Cryptographic software engineering, part 1

Daniel J. Bernstein

This is easy, right?

1. Take general principles of software engineering.
2. Apply principles to crypto.

Let's try some examples . . .

1972 Parnas "On the criteria to be used in decomposing systems into modules":

"We propose instead that one begins with a list of difficult design decisions or design decisions which are likely to change. Each module is then designed to hide such a decision from the others."

e.g. If number of cipher rounds is properly modularized as

```
#define ROUNDS 20
```

then it is easy to change.

Another general principle
of software engineering:
Make the right thing simple
and the wrong thing complex.

Another general principle
of software engineering:
Make the right thing simple
and the wrong thing complex.

e.g. Make it difficult to
ignore invalid authenticators.

Another general principle
of software engineering:
Make the right thing simple
and the wrong thing complex.

e.g. Make it difficult to
ignore invalid authenticators.

Do not design APIs like this:
“The sample code used in
this manual omits the checking
of status values for clarity, but
when using cryptlib you should
check return values, particularly
for critical functions . . .”

Not so easy: Timing attacks

1970s: TENEX operating system
compares user-supplied string
against secret password
one character at a time,
stopping at first difference:

- `AAAAAA` vs. `FRIEND`: stop at 1.
- `FAAAAA` vs. `FRIEND`: stop at 2.
- `FRAAAA` vs. `FRIEND`: stop at 3.

Not so easy: Timing attacks

1970s: TENEX operating system
compares user-supplied string
against secret password
one character at a time,
stopping at first difference:

- `AAAAAA` vs. `FRIEND`: stop at 1.
- `FAAAAA` vs. `FRIEND`: stop at 2.
- `FRAAAA` vs. `FRIEND`: stop at 3.

Attacker sees comparison time,
deduces position of difference.
A few hundred tries
reveal secret password.

How typical software checks 16-byte authenticator:

```
for (i = 0;i < 16;++i)
  if (x[i] != y[i]) return 0;
return 1;
```

How typical software checks
16-byte authenticator:

```
for (i = 0;i < 16;++i)
  if (x[i] != y[i]) return 0;
return 1;
```

Fix, eliminating information flow
from secrets to timings:

```
diff = 0;
for (i = 0;i < 16;++i)
  diff |= x[i] ^ y[i];
return 1 & ((diff-1) >> 8);
```

Notice that the language
makes the wrong thing simple
and the right thing complex.

Language designer's notion of "right" is too weak for security.

So mistakes continue to happen.

Language designer's notion of "right" is too weak for security.

So mistakes continue to happen.

One of many examples,
part of the reference software for
CAESAR candidate CLOC:

```
/* compare the tag */
int i;
for(i = 0;i < CRYPTO_ABYTES;i++)
  if(tag[i] != c[(*mlen) + i]){
    return RETURN_TAG_NO_MATCH;
  }
return RETURN_SUCCESS;
```

Do timing attacks really work?

Objection: "Timings are noisy!"

Do timing attacks really work?

Objection: "Timings are noisy!"

Answer #1:

Does noise stop *all* attacks?

To guarantee security, defender must block *all* information flow.

Do timing attacks really work?

Objection: "Timings are noisy!"

Answer #1:
Does noise stop *all* attacks?
To guarantee security, defender must block *all* information flow.

Answer #2: Attacker uses statistics to eliminate noise.

Do timing attacks really work?

Objection: "Timings are noisy!"

Answer #1:
Does noise stop *all* attacks?
To guarantee security, defender
must block *all* information flow.

Answer #2: Attacker uses
statistics to eliminate noise.

Answer #3, what the
1970s attackers actually did:
Cross page boundary,
inducing page faults,
to amplify timing signal.

Defenders don't learn

Some of the literature:

1996 Kocher pointed out timing attacks on cryptographic key bits.

Briefly mentioned by Kocher and by 1998 Kelsey–Schneier–Wagner–Hall: secret array indices can affect timing via cache misses.

2002 Page, 2003 Tsunoo–Saito–Suzaki–Shigeri–Miyauchi: timing attacks on DES.

“Guaranteed” countermeasure:
load entire table into cache.

"Guaranteed" countermeasure:
load entire table into cache.

2004.11/2005.04 Bernstein:
Timing attacks on AES.
Countermeasure isn't safe;
e.g., secret array indices can affect
timing via cache-bank collisions.
What *is* safe: kill all data flow
from secrets to array indices.

"Guaranteed" countermeasure:
load entire table into cache.

