Crypto horror stories

Daniel J. Bernstein, Tanja Lange

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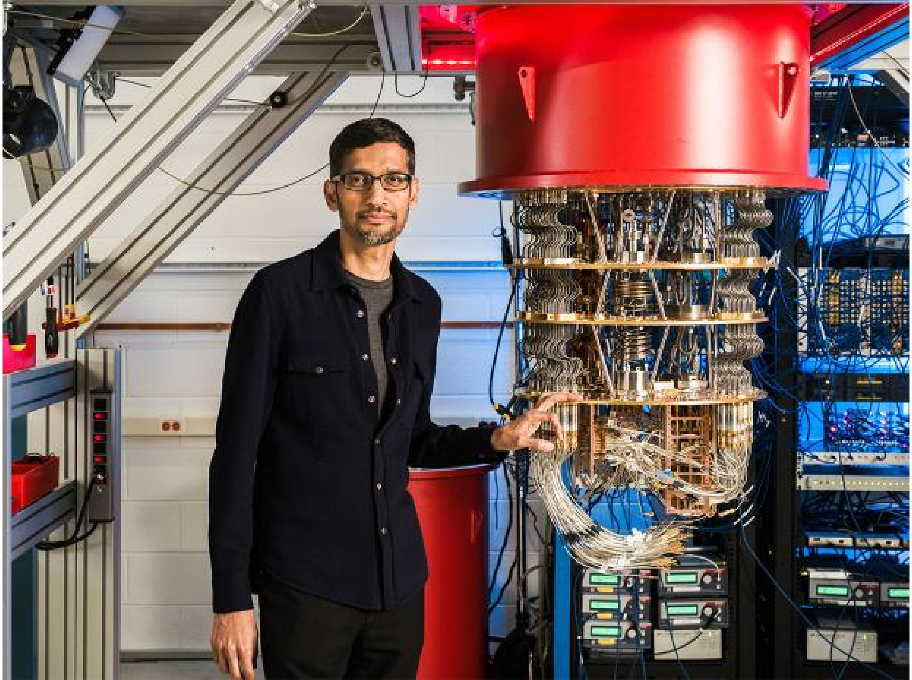
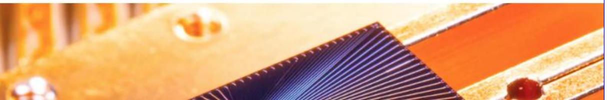


◆ Premium

Quantum computing could end encryption within five years, says Google boss



Mr Pichai said a combination of artificial intelligence and quantum would "help us tackle some of the biggest problems we see", but said it was important encryption evolved to match this.

"In a five to ten year time frame, quantum computing will break encryption as we know it today."

This is because current encryption methods, by which information such as texts or passwords is turned into code to make it unreadable, rely upon the fact that classic computers would take billions of years to decipher that code.

Quantum computers, with their ability to be

U.S. National Academy of Sciences report

Don't panic. "Key Finding 1: Given the current state of quantum computing and recent rates of progress, it is highly unexpected that a quantum computer that can compromise RSA 2048 or comparable discrete logarithm-based public key cryptosystems will be built within the next decade."

U.S. National Academy of Sciences report

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Panic. "Key Finding 10: Even if a quantum computer that can decrypt current cryptographic ciphers is more than a decade off, the hazard of such a machine is high enough—and the time frame for transitioning to a new security protocol is sufficiently long and uncertain—that prioritization of the development, standardization, and deployment of post-quantum cryptography is critical for minimizing the chance of a potential security and privacy disaster."

Many stages of research from design to deployment

1. Define the goals
2. Explore space of cryptosystems
3. Study algorithms for the attackers
4. Focus on secure cryptosystems
5. Study algorithms for the users
6. Study implementations on real hardware
7. Study side-channel attacks, fault attacks, etc.
8. Focus on secure, reliable implementations
9. Focus on implementations meeting performance requirements
10. Integrate securely into real-world applications

Is post-quantum crypto moving quickly enough?

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2014: EU solicits grant proposals in post-quantum crypto.

2014: ETSI starts working group on "Quantum-safe" crypto.

2015: NIST hosts workshop on post-quantum cryptography.

After public input, NIST calls for submissions of public-key systems to "Post-Quantum Cryptography Standardization Project". Deadline 2017.11.

