MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

Formosa Crypto – high-assurance crypto software in practice

Peter Schwabe

February 20, 2024

The setting for this talk

Cryptographic software

- Primitives, no protocols
- “Secure-channel” primitives

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- Only software-visible side channels
- Big CPUs

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- Follow “constant-time” paradigm
  - No secret-dependent branches
  - No memory access at secret-dependent location
  - No variable-time arithmetic (e.g., DIV)

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  - No variable-time arithmetic (e.g., DIV)
- Fairly little code, doesn't even need function calls!

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- More assumptions, more schemes, more parameters, **more code**
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    - Confidence in functional correctness through test vectors . . . ?

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- Shattered by Hwang, Liu, Seiler, Shi, Tsai, Wang, and Yang (CHES 2022): *Verified NTT Multiplications for NISTPQC KEM Lattice Finalists: Kyber, SABER, and NTRU.*

Advanced microarchitectural side channels

Tools that aren't built for crypto

"*. . . implementations shall consist of source code written in ANSI C.*"

—NIST PQC Call for Proposals, 2017

- No memory safety
- Finicky semantics
  - Undefined behavior
  - Implementation-specific behavior
  - Context-specific behavior
- No mandatory initialization
- No (optional) runtime checks

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but… Rust!

- Memory safe
- More clear semantics (?)
- Mandatory variable initialization
- (Optional) runtime checks for, e.g., overflows

Tools that aren't built for crypto

Lack of security features

- **No concept of secret vs. public data**
- No preservation of "constant-time"
- Limited protection against microarchitectural attacks
- Limited support for erasure of sensitive data

Let's fix those tools!

"We argue that we must stop fighting the compiler, and instead make it our ally."

—Simon, Chisnall, Anderson, 2018

Let's fix those tools!

Secure erasure in LLVM

- Simon, Chisnall, Anderson implement secure erasure in LLVM
- Code available at https://github.com/lmrs2/zerostack
- **Not adopted in mainline LLVM**

Let's fix those tools!

Secret types in Rust + LLVM

- Initiative at HACS 2020: secret integer types in Rust, C++, **and LLVM**
- Rust draft RFC online at `https://github.com/rust-lang/rfcs/pull/2859`
- Implementation in LLVM is massive effort, **no real progress, yet**

Let's fix those tools!

Spectre protections in LLVM

- Carruth, 2019: Spectre v1 countermeasure in LLVM[1] (see later in the talk)
- *"does not defend against secret data already loaded from memory and residing in registers"*

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[2] *Ultimate SLH: Taking Speculative Load Hardening to the Next Level.* USENIX Security, 2023

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- *"does not defend against secret data already loaded from memory and residing in registers"*
- Zhang, Barthe, Chuengsatiansup, Schwabe, Yarom, 2023: More principled approach[2]
- Report and proposed patches to LLVM in March 2022
- September 2022: **Status: WontFix (was: New)**

