Can cryptographic software be fixed?

D. J. Bernstein

Bob's laptop screen:

```
From: Alice


Thank you for your
submission. We received
many interesting papers,
and unfortunately your
```

Bob assumes this message is something Alice actually sent.

But today's "security" systems fail to guarantee this property. Attacker could have modified or forged the message.

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Critical vulnerabilities fixed in 61: CVE-2018-12359, “Buffer overflow using computed size of canvas element”; CVE-2018-12360, “Use-after-free when using focus()”; CVE-2018-12361, “Integer overflow in SwizzleData”.

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Security policy for this talk:
If message is displayed on Bob's screen as "`From: Alice`" then message is from Alice.

If TCB works correctly, then message is guaranteed to be from Alice, no matter what the rest of the system does.

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Massive TCB has many bugs, including many security holes.
Any hope of fixing this?

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VM A
Alice data

VM C
Charlie data

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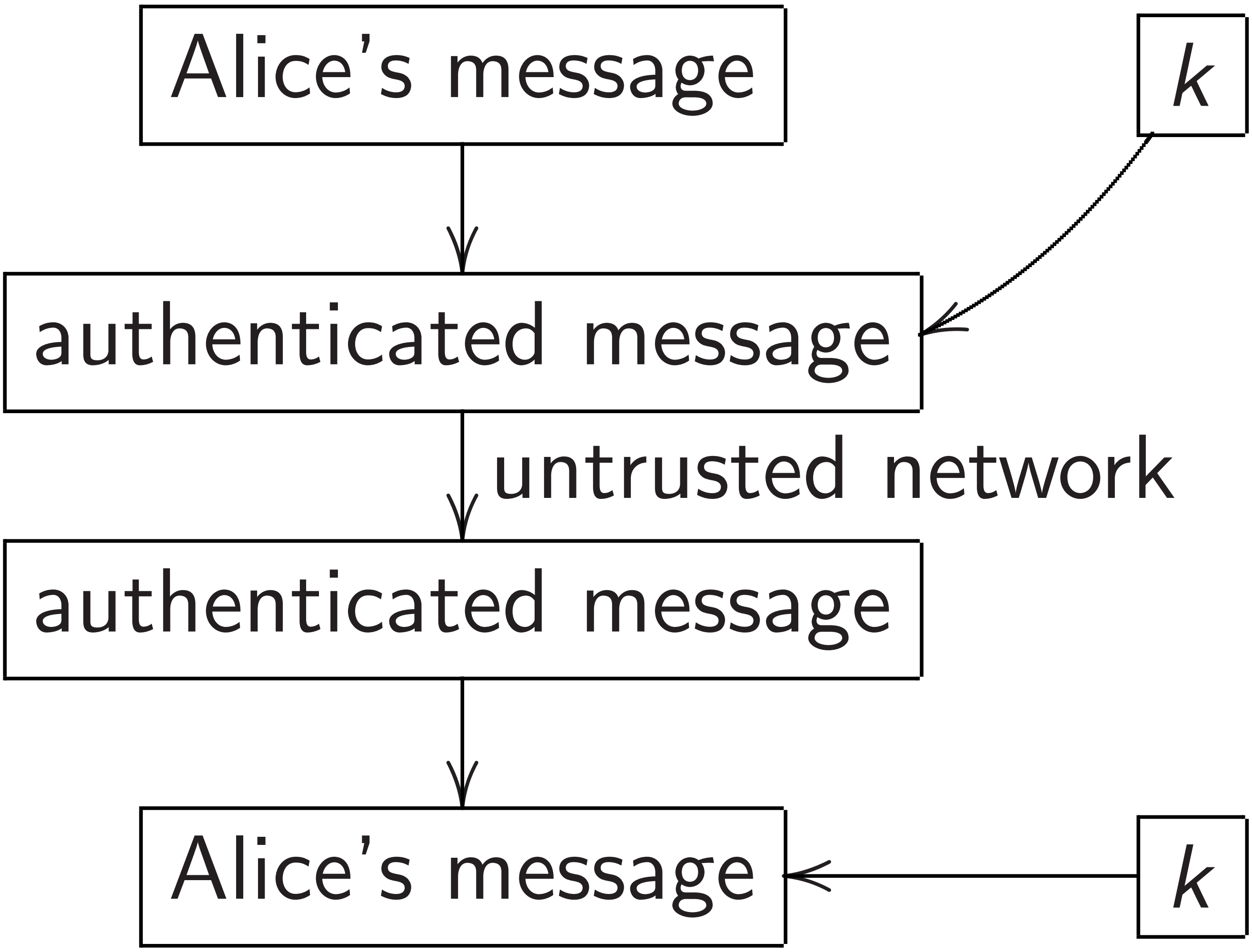
Alice also runs many VMs.