2017: Submissions to the NIST competition

21 December 2017: NIST posts 69 submissions from 260 people.

BIG QUAKE. BIKE. CFPKM. Classic McEliece. Compact LWE. CRYSTALS-DILITHIUM. CRYSTALS-KYBER. DAGS. Ding Key Exchange. DME. DRS. DualModeMS. Edon-K. EMBLEM and R.EMBLEM. FALCON. FrodoKEM. GeMSS. Giophantus. Gravity-SPHINCS. Guess Again. Gui. HILA5. HiMQ-3. HK17. HQC. KINDI. LAC. LAKE. LEDAkem. LEDApkc. Lepton. LIMA. Lizard. LOCKER. LOTUS. LUOV. McNie. Mersenne-756839. MQDSS. NewHope. NTRUEncrypt. pqNTRUSign. NTRU-HRSS-KEM. NTRU Prime. NTS-KEM. Odd Manhattan. OKCN/AKCN/CNKE. Ouroboros-R. Picnic. pqRSA encryption. pqRSA signature. pqsigRM. QC-MDPC KEM. qTESLA. RaCoSS. Rainbow. Ramstake. RankSign. RLCE-KEM. Round2. RQC. RVB. SABER. SIKE. SPHINCS+. SRTPI. Three Bears. Titanium. WalnutDSA.

Some submissions are broken within days

By end of 2017: 8 out of 69 submissions attacked.

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Some less secure than claimed; some smashed; some attack scripts.

Do cryptographers have any idea what they're doing?

By end of 2018: 22 out of 69 submissions attacked.

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An attempt to explain the situation

People often categorize submissions. Examples of categories:

- Code-based encryption and signatures.
- Hash-based signatures.
- Isogeny-based encryption.
- Lattice-based encryption and signatures.
- Multivariate-quadratic encryption and signatures.

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2017 Peikert: "The underlying worst-case problems—e.g., approximating short vectors in lattices—have been deeply studied by some of the great mathematicians and computer scientists going back at least to Gauss, and appear to be very hard."

Reality: SVP hardness is poorly understood

Best SVP algorithms known by 2000:
time $2^{\Theta(N \log N)}$ for almost all dimension-N lattices.

Best SVP algorithms known today: $2^{\Theta(N)}$. Huge change!

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0.378: 2013 Zhang–Pan–Hu.
0.337: 2014 Laarhoven.

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0.378: 2013 Zhang–Pan–Hu.
0.337: 2014 Laarhoven.
0.298: 2015 Laarhoven–de Weger.
0.292: 2015 Becker–Ducas–Gama–Laarhoven.

Lattice security is even more poorly understood

Lattice-based crypto has many more attack avenues than SVP.

Lattice-based submissions: Compact LWE.
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Lattice security estimates are so imprecise that nobody is sure whether the remaining submissions are damaged by a 2019 paper solving a lattice problem "more than a million times faster".

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Minerva attack can recover private keys from smart cards, cryptographic libraries

Older Athena IDProtect smart cards are impacted, along with the WolfSSL, MatrixSSL, Crypto++, Oracle SunEC, and Libgcrypt crypto libraries.

By Catalin Cimpanu for Zero Day | October 3, 2019 -- 12:54 GMT (13:54 BST) | Topic: Security

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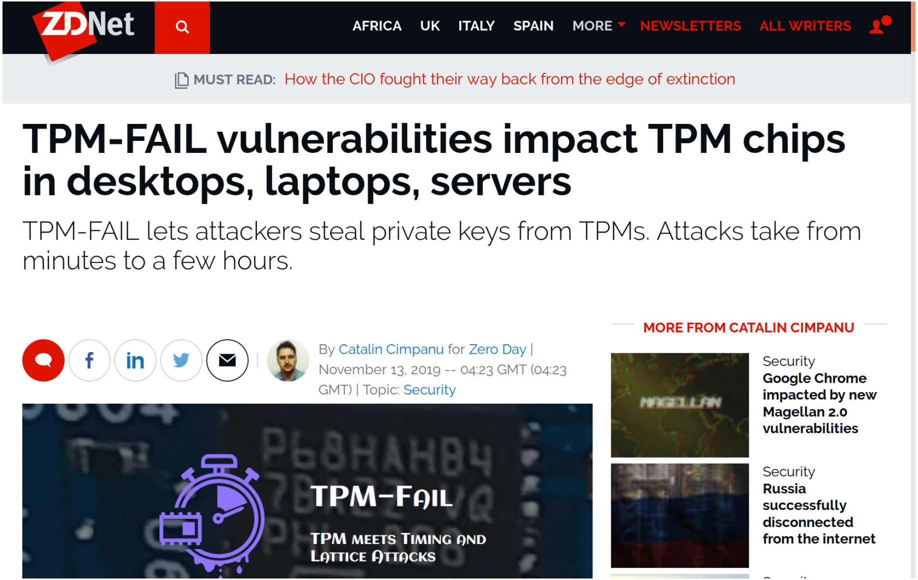

