MAX PLANCK INSTITUTE
FOR SECURITY AND PRIVACY

Kyber – Implementation aspects

August 1, 2024

Three properties

1. Efficiency
2. Security
3. Correctness

1. Efficiency

What I mean by efficiency

"Oh, you mean numbers?!"

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- Saving a hash of 1KB may save an Internet giant some million USD per year
- Consequence:
  - Crypto is commonly hand-optimized on ASM level
  - Interaction between design and low-level implementation

Parallel computation

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- **Many crypto operations are trivially parallel on multiple cores**

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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  - 8$\times$ 32-bit add throughput: 3 per cycle
  - 256-bit store throughput: 1 per cycle
- **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.)

The NTT

Core operation in LPR encryption: multiply in $\mathcal{R}_q$

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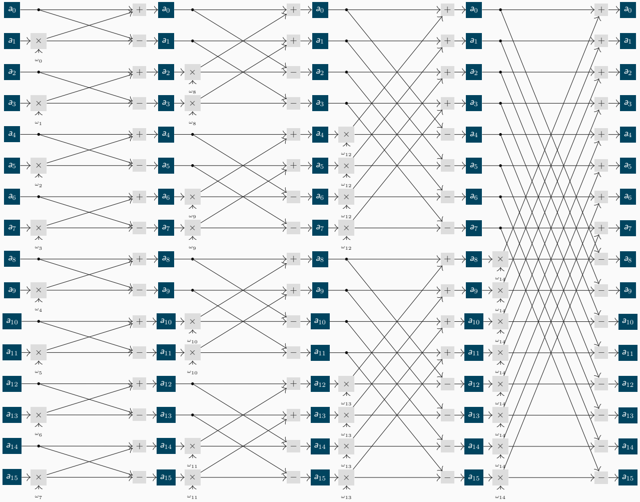
- $\circ$ is "pointwise" multiplication
- Requires that $2n$ divides $q - 1$
- Split $(X^n + 1)$, perform multiplication modulo factors

Structure of (INV)NTT



Picture credit: Matthias Kannwischer

- $\log n$ layers of "butterfly operations"
- Each layer has $n/2$ butterflies
- On most layers straight-forwardly vectorizable
- Some layers need vector-permutation instructions

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- Kyber needs to generate $\mathbf{A} \leftarrow \text{Parse}(\text{XOF}(\textit{seed}))$
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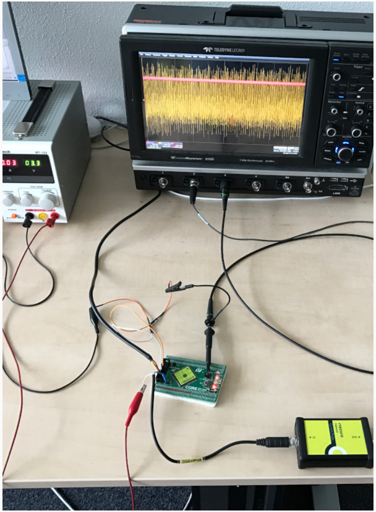
- Kyber uses Option 2

2. Security

Side-channel attacks

Side-channel attacks



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  - Power consumption
  - Electromagnetic radiation
  - Timing
- Side-channel attacks:
  - Measure information
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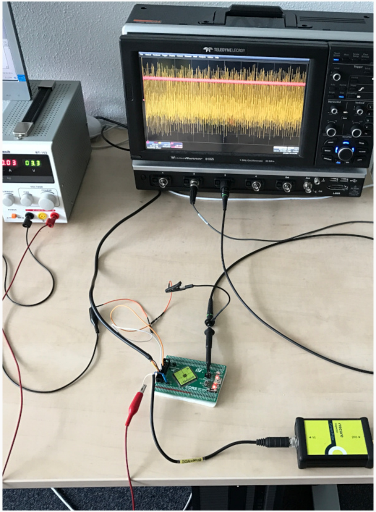

- Attackers see more than input/output:
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- Side-channel attacks:
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- **Timing** attacks
  - Software visible
  - Can be performed **remotely**