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High-assurance crypto

FORMOSA CRYPTO

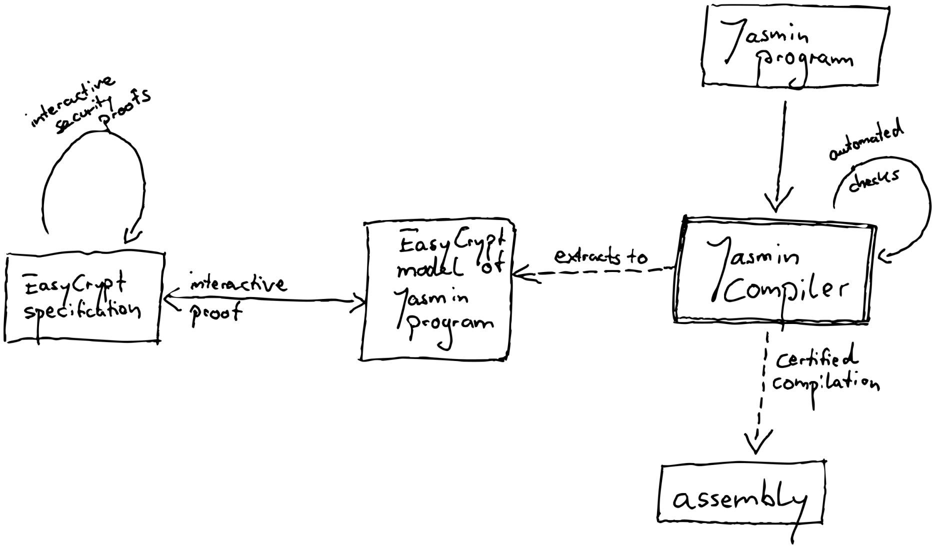
- Effort to formally verify crypto
- Goal: **verified PQC ready for deployment**
- Three main projects:
  - EasyCrypt proof assistant
  - Jasmin programming language
  - Libjade (PQ-)crypto library
- Core community of $\approx$ 30–40 people
- Discussion forum with >200 people

University of Bristol
The University of Melbourne
CASA – Cyber Security in the Age of Large-Scale Adversaries
Max Planck Institute for Security and Privacy
IMDEA Software Institute
U. Porto
Radboud University
INESC TEC
Ruhr Universität Bochum
Inria – Inventeurs du monde numérique
Eindhoven University of Technology

Joint work with. . .

Aaron Kaiser, Adrien Koutsos, Alley Stoughton, Amber Sprenkels, Andreas Hülsing, Antoine Séré, Basavesh Ammanaghatta Shivakumar, **Benjamin Grégoire**, Benjamin Lipp, Bo-Yin Yang, Bow-Yaw Wang, Chitchanok Chuengsatiansup, Christian Doczkal, Daniel Genkin, Denis Firsov, Fabio Campos, François Dupressoir, Gilles Barthe, Hugo Pacheco, Jack Barnes, **Jean-Christophe Léchenet**, José Bacelar Almeida, Kai-Chun Ning, Lionel Blatter, Lucas Tabary-Maujean, Manuel Barbosa, Matthias Meijers, Miguel Quaresma, Ming-Hsien Tsai, Peter Schwabe, Pierre Boutry, Pierre-Yves Strub, Ruben Gonzalez, Rui Qi Sim, Sabrina Manickam, **Santiago Arranz Olmos**, Sioli O'Connell, Sunjay Cauligi, Swarn Priya, Tiago Oliveira, Vincent Hwang, **Vincent Laporte**, William Wang, Yi Lee, Yuval Yarom, Zhiyuan Zhang

The toolchain and workflow



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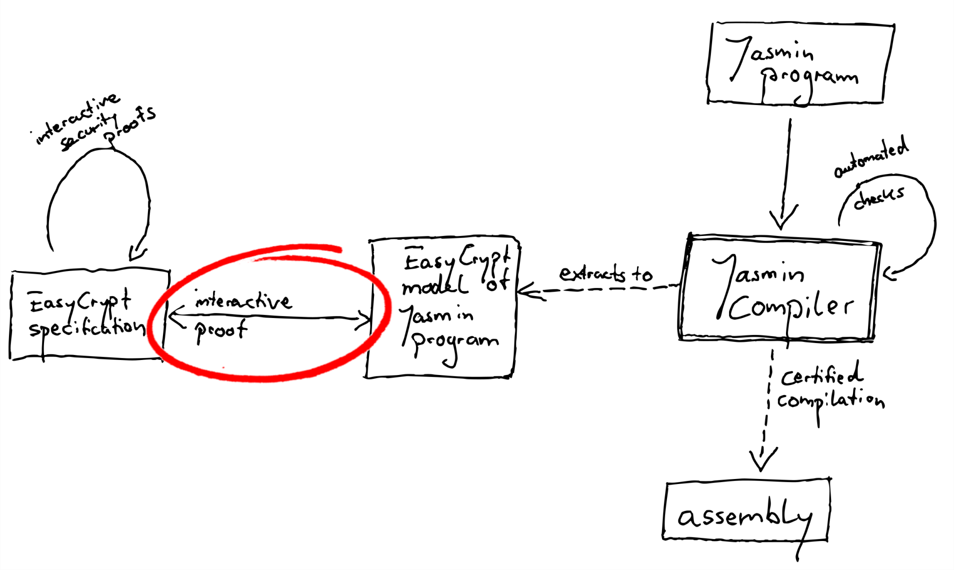

