Radboud University

Engineering Cryptographic Software

High-assurance crypto and Jasmin

Winter 2024/25

This course

1. Limit crypto to “secure-channel” crypto
2. Make crypto software fast and secure (against software attacks)

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Secure-channel crypto

- Symmetric crypto (block/stream cipher, hash function, MAC)
- ECC (ECDH, Schnorr signatures)

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Secure-channel crypto

- Symmetric crypto (block/stream cipher, hash function, MAC)
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Fast and secure

- Optimize in C/assembly
- Follow the "constant-time" paradigm

Some things I like about the course

- Low-level programming on predictable platform
- Algorithmics of multiprecision arithmetic
- Scalar-multiplication algorithms

The times they are a-changin'

Post-quantum crypto

- The world is moving from ECC to PQC
- (Almost) no need for multiprecision arithmetic
- (Almost) no need for scalar multiplication
- More complex than optimizing just ECC scalar multiplication
- Starting to become part of standard crypto courses

The times they are a-changin'

Advanced microarchitectural attacks

- Spectre: exploit leaks in speculative execution
- Hertzbleed: power leakage translates to frequency changes
- Augury+GoFetch: attacks exploiting data-dependent prefetchers
- Three categories of CPUs/platforms:
  - Platforms that support secure implementations (e.g., OpenTitan)
  - Platforms that actively make secure implementations hard (large general-purpose CPUs)
  - Platforms that are in between (e.g., Cortex-M4)

The times they are a-changin'

High-assurance crypto

- Formal methods to improve crypto (software)
- Possibly move away from C/assembly

3 properties for crypto code

1. Correctness

- Functionally correct
- Memory safety
- Thread safety
- Termination

2. Security

- Don't leak secrets
- "Constant-time"
- Resist Spectre attacks
- Resist Power/EM attacks
- Fault protection
- Easy-to-use APIs

3. Efficiency

- Speed (clock cycles)
- RAM usage
- Binary size
- Energy consumption

The “traditional approach”

1. Implement crypto in C
2. Identify most relevant parts for performance
3. Re-implement those in assembly

Correctness?

“Are you actually sure that your software is correct?”

—prof. Gerhard Woeginger, Jan. 24, 2011.

#epicfail

```
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%r13
adc %rdx,%r14
adc $0,%r14
mov  %r9,%rax
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%r14
adc %rdx,%r15
adc $0,%r15
mov  %r10,%rax
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%r15
adc %rdx,%rbx
adc $0,%rbx
mov  %r11,%rax
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%rbx
mov  $0,%rsi
adc %rdx,%rsi
```

- Code snippet is from > 8000 lines of assembly
- Crypto **always** has more possible inputs than we can exhaustively test
- Some bugs are triggered with very low probability
- Testing won't catch these bugs
- Audits might, but this requires expert knowledge!

Security?

Traditional timing attacks

- Software only, can be carried out remotely
- In principle, we know how to systematically avoid them
- Increasingly standard requirement: “constant-time”

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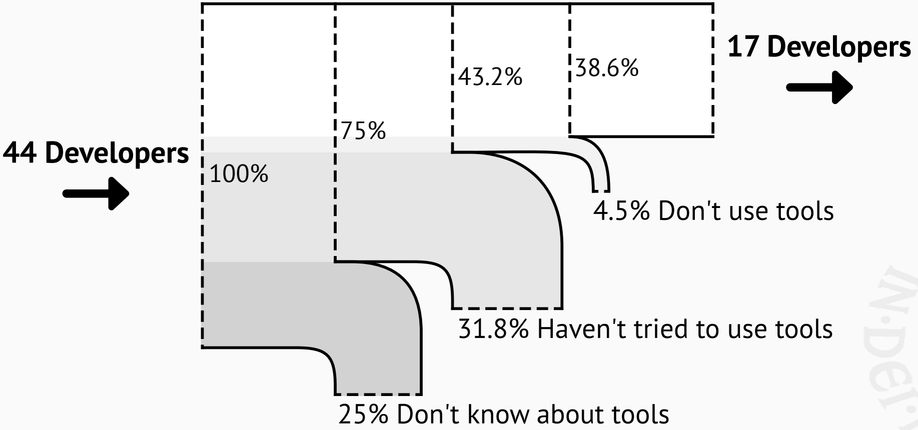
Plus side

- Full control (at least for assembly)
- Various tools to check for timing leaks

Minus side

- Many ways to screw up
- C compiler isn’t built for crypto

Security?



