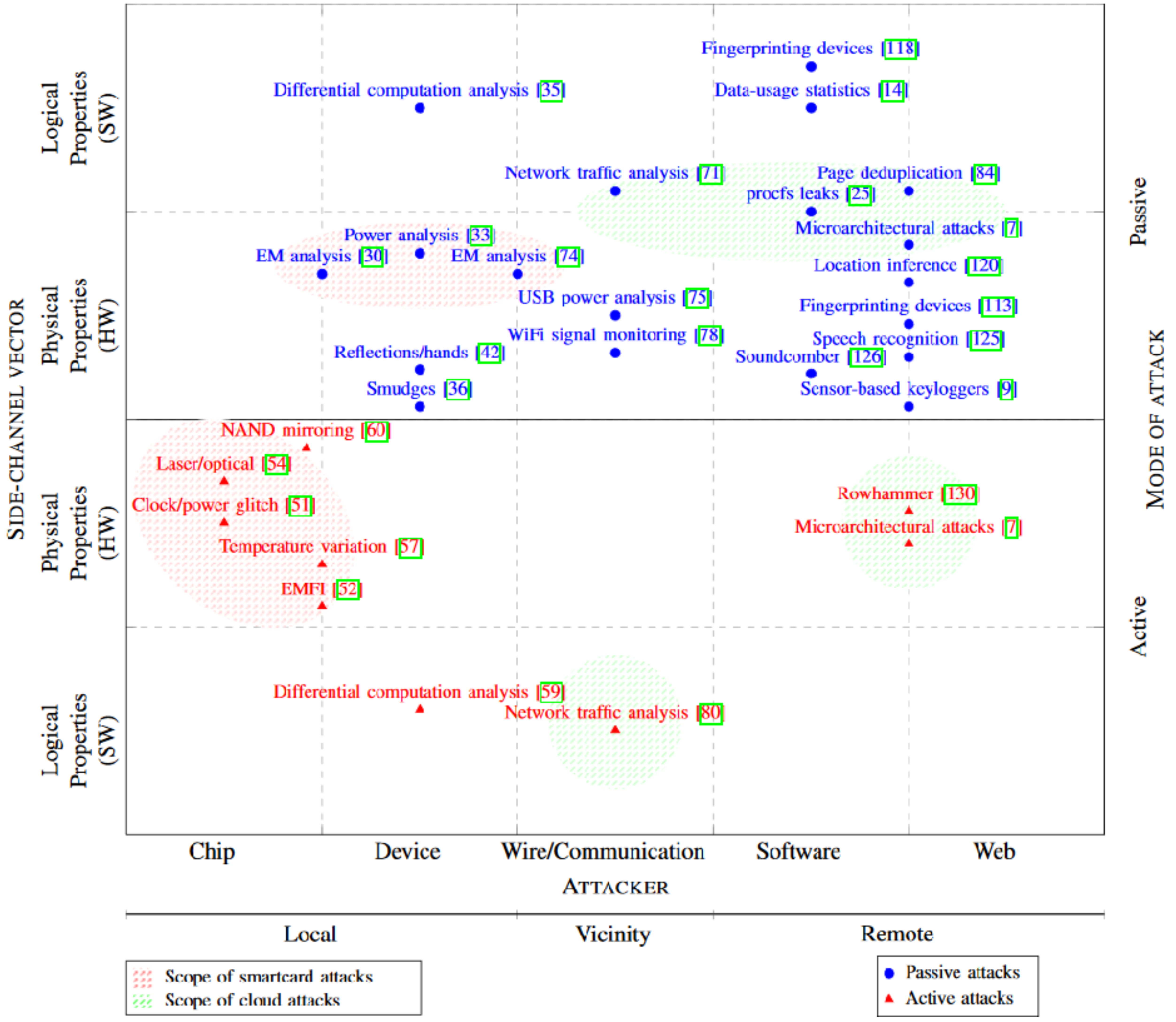
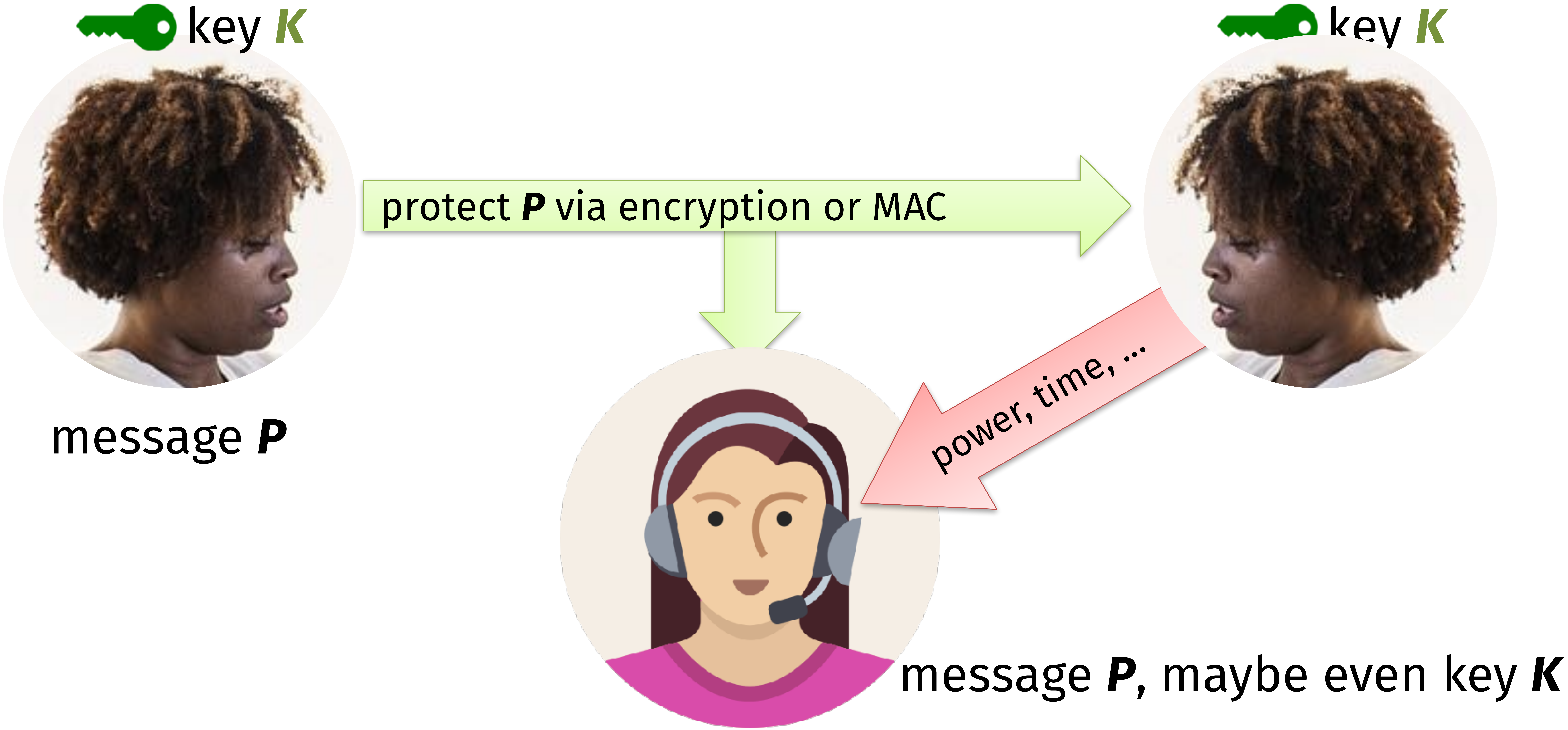
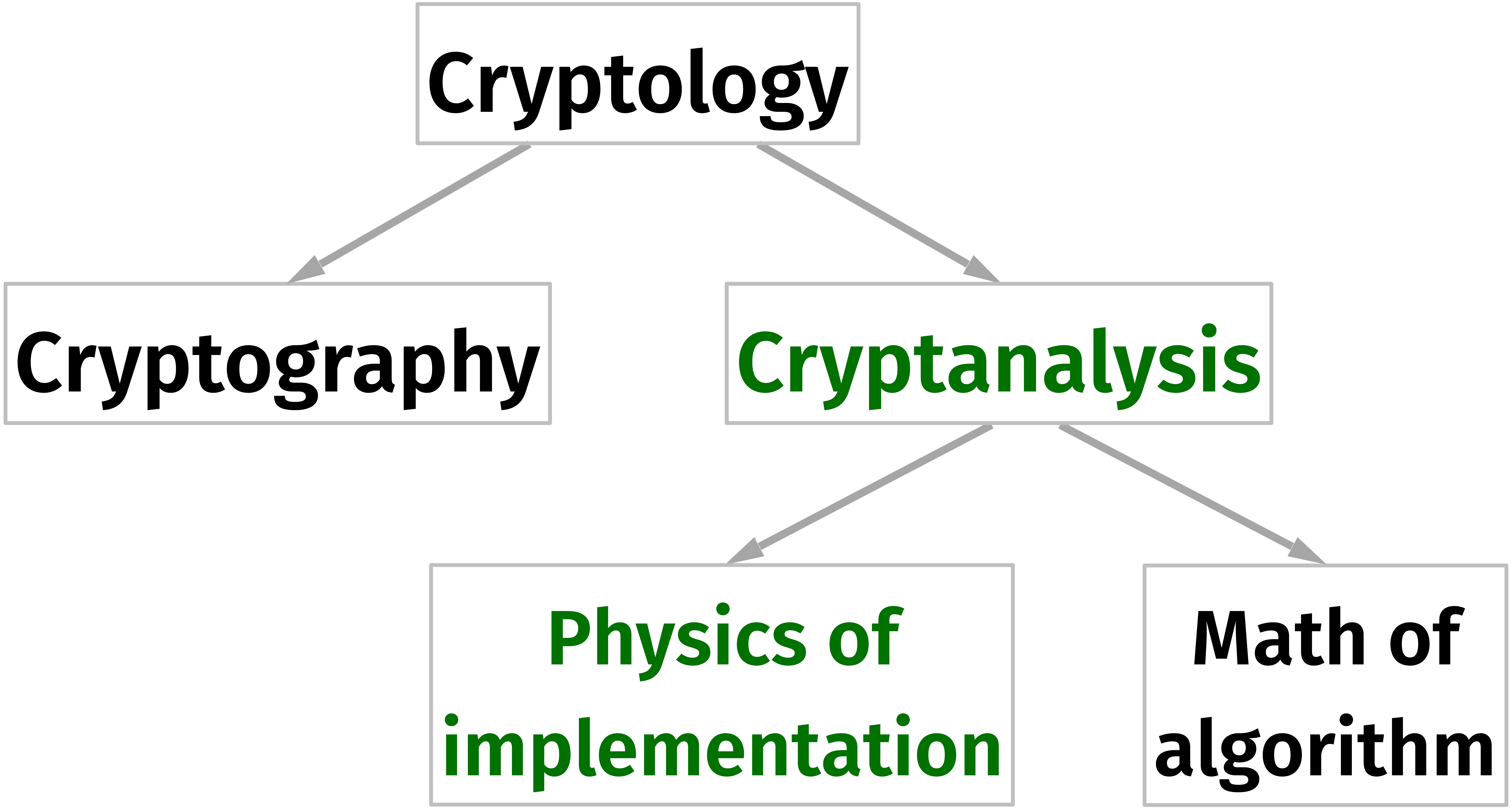
Lecture 10: Time attacks