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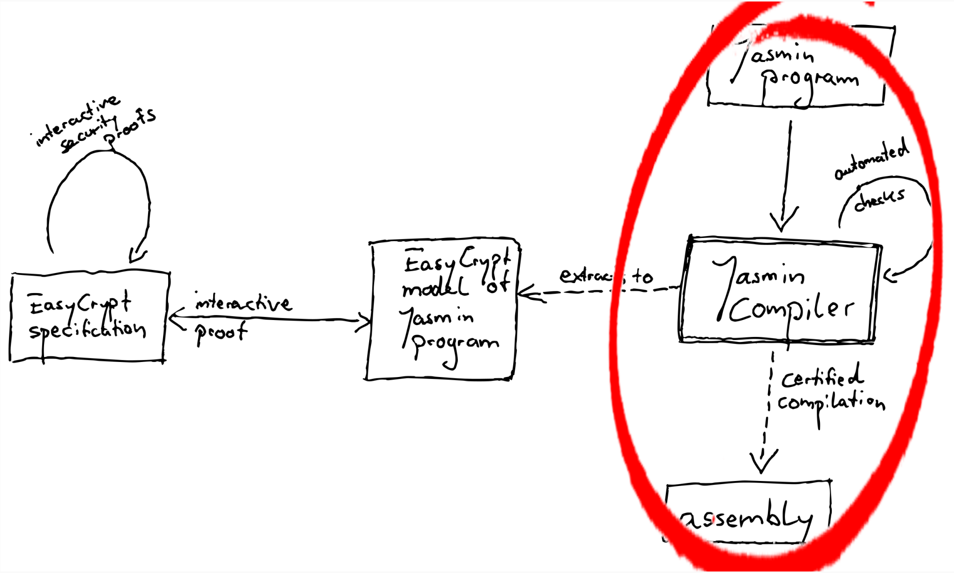


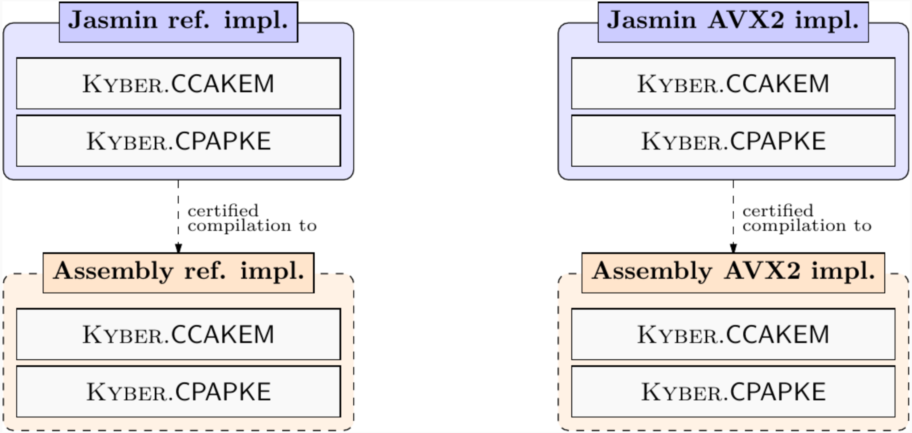
Running example: Kyber

"The public-key encryption and key-establishment algorithm that will be standardized is CRYSTALS-KYBER."