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MUST READ: How the CIO fought their way back from the edge of extinction

TPM-FAIL vulnerabilities impact TPM chips in desktops, laptops, servers

TPM-FAIL lets attackers steal private keys from TPMs. Attacks take from minutes to a few hours.

By Catalin Cimpanu for Zero Day | November 13, 2019 -- 04:23 GMT (04:23 GMT) | Topic: Security

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Security

Don't trust the Trusted Platform Module – it may leak your VPN server's private key (depending on your configuration)

You know what they say: Timing is... everything

By Thomas Claburn in San Francisco 12 Nov 2019 at 19:43

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ELLIPTISCHE KURVEN

Minerva-Angriff zielt auf zertifizierte Krypto-Chips

Forscher konnten zeigen, wie sie mit einem Timing-Angriff die privaten Schlüssel von Signaturen mit elliptischen Kurven auslesen konnten. Verwundbar sind Chips, deren Sicherheit eigentlich zertifiziert wurde.

4. Oktober 2019, 13:41 Uhr, Hanno Böck

s Hollar, Wikimedia Commons)

Golem article

Timing attacks are not a new phenomenon

Password recovery if server compares letter by letter:

Try `AAA`,

Timing attacks are not a new phenomenon

Password recovery if server compares letter by letter:

Try `AAA`, `BBB`,

Timing attacks are not a new phenomenon

Password recovery if server compares letter by letter:

Try `AAA`, `BBB`, `CCC`, . . .

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Try `AAA`, `BBB`, `CCC`, . . . , `MMM` takes slightly longer to fail.
Try `MAA`,

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Try `MUA`, `MUB`, `MUC`, . . . , `MUN` takes slightly longer to fail.
⋮
Password is `MUNICH`.

1974: Exploit developed by Alan Bell for TENEX operating system.

Exponentiation with secret exponent (RSA, DH)

Compute c^d given c and d.

```
n = 1000001
d = 12473
c = 41241
l = d.nbits()
D = d.bits()
m = c
for i in range(l-2,-1,-1):
  m = m^2 % n
  if D[i] == 1:
    m = m * c % n
print(m)
```

