Fast verified post-quantum software

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My talk at ICMC 2019: "Does open-source cryptographic software work correctly?"

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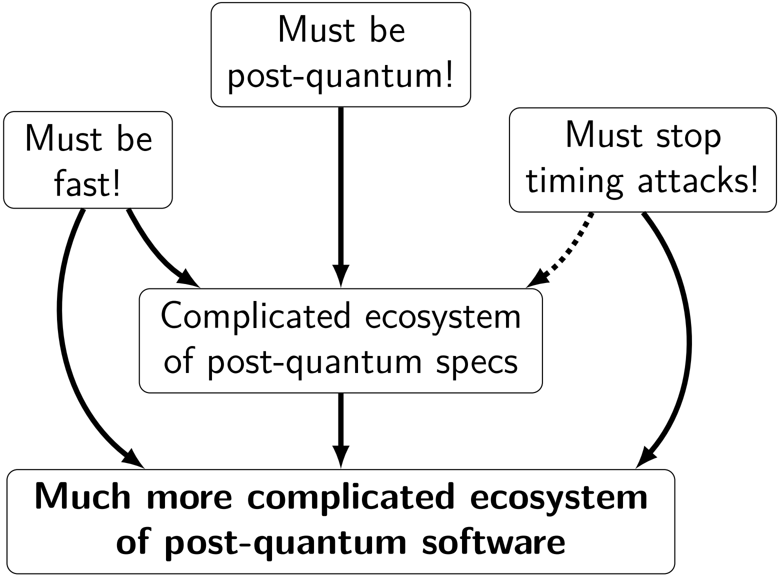
2021.07 Blessing–Specter–Weitzner "You really shouldn't roll your own crypto: an empirical study of vulnerabilities in cryptographic libraries": 73 "actual" cryptographic vulnerabilities, including 11 "severe" cryptographic vulnerabilities, among OpenSSL, GnuTLS, Mozilla TLS, WolfSSL, Botan, Libgcrypt, LibreSSL, BoringSSL post-2010 CVEs.

. . . and the complexity is getting worse



The good news: symbolic testing

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optimized software equals reference software.
"Equals": gives the same outputs **for all inputs**.

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Under the hood, doing most of the work:
`valgrind`; its VEX library; Z3 theorem prover;
`angr.io` binary-analysis/symbolic-execution toolkit.

Case study: int16[64] comparison

Subroutine used inside Frodo post-quantum KEM.

My ref version, cmp_64xint16/ref/verify.c:

```
#include <stdint.h>

int cmp_64xint16(const uint16_t *x,
                 const uint16_t *y)
{ for (int i = 0;i < 64;++i)
    if (x[i] != y[i])
      return -1;
  return 0;
}
```

Automatic `saferewrite` analysis

Using `clang -O1 -fwrapv -march=native`:

- `saferewrite` says `unsafe-valgrindfailure`:
  Code has variable branches/indices,
  violating constant-time coding discipline.
- And `unsafe-unrollsplit-65`:
  Unrolling split the code into 65 cases.

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Using `gcc -O3 -march=native -mtune=native`:

- `unsafe-valgrindfailure`
- `unsafe-unrollsplit-65`
- `equals-ref-clang_-O1_...`:
  `cmp_64xint16` binaries give same outputs.

Automatic analysis of a rewrite

```
#include <stdint.h>
#include <string.h>

int cmp_64xint16(const uint16_t *x,
                 const uint16_t *y)
{
  return memcmp(x,y,128);
}
```

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Again `unsafe-valgrindfailure`: variable time.
Also `unsafe-differentfrom-ref-clang_...`.
Why? Nonzero `memcmp` output isn't always −1.

Automatic analysis of another rewrite

```
#include <stdint.h>
#include <string.h>
int cmp_64xint16(const uint16_t *x,
                 const uint16_t *y)
{ int r = memcmp(x,y,128);
  if (r != 0) return -1;
  return 0;
}
```

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Now `equals-ref-clang_...` but still `unsafe-valgrindfailure`. 2017 Frodo software used `memcmp`; broken by 2020.06 timing attack.

