Usable verification of fast cryptographic software

Daniel J. Bernstein

University of Illinois at Chicago & Technische Universiteit Eindhoven

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Attack: guess my password.
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Defense: I have a high-entropy randomly generated password.
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Two-part defense:
1. “Memory protection”. Hardware does not allow processes to access data outside areas marked by kernel.
2. Kernel keeps track of which parts of RAM and disk are mine, and which parts are Donald’s.
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Fix: Eliminate the bugs!

Bug-free code is expensive but not impossible when code volume is small enough.

Successful example: computer-verified proof of seL4 microkernel correctness, including RAM partitioning etc.
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The **trusted computing base** (TCB) is the part of the system that enforces security policy. The 10000000-line program is not part of the TCB.
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VANCOUVER, British Columbia, March 17, 2016 /PRNewswire/ -- 360Vulcan Team from Qihoo 360 hacked Google Chrome, the browser with the least vulnerabilities, and obtained the highest system privilege. It's the first time a Chinese security team has hacked Google Chrome at the Pwn2Own contest.

360Vulcan Team also hacked Adobe Flash Player based on Edge browser, obtaining the highest system privilege, which won the team a USD 80,000
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Widely deployed software systems make no real efforts to limit this. There is some “security” code inside kernel and browser. But bugs in other code can and do compromise security. TCB has >30000000 lines.
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Fix: rearchitect entire system so that a small TCB tracks sources of all data. Eliminate all bugs in TCB.
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Solution: Sender and receiver scramble communication in a way that Donald cannot understand and cannot silently corrupt.
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OpenSSL crypto library has $500000$ lines of code, and there are many other crypto libraries. All of this is in the TCB. Many devastating security bugs.

Why is crypto so big?
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**Why is crypto so big?**

Most important answer: the pursuit of performance.

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E.g. ECDSA signature verification:

\[(H(M)/S)B + (x(R)/S)A = R,\]

with \( S \) checked to be nonzero.

OpenSSL has complicated code for fast computation of \( 1/S \).

Checking \( H(M)B + x(R)A = SR \) would be somewhat slower.
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e.g. NIST P-256 prime \(p = 2^{256} - 2^{224} + 2^{192} + 2^{96} - 1\). ECDSA standard specifies reduction procedure given an integer \(A\) less than \(p\): Write \(A = (A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\), meaning

\[P_i A_i 2^{32 i}\].

Define \(T; S_1; S_2; S_3; S_4; D_1; D_2; D_3; D_4\) as
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ECDSA standard specifies reduction procedure for an integer “\(A\) less than \(p\):”

Write \(A\) as \((A_{15}, A_{14}, A_{13}, A_{12}, \ldots, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\), meaning \(\sum_i A_i 2^{32i}\).

Define \(T, S_1, S_2, S_3, S_4, D_1, D_2, D_3, D_4\) as
OpenSSL crypto library has 500000 lines of code, and there are many other crypto libraries. All of this is in the TCB.

Many devastating security bugs. Why is crypto so big? Most important answer: the pursuit of performance. (Same issue elsewhere in TCB, but most blatant for crypto. The rest of this talk will focus on crypto.)

e.g. Variable-length-big-integer arithmetic library inside OpenSSL consumes 50000 lines of code. Includes 38 asm implementations optimized for various CPUs.

e.g. ECDSA signature verification:

\[(H(M)/S)B + (x(R)/S)A = R,\]

with \(S\) checked to be nonzero.

OpenSSL has complicated code for fast computation of \(1/S\).