Jan Jancar, Marcel Fourné, Daniel De Almeida Braga, Mohamed Sabt, Peter Schwabe, Gilles Barthe, Pierre-Alain Fouque, and Yasemin Acar: *"They're not that hard to mitigate": What Cryptographic Library Developers Think About Timing Attacks*. IEEE S&P 2022

3. Efficiency!

High-assurance crypto

Traditional approach is great at producing very efficient software that is neither (guaranteed to be) correct nor (guaranteed to be) secure.

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  - Has precise formal specification (**+**)
  - Inherently security-critical (**+**)

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We want formal guarantees without giving up on performance.

High-assurance crypto

FORMOSA CRYPTO

- Effort to formally verify crypto
- Goal: **verified PQC ready for deployment**
- Three main projects:
  - EasyCrypt proof assistant
  - Jasmin programming language
  - Libjade (PQ-)crypto library
- Core community of ≈ 30–40 people
- Discussion forum with >280 people

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Radboud University

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INVENTEURS DU MONDE NUMÉRIQUE

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High-assurance crypto

Formosan black bear

文A 24 languages

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From Wikipedia, the free encyclopedia

The **Formosan black bear** (臺灣黑熊, ***Ursus thibetanus formosanus***), also known as the **Taiwanese black bear** or **white-throated bear**, is a subspecies of the Asiatic black bear. It was first described by Robert Swinhoe in 1864. Formosan black bears are endemic to Taiwan. They are also the largest land animals and the only native bears (*Ursidae*) in Taiwan. They are seen to represent the Taiwanese nation.

Because of severe exploitation and habitat degradation in recent decades, populations of wild Formosan black bears have been declining. This species was listed as "endangered" under Taiwan's Wildlife Conservation Act (Traditional Chinese: 野生動物保育法) in 1989. Their geographic distribution is restricted to remote, rugged areas at elevations of 1,000–3,500 metres (3,300–11,500 ft). The estimated number of individuals is 200 to 600.[3]

Physical characteristics [edit]

The V-shaped white mark on a bear's chest

The Formosan black bear is sturdily built and has a round head, short neck, small eyes, and long snout. Its head measures 26–35 cm (10–14 in) in length and 40–60 cm (16–24 in) in circumference. Its ears are 8–12 cm (3.1–4.7 in) long. Its snout resembles a dog's, hence its nickname is "dog bear". Its tail is inconspicuous and short—usually less than 10 cm (3.9 in) long. Its body is well covered with rough, glossy, black hair, which can grow over 10 cm long around the neck. The tip of its chin is white. On the chest, there is a

Formosan black bear

Conservation status

Vulnerable (IUCN 3.1)[1]

https://en.wikipedia.org/wiki/Formosan_black_bear

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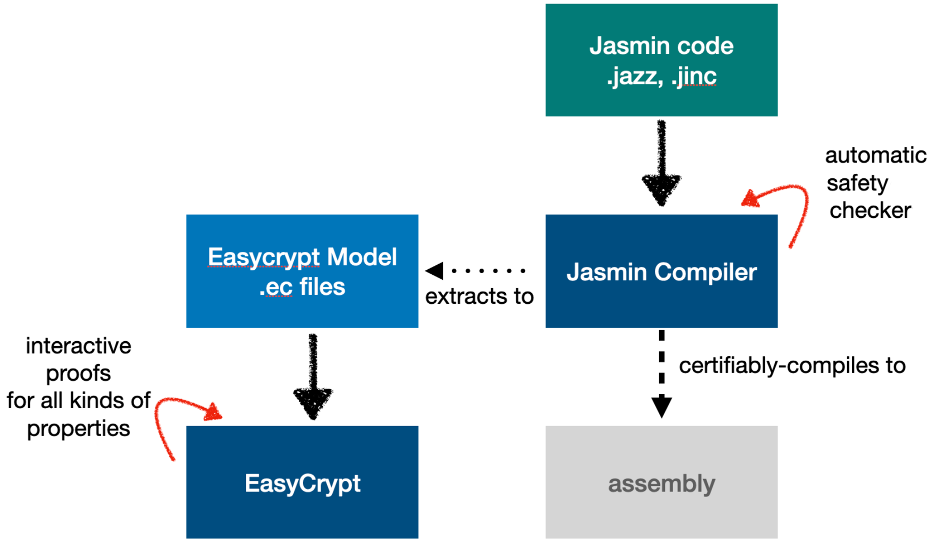
University of Bristol · CASA Cyber Security in the Age of Large-Scale Adversaries · IMDEA Software Institute · INESCTEC · Inria Inventeurs du monde numérique · Universität Klagenfurt · Max Planck Institute for Security and Privacy · U.Porto · Radboud University · Ruhr Universität Bochum · TU/e Eindhoven University of Technology