- Lab 5 schedule
  - Posted today
  - Due next Friday 3/8
- Read this week's assigned reading *before* discussion tomorrow
- Guest lecture by Sarah Scheffler next Tuesday



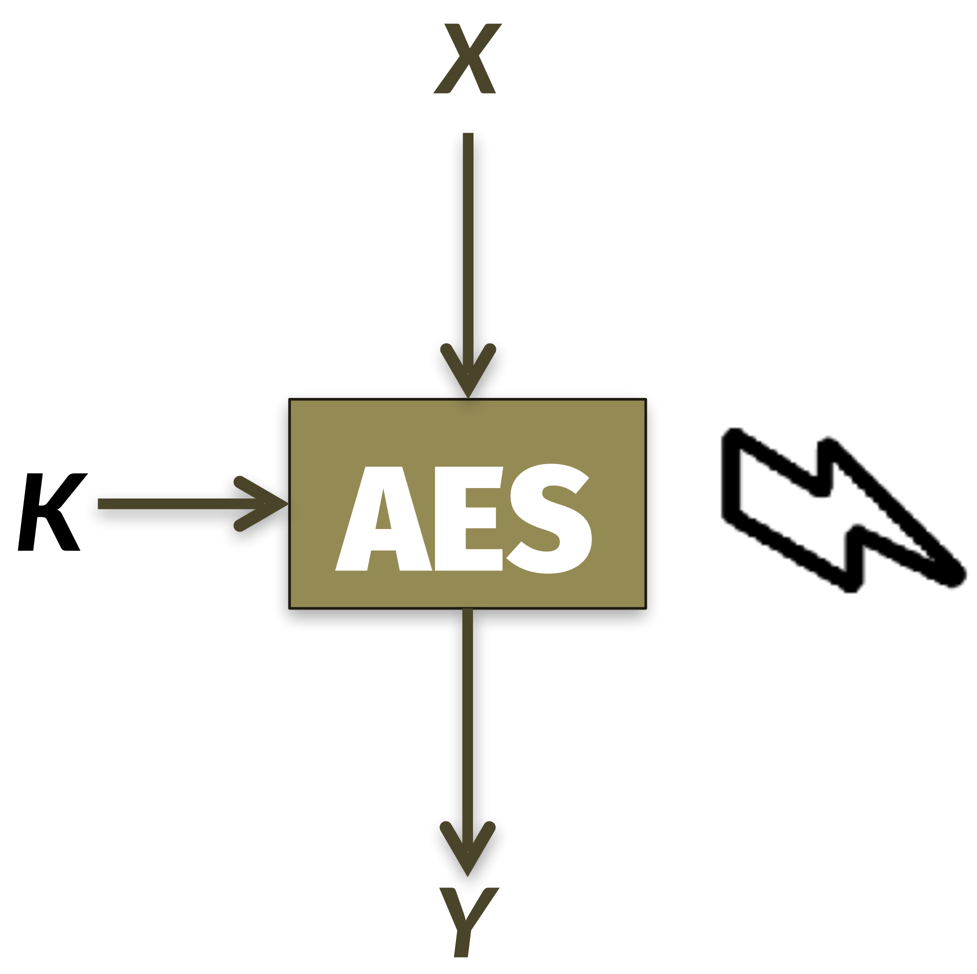
Part 2: *Breaking* data at rest

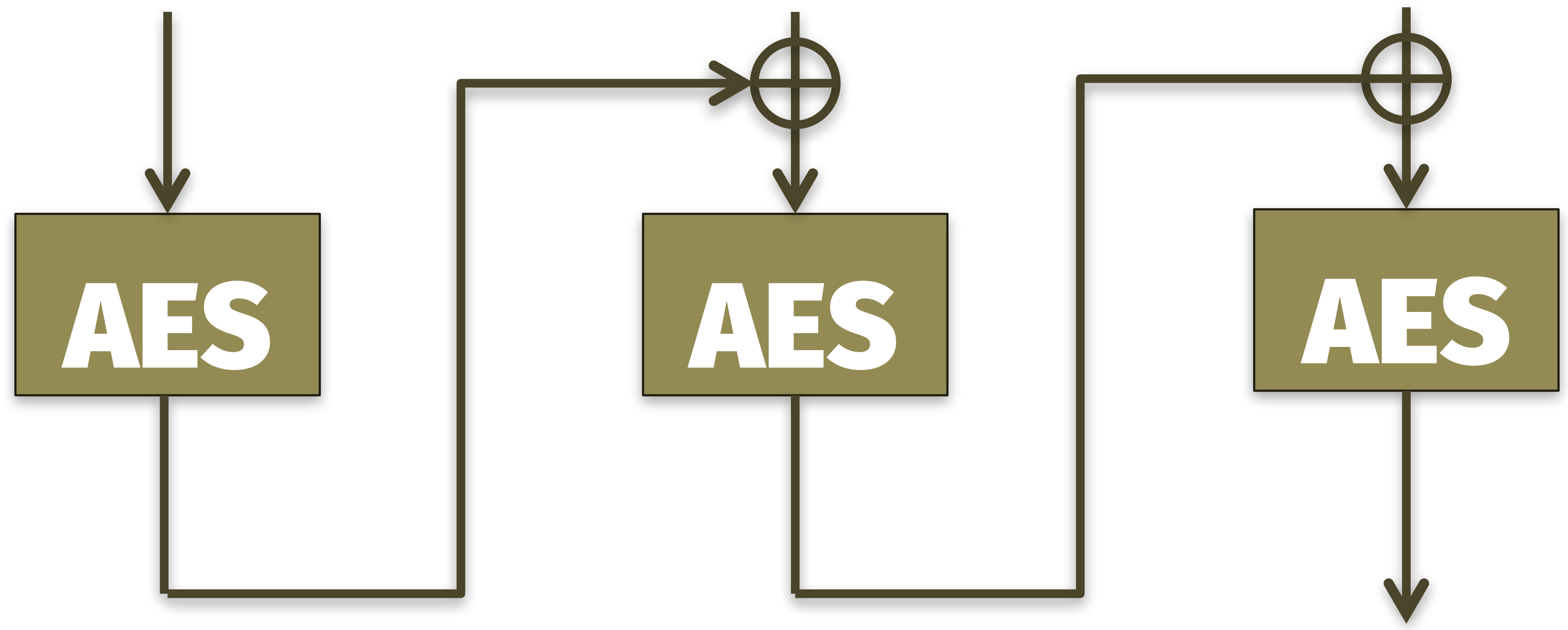



Cryptology
Cryptography
Cryptanalysis
Physics of implementation
Math of algorithm

