costly

- Load the whole array
- Rewrite the whole array
- See src/copyMAC.jazz

To avoid table lookups:

- Bit-slicing
- Hardware support (e.g., AES-NI)
- Take constant-time security into account during design

Declassification

Look at nbaesenc.jazz again.

- Sometimes, we need to argue that a tainted value is public

Questions?

A programming language and associated tools for writing & verifying low-level implementations.

https://formosa-crypto.org/

Thanks for your attention.

References

Literature

Barthe, Gilles, Benjamin Grégoire, Vincent Laporte, and Swarn Priya. 2021. "Structured Leakage and Applications to Cryptographic Constant-Time and Cost." In *CCS '21: 2021 ACM SIGSAC Conference on Computer and Communications Security, Virtual Event, Republic of Korea, November 15 - 19, 2021*, 462–76. https://doi.org/10.1145/3460120.3484761.