CS 453 / 698: Software and Systems Security

Module: Hardware Security

Lecture: side-channel attacks and countermeasures

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Outline

How to steal sensitive information?

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- Side channels
  - e.g., timing, bandwidth, power, etc.

Locard's exchange principle

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> *Wherever he steps, whatever he touches, whatever he leaves, even unconsciously, will serve as a silent witness against him. Not only his fingerprints or his footprints, but his hair, the fibres from his clothes, the glass he breaks, the tool mark he leaves, the paint he scratches, the blood or semen he deposits or collects. All of these and more, bear mute witness against him. This is evidence that does not forget.*
>
> — Paul L. Kirk

Locard's exchange principle (in code execution)

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$\longrightarrow$ *"Every contact leaves a trace"*

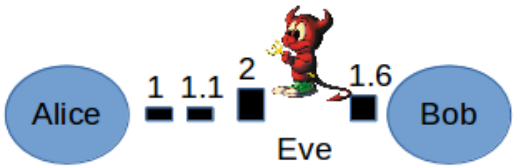
~~Wherever he steps~~ Every CPU instruction executed, ~~whatever he touches~~ every memory access, ~~whatever he leaves~~ every IO operation, even unconsciously, will serve as a silent witness against ~~him~~ the code.

My personal story

Examples of side channels

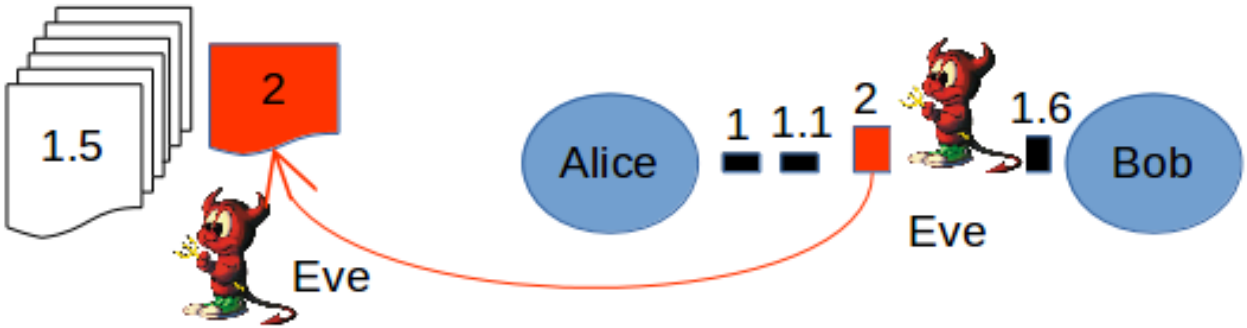
- Bandwidth consumption
- Reflections
- Cache-timing channels

Bandwidth consumption: scenario



- Eve observes communication going via Alice's Router
- Alice accesses health forum via encrypted connection
- Eve knows that Alice connects to health forum
- But cannot decrypt downloaded content

