High-assurance crypto software

Peter Schwabe
Radboud University, Nijmegen, The Netherlands

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Some questions... 

Who has ever implemented cryptography?
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Who has ever implemented cryptography that is actually being used?
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Who has ever implemented cryptography that is actually being used? 

Who believes that their software is secure and correct?
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Who believes that their software is secure and correct?

Who is sure that their software is secure and correct?
Bug attacks

- Imagine bug in crypto that is triggered with very low probability
- Attacker finds this bug, crafts input that
  - triggers the bug if secret bit is 0
  - does not trigger the bug if secret bit is 1
- Attacker observes output, learns secret bit
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- Bug was a mis-handled carry bit (which was almost always zero)
- Similar bug, again in OpenSSL, fixed in Jan. 2015
- Unclear whether that one can be exploited
- Similar bug, again in OpenSSL, fixed in Dec. 2015
- Hard to exploit, but probably possible
Timing Attacks

General idea of those attacks

- Secret data has influence on timing of software
- Attacker measures timing
- Attacker computes influence$^{-1}$ to obtain secret data
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Two kinds of remote... 

- Timing attacks are a type of side-channel attacks
- Unlike other side-channel attacks, they work remotely:
  - Some need to run attack code in parallel to the target software
  - Attacker can log in remotely (ssh)
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  - Some attacks work by measuring network delays
  - Attacker does not even need an account on the target machine
- Can’t protect against timing attacks by locking a room
Examples of timing attacks

- Osvik, Shamir, Tromer, 2006: Recover AES-256 secret key of Linux’s dmcrypt in just 65 ms
- AlFardan, Paterson, 2013: “Lucky13” recovers plaintext of CBC-mode encryption in pretty much all TLS implementations
- Yarom, Falkner, 2014: Attack against RSA-2048 in GnuPG 1.4.13: “On average, the attack is able to recover 96.7% of the secret key by observing a single signature or decryption round.”
- Benger, van de Pol, Smart, Yarom, 2014: “reasonable level of success in recovering the secret key” for OpenSSL ECDSA using secp256k1 “with as little as 200 signatures.”
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Example for this talk: X25519

- Bernstein 2006: X25519 Diffie-Hellman key exchange (originally: “Curve25519”)
- Secret keys: 32-byte little-endian scalars
- Public keys: 32-byte arrays, encoding $x$-coordinate of a point on
  $$E : y^2 = x^3 + 486662x^2 + x$$
  over $\mathbb{F}_{2^{255} - 19}$
- Base point: $(9, 0, \ldots, 0)$
Example for this talk: X25519

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- Secret keys: 32-byte little-endian scalars
- Public keys: 32-byte arrays, encoding $x$-coordinate of a point on

$$E : y^2 = x^3 + 486662x^2 + x$$

over $\mathbb{F}_{2^{255} - 19}$
- Base point: $(9, 0, \ldots, 0)$
- Given secret key $s$ and public key (or base point) $P$:
  - Copy $s$ to $s'$
  - Set least significant 3 bits of $s'$ to zero
  - Set most significant bit of $s'$ to zero
  - Set second-most significant bit of $s'$ to one
  - Compute $x$-coordinate of $s'P$
The Montgomery ladder

Require: A scalar $0 \leq k \in \mathbb{Z}$ and the $x$-coordinate $x_P$ of some point $P$

Ensure: $x_{kP}$

$X_1 = x_P; \ X_2 = 1; \ Z_2 = 0; \ X_3 = x_P; \ Z_3 = 1$

for $i \leftarrow n - 1$ downto 0 do

if bit $i$ of $k$ is 1 then

$(X_3, Z_3, X_2, Z_2) \leftarrow$ ladderstep($X_1, X_3, Z_3, X_2, Z_2$)

else

$(X_2, Z_2, X_3, Z_3) \leftarrow$ ladderstep($X_1, X_2, Z_2, X_3, Z_3$)

end if

end for

return $X_2 \cdot Z_2^{-1}$
One Montgomery “ladder step”

\[
\text{const } a_{24} = (A + 2)/4 \quad (A \text{ from the curve equation})
\]

\[
\text{function ladderstep}(X_{Q-P}, X_P, Z_P, X_Q, Z_Q)
\]

\[
t_1 \leftarrow X_P + Z_P
\]

\[
t_6 \leftarrow t_1^2
\]

\[
t_2 \leftarrow X_P - Z_P
\]

\[
t_7 \leftarrow t_2^2
\]

\[
t_5 \leftarrow t_6 - t_7
\]

\[
t_3 \leftarrow X_Q + Z_Q
\]

\[
t_4 \leftarrow X_Q - Z_Q
\]