—NIST IR 8413-upd1

- Lattice-based KEM, joint work with Avanzi, Bos, Ding, Ducas, Kiltz, Lepoint, Lyubashevsky, Schanck, Schwabe, Seiler, and Stehlé.
- Three parameter sets; "recommended" is **Kyber768**
- FIPS draft standard public for comments: https://csrc.nist.gov/pubs/fips/203/ipd
- Already deployed in TLS by Google and Cloudflare

Functional correctness of Kyber implementations



Almeida, Barbosa, Barthe, Grégoire, Laporte, Léchenet, Oliveira, Pacheco, Quaresma, Schwabe, Séré, and Strub. *Formally verifying Kyber – Episode IV: Implementation Correctness.* TCHES 2023-3.

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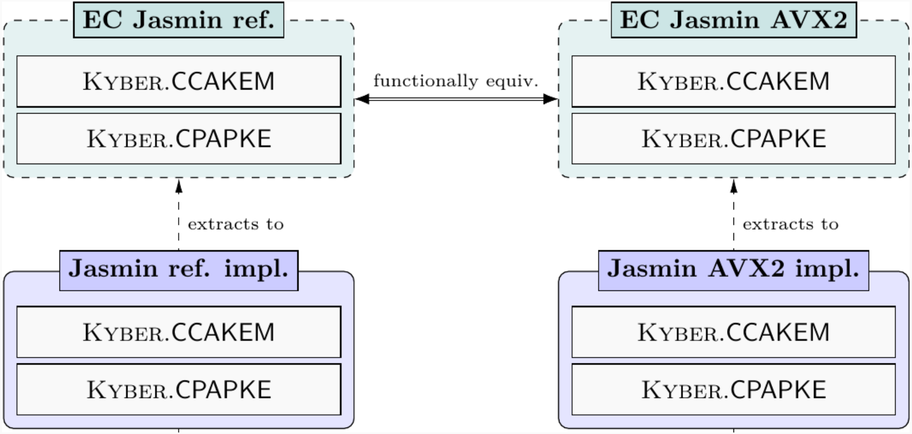

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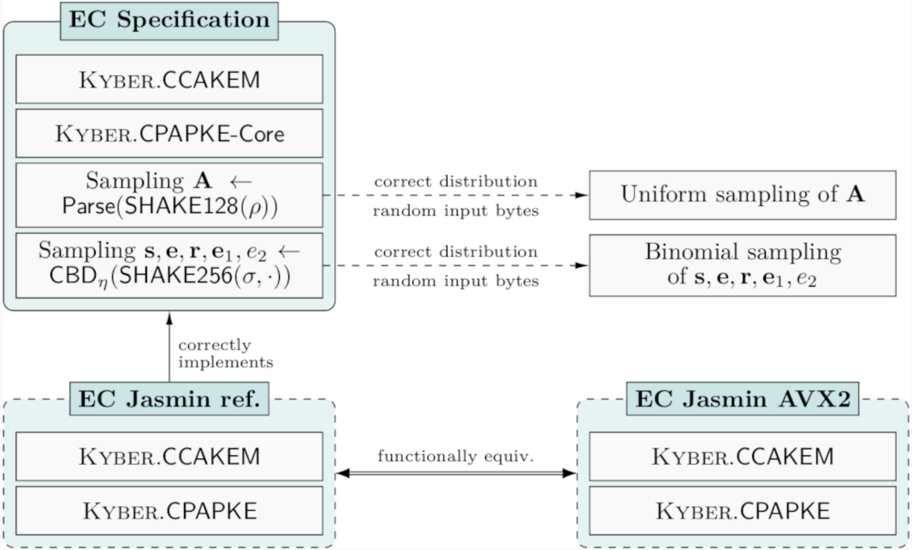