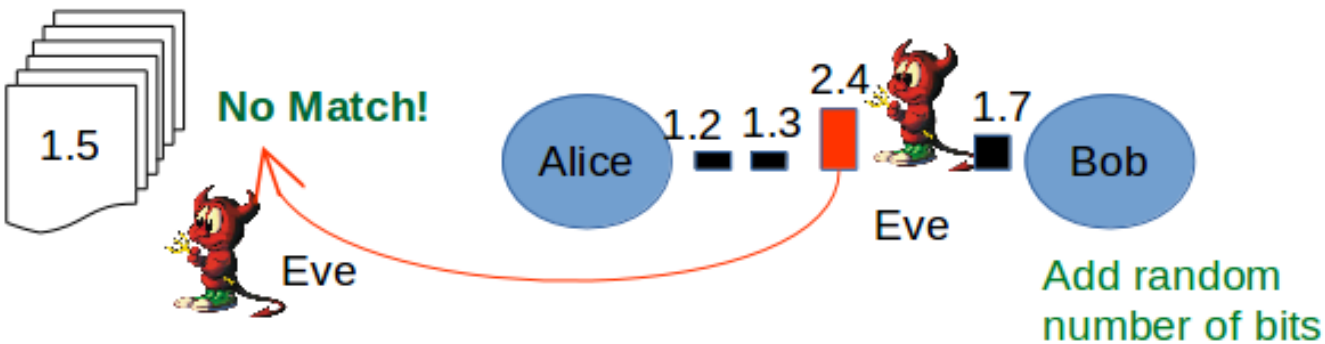
Bandwidth consumption: attack



- Eve determines size of all pages on health forum
- Eve measures size of Alice's downloaded pages
- Likely: Eve can uniquely map download to page
- This attack is called *webpage fingerprinting*
  - or *website fingerprinting*, when targeting landing pages

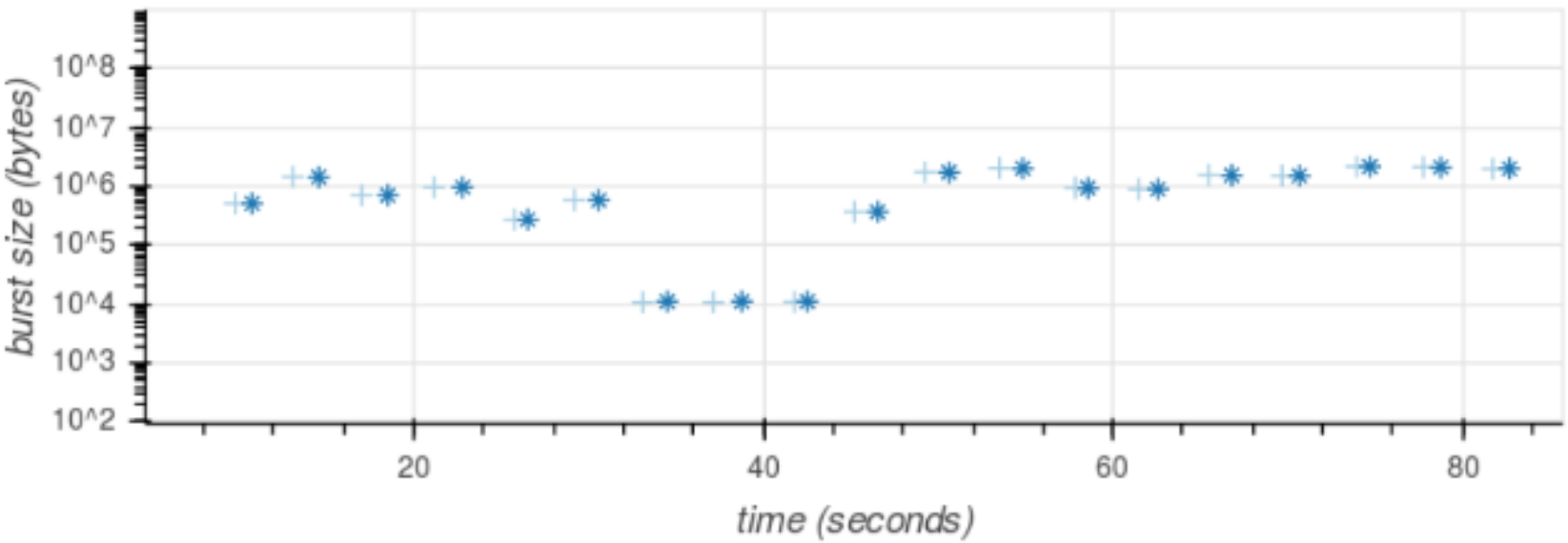
Bandwidth consumption: defense

- Pad all pages to common size (inflexible + inefficient )
- Dynamic personalized websites
- (Finally a benefit of targeted advertisement)