\[
t_8 \leftarrow t_4 \cdot t_1
\]

\[
t_9 \leftarrow t_3 \cdot t_2
\]

\[
X_{P+Q} \leftarrow (t_8 + t_9)^2
\]

\[
Z_{P+Q} \leftarrow X_{Q-P} \cdot (t_8 - t_9)^2
\]

\[
X_{2P} \leftarrow t_6 \cdot t_7
\]

\[
Z_{2P} \leftarrow t_5 \cdot (t_7 + a_{24} \cdot t_5)
\]

\[
\text{return } (X_{2P}, Z_{2P}, X_{P+Q}, Z_{P+Q})
\]

end function
Curve25519 implementations

- Bernstein, 2006: X25519 for various 32-bit Intel and AMD processors
- Gaudry, Thomé, 2007: X25519 for 64-bit Intel and AMD processors
- Costigan, Schwabe, 2009: X25519 for Cell Broadband Engine
- Bernstein, Duif, Lange, Schwabe, Yang, 2011: X25519 for Intel Nehalem/Westmere
- Düll, Haase, Hinterwälder, Hutter, Paar, Sánchez, Schwabe, 2015: X25519 for AVR ATmega, TI MSP430, and ARM Cortex-M0
- Chou, 2015: The fastest Curve25519 software ever
- Many more implementations, most without scientific papers
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Constant-time software

Avoid secret branch conditions

- Branches largely influence timing of program
- Secret branch conditions leak information
- “Balancing branches” is typically insufficient
- \[\Rightarrow\] No data flow from secret data into branch conditions!
Constant-time software

Avoid secret branch conditions

- Branches largely influence timing of program
- Secret branch conditions leak information
- “Balancing branches” is typically insufficient
- ⇒ No data flow from secret data into branch conditions!

Avoid memory access at secret positions

- Caches influence timing depending on address
- Attackers can potentially control cache lines
- Caches are not the only problem (e.g., store-to-load forwarding)
- ⇒ No data flow from secret data into addresses!
The Montgomery ladder

**Require:** A scalar $0 \leq k \in \mathbb{Z}$ and the $x$-coordinate $x_P$ of some point $P$

**Ensure:** $x_{kP}$

$X_1 = x_P; X_2 = 1; Z_2 = 0; X_3 = x_P; Z_3 = 1$

for $i \leftarrow n - 1$ downto 0 do

if bit $i$ of $k$ is 1 then

$(X_3, Z_3, X_2, Z_2) \leftarrow \text{ladderstep}(X_1, X_3, Z_3, X_2, Z_2)$

else

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end if

end for

return $X_2 \cdot Z_2^{-1}$
The Montgomery ladder rewritten

Require: A scalar $0 \leq k \in \mathbb{Z}$ and the $x$-coordinate $x_P$ of some point $P$

Ensure: $x_{kP}$

1. $X_1 = x_P$; $X_2 = 1$; $Z_2 = 0$; $X_3 = x_P$; $Z_3 = 1$
2. For $i \leftarrow n - 1$ downto 0 do
   1. $b \leftarrow$ bit $i$ of $s$
   2. $c \leftarrow b \oplus p$
   3. $p \leftarrow b$
   4. $(X2, X3) \leftarrow \text{cswap}(X2, X3, c)$
   5. $(Z2, Z3) \leftarrow \text{cswap}(Z2, Z3, c)$
   6. $(X2, Z2, X3, Z3) \leftarrow \text{ladderstep}(X1, X2, Z2, X3, Z3)$
3. end for
4. return $X_2 \cdot Z_2^{-1}$
/* decision bit b has to be either 0 or 1 */
void cmov(uint64_t *r, uint64_t *a, uint64_t b) {
  uint64_t t;

  b = -b; /* Now b is either 0 or 0xffffffff */
  t = (*r ^ *a) & b;
  *r ^= t;
}
“Verifying” constant-time behavior

Run in valgrind with *uninitialized secret data* (or use Langley’s ctgrind)

[short demo]
“Verifying” constant-time behavior

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**Static verification**

**Vagrant** (Almeida, Barbosa, Barthe, Dupressoir, Emmi):
https://github.com/imdea-software/verifying-constant-time

**FlowTracker** (Rodrigues, Pereira, Aranha):
http://cuda.dcc.ufmg.br/flowtracker/
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- Both work on LLVM IL level
Correct software?

“Are you actually sure that your software is correct?”

