MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

Engineering high-assurance crypto software

Peter Schwabe

September 30, 2022

MPI-SP?

Max-Planck Institute for Security and Privacy

- Founded in 2019
- Currently: 2 directors +
  - 2 directors
  - 6 (soon 8) research group leaders
  - ≈35 postdocs and Ph.D. students
- Long-term plan
  - 6 directors
  - 12 research group leaders
  - 200+ scientific staff

MPI-SP?

MPI-SP?

What crypto software (libraries) do you know?

What properties do you expect from crypto software?

3 properties

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?

Timing attacks

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

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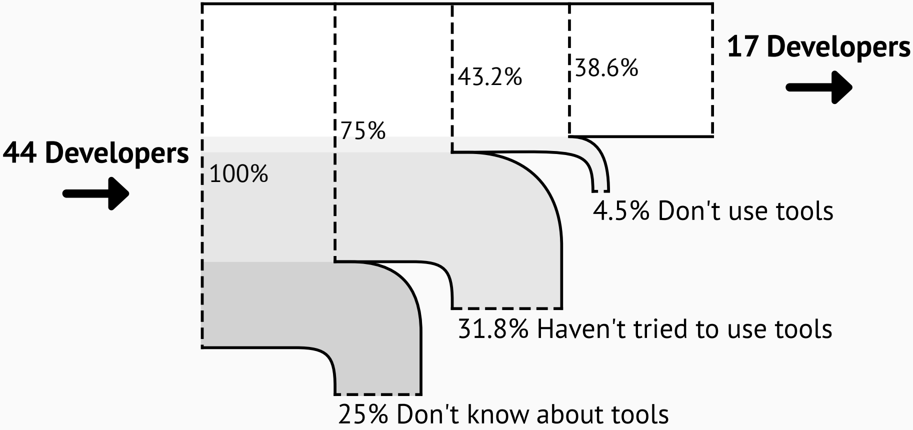
Plus side

- 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!

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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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  - certain implementation security properties; (and
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  - Has precise formal specification (**+**)
  - Inherently security-critical (**+**)

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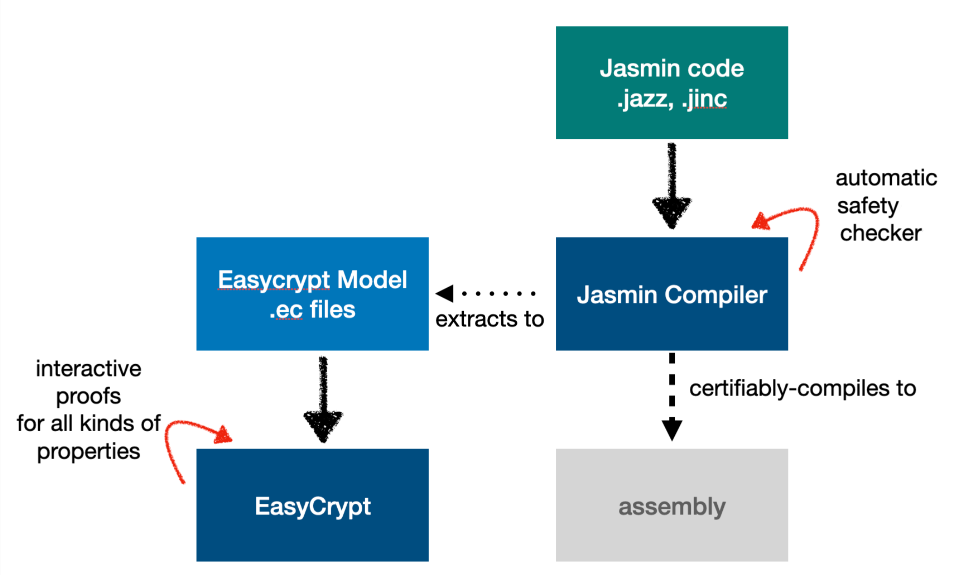
We want formal guarantees without giving up on performance.