Bandwidth consumption: another example

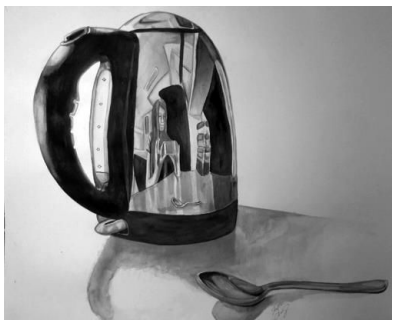
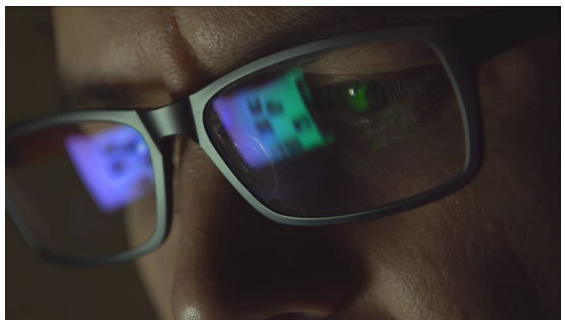
- Re-identification of Netflix video streaming
- Burst sizes of a streamed scene of "Reservoir Dogs"
  - Very similar, even when watched over different networks



Schuster et al., USENIX SEC '17

Reflections: scenario

- Alice types her password on a device in a public place
- Alice hides her screen
- But there is a reflecting surface close by

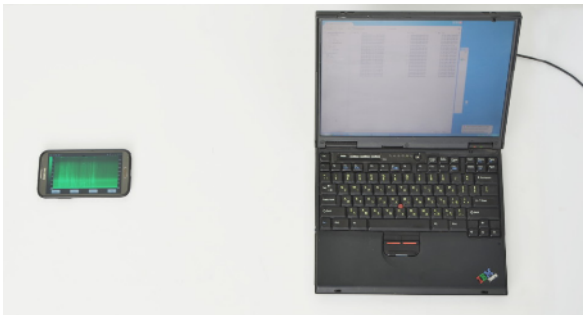

Reflections: attack

- Eve uses a camera and a telescope
- Off-the-shelf: less than CA$2,000
- Photograph reflection of screen through telescope
- Reconstruct original image
- Distance: 10–30 m
- Depends on equipment and type of reflecting surface