Arithmetic in $\mathbb{F}_{2^{255}-19}$ for AMD64

Radix $2^{64}$

- Standard: break elements of $\mathbb{F}_{2^{255}-19}$ into 4 64-bit integers
- (Schoolbook) multiplication breaks down into 16 64-bit integer multiplications
- Adding up partial results requires many add-with-carry (adc)
- Westmere bottleneck: 1 adc every two cycles vs. 3 add per cycle
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Radix $2^{51}$
- Instead, break into 5 64-bit integers, use radix $2^{51}$
- Can delay carry operations; carry “en bloc”
- Schoolbook multiplication now 25 64-bit integer multiplications
- Easy to merge multiplication with reduction (multiplies by 19)
- Better performance on Westmere/Nehalem, worse on 65 nm Core 2 and AMD processors
Bug in the radix-64 reduction

```
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%r13
adc  %rdx,%r14
adc  $0,%r14
mov  %r9,%rax
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%r14
adc  %rdx,%r15
adc  $0,%r15
mov  %r10,%rax
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%r15
adc  %rdx,%rbx
adc  $0,%rbx
mov  %r11,%rax
mulq  crypto_sign_ed25519_amd64_64_38
add  %rax,%rbx
mov  $0,%rsi
adc  %rdx,%rsi
```
Bug in the radix-64 reduction

```c
(uint128) mulrdx mulrax = mulrax * *(uint64 *)&crypto_sign_ed25519_amd64_64_38
carry? r0 += mulrax
carry? r1 += mulrdx + carry
r1 += 0 + carry
mulrax = mulr5
(uint128) mulrdx mulrax = mulrax * *(uint64 *)&crypto_sign_ed25519_amd64_64_38
carry? r1 += mulrax
carry? r2 += mulrdx + carry
r2 += 0 + carry
mulrax = mulr6
(uint128) mulrdx mulrax = mulrax * *(uint64 *)&crypto_sign_ed25519_amd64_64_38
carry? r2 += mulrax
carry? r3 += mulrdx + carry
r3 += 0 + carry
mulrax = mulr7
(uint128) mulrdx mulrax = mulrax * *(uint64 *)&crypto_sign_ed25519_amd64_64_38
carry? r3 += mulrax
mulr4 = 0
mulr4 += mulrdx + carry
```
Bug in the radix-64 reduction

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mulr4 = 0
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```

Full software package contains 8912 lines of qasm code!
Directions to correct crypto

Testing

- Is cheap, catches many bugs
- Does not conflict with performance
- Provides very high confidence in correctness for some crypto algorithms
- Typically fails to catch very rarely triggered bugs
Directions to correct crypto

Audits

- Expensive (time and/or money)
- Conflicts with performance
- Standard approach to ensure correctness and quality of crypto software
Directions to correct crypto

Formal verification
  ▶ Strongest guarantees of correctness
  ▶ Probably conflicts with performance
Directions to correct crypto

Formal verification

- Strongest guarantees of correctness
- Probably conflicts with performance
- **Should focus on cases where tests fail**
Verification: the vision

- C or assembly programmer adds high-level annotations
- More specifically, for example:
  - Limbs $a_0, \ldots, a_n$ compose a field element $A$
  - Limbs $b_0, \ldots, b_n$ compose a field element $B$
  - Limbs $r_0, \ldots, r_n$ compose a field element $R$
  - $R = A \cdot B$
Verification: the vision

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- Annotated code gets fed to verification tool
- Verification ensures that operation on limbs corresponds to high-level arithmetic
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  - $R = A \cdot B$

- Annotated code gets fed to verification tool
- Verification ensures that operation on limbs corresponds to high-level arithmetic
- Audits look at high-level annotations
- Even better: feed to even higher level verification
- Verify that the sequence of field operations accomplishes EC arithmetic
Verification approach I

Joint work with Yu-Fang Chen, Chang-Hong Hsu, Hsin-Hung Lin, Ming-Hsien Tsai, Bow-Yaw Wang, Bo-Yin Yang, and Shang-Yi Yang.
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- qhasm is a portable assembly language by Bernstein
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  - Annotate qhasm code
  - Translate annotated qhasm automatically to SMT-solver boolector
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  - Translate annotated \texttt{qhasm} automatically to SMT-solver \texttt{boolector}
  - Use \texttt{boolector} to verify software
- Verification target: Montgomery ladder step of X25519:
  - 5 multiplications in $\mathbb{F}_{2^{255} - 19}$
  - 4 squarings in $\mathbb{F}_{2^{255} - 19}$
  - 1 multiplication by 121666
  - Several additions and subtractions
Example: Addition in radix $2^{51}$

```plaintext
// assume 0 <= u x0, x1, x2, x3, x4 <= u 2**51 + 2**15
// assume 0 <= u y0, y1, y2, y3, y4 <= u 2**51 + 2**15
r0 = x0
r1 = x1
r2 = x2
r3 = x3
r4 = x4
r0 += y0
r1 += y1
r2 += y2
r3 += y3
r4 += y4

// var sum_x = x0@u320 + x1@u320 * 2**51 + x2@u320 * 2**102 + x3@u320 * 2**153 + x4@u320 * 2**204
// sum_y = y0@u320 + y1@u320 * 2**51 + y2@u320 * 2**102 + y3@u320 * 2**153 + y4@u320 * 2**204
// sum_r = r0@u320 + r1@u320 * 2**51 + r2@u320 * 2**102 + r3@u320 * 2**153 + r4@u320 * 2**204
// assert (sum_r - (sum_x + sum_y)) % (2**255 - 19) = 0 &&
// 0 <= u r0, r1, r2, r3, r4 < u 2**53
```
How about multiplication?