Focus of this talk: Cryptography

How does Bob's laptop know that incoming network data is from Alice's laptop?

Cryptographic solution: Message-authentication codes.



Alice's message

k

authenticated message

untrusted network

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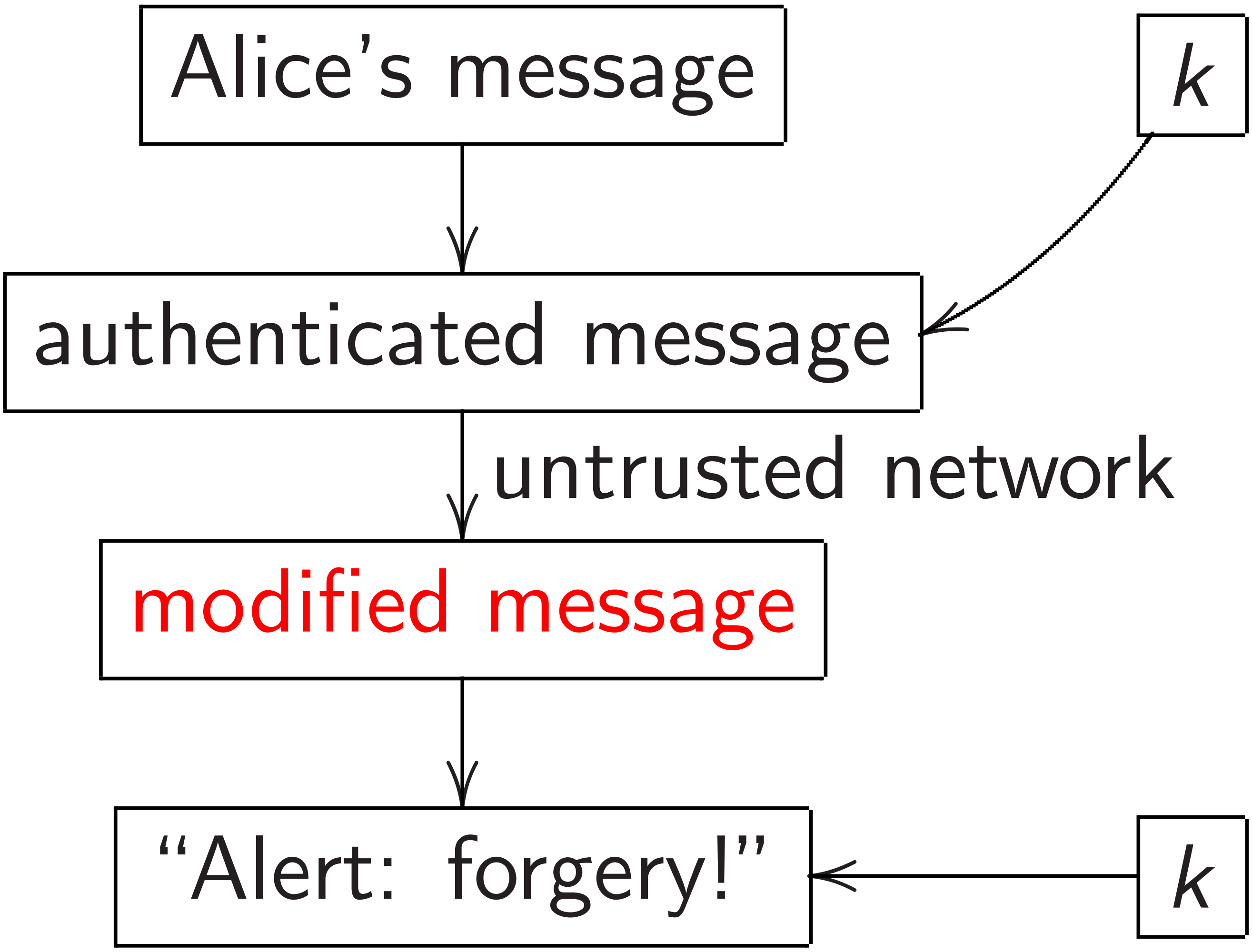

Alice's message

k

authenticated message

untrusted network

modified message

"Alert: forgery!"

k

Important for Alice and Bob to share the same secret k.