2004.11/2005.04 Bernstein:
Timing attacks on AES.
Countermeasure isn't safe;
e.g., secret array indices can affect
timing via cache-bank collisions.
What *is* safe: kill all data flow
from secrets to array indices.

2005 Tromer–Osvik–Shamir:
65ms to steal Linux AES key
used for hard-disk encryption.

Intel recommends, and OpenSSL integrates, cheaper countermeasure: always loading from known *lines* of cache.

Intel recommends, and
OpenSSL integrates, cheaper
countermeasure: always loading
from known *lines* of cache.

2013 Bernstein–Schwabe
"A word of warning":
This countermeasure isn't safe.
Variable-time lab experiment.
Same issues described in 2004.

Intel recommends, and OpenSSL integrates, cheaper countermeasure: always loading from known *lines* of cache.

2013 Bernstein–Schwabe
"A word of warning":
This countermeasure isn't safe.
Variable-time lab experiment.
Same issues described in 2004.

2016 Yarom–Genkin–Heninger
"CacheBleed" steals RSA secret key via timings of OpenSSL.

2008 RFC 5246 “The Transport Layer Security (TLS) Protocol, Version 1.2”: “This leaves a small timing channel, since MAC performance depends to some extent on the size of the data fragment, but it is not believed to be large enough to be exploitable, due to the large block size of existing MACs and the small size of the timing signal.”

2008 RFC 5246 “The Transport Layer Security (TLS) Protocol, Version 1.2”: “This leaves a small timing channel, since MAC performance depends to some extent on the size of the data fragment, but it is not believed to be large enough to be exploitable, due to the large block size of existing MACs and the small size of the timing signal.”

2013 AlFardan–Paterson “Lucky Thirteen: breaking the TLS and DTLS record protocols”: exploit these timings; steal plaintext.

How to write constant-time code

If possible, write code in asm to control instruction selection.

Look for documentation identifying variability: e.g., "Division operations terminate when the divide operation completes, with the number of cycles required dependent on the values of the input operands."

Measure cycles rather than trusting CPU documentation.

Cut off all data flow from secrets to branch conditions.

Cut off all data flow from secrets to array indices.

Cut off all data flow from secrets to shift/rotate distances.

Prefer logic instructions.

Prefer vector instructions.

Watch out for CPUs with variable-time multipliers: e.g., Cortex-M3 and most PowerPCs.

Suppose we know (some) const-time machine instructions.

Suppose programming language has "`secret`" types.

Easy for compiler to guarantee that `secret` types are used only by const-time instructions.

Proofs of concept: Valgrind (uninitialized data as `secret`), ctgrind, ct-verif, FlowTracker.

Suppose we know (some) const-time machine instructions.

Suppose programming language has "`secret`" types.

Easy for compiler to guarantee that `secret` types are used only by const-time instructions.

Proofs of concept: Valgrind (uninitialized data as `secret`), ctgrind, ct-verif, FlowTracker.

How can we implement, e.g., sorting of a `secret` array?

Eliminating branches

Let's try sorting 2 integers.

Assume `int32` is `secret`.

Eliminating branches

Let's try sorting 2 integers.

Assume `int32` is `secret`.

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  if (x1 < x0) {
    x[0] = x1;
    x[1] = x0;
  }
}
```

Eliminating branches

Let's try sorting 2 integers.

Assume `int32` is `secret`.

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  if (x1 < x0) {
    x[0] = x1;
    x[1] = x0;
  }
}
```

Unacceptable: not constant-time.

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  if (x1 < x0) {
    x[0] = x1;
    x[1] = x0;
  } else {
    x[0] = x0;
    x[1] = x1;
  }
}
```

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  if (x1 < x0) {
    x[0] = x1;
    x[1] = x0;
  } else {
    x[0] = x0;
    x[1] = x1;
  }
}
```

Safe compiler won't allow this.

Branch timing leaks secrets.

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  int32 c = (x1 < x0);
  x[0] = (c ? x1 : x0);
  x[1] = (c ? x0 : x1);
}
```

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  int32 c = (x1 < x0);
  x[0] = (c ? x1 : x0);
  x[1] = (c ? x0 : x1);
}
```

Syntax is different but "?:"
is a branch by definition:

```
  if (x1 < x0) x[0] = x1;
  else x[0] = x0;
  if (x1 < x0) x[1] = x0;
  else x[1] = x1;
```

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  int32 c = (x1 < x0);
  x[c] = x0;
  x[1 - c] = x1;
}
```

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  int32 c = (x1 < x0);
  x[c] = x0;
  x[1 - c] = x1;
}
```

Safe compiler won't allow this:
won't allow `secret` data
to be used as an array index.