Implementing in Jasmin

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:
  - Generally: 1 line in Jasmin $\rightarrow$ 1 line in assembly
  - A few exceptions, but highly predictable
  - Compiler does not schedule code
  - Compiler does not spill registers

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  - Generally: 1 line in Jasmin → 1 line in assembly
  - 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[3]

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Efficiency of Jasmin code

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- Can do (almost) everything you can do in assembly
- Architecture-specific implementations
- Small limitations to enable static safety checking (no raw pointers)
- Easier to write and maintain than assembly
  - Loops, conditionals
  - Function calls (optional: inline)
  - Function-local variables
  - Register and stack arrays
  - Register and stack allocation

Efficiency of Jasmin code

Performance of Kyber code

Implementation	operation	Skylake	Haswell	Comet Lake
C/asm AVX2	keygen	49572	47280	41682
	encaps	60018	62900	55956
	decaps	45854	47784	43906
Jasmin AVX2	keygen	106578	96296	93244
(fully verified)	encaps	119308	111536	107474
	decaps	105336	98328	96564
Jasmin AVX2	keygen	50004	48800	45046
(fully optimized)	encaps	65132	63988	59496
	decaps	50340	51444	48172

Security – "constant time"

- 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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- **Remember: Jasmin compiler is verified to preserve constant-time!**
- Explicit `#declassify` primitive to move from `secret` to `public`

Security – 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);
  ...
}
```

Extending the type system

- Type system gets three security levels:
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  - `public`: public, also during misspeculation
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- Selective speculative load hardening (selSLH):
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  - Mask "transient" values with flag before leaking them
- Overhead for Kyber768 (on Intel Comet Lake):
  - 0.28% for Keypair
  - 0.55% for Encaps
  - 0.75% for Decaps
- Exploits synergies with protections against "traditional" timing attacks

Ammanaghatta Shivakumar, Barthe, Grégoire, Laporte, Oliveira, Priya, Schwabe, and Tabary-Maujean. *Typing High-Speed Cryptography against Spectre v1.* IEEE S&P 2023.

Security – zeroization

"... A cryptographic module shall provide methods to zeroize all plaintext secret and private cryptographic keys"

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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.

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- Make use of multiple features of Jasmin:
  - Compiler has global view
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- Example:

```
cd src/crypto_kem/kyber/kyber768/amd64/ref/ && make
```

  will build

```
src/crypto_kem/kyber/kyber768/amd64/ref/kem.s
```

  with API described in

```
src/crypto_kem/kyber/kyber768/amd64/ref/include/api.h
```

Libjade – releases and plans

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- Latest release: 2023.05-1
- Plans for next release:
  - Integrate EasyCrypt proofs (covered by CI)
  - Integrate/consolidate various features
  - Special focus on Kyber-768

More proof automation!

- Integrate with CryptoLine (https://github.com/fmlab-iis/cryptoline)[4]
    - (semi-)automated proof of branch-free arithmetic
    - "Prove without understanding code"
- Automated equivalence proving...

[4] Fu, Liu, Shi, Tsai, Wang, and Yang. Signed Cryptographic Program Verification with Typed CryptoLine. ACM CCS 2019

Challenges, ongoing work, TODOs

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Beyond Spectre v1

- Spectre v2: Avoid by not using indirect branches
- Spectre v4: Use SSBD: https://github.com/tyhicks/ssbd-tools
- **Spectre protection requires separation of crypto code!**

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Support more architectures

- 32-bit Arm (ARMv7ME): works, still "experimental"
- Opentitan's OTBN: work in progress
- 64-bit ARM and RISC-V: very early WIP

Challenges, ongoing work, TODOs, part 2

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Secure interfacing

- Currently use C function-call ABI (caller/callee contract through documentation)
- Check/Enforce caller requirements?
- Stronger safety notions (e.g., interfacing with Rust)

The big challenge

Make high-assurance tools mainstream/default!

https://formosa-crypto.org