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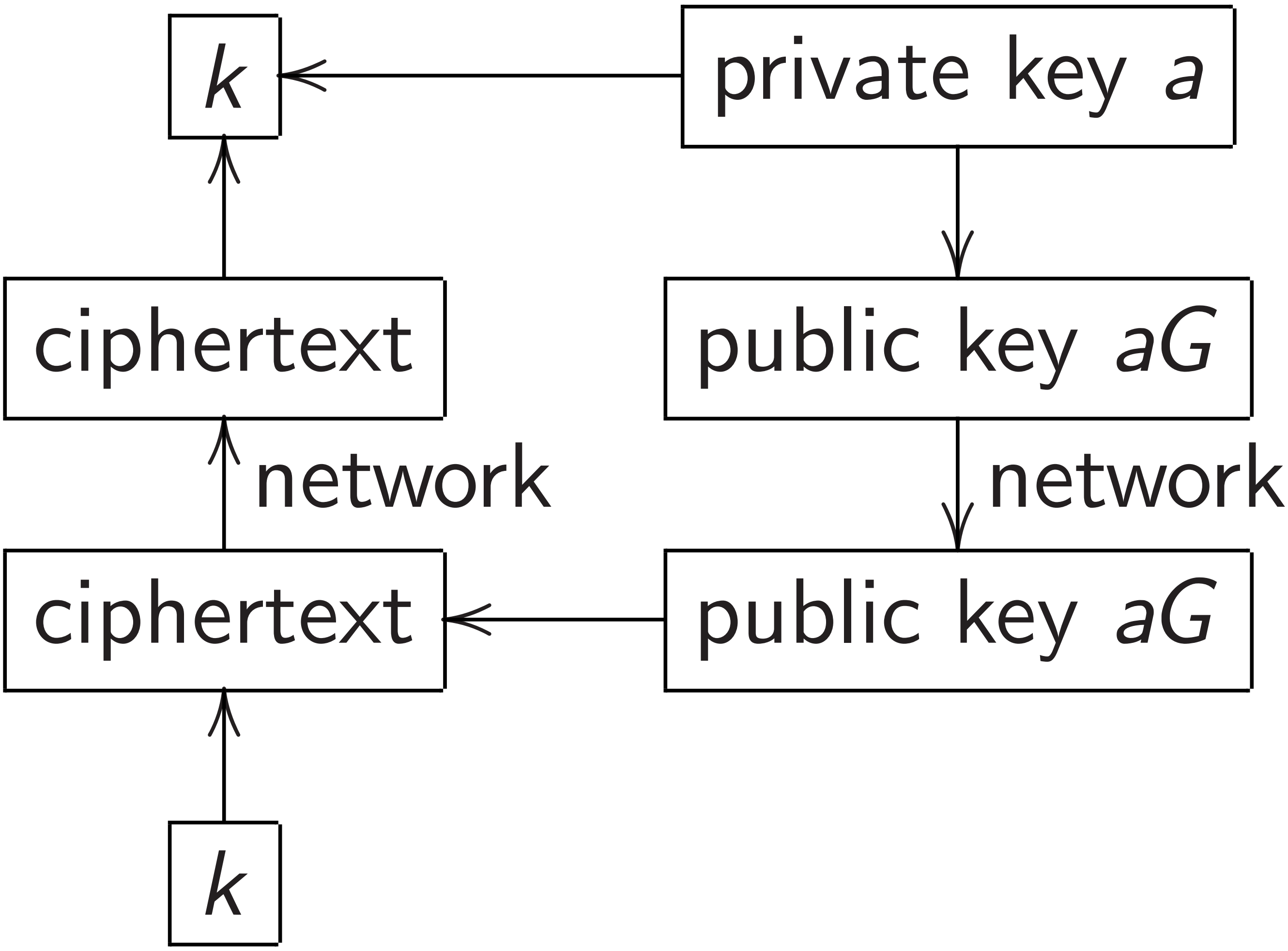
Solution 1:
Public-key encryption.



