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 . . .

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"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."

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diff = 0;
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  diff |= x[i] ^ y[i];
return 1 & ((diff-1) >> 8);
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Notice that the language makes the wrong thing simple and the right thing complex.

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/* compare the tag */
int i;
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Branch timing leaks secrets.

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

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  int32
  x[c] =
  x[1 -
}
```

```
*x)
];
];
```

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ks 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);
}
```

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
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  int32 c = (x1
  x[c] = x0;
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}
```

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.

```
rt2(int32 *x)
 x0 = x[0];
 x1 = x[1];
 c = (x1 < x0);
= (c ? x1 : x0);
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  c *= x1 - x0;
  x[0] = x0 + c;
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Does safe compiler allow multiplication of secrets?

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

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

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int64 x; int32 c;
for (x = INT32_MIN;
     x <= INT32_MAX;++x) {
  c = ispositive(x);
  assert(c == -(x > 0));
}
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int64 x; int32 c;
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  assert(c == -(x > 0));
}
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Wrong for inputs $(0, -2^{31})$.

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Caught quickly by random tests:

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

```
ssmaller(int32 x,int32 y)
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quickly by random tests:

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= 0;j < 10000000;++j) {
random(); y += random();
ssmaller(x,y);
t(c == -(x < y));
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  c &= a
  *x = a
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void so
{ minma
```

```
int32 x,int32 y)
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void minmax(int3
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  int32 b = *y;
  int32 ab = b ^
  int32 c = b -
  c ^= ab & (c ^
  c >>= 31;
  c &= ab;
  *x = a ^ c;
  *y = b ^ c;
}

void sort2(int32
{ minmax(x,x + 1
```

```
nt32 y)
); }
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+j) {
dom();
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int32 issmaller(int32 x,int32 y)
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void so
{ long l
  for (
    for
      mi
}
```

Safe con
if array l

```
int32 x,int32 y)
 y;
y;
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int32 ispositive
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  return isnegat
}

void sort(int32
{ long long i,j;
  for (j = 0;j <
    for (i = j -
      minmax(x +
}
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Safe compiler will
if array length `n` is

nt32 y)

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}

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

Safe compiler will allow this
if array length n is not secr

```
void minmax(int32 *x,int32 *y)
{ int32 a = *x;
  int32 b = *y;
  int32 ab = b ^ a;
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  c ^= ab & (c ^ b);
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int32 ispositive(int32 x)
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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.

```
nmax(int32 *x,int32 *y)
 a = *x;
 b = *y;
 ab = b ^ a;
 c = b - a;
ab & (c ^ b);
 31;
ab;
a ^ c;
b ^ c;


rt2(int32 *x)
x(x,x + 1); }
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Software

Almost a
much slo

```
2 *x,int32 *y)
 a;
a;
 b);
 *x)
); }
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Safe compiler will allow this
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Software optimiza

Almost all softwar
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2 *y)
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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.

```
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.

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 ⇒ fewer users ⇒ fewer cryptanalysts ⇒ less attractive for everybody.

```
spositive(int32 x)

 c = -x;
x & c;
n isnegative(c);


rt(int32 *x,long long n)
long i,j;
j = 0;j < n;++j)
 (i = j - 1;i >= 0;--i)
inmax(x + i,x + i + 1);
```

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{
  int result = 0
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}
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A simplified example

Target CPU: TI LM4F120H5 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;
}
```

Typical situation:

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A simplified example

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Reference implementation:

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}
```

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```

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```

Counting cycles:

```
static volatile
  *const DWT_CYC
  = (void *) 0xE
...

int beforesum =
int result = sum
int aftersum = *
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  int i;
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    result += x[i];
  return result;
}
```


Counting cycles:

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

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

Output shows 8012 cycles.

Change 1000 to 500: 4012.

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Can achieve this speed in other ways (LDRD, LDM)
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Lower bound for n LDR + n
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Why observed time is higher
non-consecutive LDRs;
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```
int sum
{
  int r
  int *
  int x
      x
      
  while
    x0 
    x1 
    x2 
    x3 
    x4 
    x5 
    x6 
```