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  m = m^2 % n
  if D[i] == 1: # branch depends on d
    m = m * c % n
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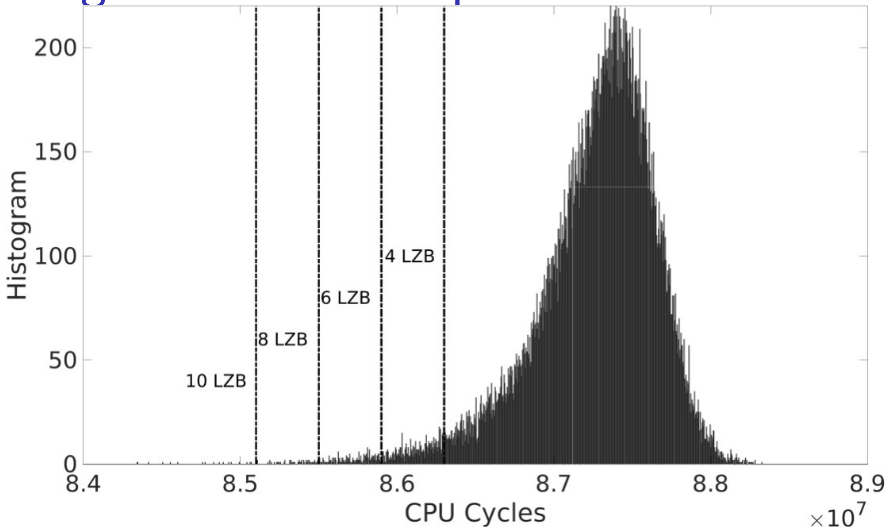
```

Timings of scalar multiplication on NIST P-256



(Picture from TPM-Fail)

Other exponentiation methods

- The timing variation depends strongly on the length of the scalar/exponent.
- Very sparse or very dense scalars will be miscategorized.
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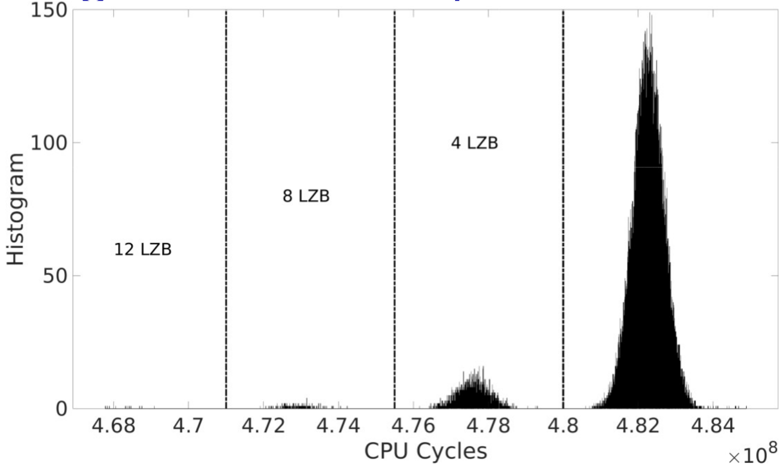
  Precompute c, c^2, and c^3.

$$c^{14019} = \left(\left(\left(\left(\left(\left(c^3\right)^4 \cdot c\right)^4 \cdot c^2\right)^4 \cdot c^3\right)^4\right)^4\right)^4 \cdot c^3.$$

Same number of squarings, 4 instead of 7 multiplications.

Timings of scalar multiplication on NIST P-256



Larger windows reduce the variability through branching but accentuate the length.

(Picture from TPM-Fail)

How much can a few bits do?

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  - TPM–Fail: TPM meets Timing and Lattice Attacks
    Daniel Moghimi, Berk Sunar, Thomas Eisenbarth, Nadia Heninger
    `https://tpm.fail/`
  - Minerva attack
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    `https://minerva.crocs.fi.muni.cz/`

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  With just a small bias in the nonces (one-time scalars) the secret signing key leaks.
- Lots of libraries, smart cards, and TPMs affected.
- Even worse: hyperthreading attacks, cache-timing attacks, etc. give more fine-grained timing information $\Rightarrow$ more exploits.

Constant-time exponentiation

```
n = 1000001
d = 12473
c = 41241
l = n.nbits()
D = d.digits(2,padto = l)
m = 1 # so initial squarings don't matter
for i in range(l-1,-1,-1): # fixed-length loop
  m = m^2 % n
  h = m * c % n
  m = (1 - D[i]) * m + D[i] * h # selection by arithmetic
print(m)
```

This costs 1 multiplication per bit, so as slow as worst case.

Interplay with elliptic-curve formulas

- We can translate this to scalar multiplication on elliptic curves: Initialize with the neutral element, for every bit compute a doubling and an addition.
- Formulas for addition on Weierstrass curves have exceptions for adding ∞, so initialization at ∞ does not work.
- Edwards curves have a complete addition law, **easy** to double or add the neutral element $(0, 1)$.
- The Montgomery ladder has a similar data flow, but the costs per bit of the scalar are **less** than one addition plus one doubling for Montgomery curves.

For more see `https://ecchacks.cr.yp.to`.

Forbes Billionaires Innovation Leadership Money Business Small Business Lifest

210,878 views | Jun 12, 2019, 08:10am

Warning: Google Researcher Drops Windows 10 Zero-Day Security Bomb

Davey Winder Senior Contributor
Cybersecurity
I report and analyse breaking cybersecurity and privacy stories

It's actually a bug within SymCrypt, the core cryptographic library responsible for implementing asymmetric crypto algorithms in Windows 10 and symmetric crypto algorithms in Windows 8. What Ormandy found was that by using a malformed digital certificate he could force the SymCrypt calculations into an infinite loop. This will effectively perform a denial-of-service (DoS) attack on Windows servers such as those running the IPsec protocols that are required when using a VPN or the Microsoft Exchange Server for email and calendaring for example.

Ormandy also notes that, "lots of software that processes untrusted content (like antivirus) call these routines on untrusted data, and this will cause them to deadlock." Despite this, he rated it a low severity vulnerability while adding, "you could take down an entire Windows fleet relatively easily, so it's worth being aware of." The advisory that Ormandy has published gives details of the vulnerability as well as proof-of-concept in the form of an example malformed certificate that would cause the denial of service.

Forbes article

Forbes Billionaires Innovation Leadership Money Business Small Business Lifes

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Forbes article

Using Valgrind to check for secret branches/addresses