Side channel attacks on crypto implementations

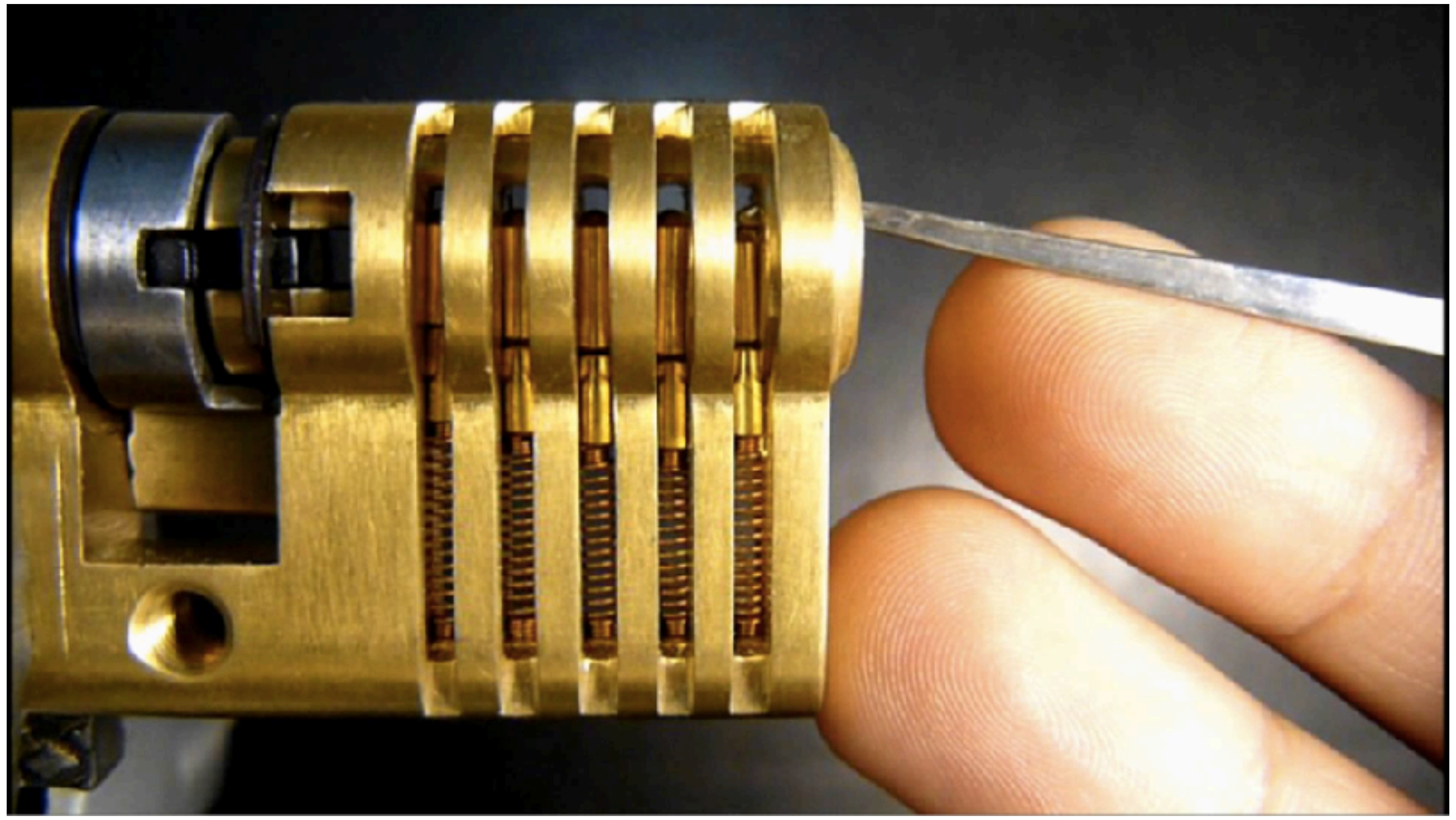
- Crypto security definitions ensure that the output is "harmless"
- But, crypto implementations can reveal more than its desired outputs! These *side channels* of information weren't captured in our definitions
- Focus for this week: side channels on AES $\Rightarrow$ and thus any AES mode



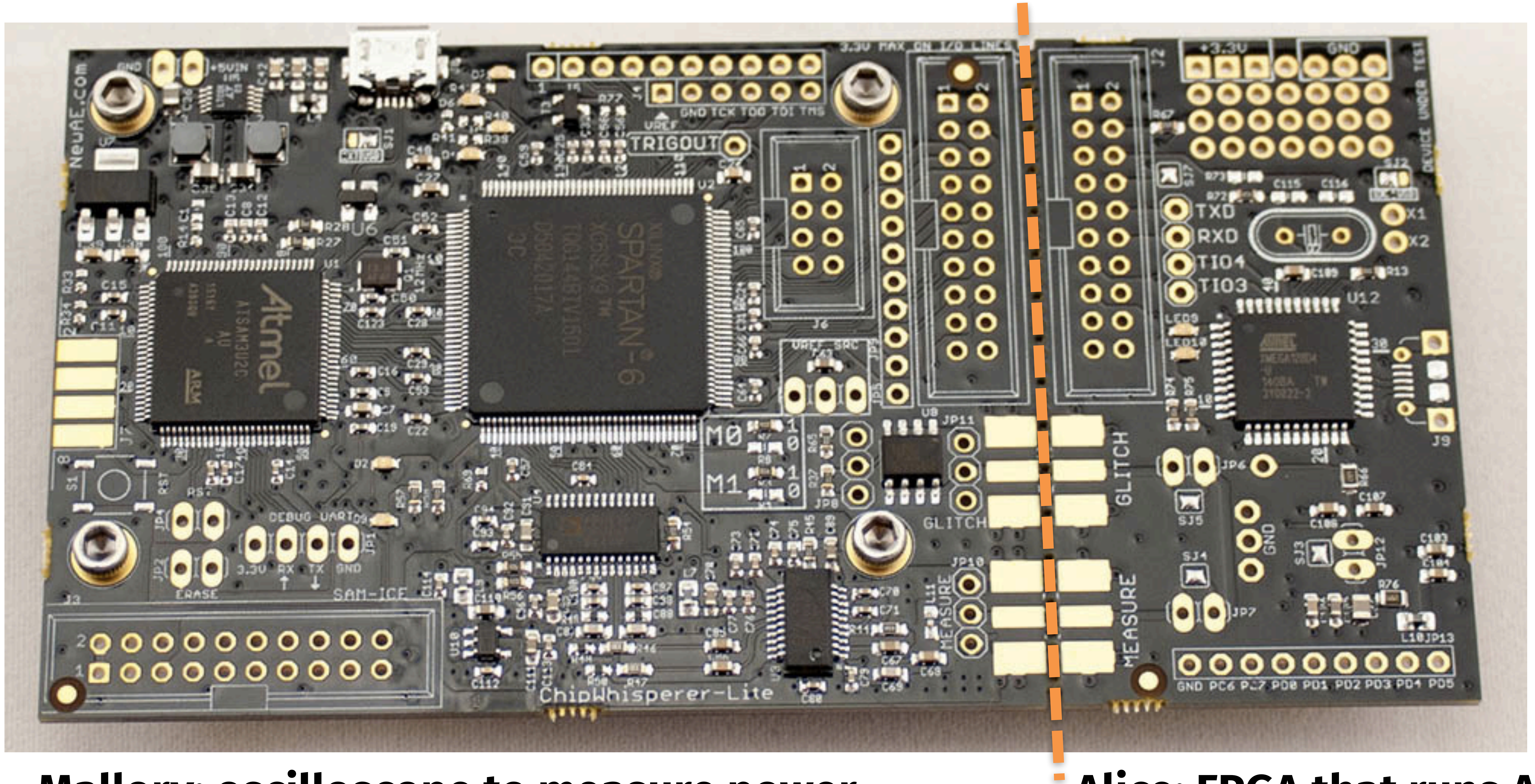


Divide and conquer

- Break 1 byte of the message or key at a time
- For each byte: guess all 256 values and check which works
- (Think: how you see crypto broken in any Hollywood movie)



