Usable verification of fast cryptographic software

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Operating-system kernel divides RAM among processes, divides disk among files. Provides convenient functions for processes to access files, start new processes, etc.
my terminal

my processes

RAM

Donald’s processes

Donald’s terminal

my files

disk

Donald’s files
Can Donald corrupt the data appearing on my terminal?
Can Donald corrupt the data appearing on my terminal?

Attack: guess my password.
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**Defense:** I have a high-entropy randomly generated password.
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Attack: use my terminal earlier and leave a program running that looks like the usual login screen but intercepts my password.
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Defense: physical security.

Attack: use my terminal earlier and leave a program running that looks like the usual login screen but intercepts my password.
Defense: secure attention key.
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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.
Bugs in this kernel code can compromise security, allowing Donald to write to my part of RAM or disk.
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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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I can run a 10000000-line program filled with bugs, and still be confident that Donald is unable to corrupt the output of the program.
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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.
But we want communication!

Today: Alice sends me email. I download Bob’s web page. These users are authorized to put data on my screen.
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If Donald creates a file and convinces the computer to show me the file as having source “Alice” then this policy is violated.
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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There is some “security” code inside kernel and browser. But bugs in other code can and do compromise security. TCB has >30000000 lines.

Fix: rearchitect entire system so that a small TCB tracks sources of all data. Eliminate all bugs in TCB.
Cryptography in the TCB

What happens if data is sent through Donald’s network?
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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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**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.
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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.
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 $\sum_i A_i2^{32i}$.

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 \( p \).
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.
NaCl: fast easy-to-use high-security crypto library. Joint work with Lange and Schwabe.

nacl.cr.yp.to
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TweetNaCl: self-contained 100-tweet C library providing the same easy-to-use high-security functions. Joint work with van Gastel, Janssen, Lange, Schwabe, Smetsers. 

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Can we guarantee zero bugs in TweetNaCl? And in NaCl?
Biggest challenge: the gap between big-integer operations such as \( a, b \mapsto ab \mod 2^{255} - 19 \) and (e.g.) 32-bit operations.
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1. Not state-of-the-art speed.
   Okay for TweetNaCl; not NaCl.

2. Input-dependent timing.
   Timing can leak secret keys.
   Not okay even for TweetNaCl.
“Verifying Curve25519 software”: computer-aided proof of
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Each proof also required many hours of computer time.
Joint work with Schwabe: new verifier gfverif focusing on arithmetic mod $p$.

gfverif.cryptojedi.org

Automatically build computation graph from original code.

Automatically analyze ranges, convert ops into polynomials.

New peephole range optimizer.

Ask human for occasional annotations expressing high-level computations on integers mod $p$. 
Have verified entire Curve25519 computation, not just main loop, for another implementation.

Only 1 minute of computer time.

Under 300 lines of easy annotations per implementation.

**Usable by crypto developers.**

Continuing to improve gfverif annotation language. Should be able to reduce below 100 annotations per implementation.