Formosa Crypto

- Effort to formally verify crypto
- Currently three main projects:
  - EasyCrypt proof assistant
  - jasmin programming language
  - libjade (PQ-)crpyto library
- Core community of $\approx$ 30–40 people
- Discussion forum with $>$100 people

The toolchain and workflow



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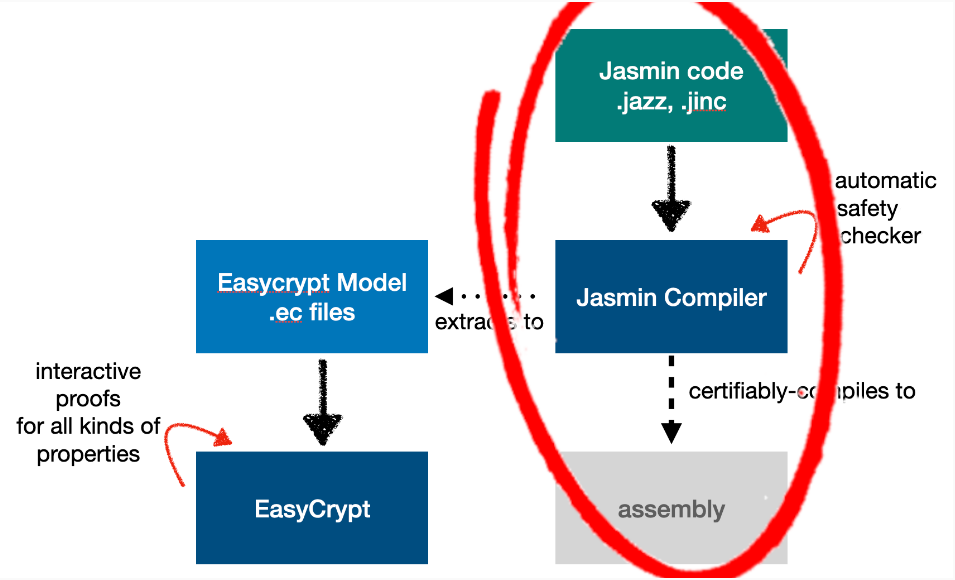

Jasmin – assembly in your head

José Bacelar Almeida, Manuel Barbosa, Gilles Barthe, Arthur Blot, Benjamin Grégoire, Vincent Laporte, Tiago Oliveira, Hugo Pacheco, Benedikt Schmidt, Pierre-Yves Strub: *Jasmin: High-Assurance and High-Speed Cryptography*. ACM CCS 2017

- Language with "C-like" syntax
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  - Compiler does not schedule code
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- Compiler is formally proven to preserve semantics
- Compiler is formally proven to preserve constant-time property
- Many new features since 2017 paper!

C code

```c
#include <stdio.h>

int main(void) {
  printf("Hello World!\n");
  return 0;
}
```

jasmin code

Jasmin – first steps

C code

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#include <stdio.h>

int main(void) {
  printf("Hello World!\n");
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}
```

jasmin code

- We don't implement main in jasmin
- We don't have I/O in jasmin

Jasmin – first steps

```
export fn add42(reg u64 x) -> reg u64 {
  reg u64 r;
  r = x;
  r += 42;
  return r;
}
```

Jasmin – first steps

https://cryptojedi.org/programming/jasmin.shtml

Registers, stack, and arrays

- For each variable you need to decide if it is
  - living in a register: `reg`,
  - living on the stack: `stack`, or
  - replaced by immediates during compilation: `inline int`
- Integer types are called `u64`, `u32`, etc.
- Jasmin supports arrays of `reg` and `stack` variables:
  - `reg u32[10] a;`
  - `stack u64[100] b;`
- Arrays have **fixed** length
- Jasmin supports sub-arrays with fixed offsets and lengths, e.g. `b[16:32]` is the subarray of length 32 starting at index 16

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- `for` iterate over an `inline int`
- `while` loops are *real* loops with branch

Three kinds of “functions”

`export` functions

- Entry points into jasmin-generated code
- Need at least one `export` function in a jasmin program
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- Can receive stack-array arguments

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“Regular” functions

- Array arguments passed through `reg ptr`
- `reg ptr` cannot be modifed through arithmetic
- No fixed function-call ABI (compilation has global view)
- Stack pointer decreased **by caller**

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- Example 1: constraints not satisfiable

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- Example 2: Running out of registers