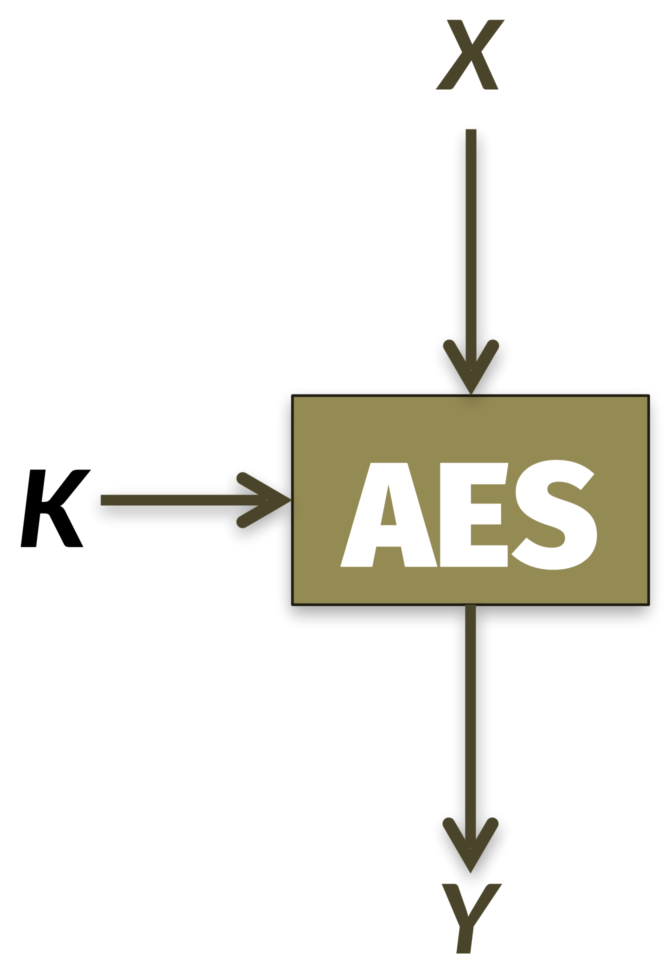
Last time: Power analysis of AES in hardware

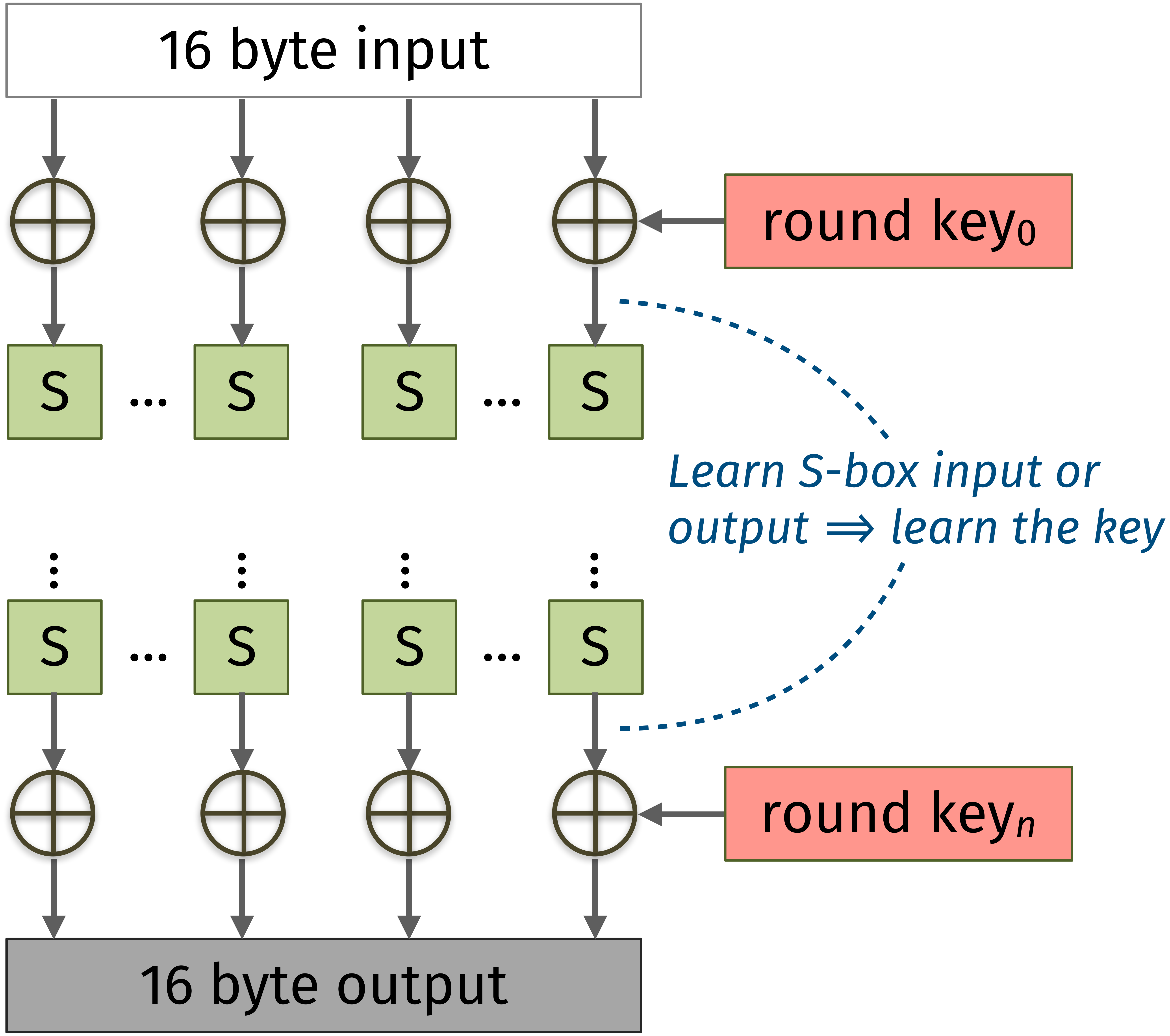


Mallory: oscilloscope to measure power

Alice: FPGA that runs AES

Today: Timing attacks on AES in software





Question: what might affect the runtime of AES?

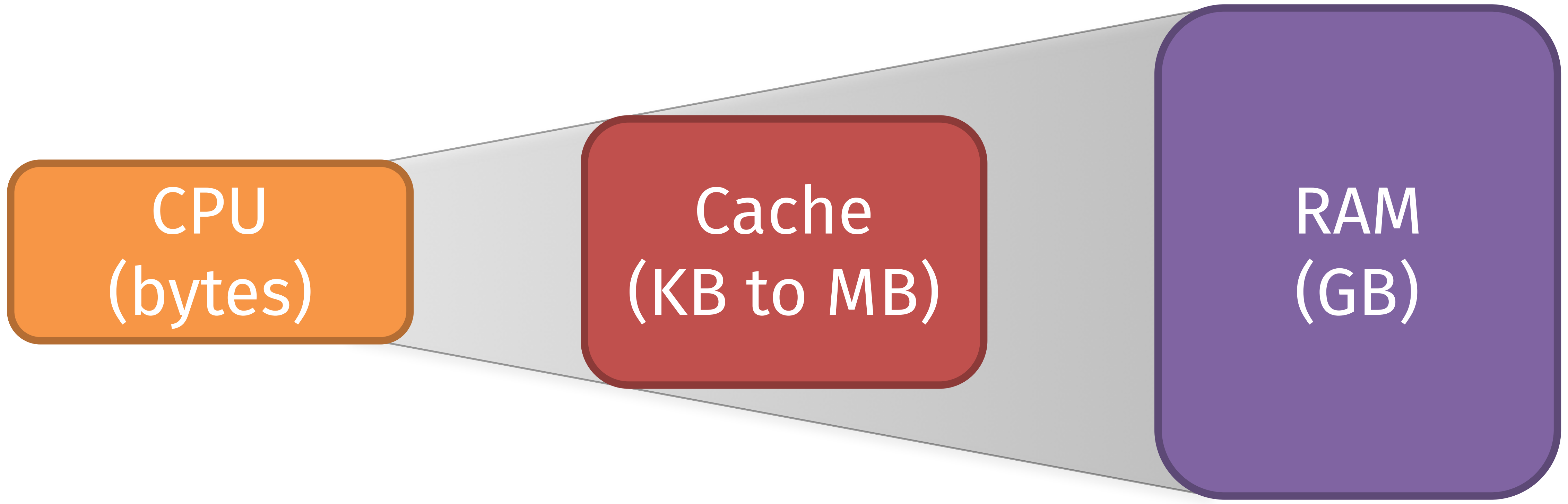
Answer: the S-box!
Let's look at simplified first and last rounds of AES