```
#include <stdlib.h>
#include <openssl/rc4.h>

int main()
{
  RC4_KEY expandedkey;
  unsigned char *key = malloc(32);
  if (!key) abort();
  RC4_set_key(&expandedkey,32,key);
  free(key);
  return 0;
}
```

Using Valgrind to check for secret branches/addresses

```
$ valgrind ./rc4
==2599== Memcheck, a memory error detector
==2599== Copyright (C) 2002-2017, and GNU GPL'd, by Julian
==2599== Using Valgrind-3.14.0 and LibVEX; rerun with -h f
==2599== Command: ./rc4
==2599==
==2599== Use of uninitialised value of size 8
==2599==    at 0x4A1A0EF: RC4_set_key (in /usr/lib/x86_64-
==2599==    by 0x1090BD: main (in /home/.../rc4)
...
==2599== ERROR SUMMARY: 256 errors from 1 contexts (suppre
```

All good now?

Now we have constant-time exponentation / scalar multiplication if

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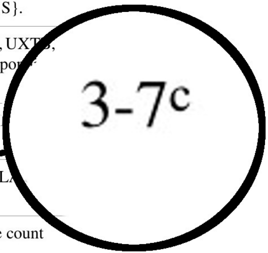
- the processor provides constant-time arithmetic instructions.

Single-clock-cycle instructions are probably OK.

ARM Cortex-M3

Table 18-1 Instruction timings (continued)

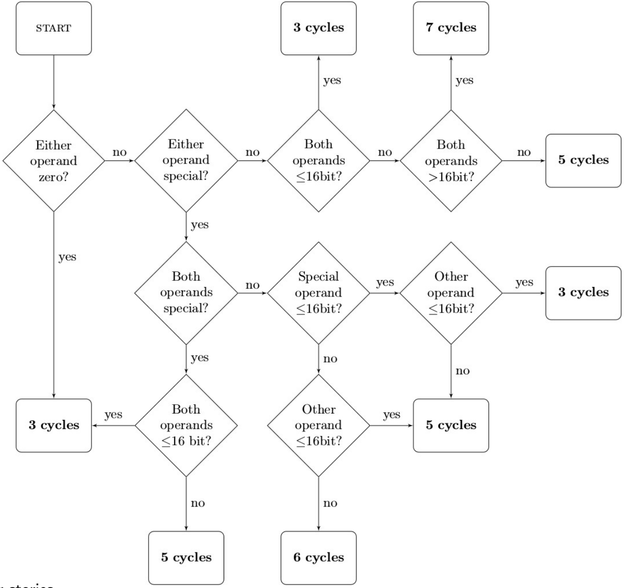
Instruction type	Size	Cycles count	Description
Shift operations	32	1	ASR{S}, LSL{S}, LSR{S}, ROR{S}, and RRX{S}.
Miscellaneous	32	1	REV, REVH, REVSH, RBIT, CLZ, SXTB, SXTH, UXT and UXTH. Extension instructions same as correspo ARM v6 16-bit instructions.
Table Branch	16	4+P[a]	Table branches for switch/case use. These are LD shifts and then branch.
Multiply	32	1 or 2	MUL, MLA, and MLS. MUL is one cycle and MLA MLS are two cycles.
Multiply with 64-bit result	32	3-7[c]	UMULL, SMULL, UMLAL, and SMLAL. Cycle count based on input sizes. That is, ABS(inputs) < 64K terminates early.
Load-store addressing	32	-	Supports Format PC+/-imm12, Rbase+imm12, Rbase+/-imm8, and adjusted register including shifts. T variants used when in Privilege mode.



c. UMULL/SMULL/UMLAL/SMLAL use early termination depending on the size of source values. These are interruptible (abandoned/restarted), with worst case latency of one cycle. MLAL versions take four to seven cycles and MULL versions take three to five cycles. For MLAL, the signed version is one cycle longer than the unsigned.

Cortex-M3 Technical Reference Manual - ARM architecture

ARM Cortex-M3 – what does it really do?



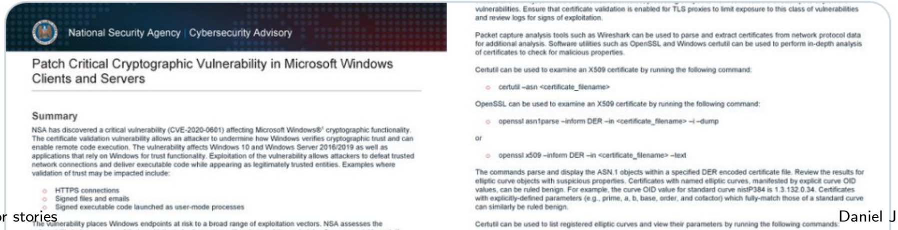
Flow chart for UMLAL (unsigned multiply add) from [A performance study of X25519 on Cortex-M3 and M4] by Wouter de Groot.

Microsoft CVE-2020-0601

NSA/CSS
@NSAGov

This #PatchTuesday you are strongly encouraged to implement the recently released CVE-2020-0601 patch immediately.

media.defense.gov/2020/Jan/14/20...


National Security Agency | Cybersecurity Advisory

Patch Critical Cryptographic Vulnerability in Microsoft Windows Clients and Servers

Summary

NSA has discovered a critical vulnerability (CVE-2020-0601) affecting Microsoft Windows®[1] cryptographic functionality. The certificate validation vulnerability allows an attacker to undermine how Windows verifies cryptographic trust and can enable remote code execution. The vulnerability affects Windows 10 and Windows Server 2016/2019 as well as applications that rely on Windows for trust functionality. Exploitation of the vulnerability allows attackers to defeat trusted network connections and deliver executable code while appearing as legitimately trusted entities. Examples where validation of trust may be impacted include:

- HTTPS connections
- Signed files and emails
- Signed executable code launched as user-mode processes

The vulnerability places Windows endpoints at risk to a broad range of exploitation vectors. NSA assesses the

vulnerabilities. Ensure that certificate validation is enabled for TLS proxies to limit exposure to this class of vulnerabilities and review logs for signs of exploitation.

Packet capture analysis tools such as Wireshark can be used to parse and extract certificates from network protocol data for additional analysis. Software utilities such as OpenSSL and Windows certutil can be used to perform in-depth analysis of certificates to check for malicious properties.

Certutil can be used to examine an X509 certificate by running the following command:

- certutil –asn <certificate_filename>

OpenSSL can be used to examine an X509 certificate by running the following command:

- openssl asn1parse –inform DER –in <certificate_filename> –i –dump

or

- openssl x509 –inform DER –in <certificate_filename> –text

The commands parse and display the ASN.1 objects within a specified DER encoded certificate file. Review the results for elliptic curve objects with suspicious properties. Certificates with named elliptic curves, manifested by explicit curve OID values, can be ruled benign. For example, the curve OID value for standard curve nistP384 is 1.3.132.0.34. Certificates with explicitly-defined parameters (e.g., prime, a, b, base, order, and cofactor) which fully-match those of a standard curve can similarly be ruled benign.

Certutil can be used to list registered elliptic curves and view their parameters by running the following commands:

Microsoft CVE-2020-0601

- Certificate shows Alice's public key Q and params E, P.
- Signed message consists of ECDSA signature (m, r, s) as well as Alice's public key Q and E, P. After checking certificate, Windows remembers that Q is Alice's trusted public key.