k

private key a

ciphertext

public key aG

network

network

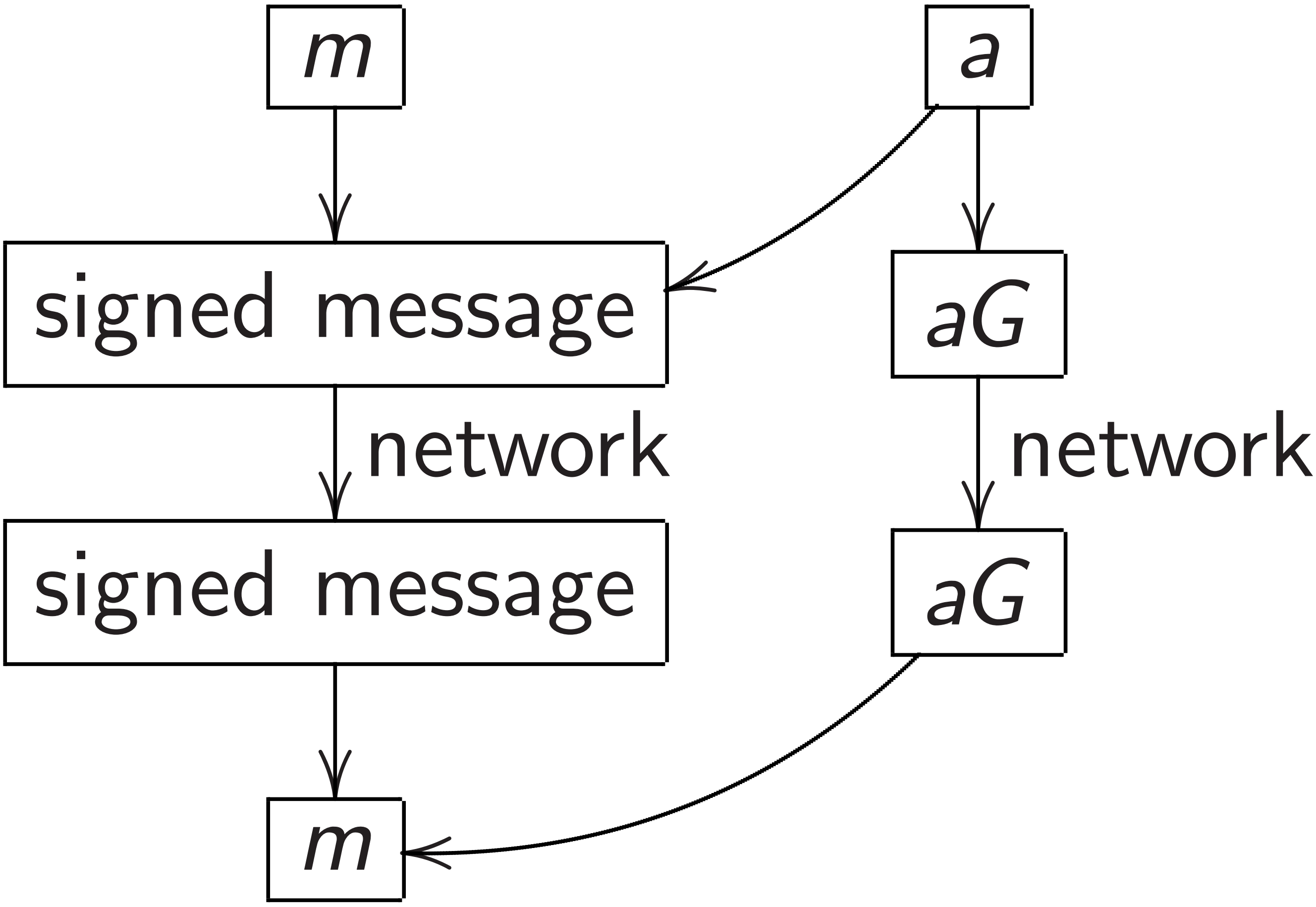
ciphertext

public key aG

k

Solution 2:

Public-key signatures.