Checking \(H(M)B + x(R)A = SR\) would be somewhat slower.

e.g. NIST P-256 prime \(p\) is

\[2^{256} - 2^{224} + 2^{192} + 2^{96} - 1.\]

ECDSA standard specifies reduction procedure given an integer “A less than \(p^2\)”: Write \(A\) as

\[(A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, \ldots, A_{8}, A_{7}, A_{6}, A_{5}, A_{4}, A_{3}, A_{2}, A_{1}, A_{0}),\]

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\((A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_{9},\]

\(A_{8}, A_{7}, A_{6}, A_{5}, A_{4}, A_{3}, A_{2}, A_{1}, A_{0})\),

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\[(A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0);
(A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0);
(0, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0);
(A_{10}, A_8, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0);
(A_{11}, A_9, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0);
(A_{12}, 0, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0);
(A_{13}, 0, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\)

Compute \(T + 2S_1 + 2S_2 + S_3 + S_4 - D_1 - D_2 - D_3 - D_4\).

Reduce \(T + 2S_1 + 2S_2 + S_3 + S_4\) by adding or subtracting a few copies of \(p\).
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ECDSA signature verification:
\[(H(M)B + x(R)A = S)\]

with \(S\) checked to be nonzero.

OpenSSL has complicated code for fast computation of \(1 = S\).

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Define \(T; S_1; S_2; S_3; S_4; D_1; D_2; D_3; D_4\) as

\((A_{7}, A_{6}, A_{5}, A_{4}, A_{3}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)\)
\((A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\)
\((A_{10}, A_8, 0, 0, 0, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\)
\((A_{11}, A_9, 0, 0, 0, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\)
\((A_{12}, 0, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\)
\((A_{13}, 0, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0)\)

Compute \(T + 2S_1 + 2S_2 + S_3 + S_4 - D_1 - D_2 - D_3 - D_4\).

Reduce modulo \(p\) by adding or subtracting a few copies of \(p\).
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Define
\(T; S_1; S_2; S_3; S_4; D_1; D_2; D_3; D_4\)
as
\[(A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0); (A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, 0, 0, 0); (0, A_{15}, A_{14}, A_{13}, A_{12}, 0, 0, 0); (A_{15}, A_{14}, 0, 0, 0, A_{10}, A_9, A_8); (A_8, A_{13}, A_{15}, A_{14}, A_{13}, A_{11}, A_{10}, A_9, A_8); (A_{10}, A_8, 0, 0, 0, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8); (A_{11}, A_9, 0, 0, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8); (A_{12}, 0, A_{10}, A_9, A_8, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8); (A_{13}, 0, A_{11}, A_{10}, A_9, 0, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8); (A_{14}, 0, A_{12}, A_{11}, A_{10}, A_9, 0, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8); (A_{15}, 0, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, 0, A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8); \]

Compute \(T + 2S_1 + 2S_2 + S_3 + S_4 - D_1 - D_2 - D_3 - D_4\).

Reduce modulo \(p\) “by adding or subtracting a few copies” of \(p\).
e.g. NIST P-256 prime $p$ is $2^{256} - 2^{224} + 2^{192} + 2^{96} - 1$.

ECDSA standard specifies reduction procedure given an integer “$A$ less than $p^2$”:

Write $A$ as:

$$(A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_{10}, A_9, A_8, A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0),$$

meaning $\sum_i A_i 2^{32i}$.

Define

$$T; S_1; S_2; S_3; S_4; D_1; D_2; D_3; D_4$$

as:

$$(A_7, A_6, A_5, A_4, A_3, A_2, A_1, A_0);$$
$$(A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, 0, 0, 0);$$
$$(0, A_{15}, A_{14}, A_{13}, A_{12}, 0, 0, 0);$$
$$(A_{15}, A_{14}, 0, 0, 0, A_{10}, A_9, A_8);$$
$$(A_8, A_{13}, A_{15}, A_{14}, A_{13}, A_{11}, A_{10}, A_9);$$
$$(A_{10}, A_8, 0, 0, 0, A_{13}, A_{12}, A_{11});$$
$$(A_{11}, A_9, 0, 0, A_{15}, A_{14}, A_{13}, A_{12});$$
$$(A_{12}, 0, A_{10}, A_9, A_8, A_{15}, A_{14}, A_{13});$$
$$(A_{13}, 0, A_{11}, A_{10}, A_9, 0, A_{15}, A_{14}).$$

Compute $T + 2S_1 + 2S_2 + S_3 + S_4 - D_1 - D_2 - D_3 - D_4$.