```
"kem.jazz", line 14 (1) to line 27 (1):
compilation error:
register allocation: variable shkp.3135 must be allocated to conflicting register RSI { RSI.83 }
make: *** [../../../../../Makefile.common:73: kem.s] Error 1
```

- Register allocation is global
  - Changes at one place may cause allocation to fail somewhere else
  - Error messages not super-helpful

Vector computations

Scalar computation

- Load 32-bit integer a
- Load 32-bit integer b
- Perform addition $c \leftarrow a + b$
- Store 32-bit integer c

Vectorized computation

- Load 4 consecutive 32-bit integers (a_0, a_1, a_2, a_3)
- Load 4 consecutive 32-bit integers (b_0, b_1, b_2, b_3)
- Perform addition $(c_0, c_1, c_2, c_3) \leftarrow (a_0 + b_0, a_1 + b_1, a_2 + b_2, a_3 + b_3)$
- Store 128-bit vector (c_0, c_1, c_2, c_3)

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- Vector instructions available on most “large” processors
- Instructions for vectors of bytes, integers, floats...

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- Perform the same operations on independent data streams (SIMD)
- Vector instructions available on most “large” processors
- Instructions for vectors of bytes, integers, floats...
- Need to interleave data items (e.g., 32-bit integers) in memory

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- **AVX2 vector instructions are almost as fast as scalar instructions but do $8\times$ the work**
- Situation on other architectures/microarchitectures is similar
- Reason: cheap way to increase arithmetic throughput (less decoding, address computation, etc.)

Vectorization in jasmin

- Jasmin supports 128-bit XMM and 256-bit YMM registers: `u128` and `u256`
- Operations through "intrinsics", e.g.,

```
reg u256 t0, t1;

for i = 0 to VLEN/8 {
  t0 = a.[u256 (int)(32 *64u i)];
  t1 = b.[u256 (int)(32 *64u i)];
  t0 = #VPADD_8u32(t0, t1);
  r.[u256 (int)(32 *64u i)] = t0;
}
```

Some current limitations

AMD64 only

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No “slice” arguments

- Arrays have to have fixed length also in function arguments
- Separate function for each input length, e.g.

```
fn _ishake256_128_33(reg ptr u8[128] out, reg const ptr u8[33] in) -> stack u8[128]
```

- Not an issue for variable-length arguments to `export` functions

Some current limitations

No register-indexed subarrays

This works

```
stack u16[768] a;
inline int i;
for i=0 to 3
{
  a[i*256:256] = foo(a[i*256:256]);
}
```

This does not

```
stack u16[768] a;
reg u64 i;
i = 0;
while(i < 3)
{
  a[i*256:256] = foo(a[i*256:256]);
  i += 1;
}
```

Some current limitations

No typed export functions

- Inputs to `export` functions are of type `reg u64`
- Output is also a `reg u64`
- No argument passing over the stack
- No more than 6 arguments
- Distinguish between pointers and data only by usage/context

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

So, where are we?

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Efficiency

Security

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Security

- ???

Timing attacks – secret branches

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

Eliminating branches

- So, what do we do with code like this?

  if s **then**

  $\quad r \leftarrow A$

  else

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- Can expand s to all-one/all-zero mask and use XOR instead of addition, AND instead of multiplication
- For very fast A and B this can even be faster

Timing attacks – secret indices

```
table[secret]
```

Scanning through tables (in C)

```
uint32 table[TABLE_LENGTH];

uint32 lookup(size_t pos)
{
  size_t i;
  int b;
  uint32 r = table[0];
  for(i=1;i<TABLE_LENGTH;i++)
  {
    b = isequal(i, pos);
    cmov(&r, &table[i], b);
  }
  return r;
}
```

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.)"

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Option 2: Check/verify

- Implement, use tool to check "constant-time" property
- Problems in practice:
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  - Some tools not on binary/asm level
  - Some tools not usable

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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

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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

```
void victim_function(size_t x,
                     size_t array1_size,
                     const uint8_t *array1,
                     const uint8_t *array2,
                     uint8_t *temp)
{
  if (x < array1_size) {
    *temp &= array2[array1[x] * 512];
  }
}
```

Spectre v1