AES code has table lookups

```
static const u8 Te4[256] = {
    0x63U, 0x7cU, 0x77U, 0x7bU, 0xf2U, 0x6bU, 0x6fU, 0xc5U,
    0x30U, 0x01U, 0x67U, 0x2bU, 0xfeU, 0xd7U, 0xabU, 0x76U,
    0xcaU, 0x82U, 0xc9U, 0x7dU, 0xfaU, 0x59U, 0x47U, 0xf0U,
    0xadU, 0xd4U, 0xa2U, 0xafU, 0x9cU, 0xa4U, 0x72U, 0xc0U,
    0xb7U, 0xfdU, 0x93U, 0x26U, 0x36U, 0x3fU, 0xf7U, 0xccU,
    0x34U, 0xa5U, 0xe5U, 0xf1U, 0x71U, 0xd8U, 0x31U, 0x15U,
    0x04U, 0xc7U, 0x23U, 0xc3U, 0x18U, 0x96U, 0x05U, 0x9aU,
    0x07U, 0x12U, 0x80U, 0xe2U, 0xebU, 0x27U, 0xb2U, 0x75U,
    0x09U, 0x83U, 0x2cU, 0x1aU, 0x1bU, 0x6eU, 0x5aU, 0xa0U,
    0x52U, 0x3bU, 0xd6U, 0xb3U, 0x29U, 0xe3U, 0x2fU, 0x84U,
    0x53U, 0xd1U, 0x00U, 0xedU, 0x20U, 0xfcU, 0xb1U, 0x5bU,
    0x6aU, 0xcbU, 0xbeU, 0x39U, 0x4aU, 0x4cU, 0x58U, 0xcfU,
    0xd0U, 0xefU, 0xaaU, 0xfbU, 0x43U, 0x4dU, 0x33U, 0x85U,
    0x45U, 0xf9U, 0x02U, 0x7fU, 0x50U, 0x3cU, 0x9fU, 0xa8U,
    0x51U, 0xa3U, 0x40U, 0x8fU, 0x92U, 0x9dU, 0x38U, 0xf5U,
    0xbcU, 0xb6U, 0xdaU, 0x21U, 0x10U, 0xffU, 0xf3U, 0xd2U,
    0xcdU, 0x0cU, 0x13U, 0xecU, 0x5fU, 0x97U, 0x44U, 0x17U,
    0xc4U, 0xa7U, 0x7eU, 0x3dU, 0x64U, 0x5dU, 0x19U, 0x73U,
    0x60U, 0x81U, 0x4fU, 0xdcU, 0x22U, 0x2aU, 0x90U, 0x88U,
    0x46U, 0xeeU, 0xb8U, 0x14U, 0xdeU, 0x5eU, 0x0bU, 0xdbU,
    0xe0U, 0x32U, 0x3aU, 0x0aU, 0x49U, 0x06U, 0x24U, 0x5cU,
    0xc2U, 0xd3U, 0xacU, 0x62U, 0x91U, 0x95U, 0xe4U, 0x79U,
    0xe7U, 0xc8U, 0x37U, 0x6dU, 0x8dU, 0xd5U, 0x4eU, 0xa9U,
    0x6cU, 0x56U, 0xf4U, 0xeaU, 0x65U, 0x7aU, 0xaeU, 0x08U,
    0xbaU, 0x78U, 0x25U, 0x2eU, 0x1cU, 0xa6U, 0xb4U, 0xc6U,
    0xe8U, 0xddU, 0x74U, 0x1fU, 0x4bU, 0xbdU, 0x8bU, 0x8aU,
    0x70U, 0x3eU, 0xb5U, 0x66U, 0x48U, 0x03U, 0xf6U, 0x0eU,
    0x61U, 0x35U, 0x57U, 0xb9U, 0x86U, 0xc1U, 0x1dU, 0x9eU,
    0xe1U, 0xf8U, 0x98U, 0x11U, 0x69U, 0xd9U, 0x8eU, 0x94U,
    0x9bU, 0x1eU, 0x87U, 0xe9U, 0xceU, 0x55U, 0x28U, 0xdfU,
    0x8cU, 0xa1U, 0x89U, 0x0dU, 0xbfU, 0xe6U, 0x42U, 0x68U,
    0x41U, 0x99U, 0x2dU, 0x0fU, 0xb0U, 0x54U, 0xbbU, 0x16U
```

Source: github.com/openssl/openssl/blob/master/crypto/aes/aes_core.c

Computer caching



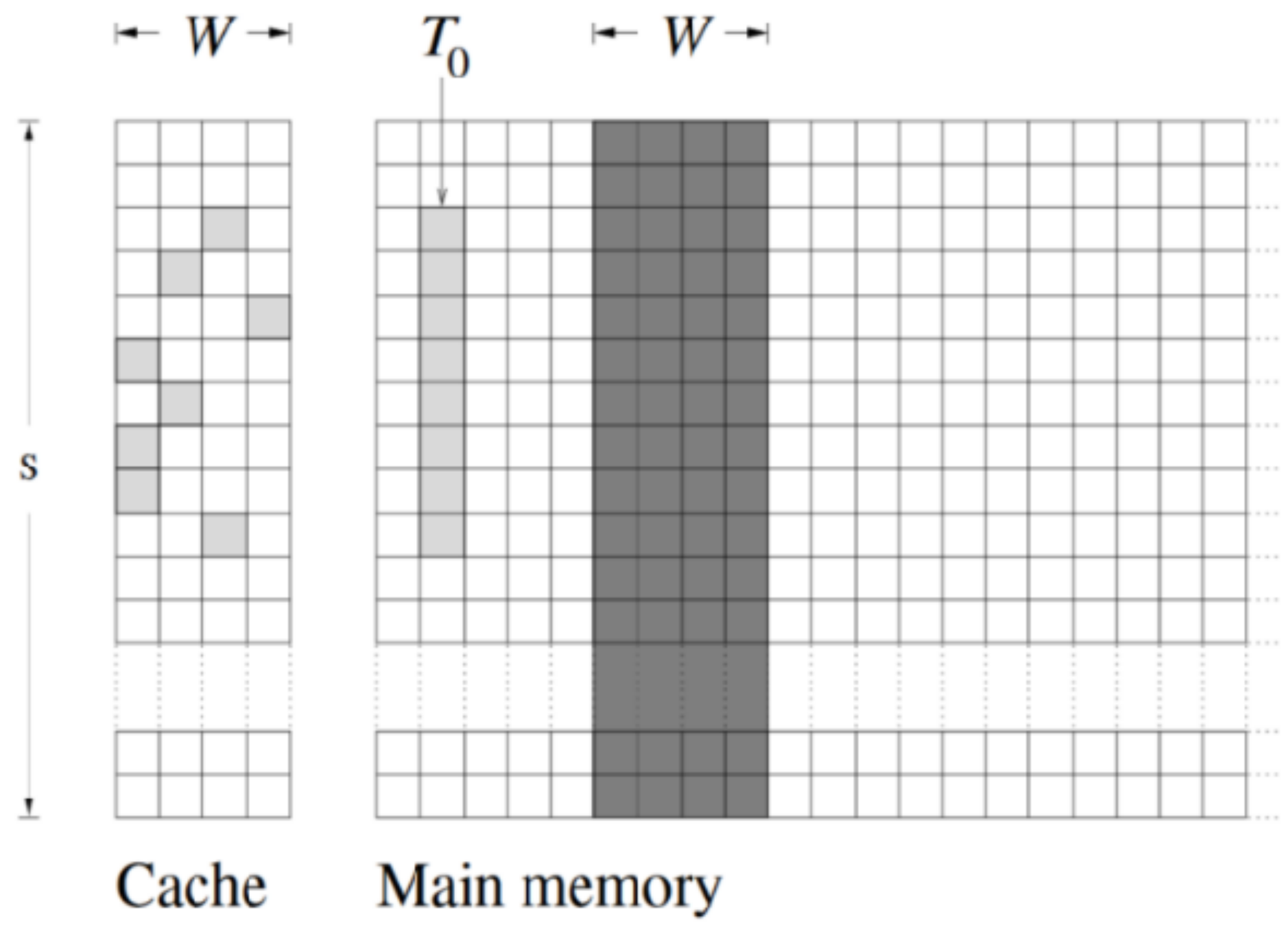
Computers *cache* recently-accessed data, assuming that if you wanted it before, then you may want it again