Cache timing is not constant:
see earlier attack examples.

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  int32 c = (x1 < x0);
  c *= x1 - x0;
  x[0] = x0 + c;
  x[1] = x1 - c;
}
```

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  int32 c = (x1 < x0);
  c *= x1 - x0;
  x[0] = x0 + c;
  x[1] = x1 - c;
}
```

Does safe compiler allow multiplication of secrets?

Recall that multiplication takes variable time on, e.g., Cortex-M3 and most PowerPCs.

Will want to handle this issue
for fast prime-field ECC etc.,
but let's dodge the issue
for this sorting code:

```
void sort2(int32 *x)
{ int32 x0 = x[0];
  int32 x1 = x[1];
  int32 c = -(x1 < x0);
  c &= x1 ^ x0;
  x[0] = x0 ^ c;
  x[1] = x1 ^ c;
}
```

1. Possible correctness problems (also for previous code):

C standard does not define `int32` as twos-complement; says "undefined" behavior on overflow.

Real CPU uses twos-complement but *C compiler can screw this up*.

1. Possible correctness problems (also for previous code):

C standard does not define `int32` as twos-complement; says "undefined" behavior on overflow.

Real CPU uses twos-complement but *C compiler can screw this up*.

Fix: use `gcc -fwrapv`.

1. Possible correctness problems (also for previous code):
C standard does not define `int32` as twos-complement; says "undefined" behavior on overflow.
Real CPU uses twos-complement but *C compiler can screw this up*.

Fix: use `gcc -fwrapv`.

2. Does safe compiler allow "`x1 < x0`" for secrets?
What do we do if it doesn't?

1. Possible correctness problems (also for previous code):
C standard does not define `int32` as twos-complement; says "undefined" behavior on overflow.
Real CPU uses twos-complement but *C compiler can screw this up*.

Fix: use `gcc -fwrapv`.

2. Does safe compiler allow "`x1 < x0`" for secrets?
What do we do if it doesn't?

C compilers *sometimes* use constant-time instructions for this.

Constant-time comparisons

```
int32 isnegative(int32 x)
{ return x >> 31; }
```

Returns -1 if `x` < 0, otherwise 0.

Constant-time comparisons

```
int32 isnegative(int32 x)
{ return x >> 31; }
```

Returns -1 if `x` < 0, otherwise 0.

Why this works: the bits $(b_{31}, b_{30}, \ldots, b_2, b_1, b_0)$ represent the integer $b_0 + 2b_1 + 4b_2 + \cdots + 2^{30}b_{30} - 2^{31}b_{31}$.

"1-bit signed right shift": $(b_{31}, b_{31}, \ldots, b_3, b_2, b_1)$.

"31-bit signed right shift": $(b_{31}, b_{31}, \ldots, b_{31}, b_{31}, b_{31})$.

```
int32 ispositive(int32 x)
{ return isnegative(-x); }
```

```
int32 ispositive(int32 x)
{ return isnegative(-x); }
```

This code is incorrect!
Fails for input -2^{31},
because "-x" produces -2^{31}.

```
int32 ispositive(int32 x)
{ return isnegative(-x); }
```

This code is incorrect!
Fails for input -2^{31},
because "-x" produces -2^{31}.

Can catch this bug by testing:

```
int64 x; int32 c;
for (x = INT32_MIN;
     x <= INT32_MAX;++x) {
  c = ispositive(x);
  assert(c == -(x > 0));
}
```

Side note illustrating `-fwrapv`:

```
int32 ispositive(int32 x)
{ if (x == -x) return 0;
  return isnegative(-x); }
```

Side note illustrating `-fwrapv`:

```
int32 ispositive(int32 x)
{ if (x == -x) return 0;
  return isnegative(-x); }
```

Not constant-time.

Side note illustrating `-fwrapv`:

```
int32 ispositive(int32 x)
{ if (x == -x) return 0;
  return isnegative(-x); }
```

Not constant-time.

Even worse: without `-fwrapv`, current `gcc` can remove the `x == -x` test, breaking this code.

Side note illustrating `-fwrapv`:

```
int32 ispositive(int32 x)
{ if (x == -x) return 0;
  return isnegative(-x); }
```

Not constant-time.