2020.06 Frodo official constant-time code

```
int8_t ct_verify(const uint16_t *a,
                 const uint16_t *b, size_t len)
{ // Compare two arrays in constant time.
  // Returns 0 if the byte arrays are equal,
  // -1 otherwise.
    uint16_t r = 0;
    for (size_t i = 0; i < len; i++) {
        r |= a[i] ^ b[i];
    }
    r=(-(int16_t)r)>>(8*sizeof(uint16_t)-1);
    return (int8_t)r;
}
```

Use saferewrite to analyze this . . .

Add wrapper to fit the cmp_64xint16 interface:

```
int cmp_64xint16(const uint16_t *x,
                 const uint16_t *y)
{ return ct_verify(x,y,64); }
```

saferewrite focuses on constant lengths.
(Frodo uses int16[N] for a few choices of N.)

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Feed ct_verify and wrapper to saferewrite:

- No more unsafe-valgrindfailure: Great.

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Feed ct_verify and wrapper to saferewrite:

- No more unsafe-valgrindfailure: Great.
- unsafe-differentfrom-ref-...: Oops!

Bug discovered 2020.12 by Saarinen; easy to exploit.

A safe rewrite: correct constant-time code

```
#include <stdint.h>
int cmp_64xint16(const uint16_t *x,
                 const uint16_t *y)
{ uint32_t differences = 0;
  for (long long i = 0;i < 64;++i)
    differences |= x[i] ^ y[i];
  return (1 & ((differences - 1) >> 16)) - 1;
}
```

Now `saferewrite` analysis with both compilers says `equals-ref-...` and no more `unsafe`.

Examples in `saferewrite` package

10 sample implementations of `cmp_64xint16`.
One uses OpenSSL's `CRYPTO_memcmp` Intel asm;
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97 sample implementations of 26 other functions.
Some functions much bigger than `cmp_64xint16`.
Some simple functions for exercising `saferewrite`.

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example of an input triggering the difference.
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Analysis of everything (multicore) done in 8 mins.
Laptop tip: `chmod +t src/*`; `chmod -t src/cmp*`

Example: integer-sequence encoders

Existing optimized code from NTRU Prime,
with heavy use of Intel AVX2 vector instructions:

- 245-line `encode_761x1531/avx/encode.c`

`encode.c` and similar encoders for other sizes are automatically generated by 239-line Python script.

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"Is the optimized code a safe rewrite of `ref`?"
Automatic `saferewrite` analysis: `equals-ref`.