m

a

signed message

aG

network

signed message

network

aG

m

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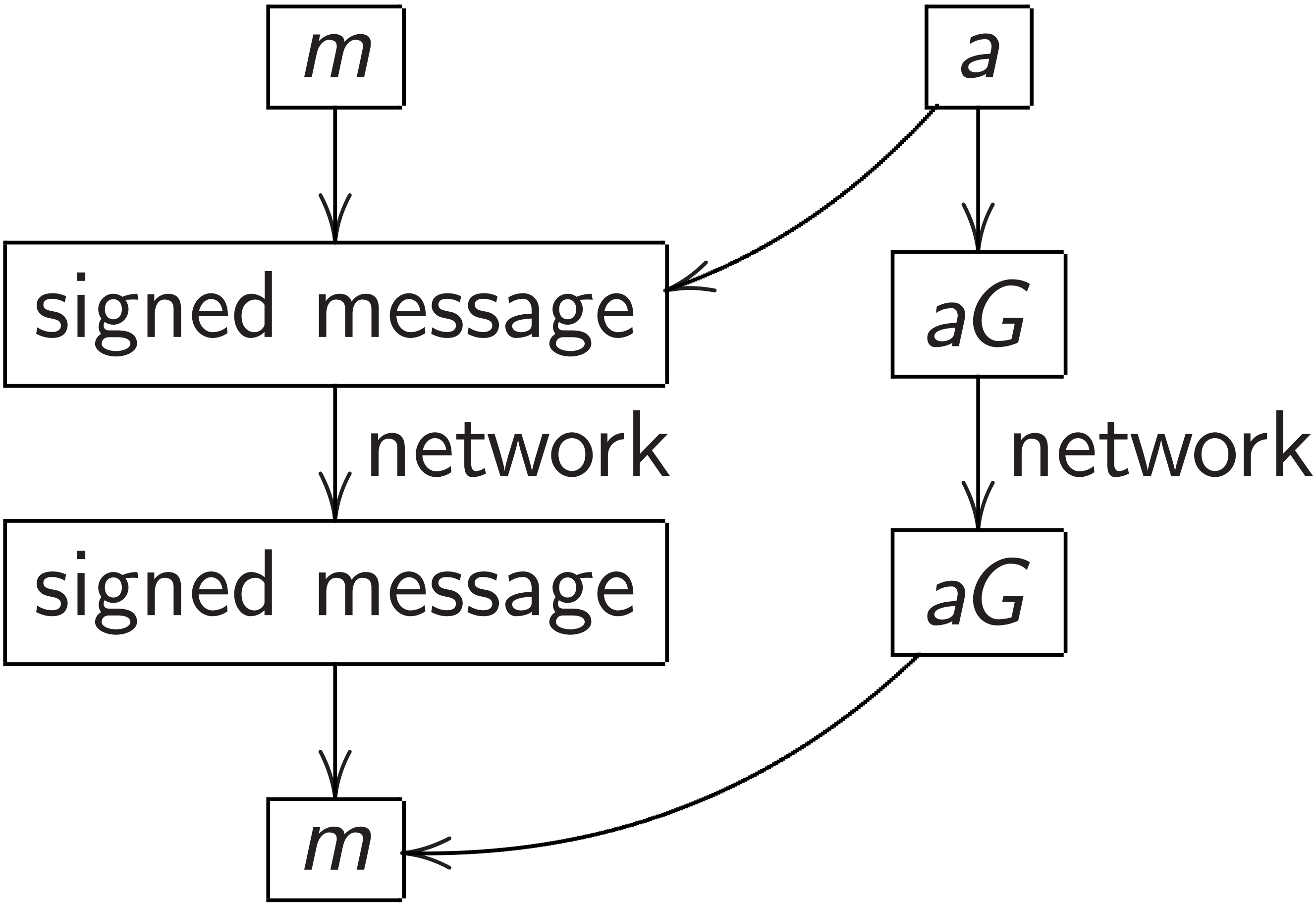

Fantasy world: software for authentication/encryption/sigs is small and carefully audited ⇒ no cryptographic security failures.

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August 2018: Google switches from Speck to ChaCha12, again using hand-written assembly. Why not ChaCha20? Speed.

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Another example: many different primitives in NIST competition for post-quantum public-key cryptography. (See next talk.)

Some overlap in implementations, but still huge volume of code.

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Many security failures from variable-time computations: e.g. CVE-2018-0495, CVE-2018-0737, CVE-2018-5407 in OpenSSL.

Timing attacks

Large portion of CPU hardware:
optimizations depending on
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Many attacks (e.g. TLBleed from 2018 Gras–Razavi–Bos–Giuffrida) show that this portion of the CPU has trouble keeping secrets.

Typical literature on this topic:

Understand this portion of CPU.
But details are often proprietary,
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Try to push attacks further.
This becomes very complicated.

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For researchers: This is great!

For auditors: This is a nightmare.
Many years of security failures.
No confidence in future security.

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Good match for attitude and
experience of CPU designers: e.g.,
Intel issues errata for correctness
bugs, not for information leaks.