Even worse: without `-fwrapv`, current `gcc` can remove the `x == -x` test, breaking this code.

Incompetent `gcc` engineering: source of many security holes. Incompetent language standard.

```
int32 isnonzero(int32 x)
{ return isnegative(x)
  || isnegative(-x); }
```

```
int32 isnonzero(int32 x)
{ return isnegative(x)
  || isnegative(-x); }
```

Not constant-time.

Second part is evaluated
only if first part is zero.

```
int32 isnonzero(int32 x)
{ return isnegative(x)
  || isnegative(-x); }
```

Not constant-time.

Second part is evaluated
only if first part is zero.

```
int32 isnonzero(int32 x)
{ return isnegative(x)
  | isnegative(-x); }
```

Constant-time logic instructions.

Safe compiler will allow this.

```
int32 issmaller(int32 x,int32 y)
{ return isnegative(x - y); }
```

```
int32 issmaller(int32 x,int32 y)
{ return isnegative(x - y); }
```

This code is incorrect!

Generalization of `ispositive`.

Wrong for inputs $(0, -2^{31})$.

```
int32 issmaller(int32 x,int32 y)
{ return isnegative(x - y); }
```

This code is incorrect!

Generalization of `ispositive`.

Wrong for inputs $(0, -2^{31})$.

Wrong for many more inputs.

Caught quickly by random tests:

```
for (j = 0;j < 10000000;++j) {
  x += random(); y += random();
  c = issmaller(x,y);
  assert(c == -(x < y));
}
```

```
int32 issmaller(int32 x,int32 y)
{ int32 xy = x ^ y;
  int32 c = x - y;
  c ^= xy & (c ^ x);
  return isnegative(c);
}
```

```
int32 issmaller(int32 x,int32 y)
{ int32 xy = x ^ y;
  int32 c = x - y;
  c ^= xy & (c ^ x);
  return isnegative(c);
}
```

Some verification strategies:

- Think this through.
- Write a proof.
- Formally verify proof.
- Automate proof construction.
- Test many random inputs.
- A bit painful: test all inputs.
- Faster: test `int16` version.

```
void minmax(int32 *x,int32 *y)
{ int32 a = *x;
  int32 b = *y;
  int32 ab = b ^ a;
  int32 c = b - a;
  c ^= ab & (c ^ b);
  c >>= 31;
  c &= ab;
  *x = a ^ c;
  *y = b ^ c;
}

void sort2(int32 *x)
{ minmax(x,x + 1); }
```

```
int32 ispositive(int32 x)
{ int32 c = -x;
  c ^= x & c;
  return isnegative(c);
}

void sort(int32 *x,long long n)
{ long long i,j;
  for (j = 0;j < n;++j)
    for (i = j - 1;i >= 0;--i)
      minmax(x + i,x + i + 1);
}
```

Safe compiler will allow this
if array length `n` is not `secret`.

Software optimization

Almost all software is
much slower than it could be.

Software optimization

Almost all software is
much slower than it could be.

Is software applied to much data?
Usually not. Usually the
wasted CPU time is negligible.

Software optimization

Almost all software is
much slower than it could be.

Is software applied to much data?
Usually not. Usually the
wasted CPU time is negligible.

But *crypto software* should be
applied to all communication.

Crypto that's too slow $\Rightarrow$
fewer users $\Rightarrow$ fewer cryptanalysts
$\Rightarrow$ less attractive for everybody.

Typical situation:

X is a cryptographic system.

You have written a (const-time) reference implementation of X.

You want (const-time) software that computes X as efficiently as possible.

You have chosen a target CPU. (Can repeat for other CPUs.)

You measure performance of the implementation. Now what?

A simplified example

Target CPU: TI LM4F120H5QR microcontroller containing one ARM Cortex-M4F core.

Reference implementation:

```
int sum(int *x)
{
  int result = 0;
  int i;
  for (i = 0;i < 1000;++i)
    result += x[i];
  return result;
}
```

Counting cycles:

```
static volatile unsigned int
  *const DWT_CYCCNT
  = (void *) 0xE0001004;
...

int beforesum = *DWT_CYCCNT;
int result = sum(x);
int aftersum = *DWT_CYCCNT;
UARTprintf("sum %d %d\n",
  result,aftersum-beforesum);
```

Output shows 8012 cycles.

Change 1000 to 500: 4012.

“Okay, 8 cycles per addition.
Um, are microcontrollers
really this slow at addition?”

“Okay, 8 cycles per addition.
Um, are microcontrollers
really this slow at addition?”