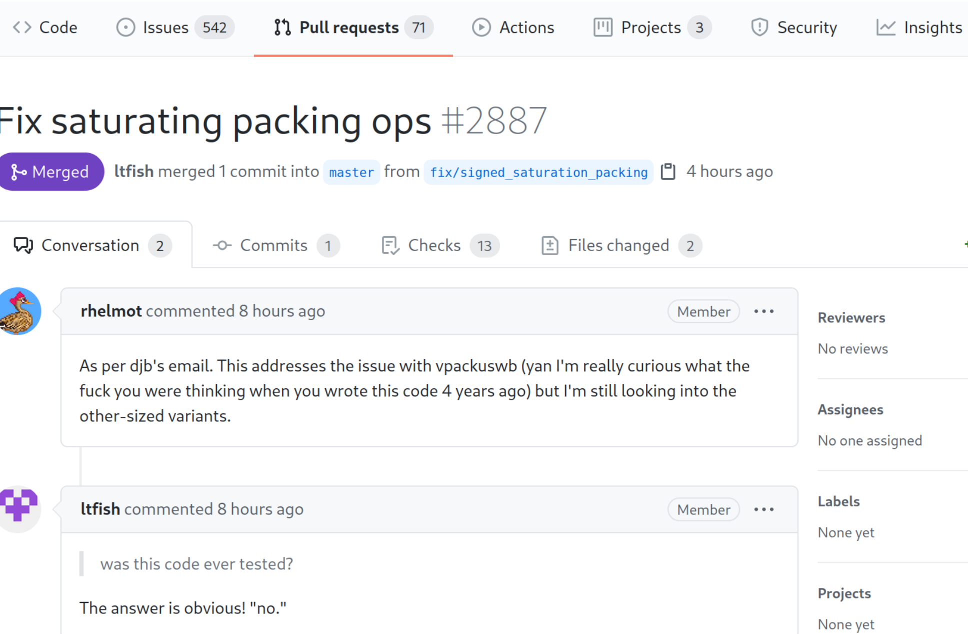
Excerpt from avx/encode.c

```
x = _mm256_loadu_si256((__m256i *) reading);
x = _mm256_add_epi16(x,_mm256_set1_epi16(2295));
x &= _mm256_set1_epi16(16383);
x = _mm256_mulhi_epi16(x,_mm256_set1_epi16(21846));
y = x & _mm256_set1_epi32(65535);
x = _mm256_srli_epi32(x,16);
x = _mm256_mullo_epi32(x,_mm256_set1_epi32(1531));
x = _mm256_add_epi32(y,x);
x = _mm256_shuffle_epi8(x,_mm256_set_epi8(
  12,8,4,0,12,8,4,0,14,13,10,9,6,5,2,1,
  12,8,4,0,12,8,4,0,14,13,10,9,6,5,2,1
  ));
x = _mm256_permute4x64_epi64(x,0xd8);
_mm_storeu_si128((__m128i *) writing,
                 _mm256_extractf128_si256(x,0));
*((uint32 *) (out+0)) = _mm256_extract_epi32(x,4);
*((uint32 *) (out+4)) = _mm256_extract_epi32(x,6);
```

More subroutines in NTRU Prime code

	equals; total core-minutes
decode_761x1531:	avx=int16=p=ref; 38 min
decode_761x3:	avx=ref; 0.3 min
decode_761x4591:	avx=int16=p=ref; 39 min
decode_761xint16:	little=ref; 0.3 min
decode_761xint32:	little=ref; 0.3 min
encode_761x1531:	avx=portable=ref; 17 min
encode_761x1531round:	avx=ref; 6 min
encode_761x3:	avx=ref; 0.4 min
encode_761x4591:	avx=portable=ref; 6 min
encode_761xfreeze3:	missing asm insn in angr!
encode_761xint16:	little=ref; 0.4 min

Active, responsive angr development team



Other subroutines in NTRU Prime code

`decode_256x2`:	`avx`=`ref`; 0.3 min
`encode_256x2`:	`avx`=`ref`; 0.2 min
`core_scale3sntrup761`:	`avx`=`ref`; 11 min
`core_weightsntrup761`:	`avx`=`ref`; 10 min
`core_wforcesntrup761`:	`avx`=`ref`=`r2`=`s`; 31 min

Not integrated into `saferewrite` yet:

- `core_inv3sntrup761`: `avx` vs. `ref`
- `core_invsntrup761`: `avx` vs. `ref`
- `core_mult3sntrup761`: `avx` vs. `32` vs. `ref`
- `core_multsntrup761`: `avx` vs. `ref`

Status: Multiplication software is partially verified.

Links, TODO #saferewrite

`saferewrite` package is available now from https://pqsrc.cr.yp.to. Work in progress:

- More post-quantum case studies.
- More pre-quantum case studies: e.g., Ed25519.
- More languages: e.g., support Python `ref`.
- Developer integration: incremental testing etc.
- "Cuts": subroutine swaps etc. for faster testing.
- Plugins for dedicated equivalence testers.
- Higher assurance for the entire toolchain.

Related work: Cryptol/SAW/hacrypto, Cryptoline, Fiat-Crypto, HACL*, Jasmin, ValeCrypt, VST.