- Next verification of a signature by Alice checks validity of (m', r', s') under supplied (E, P, Q) if Q is in database.

Microsoft CVE-2020-0601

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- Landed in Windows code base in a move to support arbitrary elliptic curves . . . in 2015.

Microsoft CVE-2020-0601

Daniel J. Bernstein
@hashbreaker

Replying to @hanno

See cr.yp.to/newelliptic/ni... (from @hyperelliptic and me), which says in §1 that "unnecessary complexity in ECC implementations" creates "ECC security failures", and says in §11 that allowing run-time curve choices causes "obvious damage to implementation simplicity". Told ya so.

8:35 PM · Jan 15, 2020 · Twitter Web App

CVE-2018-0733, an OpenSSL bug

"Because of an implementation bug the PA-RISC `CRYPTO_memcmp` function is effectively reduced to only comparing the least significant bit of each byte." Bug introduced May 2016.

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— 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."
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Bug introduced July 2013.

"Attacks against DH1024 are considered just feasible"
— How much time? How much hardware?

CVE-2017-3738, continued

Are you safe if you aren't using DH1024? "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."

CVE-2017-3738, continued

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has the actual computation received from cryptanalysts?

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6 December 2019: Similar OpenSSL advisory for CVE-2019-1551.

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      \$0x1ffffff, %eax

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

September 2019: bug announced in Falcon software

Falcon: lattice-based post-quantum signature system in round 2.

"The consequences of these bugs are the following:

- Produced signatures were valid but **leaked information on the private key**. [emphasis added]
- Performance was artificially inflated: …

The fact that these bugs existed in the first place shows that the traditional development methodology (i.e. 'being super careful') has failed."

Cryptography is notoriously hard to review

Mathematical complications in cryptography lead to subtle bugs.

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Cryptography is applied to large volumes of data.
Often individual cryptographic computations are time-consuming.
Pursuit of speed $\Rightarrow$ many different cryptographic systems, and cryptographic code optimized in many ways for particular CPUs.

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e.g. Keccak Code Package: $>$20 implementations of SHA-3.
e.g. Google added hand-written Cortex-A7 asm to Linux kernel for Speck128/128-XTS, then switched to (faster) Adiantum-XChaCha.

Formal logic to the rescue?

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

$$*54{\cdot}43.\quad \vdash :.\ \alpha, \beta \in 1 \,.\supset :\ \alpha \cap \beta = \Lambda \,.\equiv.\, \alpha \cup \beta \in 2$$

Dem.

$$\vdash .\, *54{\cdot}26 \,.\supset \vdash :.\ \alpha = \iota\text{‘}x \,.\, \beta = \iota\text{‘}y \,.\supset :\ \alpha \cup \beta \in 2 \,.\equiv.\, x \neq y \,.$$

$$[*51{\cdot}231] \qquad \equiv .\, \iota\text{‘}x \cap \iota\text{‘}y = \Lambda \,.$$

$$[*13{\cdot}12] \qquad \equiv .\, \alpha \cap \beta = \Lambda \qquad (1)$$

$$\vdash .\, (1) \,.\, *11{\cdot}11{\cdot}35 \,.\supset$$

$$\vdash :.\ (\exists x, y) \,.\, \alpha = \iota\text{‘}x \,.\, \beta = \iota\text{‘}y \,.\supset :\ \alpha \cup \beta \in 2 \,.\equiv.\, \alpha \cap \beta = \Lambda \qquad (2)$$

$$\vdash .\, (2) \,.\, *11{\cdot}54 \,.\, *52{\cdot}1 \,.\supset \vdash .\, \text{Prop}$$

From this proposition it will follow, when arithmetical addition has been defined, that $1 + 1 = 2$.

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Require code reviewer to *prove* correctness.
Require proofs to pass a proof-checking tool.

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Proving crypto code correct 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 (in the code; but worry about bugs in compiler, CPU, . . .).
Bad: Tons of effort for each implementation.
e.g. EverCrypt doesn't have fast software for smartphone CPUs.

Testing

Testing is great. Test everything. Design for tests.

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

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

The most important complaint about testing

Testing can miss attacker-triggerable bugs for rare inputs.

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"On certain kinds of inputs, the code will lead to overflow conditions and hence to incorrect results.

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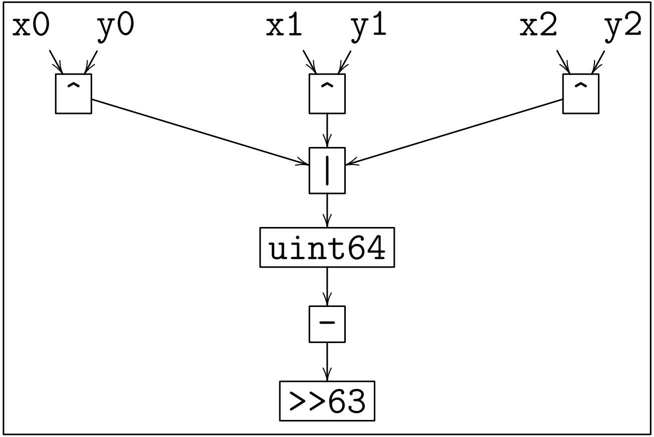
"On certain kinds of inputs, the code will lead to overflow conditions and hence to incorrect results. This, however, is a very low probability event and cannot be captured using some randomly generated known answer tests (KATs). ... We believe that it is important to have proofs of correctness of the reduction algorithms to ensure that the algorithms works correctly for all possible inputs."

Can we fix this?

Symbolic testing: beyond testing particular inputs