- Response of array lookup depends upon whether the value is already in cache
- This, in turn, depends on whether you've already looked up this value in the past

Attack setup 1: Mallory co-resident with Alice

- For now, suppose Mallory has a presence on Alice's machine
  - Co-located VMs on the cloud
  - Unprivileged user on a multi-tenant Unix machine with full-disk encryption
- Cache is shared between all tenants on a machine
- Ergo, Mallory can influence the state of Alice's cache!
  [Osvik, Shamir, Tromer 2006]

How the cache works

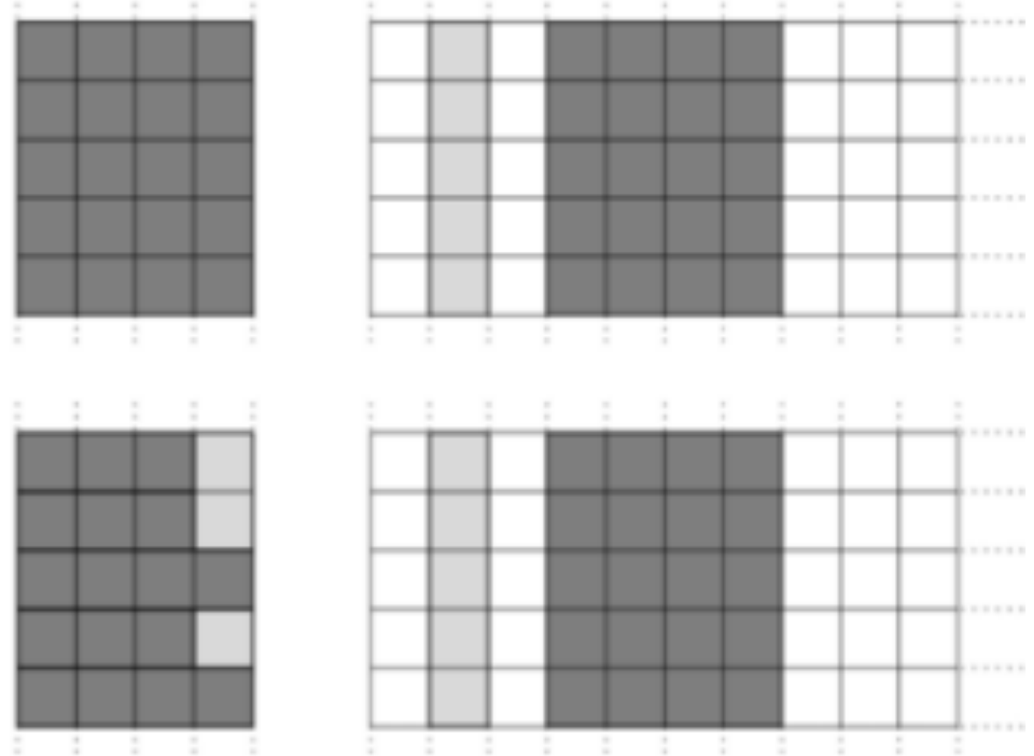


- There is a fixed mapping between locations in memory & cache
- If you control a large region of memory (~size of cache), you can fill in the cache with your own contents

Prime + Probe attack

Algorithm:

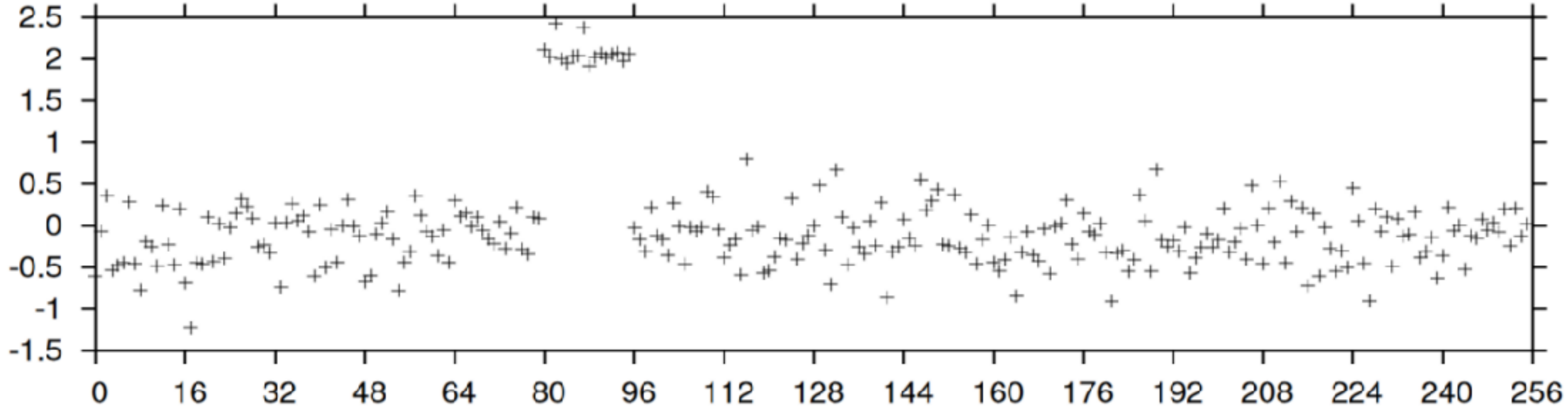
1. Fill the cache with a large array A that you control
2. Trigger an AES encryption (or wait for one to occur)
3. Re-read your array A and record the time to retrieve each byte



Upshot: AES evicted one line of your cache

Strength: Find key byte with ~800 samples over 65ms

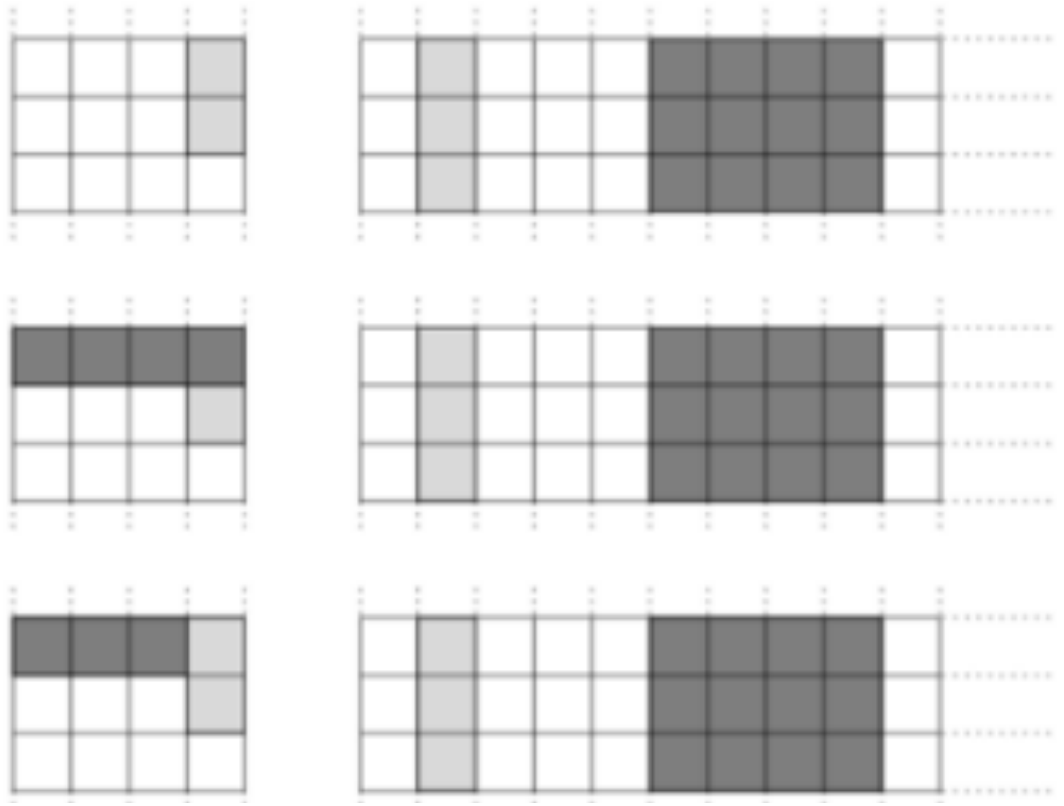
Countermeasure: check for scans of large arrays?