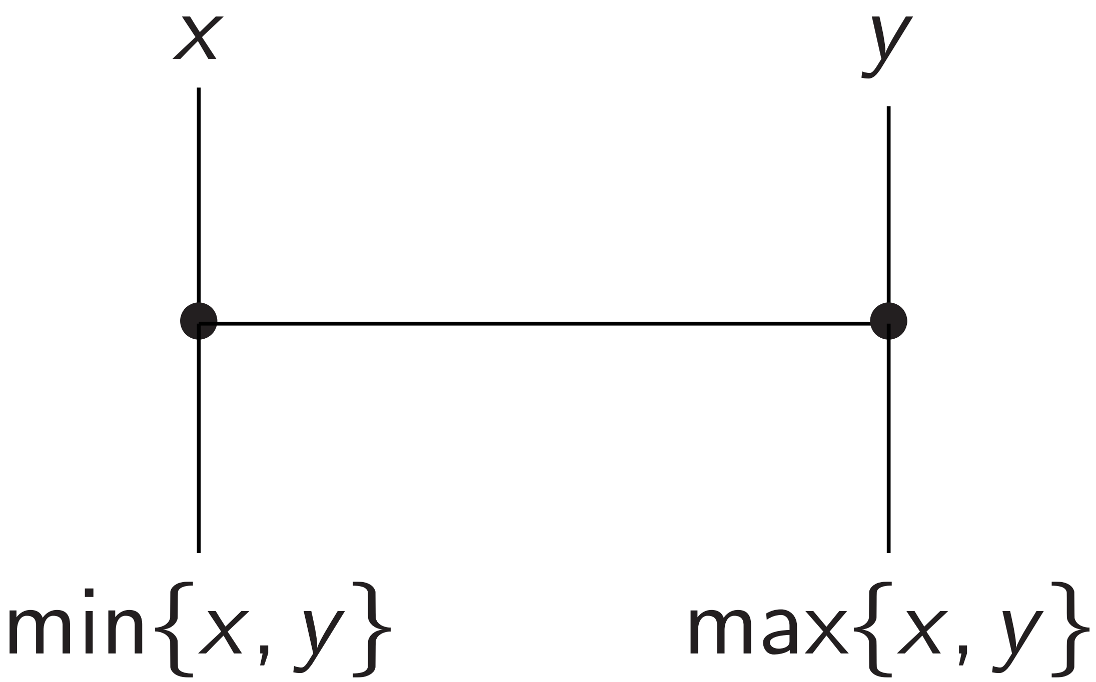
Case study: Constant-time sorting

Subroutine in (e.g.) BIG QUAKE, Classic McEliece, GeMSS, Gravity-SPHINCS, LEDAkem, LEDApkc, NTRU Prime, Round2: sort array of secret integers. e.g. sort 768 32-bit integers.

Typical sorting algorithms— merge sort, quicksort, etc.— choose load/store addresses based on secret data. Usually also branch based on secret data.

How to sort secret data without any secret addresses?

Foundation of solution:
a **comparator** sorting 2 integers.