```
.globl CRYPTO_memcmp
CRYPTO_memcmp:
xor    %rax,%rax
xor    %r10,%r10
cmp    $0x0,%rdx
je     no_data
cmp    $0x10,%rdx
jne    loop
mov    (%rdi),%r10
mov    0x8(%rdi),%r11
mov    $0x1,%rdx
xor    (%rsi),%r10
xor    0x8(%rsi),%r11
or     %r11,%r10
cmovne %rdx,%rax
repz retq
loop:
mov    (%rdi),%r10b
lea    0x1(%rdi),%rdi
xor    (%rsi),%r10b
lea    0x1(%rsi),%rsi
or     %r10b,%al
dec    %rdx
jne    loop
neg    %rax
shr    $0x3f,%rax
no_data:
repz retq
```

Arithmetic DAG for all 3-byte inputs:



The power of modern reverse-engineering tools

Easy to use `angr.io` for automatic **symbolic execution**:
machine-language software ➜ arithmetic DAG.
Simplifies analysis: simpler instructions, no memory, no jumps.

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... which we try to avoid in crypto anyway.

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`angr` (via Z3 SMT solver) often sees equivalence of small DAGs.
e.g. sees that OpenSSL `x86_64` `CRYPTO_memcmp` on 3-byte inputs outputs 0 if `x0==y0` and `x1==y1` and `x2==y2`,
and outputs 1 otherwise. Similarly for other input lengths.