The toolchain and workflow



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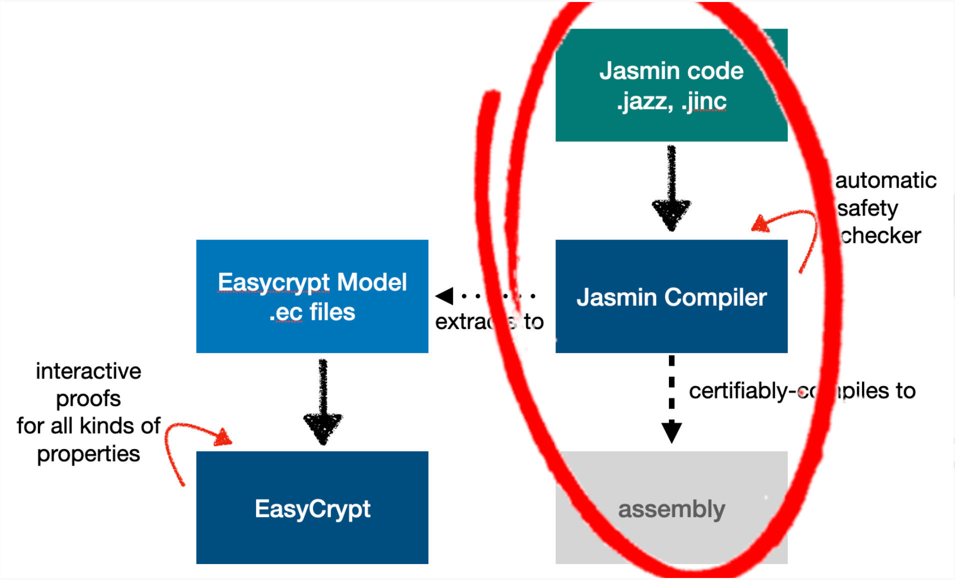

Implementing in Jasmin

Almeida, Barbosa, Barthe, Blot, Grégoire, Laporte, Oliveira, Pacheco, Schmidt, Strub. *Jasmin: High-Assurance and High-Speed Cryptography.* ACM CCS 2017

- Language with "C-like" syntax
- Programming in Jasmin is much closer to assembly:
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  - A few exceptions, but highly predictable
  - Compiler does not schedule code
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  - A few exceptions, but highly predictable
  - Compiler does not schedule code
  - Compiler **does not spill registers**
- Compiler is formally proven to preserve semantics
- Static (trusted) safety checker
- Compiler is formally proven to preserve constant-time property

Jasmin language features

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- Optionally: `inline` functions
- `export` functions to interface with C
- Stack and register arrays
- Loops (`while` and `for`)
- Conditionals (`if`, `else`)
- “Intrinsics”, e.g., for vector instructions
- Limited support for system calls

Memory and thread safety

- Jasmin does not support dynamic memory allocation
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- Jasmin does not have global variables
- Thread safe (except if external memory is shared)

So, where are we?

Correctness

- Functional correctness through EasyCrypt proofs
- Thread and **memory safety** guaranteed by Jasmin

Efficiency

Security

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- Could be addressed by machine-readable standards

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Security

- ???

Timing attacks

```
if(secret)
{
  do_A();
}
else
{
  do_B();
}
```

```
table[secret]
```

Constant-time: Avoid those!

Did we get it right?

Option 1: Auditing

"Originally, me, a glass of bourbon, and gdb were a good trio. But that got old pretty quick. (The manual analysis part – not the whiskey.)"

—Survey response in https://ia.cr./2021/1650

Did we get it right?

Option 2: Check/verify

- Implement, use tool to check "constant-time" property
- Tool overview by Ján Jančár: `https://crocs-muni.github.io/ct-tools/`
- Problems in practice:
  - Some tools not sound
  - Some tools not on binary/asm level
  - Some tools not usable

} Fairly high on my whishlist. . .

Did we get it right?