- Again, express input field elements and output field elements
- Again, express bounds on the “limb size”
- Again, express algebraic relation of a modular multiplication
- Overall slightly more annotations for an auditor to look at
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- Overall slightly more annotations for an auditor to look at
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- SMT solver cannot simply verify from inputs to outputs
- Overall:
  - 217 lines of `qhasm`, including variable declarations
  - 589 lines of annotations
- Large amount of manual work on top of assembly optimization
- Writing verifiable code requires expert knowledge from two domains!
- Verification of just multiplication takes $> 90$ hours
Overall results

- Formally verified Montgomery ladderstep
  - “Redundant” radix-$2^{51}$ representation
  - Non-redundant radix-$2^{64}$ representation
  - Reproduced bug in original version of the software
- Most verification used automatic qhasm $\rightarrow$ boolector translation
- Tiny bit of code in radix-$2^{64}$ needed proof assistant Coq
Another approach... 

- 2 problems with SMT approach:
  - Huge amount of (manual) annotations
  - Long verification time
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- Idea: automagically translate to input for computer-algebra system
- Accept failures to prove correctness
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Work in progress with Bernstein

- Annotate C code (later: also qhasm)
- (Currently) use C++ compiler and operator overloading to
  - Keep track of computation graph
  - Keep track of worst-case ranges of limbs
  - Output polynomial relations to Sage
  - Use Sage to verify correctness of C code
Example: addition (radix $2^{25.5}$)

crypto_int32 f[10];
crypto_int32 g[10];
crypto_int32 h[10];

verifier_bigint vf;
verifier_addlimbs_10_255(&vf,f);
verifier_bigint vg;
verifier_addlimbs_10_255(&vg,g);

fe_add(h,f,g);

verifier_bigint vh;
verifier_addlimbs_10_255(&vh,h);
verifier_assertsum(&vh,&vf,&vg);
Example: multiplication

crypto_int32 f[10];
crypto_int32 g[10];
crypto_int32 h[10];

verifier_bigint vf;
verifier_addlimbs_10_255(&vf,f);
verifier_bigint vg;
verifier_addlimbs_10_255(&vg,g);

fe_mul(h,f,g);

verifier_bigint vh;
verifier_addlimbs_10_255(&vh,h);
verifier_assertprodmod(&vh,&vf,&vg,"2^255-19");
A small demo

- Consider computation of $x^{2^{100}}$ in $\mathbb{F}_{2^{127}-1}$
- Input is little-endian byte array
- Convert to internal representation in radix $2^{26}$
A small demo

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A small demo

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- Put a loop around it
A small demo

- Consider computation of $x^{2^{100}}$ in $\mathbb{F}_{2^{127} - 1}$
- Input is little-endian byte array
- Convert to internal representation in radix $2^{26}$
- Verify a single squaring
- Put a loop around it
- Still too slow for big chunks of code
  - Problem: verification always goes back to the beginning
  - Idea: Declare that we trust already verified results
  - This is known as “cutting” the verification
Let’s “cut some limbs”
Let’s call it a draw
First results and TODOs

Results

- Verification of modular multiplication in a few seconds
- Verification of full X25519 Montgomery ladder in \( \approx 1:10 \) minutes
- Translate to higher-level view (ECC arithmetic, inversion)

TODOs

- Support assembly
- Support “non-redundant” arithmetic
- Support ECC signatures
- Change interface
- Test, test, test
First results and TODOs

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TODOs

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Papers and Software

  https://cryptojedi.org/papers/#verify25519

- Many X25519 implementations in SUPERCOP
  (crypto_scalarmult/curve25519)
  http://bench.cr.yp.to/supercop.html

- Verification using boolector:
  https://cryptojedi.org/crypto/#verify25519

- Verification using Sage: http://gfverif.cryptojedi.org/