```
#include <openssl/crypto.h>

unsigned char x[N];
unsigned char y[N];
int z;

int main()
{
  z = CRYPTO_memcmp(x,y,N);
  return 0;
}
```

```
#!/usr/bin/env python3

import sys
import angr

N = int(sys.argv[1]) if len(sys.argv) > 1 else 16

proj = angr.Project('cmp%d'%N)
state = proj.factory.full_init_state()

state.options |= {
  angr.options.ZERO_FILL_UNCONSTRAINED_MEMORY
}
```

```
x = {}
xaddr = proj.loader.find_symbol('x').rebased_addr
for i in range(N):
  x[i] = state.solver.BVS('x%d'%i,8)
  state.mem[xaddr+i].char = x[i]

y = {}
yaddr = proj.loader.find_symbol('y').rebased_addr
for i in range(N):
  y[i] = state.solver.BVS('y%d'%i,8)
  state.mem[yaddr+i].char = y[i]

simgr = proj.factory.simgr(state)
simgr.run()
```

```
assert len(simgr.errored) == 0
print('%d universes' % len(simgr.deadended))
for exit in simgr.deadended:
  zaddr = proj.loader.find_symbol('z').rebased_addr
  z = exit.mem[zaddr].int.resolved
  print('out = %s' % z)

  xeqy = True
  for i in range(N):
    xeqy = state.solver.And(xeqy,x[i]==y[i])
  xney = state.solver.Not(xeqy)
  for bugs in ((z!=0,z!=1),(z!=0,xeqy),(z!=1,xney)):
    assert not exit.satisfiable(extra_constraints=bugs)
```

Symbolic execution with better equivalence testing

What if the DAG is too complicated for the SMT solver?
Answer: **Build smarter tools to recognize DAG equivalence.**

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Case study, software library from `sorting.cr.yp.to`:

- New speed records for sorting of in-memory integer arrays.
  This is a subroutine in some post-quantum cryptosystems.
- Side-channel countermeasures:
  no secret branch conditions; no secret array indices.
- New tool verifies correct sorting of all size-N inputs.
  No need for manual review of per-CPU optimized code.