Evict + Time attack

Algorithm:

1. As before, create a large array A
2. Trigger an AES encipher/decipher with known input *x* /output *y*
3. Read a few bytes of your array A
4. Trigger another AES encipher/decipher with the same *x*/y



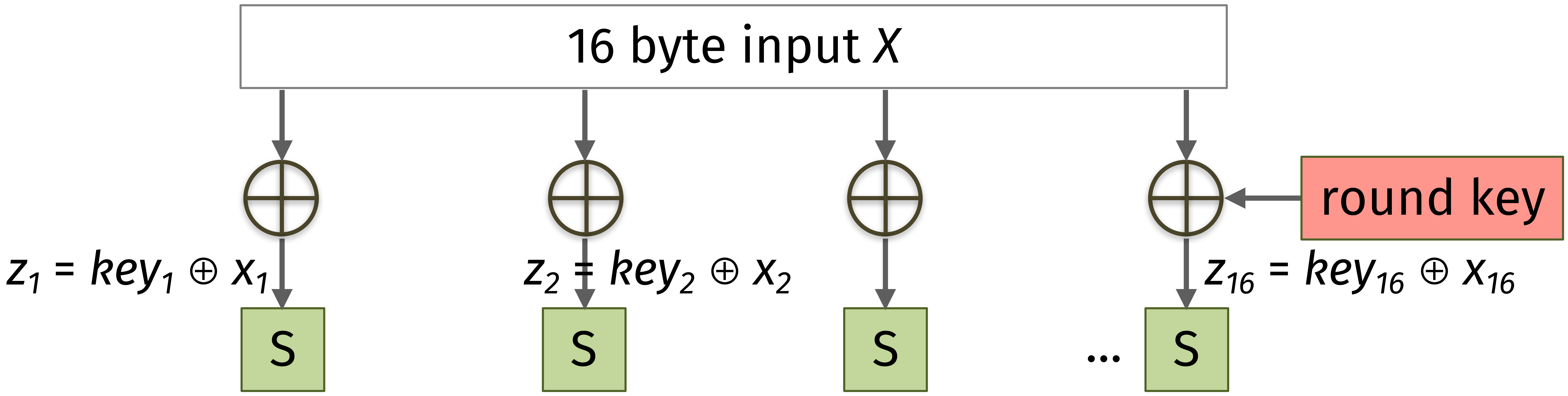
Upshot: 2nd AES is slower iff you evicted the right cacheline

Strength: Find key byte with ~50k samples over ~30s, without ever reading a really large array

Attack setup 2: Mallory observes Alice over network

- Suppose Alice kicks Mallory off of her machine
  - Mallory cannot tamper with Alice’s cache
  - Mallory doesn’t get to observe Alice’s cache directly
- Still, timing information may be viewable remotely!
  - Mallory can observe response times to Alice’s TLS packets over the internet
  - Mallory can use this info to find Alice’s key (albeit with many more samples)

First round table lookups



- In the first round, AES code makes 16 S-box table lookups
- If z_1 and z_2 are identical, then $S[z_2]$ table lookup will be *faster* than $S[z_1]$
- Generally, 1st round running time $\propto$ # of distinct intermediate values

How can Mallory exploit speed differences?

- Let’s say Mallory tells Alice to encipher an input with x_1 = 01, x_2 = 02
- Suppose for now that Mallory magically learns that a cache hit occurs in the first two S-box lookups
- Then, Mallory knows that

$$z_1 = z_2$$

$$key_1 \oplus x_1 = key_2 \oplus x_2$$

$$key_1 \oplus key_2 = x_1 \oplus x_2 = 03$$

How can Mallory find Alice's key?

- Even knowing $key_1 \oplus key_2 = x_1 \oplus x_2 = 03$ doesn't tell you key_1 or key_2
- What if *all* 16 input bytes caused collisions?
- Then Mallory can also compute $key_1 \oplus key_3$, $key_1 \oplus key_4$, …, $key_1 \oplus key_{16}$
- I claim that Mallory has effectively learned 120 of the 128 bits of key!
  - There are 256 choices for key_1
  - Each choice gives a unique remaining option for key_2, key_3, …, key_{16}
- Brute-force the rest if you have a (*pt*, *ct*) pair

Making the attack more realistic

Simplifying assumptions so far

- 1 input ***x*** $\rightarrow$ many cache collisions
- Can tell which bytes of ***z*** collide
- Timing measurement corresponds precisely to first round runtime, which is exactly proportional to # of ***z*** collisions

How to remove these assumptions

- View time for many colliding ***x*** (stronger *signal*)
- Vary ***x*** samples only in certain locations (more precise *signal*)
- Collect even more samples to overcome *noise*

Tactic 1: Collect more samples

- Strategy
  - Don't assume the existence of a single "magical" ***x*** with many collisions
  - Instead, simply try many possible ***x***
- If ***x*** is chosen randomly, then the probability that:
  - a given pair of bytes (e.g., bytes 1 and 2) collide = 1/256
  - byte 1 collides with some other byte ≈ 1/16
  - there exists a collision = 1 – (256 choose 16)/(256^{16}) ≈ 1 – 10^{-14}
- Just as before, each collision yields a constraint on the *key*
- Sample enough ***x*** until we observe 15 independent constraints

Tactic 2: Strategically vary *x*

- Mallory needs to (1) observe a collision and (2) know *where* it occurs
- We can determine which bytes collide by fixing part of x
- Example: take average timing over several inputs with
  - $x_1 = 0$, $x_2 = 0$, and the other 14 bytes randomly chosen
  - $x_1 = 0$, $x_2 = 1$, and the other 14 bytes bytes randomly chosen
  - …
  - $x_1 = 0$, $x_2 = 255$, and the other 14 bytes bytes randomly chosen
- For whichever bucket is consistently faster, $x_1 \oplus x_2 = key_1 \oplus key_2$

Tactic 3: Repeat to overcome noise

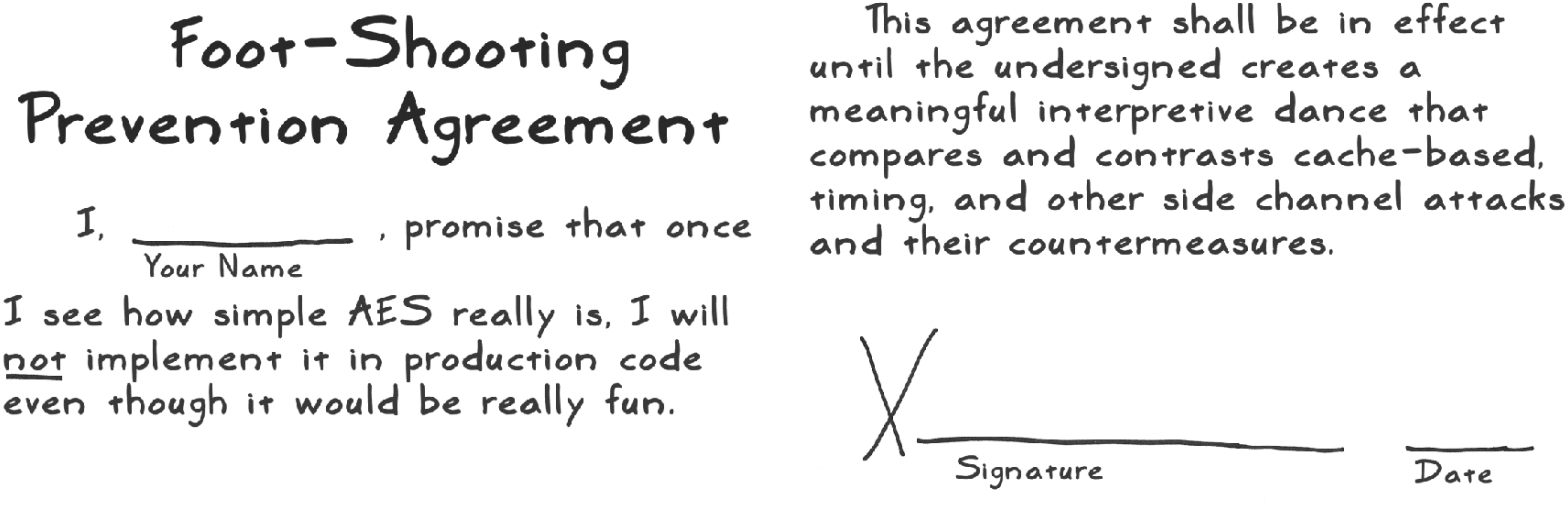
- We know that Time(AES) is smaller when $z_1 = z_2$ than when they differ
- Mallory's measurement of AES runtime depends on many other factors
  - Other bytes in the same cache line
  - Other bytes of the 1st round (or last round for a ct attack)
  - Other rounds
  - Network latency (if you're conducting this attack remotely)
- With enough samples, we can average over this noise!
- Bin running times by $x_1 \oplus x_2$, see which is smallest