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int sum(int *x)
{
  int result = 0
  int *y = x + 1
  int x0,x1,x2,x
      x5,x6,x7,x

  while (x != y)
    x0 = 0[(vola
    x1 = 1[(vola
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    x3 = 3[(vola
    x4 = 4[(vola
    x5 = 5[(vola
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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
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    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];
```

cutive LDRs
ly $n+1$ cycles
multiple LDRs can be
d together").

ieve this speed
 ways (LDRD, LDM)
ning seems faster.

ound for n LDR $+$ n ADD:
cycles,
g n cycles of arithmetic.

served time is higher:
secutive LDRs;
 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 =
x8 =
x9 =
resu
resu
resu
resu
resu
resu
resu
resu
resu
resu
x0 =
x1 =
```

Rs
ycles
DRs can be
").

peed
RD, LDM)
; faster.

n LDR + n ADD:

of arithmetic.

e is higher:
DRs;
ting i.


```
int sum(int *x)
{
  int result = 0;
  int *y = x + 1000;
  int x0,x1,x2,x3,x4,
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  while (x != y) {
    x0 = 0[(volatile int *)x];
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    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[(vola
x8 = 8[(vola
x9 = 9[(vola
result += x0
result += x1
result += x2
result += x3
result += x4
result += x5
result += x6
result += x7
result += x8
result += x9
x0 = 10[(vol
x1 = 11[(vol
```

pe

)

ADD:

etic.

r:


```
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
    x8 = 8[(volatile int
    x9 = 9[(volatile int
    result += x0;
    result += x1;
    result += x2;
    result += x3;
    result += x4;
    result += x5;
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    x0 = 10[(volatile int
    x1 = 11[(volatile int
```

```
int sum(int *x)
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  int result = 0;
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      x5,x6,x7,x8,x9;

  while (x != y) {
    x0 = 0[(volatile int *)x];
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    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];
```

```
(int *x)

esult = 0;
y = x + 1000;
0,x1,x2,x3,x4,
5,x6,x7,x8,x9;

 (x != y) {
= 0[(volatile int *)x];
= 1[(volatile int *)x];
= 2[(volatile int *)x];
= 3[(volatile int *)x];
= 4[(volatile int *)x];
= 5[(volatile int *)x];
= 6[(volatile int *)x];
```



```
x7 = 7[(volatile int *)x];
x8 = 8[(volatile int *)x];
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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 =
x3 =
x4 =
x5 =
x6 =
x7 =
x8 =
x9 =
x +=
resu
resu
resu
resu
resu
resu
```

```
;
000;
3,x4,
8,x9;

 {
tile int *)x];
tile int *)x];
tile int *)x];
tile int *)x];
tile int *)x];
tile int *)x];
tile int *)x];
```



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

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

```
*)x];
*)x];
*)x];
*)x];
*)x];
*)x];
```



```
x7 = 7[(volatile int *)x];
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result += x0;
result += x1;
result += x2;
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result += x4;
result += x5;
result += x6;
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x0 = 10[(volatile int *)x];
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x0 = 10[(volatile int *)x];
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x2 = 12[(volatile int *)x];
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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;
```

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



```
x2 = 12[(volatile int *)x];
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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;
```

```
    resu
    resu
    resu
    resu
  }

  returr
}
```

```
tile int *)x];
tile int *)x];
tile int *)x];
;
;
;
;
;
;
;
;
;
;
atile int *)x];
atile int *)x];
```



```
x2 = 12[(volatile int *)x];
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```

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

  return result;
}
```

```
*)x];
*)x];
*)x];
. *)x];
. *)x];
```



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      x2 = 12[(volatile int *)x];
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```



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

  return result;
}
```

2526 cycles. Even better in asm.

```
x2 = 12[(volatile int *)x];
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x += 20;
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    result += x6;
    result += x7;
    result += x8;
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Wikipedia: "By the late 1990s for even performance sensitive code, optimizing compilers exceeded the performance of human experts."

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      result += x6;
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    }

  return result;
}
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2526 cycles. Even better in asm.

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— [citation needed]