```
export fn victim_function(reg u64 x, reg u64 array1_size,
                          reg u64 array1, reg u64 array2, reg u64 temp) {
  reg u64 a;
  reg u8 ab bb pab pbb t;
  inline bool b;

  t = (u8)[temp];
  b = x < array1_size;
  if (b) {
    ab = (u8)[array1 + x];
    a = (64u)ab;
    a <<= 9;
    bb = (u8)[array2 + a];
    t &= bb;
  }
  (u8)[temp] = t;
}
```

It’s more subtle than this

```
fn aes_rounds (stack u128[11] rkeys, reg u128 in) -> reg u128 {
  reg u64 rkoffset;
  state = in;

  state ^= rkeys[0];
  rkoffset = 0;
  while(rkoffset < 9*16) {
    rk = rkeys.[(int)rkoffset];
    state = #AESENC(state, rk);
    rkoffset += 16;
  }
  rk = rkeys[10];
  #declassify state = #AESENCLAST(state, rk);
  return state;
}
```

It’s more subtle than this

Spectre declassified

- Caller is free to leak (declassified) state
- Very common in crypto: ciphertext is actually **sent**!
- `state` is not “out of bounds” data, it’s “early data”
- Must not speculatively `#declassify` early!

Basavesh Ammanaghatta Shivakumar, Jack Barnes, Gilles Barthe, Sunjay Cauligi, Chitchanok Chuengsatiansup, Daniel Genkin, Sioli O’Connell, Peter Schwabe, Rui Qi Sim, and Yuval Yarom: *Spectre Declassified: Reading from the Right Place at the Wrong Time*. IEEE S&P 2023. https://eprint.iacr.org/2022/426

Countermeasures

Fencing

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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`
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- Option 1: Mask every loaded value 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

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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:
  - **`secret:`** secret
  - **`public:`** public, also during misspeculation
  - **`transient:`** public, but possibly secret during misspeculation

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  - `#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!

Performance results (Comet Lake cyles)

Primitive	Impl.	Op.	CT	SCT	overhead [%]
ChaCha20	avx2	32 B	314	352	12.10
	avx2	32 B xor	314	352	12.10
	avx2	128 B	330	370	12.12
	avx2	128 B xor	338	374	10.65
	avx2	1 KiB	1190	1234	3.70
	avx2	1 KiB xor	1198	1242	3.67
	avx2	1 KiB	18872	18912	0.21
	avx2	16 KiB xor	18970	18994	0.13

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Poly1305	avx2	32 B	46	78	69.57
	avx2	32 B verif	48	84	75.00
	avx2	128 B	136	172	26.47
	avx2	128 B verif	140	170	21.43
	avx2	1 KiB	656	686	4.57
	avx2	1 KiB verif	654	686	4.89
	avx2	16 KiB	8420	8450	0.36
	avx2	16 KiB verif	8416	8466	0.59

Performance results (Comet Lake cyles)

Primitive	Impl.	Op.	CT	SCT	overhead [%]
X25519	mulx	smult	98352	98256	-0.098
	mulx	base	98354	98262	-0.094
Kyber512	avx2	keypair	25694	25912	0.848
	avx2	enc	35186	35464	0.790
	avx2	dec	27684	27976	1.055
Kyber768	avx2	keypair	42768	42888	0.281
	avx2	enc	54518	54818	0.550
	avx2	dec	43824	44152	0.748

Limitations

- Spectre v1 is not the only speculative attack vector

Basavesh Ammanaghatta Shivakumar, Gilles Barthe, Benjamin Grégoire, Vincent Laporte, Tiago Oliveira, Swarn Priya, Peter Schwabe, Lucas Tabary-Maujean: *Typing High-Speed Cryptography against Spectre v1.* https://eprint.iacr.org/2022/1270

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- Spectre v4: Use SSBD: `https://github.com/tyhicks/ssbd-tools`
- **Our protection requires separation of crypto code!**
  - Typically crypto is living in the same address space as application
  - Any Spectre v1 gadget in application can leak keys!

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Programming in jasmin gives you

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- Safety guarantees
- Systematic timing-attack protection
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- Link to computer-verified (EasyCrypt) proofs of
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    - Functional correctness
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- Spoiler: there’s more to come

Join us!

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