Countermeasures to (cache) timing attacks

1. Don't have table lookups
   - Hardware implementations of AES are not vulnerable
   - There exist other ciphers that are designed to avoid the need for table lookups (for instance, we will see later in the course that SHA-3 doesn't have any)

2. Look up the entire table
   - Pre-load the entire S-box into the cache before beginning AES
   - Then the timing doesn't depend on the particular values that you look up
   - Precarious because you might get interrupted in the middle of execution

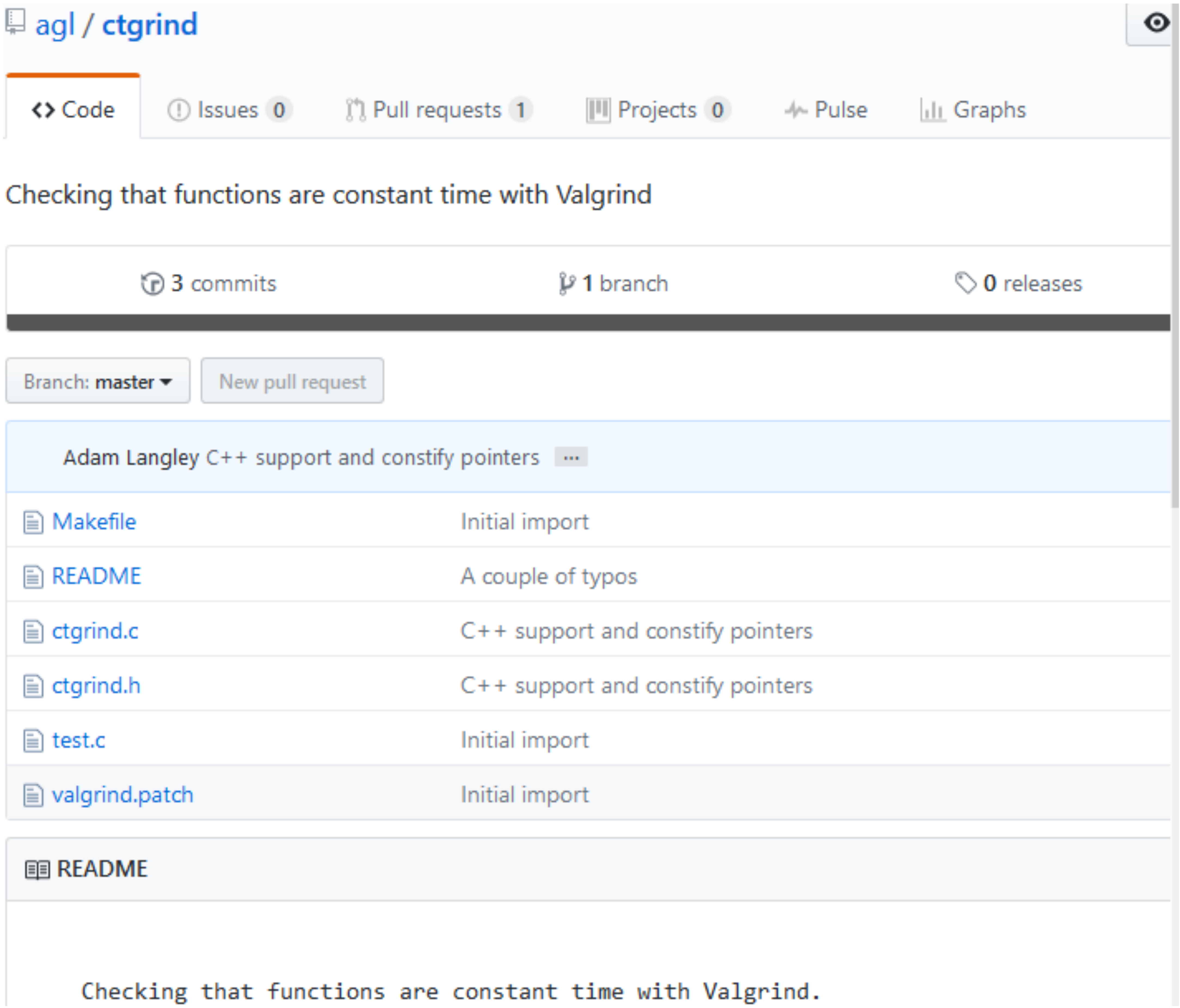
Side channels ⇒ difficult to implement crypto securely



Source:
moserware.com/2009/09/stick-figure-guide-to-advanced.html

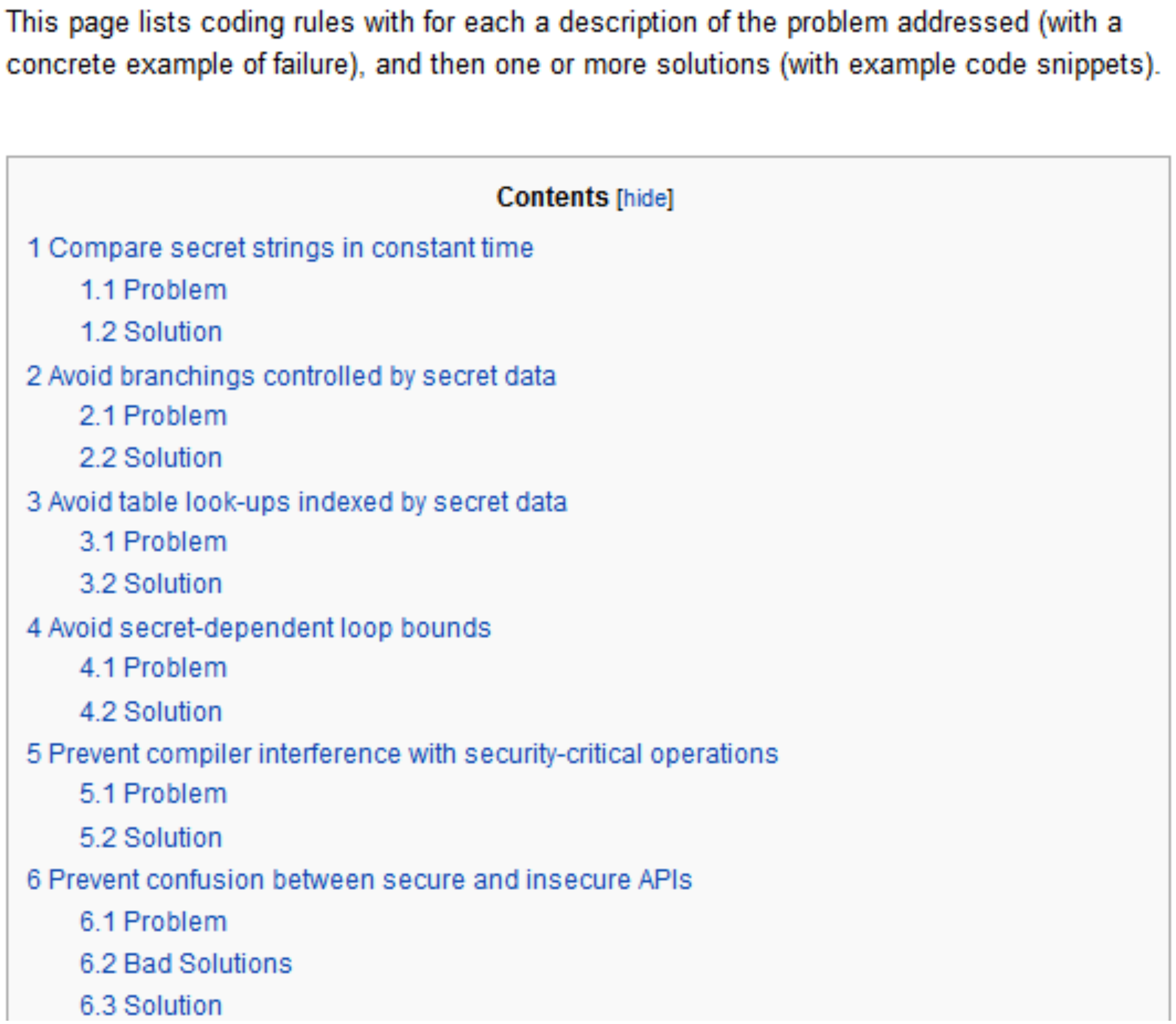
What you should do

Validate code for timing independence



Source: github.com/agl/ctgrind

Use good *crypto* coding conventions



Source: cryptocoding.net/index.php/Coding_rules

Next time: padding oracle attacks