Bad practice:
Apply random “optimizations”
(and tweak compiler options)
until you get bored.
Keep the fastest results.

“Okay, 8 cycles per addition.
Um, are microcontrollers
really this slow at addition?”

Bad practice:
Apply random “optimizations”
(and tweak compiler options)
until you get bored.
Keep the fastest results.

Good practice:
Figure out lower bound for
cycles spent on arithmetic etc.
Understand gap between
lower bound and observed time.

Find "ARM Cortex-M4 Processor Technical Reference Manual".

Rely on Wikipedia comment that M4F = M4 + floating-point unit.

Find "ARM Cortex-M4 Processor Technical Reference Manual".

Rely on Wikipedia comment that M4F = M4 + floating-point unit.

Manual says that Cortex-M4 "implements the ARMv7E-M architecture profile".

Find "ARM Cortex-M4 Processor Technical Reference Manual".
Rely on Wikipedia comment that M4F = M4 + floating-point unit.

Manual says that Cortex-M4 "implements the ARMv7E-M architecture profile".

Points to the "ARMv7-M Architecture Reference Manual", which defines instructions:
e.g., "ADD" for 32-bit addition.

First manual says that
ADD takes just 1 cycle.

Inputs and output of ADD are "integer registers". ARMv7-M has 16 integer registers, including special-purpose "stack pointer" and "program counter".

Inputs and output of ADD are "integer registers". ARMv7-M has 16 integer registers, including special-purpose "stack pointer" and "program counter".

Each element of `x` array needs to be "loaded" into a register.

Inputs and output of ADD are "integer registers". ARMv7-M has 16 integer registers, including special-purpose "stack pointer" and "program counter".

Each element of `x` array needs to be "loaded" into a register.

Basic load instruction: LDR.
Manual says 2 cycles but adds a note about "pipelining".
Then more explanation: if next instruction is also LDR (with address not based on first LDR) then it saves 1 cycle.

n consecutive LDRs
takes only $n + 1$ cycles
("more multiple LDRs can be
pipelined together").

Can achieve this speed
in other ways (LDRD, LDM)
but nothing seems faster.

Lower bound for n LDR + n ADD:
$2n + 1$ cycles,
including n cycles of arithmetic.

Why observed time is higher:
non-consecutive LDRs;
costs of manipulating `i`.

```
int sum(int *x)
{
  int result = 0;
  int *y = x + 1000;
  int x0,x1,x2,x3,x4,
      x5,x6,x7,x8,x9;

  while (x != y) {
    x0 = 0[(volatile int *)x];
    x1 = 1[(volatile int *)x];
    x2 = 2[(volatile int *)x];
    x3 = 3[(volatile int *)x];
    x4 = 4[(volatile int *)x];
    x5 = 5[(volatile int *)x];
    x6 = 6[(volatile int *)x];
```

```
x7 = 7[(volatile int *)x];
x8 = 8[(volatile int *)x];
x9 = 9[(volatile int *)x];
result += x0;
result += x1;
result += x2;
result += x3;
result += x4;
result += x5;
result += x6;
result += x7;
result += x8;
result += x9;
x0 = 10[(volatile int *)x];
x1 = 11[(volatile int *)x];
```

```
x2 = 12[(volatile int *)x];
x3 = 13[(volatile int *)x];
x4 = 14[(volatile int *)x];
x5 = 15[(volatile int *)x];
x6 = 16[(volatile int *)x];
x7 = 17[(volatile int *)x];
x8 = 18[(volatile int *)x];
x9 = 19[(volatile int *)x];
x += 20;
result += x0;
result += x1;
result += x2;
result += x3;
result += x4;
result += x5;
```

```
    result += x6;
    result += x7;
    result += x8;
    result += x9;
  }

  return result;
}
```

```
    result += x6;
    result += x7;
    result += x8;
    result += x9;
  }

  return result;
}
```

2526 cycles. Even better in asm.

```
    result += x6;
    result += x7;
    result += x8;
    result += x9;
  }

  return result;
}
```

2526 cycles. Even better in asm.

Wikipedia: "By the late 1990s for even performance sensitive code, optimizing compilers exceeded the performance of human experts."

```
    result += x6;
    result += x7;
    result += x8;
    result += x9;
  }

  return result;
}
```

2526 cycles. Even better in asm.

Wikipedia: "By the late 1990s for even performance sensitive code, optimizing compilers exceeded the performance of human experts."
— [citation needed]