Timing leakage part I

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  if s **then**

  $r \leftarrow A$

  else

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- A and B can be large computations, r can be a large state
- This code takes different amount of time, depending on s
- Obvious timing leak if s is secret
- Even if A and B take the same amount of cycles this is *generally not* constant time!
- Reasons: Branch prediction, instruction-caches
- **Never use secret-data-dependent branch conditions**

Eliminating branches

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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

Fun with optimizing compilers

```
void poly_frommsg(poly *r, const uint8_t msg[KYBER_INDCPA_MSGBYTES])
{
  unsigned int i,j;
  int16_t mask;

  for(i=0;i<KYBER_N/8;i++) {
    for(j=0;j<8;j++) {
      mask = -(int16_t)((msg[i] >> j)&1);
      r->coeffs[8*i+j] = mask & ((KYBER_Q+1)/2);
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- LLVM from version 15 optimizes this to a branch with some flags
- Pointed out by Antoon Purnal, May 2024
- Different options to fix, all amount to “fighting the compiler”

Timing leakage part II

$T[0] \dots T[15]$
$T[16] \dots T[31]$
$T[32] \dots T[47]$
$T[48] \dots T[63]$
$T[64] \dots T[79]$
$T[80] \dots T[95]$
$T[96] \dots T[111]$
$T[112] \dots T[127]$
$T[128] \dots T[143]$
$T[144] \dots T[159]$
$T[160] \dots T[175]$
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$T[208] \dots T[223]$
$T[224] \dots T[239]$
$T[240] \dots T[255]$

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- *Cache lines* have 64 bytes
- Crypto and the attacker's program run on the same CPU
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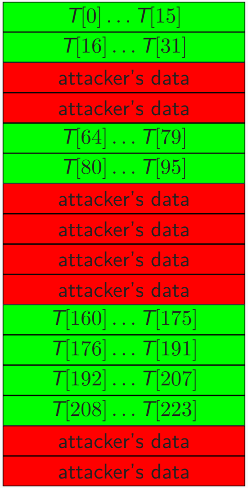

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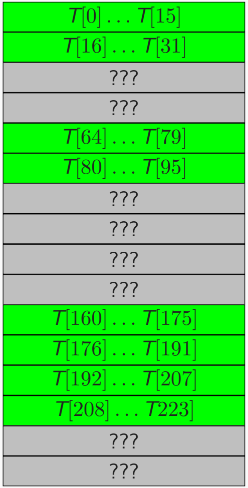

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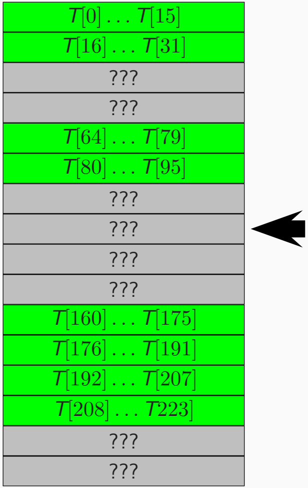

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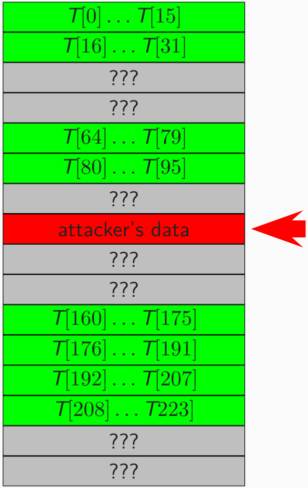

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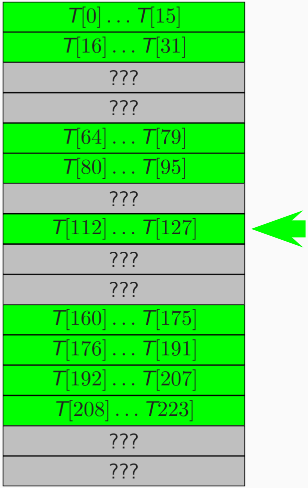

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- Crypto continues, loads from table again
- Attacker loads his data:
  - Fast: cache hit (crypto did not just load from this line)
  - Slow: cache miss (crypto just loaded from this line)

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- Problem 1: if-statements are not constant time (see before)
- Problem 2: Comparisons are not constant time, replace by, e.g.:

```
static unsigned long long eq(uint32_t a, uint32_t b)
{
  unsigned long long t = a ^ b;
  t = (-t) >> 63;
  return 1-t;
}
```

Is that all? (Timing leakage part III)

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"So the argument to the `DIV` instruction was smaller and `DIV`, on Intel, takes a variable amount of time depending on its arguments!"

—Langley, Feb. 2013

More fun with optimizing compilers

```
void poly_tomsg(uint8_t msg[KYBER_INDCPA_MSGBYTES], const poly *a)
{
  unsigned int i,j;
  uint16_t t;

  for(i=0;i<KYBER_N/8;i++) {
    msg[i] = 0;
    for(j=0;j<8;j++) {
      t  = a->coeffs[8*i+j];
      t += ((int16_t)t >> 15) & KYBER_Q;
      t  = (((t << 1) + KYBER_Q/2)/KYBER_Q) & 1;
      msg[i] |= t << j;
    }
  }
}
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- With some flags, gcc and LLVM will actually use a `DIV` instruction
- See “KyberSlash” paper by Bernstein, Bhargavan, Bhasin, Chattopadhyay, Kiah Chia, Kannwischer, Kiefer, Paiva, Ravi, Tamvada. https://eprint.iacr.org/2024/1049

More fun with optimizing compilers

- Division **by a constant** typically uses multiplication
  Division by Invariant Integers using Multiplication, Granlund, Montgomery, PLDI 1994
- With some flags, gcc and LLVM will actually use a `DIV` instruction
- See “KyberSlash” paper by Bernstein, Bhargavan, Bhasin, Chattopadhyay, Kiah Chia, Kannwischer, Kiefer, Paiva, Ravi, Tamvada. https://eprint.iacr.org/2024/1049
- Rewrite division, but still no *guarantee* that compilers won’t use `DIV`

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Problem: There is no concept of secret data in LLVM or GCC!

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- interfaces to interactive theorem provers to verify functional correctness

Jasmin – assembly in your head

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
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  - Compiler does not schedule code
  - Compiler does not spill registers
- Many new features since 2017 paper
- Big credit also to Santiago Arranz Olmos and Jean-Christophe Léchenet!
- See Ph.D. thesis by Oliveira:
  High-speed and High-assurance Cryptographic Software

Constant-time code in Jasmin

- 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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- **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);
  ...
}
```

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!

Ammanaghatta Shivakumar, Barnes, Barthe, Cauligi, Chuengsatiansup, Genkin, O'Connell, Schwabe, Sim, and 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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- 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

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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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  - `#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 impact (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

Performance impact (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

References

Ammanaghatta Shivakumar, Barthe, Grégoire, Laporte, Oliveira, Priya, Schwabe, and Tabary-Maujean: *Typing High-Speed Cryptography against Spectre v1*. IEEE S&P 2023. https://eprint.iacr.org/2022/1270

Arranz Olmos, Barthe, Blatter, Grégoire, and Laporte: *Preservation of Speculative Constant-time by Compilation*. https://eprint.iacr.org/2024/1203

FORMOSA CRYPTO

- Goal: Formally verified post-quantum crypto
- Software written in Jasmin
- Implementation security through Jasmin language features
- Proofs of functional correctness using EasyCrypt
- Security proofs in EasyCrypt

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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]

Formosan black bear

Conservation status

Extinct Threatened Least Concern

EX EW CR EN VU NT LC

Vulnerable (IUCN 3.1)[1]

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

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

Learn more

Kyber website:	https://pq-crystals.org/kyber/
NIST PQC:	https://csrc.nist.gov/projects/post-quantum-cryptography
pqc-forum:	https://groups.google.com/a/list.nist.gov/g/pqc-forum
Formosa Crypto:	https://formosa-crypto.org