Reduce modulo $p$ “by adding or subtracting a few copies” of $p$. 
The P-256 prime $p$ is $2^{224} + 2^{192} + 2^{96} - 1$.

The ECDSA standard specifies a reduction procedure given an integer “$A$ less than $p^2$”:

$$A = (A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, A_0);$$
$$0 = (A_{15}, A_{14}, A_{13}, A_{12}, 0, 0, 0);$$
$$A = (A_{15}, A_{14}, 0, 0, 0, A_{10}, A_9, A_8);$$
$$A = (A_8, A_{13}, A_{15}, A_{14}, A_{13}, A_{11}, A_{10}, A_9);$$
$$A = (A_{10}, A_8, 0, 0, 0, A_{13}, A_{12}, A_{11});$$
$$A = (A_{11}, A_9, 0, 0, A_{15}, A_{14}, A_{13}, A_{12});$$
$$A = (A_{12}, 0, A_{10}, A_9, A_8, A_{15}, A_{14}, A_{13});$$
$$A = (A_{13}, 0, A_{11}, A_{10}, A_9, 0, A_{15}, A_{14}).$$

Compute $T + 2S_1 + 2S_2 + S_3 + S_4 - D_1 - D_2 - D_3 - D_4$.

Reduce modulo $p$ “by adding or subtracting a few copies” of $p$.

---

Next-generation crypto
One of my favorite topics:
removing tensions between
security, simplicity, speed.
In particular, designing
simple high-security crypto
setting new speed records.
e.g. 2006 Bernstein “Curve25519”
is twice as fast as standard ECC
and much simpler to implement.
$>1000000000$ Curve25519 users
today: iOS, Signal, OpenSSH,
Tor, QUIC, WhatsApp, more.
The prime $p$ is
\[ p = 2^{256} - 2^{224} + 2^{192} + 2^{96} - 1. \]
ECDSA standard specifies
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Write $A$ as
\[ (A_{15}, A_{14}, A_{13}, A_{12}, A_{11}, 0, 0, 0), \]
\[ (A_{15}, A_{14}, 0, 0, 0, A_{10}, A_9, A_8), \]
\[ (A_8, A_{13}, A_{15}, A_{14}, A_{13}, A_{11}, A_{10}, A_9), \]
\[ (A_{10}, A_8, 0, 0, 0, A_{13}, A_{12}, A_{11}), \]
\[ (A_{11}, A_9, 0, 0, A_{15}, A_{14}, A_{13}, A_{12}), \]
\[ (A_{12}, 0, A_{10}, A_9, A_8, A_{15}, A_{14}, A_{13}), \]
\[ (A_{13}, 0, A_{11}, A_{10}, A_9, 0, A_{15}, A_{14}). \]
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Define $T; S_1; S_2; S_3; S_4; D_1; D_2; D_3; D_4$ as

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(A_7, A_4, A_3, A_2, A_1, A_0);
(4, A_{13}, A_{12}, A_{11}, 0, 0, 0);
(A_{14}, A_{13}, A_{12}, 0, 0, 0);
(0, 0, 0, A_{10}, A_9, A_8);
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(0, 0, 0, A_{13}, A_{12}, A_{11});
(0, 0, A_{15}, A_{14}, A_{13}, A_{12});
(A_{10}, A_9, A_8, A_{15}, A_{14}, A_{13});
(A_{11}, A_{10}, A_9, 0, A_{15}, A_{14}).

Let $T + 2S_1 + 2S_2 + S_3 + S_4 - D_1 - D_2 - D_3 - D_4$.

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Biggest challenge: the gap
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1. Not state-of-the-art speed. Okay for TweetNaCl; not NaCl.
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