Does open-source cryptographic software work correctly?

Daniel J. Bernstein
CVE-2018-0733, an OpenSSL bug

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How severe is this? “This allows an attacker to forge messages that would be considered as authenticated in an amount of tries lower than that guaranteed by the security claims of the scheme.” — Yes, $2^{16}$ is “lower than” $2^{128}$.
CVE-2017-3738, another OpenSSL bug

Don’t care about PA-RISC? How about Intel?

“There is an overflow bug in the AVX2 Montgomery multiplication procedure used in exponentiation with 1024-bit moduli.” Bug introduced July 2013.
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“Attacks against DH1024 are considered just feasible”
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“There is an overflow bug in the AVX2 Montgomery multiplication procedure used in exponentiation with 1024-bit moduli.” Bug introduced July 2013.

“Attacks against DH1024 are considered just feasible” — How long? How much hardware?
CVE-2017-3738, continued

“Analysis suggests that attacks against RSA and DSA as a result of this defect would be very difficult to perform and are not believed likely.”

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What this looks like to me: “We have analyzed our new cryptosystem and concluded that attacks are not likely.”
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— Really? How much public scrutiny has the actual computation received from cryptanalysts?

What this looks like to me: “We have analyzed our new cryptosystem and concluded that attacks are not likely.” — Don’t we require public review?
Part of the CVE-2017-3738 patch

@@ -1093,7 +1093,9 @@
    vmovdqu -8+32*2-128($ap),$TEMP2

    mov $r1, %rax
+   vpblendd $0xfc, $ZERO, $ACC9, $ACC9 # correct $ACC3
    imull $n0, %eax
+   vpaddq $ACC9,$ACC4,$ACC4 # correct $ACC3
    and $0x1fffffffff, %eax

    imulq 16-128($ap),%rbx
@@ -1329,15 +1331,12 @@

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Is open-source software bug-free?

Eric S. Raymond, 1999: “Given a large enough beta-tester and co-developer base, almost every problem will be characterized quickly and the fix obvious to someone. Or, less formally, ‘Given enough eyeballs, all bugs are shallow.’ ”
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— “Beta-tester”: Ultimately, the unhappy user?

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— “Beta-tester”: Ultimately, the unhappy user?
— “Almost every problem”: That’s not “all bugs”! Don’t we care about the exceptions? Rare bugs can be devastating, especially for security!
More reasons for skepticism

— How do we know how many exceptions there are? How many people are looking for unobvious bugs?

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More reasons for skepticism

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— How do we know how many exceptions there are? How many people are looking for unobvious bugs?
— How can there be enough people looking for bugs when most developers prefer writing new code?
— ESR advocates a development methodology that releases a constant flood of new bugs. Doesn’t this make his “law” automatically true? Is this the correctness metric that users want?

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So we should use closed source?

“Closed source stops attackers from finding bugs.”

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How long does it take for an attacker to extract, disassemble, decompile the code?

“Closed source scares away some lazy academics, so we have fewer bug announcements to deal with.”
— Sounds plausible, but is the delay worthwhile?
e.g. Infineon deployed RSALib very widely before 2017 Nemec–Sys–Svenda–Klinec–Matyas “ROCA”.

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I’m focusing on open source in this talk because

- I spend most of my time with open source and
- the only paths that I see towards real security need everything published to build confidence.
Cryptography is notoriously hard to review

Mathematical complications lead to subtle bugs.

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Cryptography is applied to large volumes of data.
Often individual computations are time-consuming.
Pursuit of speed ⇒ many cryptographic choices;
cryptographic code optimized for particular CPUs.

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e.g. Keccak Code Package: $>20$ implementations.
e.g. Google added hand-written Cortex-A7 asm to Linux kernel for Speck, then switched to ChaCha.
Formal logic to the rescue?

Whitehead and Russell, *Principia Mathematica*, volume 1, 1st edition (1910), page 379:

\[ *54\cdot43. \quad \vdash \alpha, \beta \in 1. C: \alpha \cap \beta = \Lambda. \equiv \alpha \cup \beta \in 2 \]

Dem.

\[ \vdash *54\cdot26. C \vdash \alpha = \iota'x. \beta = \iota'y. C: \alpha \cup \beta \in 2. \equiv x \neq y. \]

\[ [*51\cdot231] \]

\[ [*13\cdot12] \]

\[ \vdash (1). *11\cdot11\cdot35. C \]

\[ \vdash (\exists x, y). \alpha = \iota'x. \beta = \iota'y. C: \alpha \cup \beta \in 2. \equiv \alpha \cap \beta = \Lambda \quad (2) \]

\[ \vdash (2). *11\cdot54. *52\cdot1. C \vdash \text{Prop} \]

From this proposition it will follow, when arithmetical addition has been defined, that \(1 + 1 = 2\).
Formal verification today

Require code reviewer to prove correctness.
Require proofs to pass a proof-checking tool.
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This is tedious but not impossible.
Latest EverCrypt release: verified software for Curve25519, Ed25519, ChaCha20, Poly1305, AES-CTR (if CPU has AES-NI), AES-GCM (same), MD5, SHA-1, SHA-2, SHA-3, BLAKE2.

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Good: High confidence that subtle bugs are gone
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Bad: Tons of effort for each implementation.
Testing

Testing is great. Test everything. Design for tests.

Why wasn’t the PA-RISC CRYPTO_memcmp run through millions of tests on random inputs? And tests on inputs differing in a few positions? SUPERCOP test framework has always done this.

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Good reaction to a bug: “How can I build fast automated tests that will catch this kind of bug?” Even better to ask question before bug happens.

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Going beyond testing particular inputs

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Fix: **Run code on all inputs.**

1. Easy *if* code has no input-dependent branches: code → simple language without loops/vectors/...

(I’m using angr.io for symbolic execution.)
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2. Automatically identify equivalent computations. Don’t have to redo work for each implementation!

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2. Automatically identify equivalent computations. Don’t have to redo work for each implementation!

3. Build tools to check that the computations work.

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A case study

Subroutine in some post-quantum proposals: sorting arrays of integers.
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Subroutine in some post-quantum proposals: sorting arrays of integers.

Software library from sorting.cr.yp.to:

- New speed records for in-memory sorting.
- Side-channel countermeasures: no secret branch conditions; no secret array indices.
- Tool verifies correct sorting of all inputs. No need to review per-CPU optimized code.

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