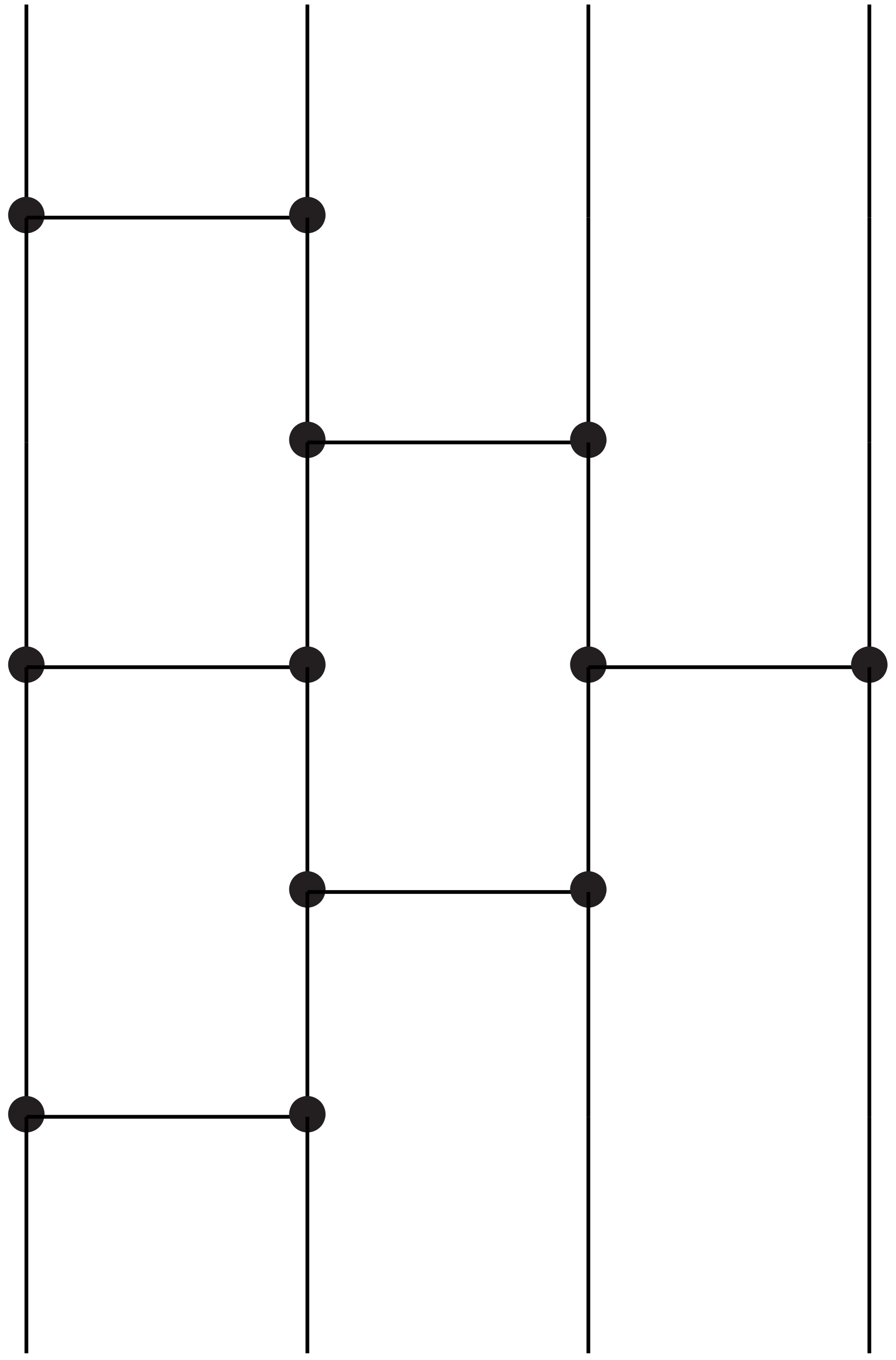


Easy constant-time exercise in C.
Warning: C standard allows
compiler to break the solution.

Even easier exercise in asm.

Combine comparators into a **sorting network** for more inputs.

Example of a sorting network:



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$(n^2 - n)/2$ comparators in bubble sort produce complaints about performance as n increases.

```
void int32_sort(int32 *x,int64 n)
{ int64 t,p,q,i;
  if (n < 2) return;
  t = 1;
  while (t < n - t) t += t;
  for (p = t;p > 0;p >>= 1) {
    for (i = 0;i < n - p;++i)
      if (!(i & p))
        minmax(x+i,x+i+p);
    for (q = t;q > p;q >>= 1)
      for (i = 0;i < n - q;++i)
        if (!(i & p))
          minmax(x+i+p,x+i+q);
  }
}
```

Previous slide: C translation of 1973 Knuth “merge exchange”, which is a simplified version of 1968 Batcher “odd-even merge” sorting networks.

$\approx n(\log_2 n)^2/4$ comparators.
Much faster than bubble sort.

Warning: many other descriptions of Batcher’s sorting networks require n to be a power of 2.
Also, Wikipedia says “Sorting networks . . . are not capable of handling arbitrarily large inputs.”

This constant-time sorting code

vectorization
(for Haswell)

Constant-time sorting code
included in 2017
Bernstein–Chuengsatiansup–
Lange–van Vredendaal
“NTRU Prime” software release

revamped for
higher speed

New: “djbsort”
constant-time sorting code

The slowdown for constant time

Massive fast-sorting literature.
Includes several efforts to optimize sorting using AVX2 instructions on modern Intel CPUs: e.g. 2015 Gueron–Krasnov quicksort.

Haswell (`titan0`) cycles, $n = 768$:
25608 `stdsort`
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No slowdown. New speed records!

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Loading a 32-bit integer from a random address: much slower.

Conditional branch: much slower.