Option 3: Avoid variable-time code

- Prevent leaking patterns on source level
- Prove that compilation doesn't introduce leakage

Information-flow type system

- Enforce constant-time on Jasmin source level
- Every piece of data is either `secret` or `public`
- Flow of secret information is traced by type system

"Any operation with a secret input produces a secret output"

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- In principle can do this also in, e.g., Rust (`secret_integers` crate)
- **Jasmin compiler is verified to preserve constant-time!**
- Explicit `#declassify` primitive to move from `secret` to `public`
- `#declassify` creates a proof obligation!

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Spectre v1 (“Speculative bounds-check bypass”)

```
stack u8[10] public;
stack u8[32] secret;
reg u8 t;
reg u64 r, i;

i = 0;
while(i < 10) {
  t = public[(int) i] ;
  r = leak(t);
  ...
}
```

Countermeasures

Fencing

- Can prevent speculation through **barriers** (LFENCE)
- Protecting *all* branches is possible but costly

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Speculative Load Hardening

- Idea: maintain misprediction predicate `ms` (in a register)
- At every branch use arithmetic to update predicate
- Option 1: Mask every loaded value with `ms`
- Option 2: Mask every address with `ms`
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- Effect: during misspeculation “leak” constant value
- Implemented in LLVM since version 8
  - Still noticable performance overhead
  - No formal guarantees of security

Selective SLH

Do we need to mask/protect all loads?

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- No need to mask loads into registers that never enter leaking instructions
- `secret` registers never enter leaking instructions!
- Obvious idea: mask only loads into `public` registers

Extending the type system

- Type system gets three security levels:
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  - `public`: public, also during misspeculation
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  - `#declassify r`: Go from `secret` to `transient`
  - `#declassify` requires cryptographic proof/argument
- Still: allow branches and indexing only for `public`

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Type system supports programmer in writing efficient Spectre-v1-protected code!

How about other Spectre variants?

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Spectre v3

- Better known as Meltdown
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Spectre v4

- “Speculative store bypass”
- Loads may speculatively retrieve stale data
- Disable with SSBD CPU flag

But wait, there's more: Spectre-RSB

The attack

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- "Speculatively return to address on top of RSB"

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High-level countermeasure idea

- Limit attacker capabilities
- Speculative return only to well-defined restricted set of locations
- Use LFENCE or selective SLH to protect at those locations

Return tables and more security typing

- Jasmin compiler has global view
- For each function, compiler knows all call sites into this function

Arranz Olmos, Barthe, Chuengsatiansup, Grégoire, Laporte, Oliveira, Schwabe, Yarom, Zhang. *Protecting cryptographic code against Spectre-RSB* ePrint 2024/1070.

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  - Misspeculation of function "return" is outside control-flow graph

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  - Misspeculation of function "return" is outside control-flow graph
- Need modifications to security type system:
  - **`public`** registers become **`transient`** after function call
  - In some situations, we can preserve **`public`** type

Arranz Olmos, Barthe, Chuengsatiansup, Grégoire, Laporte, Oliveira, Schwabe, Yarom, Zhang. *Protecting cryptographic code against Spectre-RSB* ePrint 2024/1070.

Security – zeroization

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3. Don't scrub source-level invisible data
4. Mis-estimate stack space when scrubbing from caller

Security – zeroization (ctd.)

Solution in Jasmin compiler

Zeroize used stack space and registers when returning from export function

Arranz Olmos, Barthe, Gonzalez, Grégoire, Laporte, Léchenet, Oliveira, Schwabe: *High-assurance zeroization*. TCHES 2024-1.

Security – zeroization (ctd.)

Solution in Jasmin compiler

Zeroize used stack space and registers when returning from export function

- Make use of multiple features of Jasmin:
  - Compiler has global view
  - All stack usage is known at compile time
  - Entry/return point is clearly defined

Arranz Olmos, Barthe, Gonzalez, Grégoire, Laporte, Léchenet, Oliveira, Schwabe: *High-assurance zeroization*. TCHES 2024-1.

Summary

Programming in Jasmin gives you

- A more convenient way to “write assembly”
- Safety guarantees
- Systematic timing-attack protection
- Systematic Spectre v1 protection
- Link to computer-verified (EasyCrypt) proofs of
  - Functional correctness
  - Cryptographic security

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- A more convenient way to "write assembly"
- Safety guarantees
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- Link to computer-verified (EasyCrypt) proofs of
  - Functional correctness
  - Cryptographic security
- Spoiler: there's more to come

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Research internship opportunity

- Location: Rennes, France
- Topic: Systematic Analysis of Side Channels in Novel ARM Microarchitectures
- Researchers: Daniel De Almeida Braga & Thomas Rokicki
- Possibility to follow up with Ph.D. trajectory