Verification

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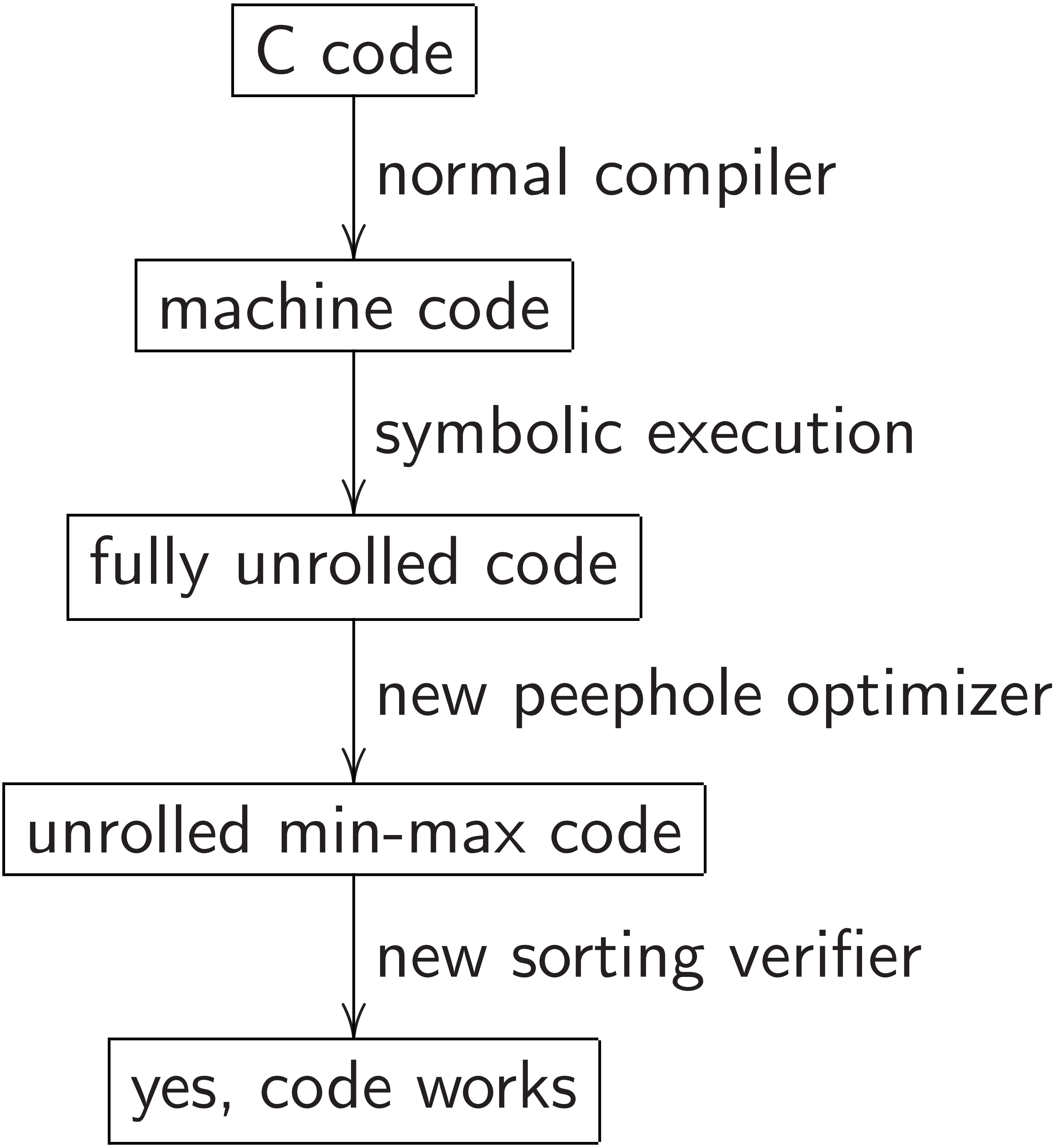
Test the sorting software on many random inputs, increasing inputs, decreasing inputs. Seems to work.

But are there *occasional* inputs where this sorting software fails to sort correctly?

History: Many security problems involve occasional inputs where TCB works incorrectly.

For each used n (e.g., 768):



C code

normal compiler

machine code

symbolic execution

fully unrolled code

new peephole optimizer

unrolled min-max code

new sorting verifier

yes, code works

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Sorting verifier: decompose
DAG into merging networks.
Verify each merging network
using generalization of 2007
Even–Levi–Litman, correction of
1990 Chung–Ravikumar.

Current djbsort release,
verified AVX2 code and
verified portable code:

`https://sorting.cr.yp.to`

Includes the sorting code;
automatic build-time tests;
simple benchmarking program;
verification tools.

Web site shows how to
use the verification tools.

Next release planned:
verified ARM NEON code.

The future

I don't think there is a fundamental tension between
- crypto performance,
- stopping timing attacks,
- making sure software works.

See the sorting example.

Firefox has already deployed verified constant-time software for Curve25519+ChaCha20+Poly1305.

I'm working on easier verification, post-quantum code, faster code.