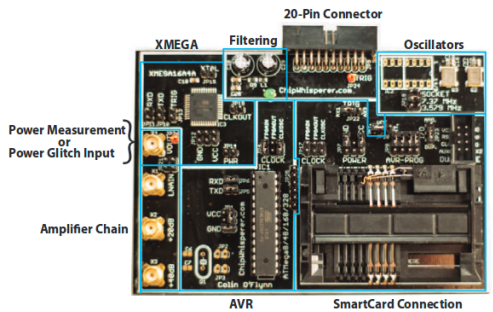
Reflections: defense

Other potential attack vectors

- Timing computations
- Electromagnetic emission
- Sound emissions

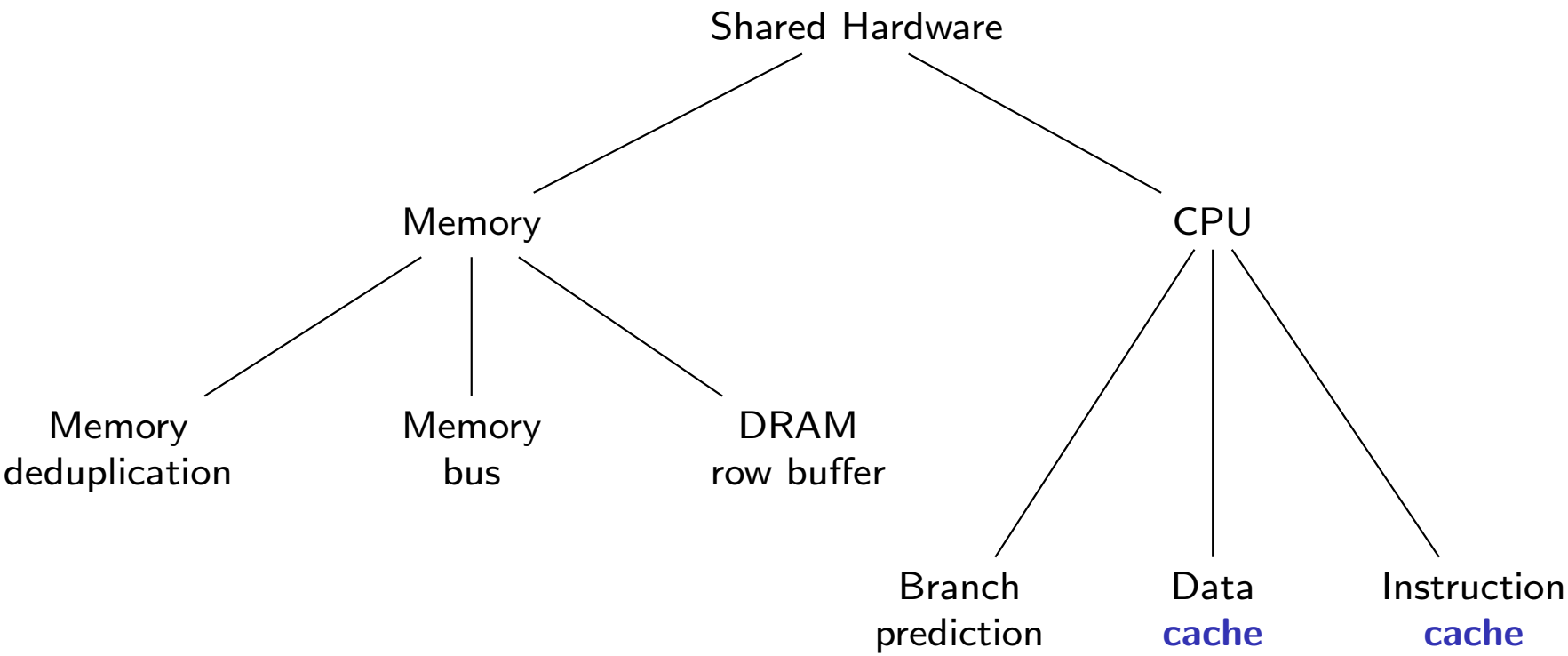


- Power consumption
- Differential power analysis
- Differential fault analysis



Outline

Common hardware shared



Cache timing side channels

- Modern architectures use caches to speed up memory access
  - Main memory access is slow. Cache access is faster.
  - Caches are micro-architectural objects, not architectural: programs typically unaware of caches.
  - Caches are shared: by timing cache access, a process can learn information about data used by another.

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- Micro-architectural features like speculative and out-of-order execution can be exploited to leak information via caches.
  - Spectre and Meltdown attacks (2017)

Why targeting cache?

- Shared across cores
  - agonistic to kernel, hypervisor, and emulators!
- Observable effect
  - data/instruction is cached → cache hit → fast
  - data/instruction is not cached → cache miss → slow

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$\Longrightarrow$ cross-core attacks!

Measuring time differences caused by cache

1. build two cases: cache hits and cache misses
2. time each case many times (get rid of noise)
3. plot a histogram
4. find a threshold to distinguish the two cases

Side note: how to measure timing accurately?

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t1 := rdtsc
⟨ ...operation ... ⟩
t2 := rdtsc
duration := t2 - t1
```

Side note: how to measure timing accurately?

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```
t1 := rdtsc
⟨ ...operation ... ⟩
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```

Q: Is this correct?
Do you measure what you think you measure?

Side note: how to measure timing accurately?

A: Out-of-order execution

```
t1 := rdtsc
⟨ . . . operation . . . ⟩
t2 := rdtsc
duration := t2 - t1
⟨ . . . other-ops . . . ⟩
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t1 := rdtsc                    t1 := rdtsc
⟨ ...operation ... ⟩           ⟨ ...other-ops ... ⟩
t2 := rdtsc                    t2 := rdtsc
duration := t2 - t1            duration := t2 - t1
⟨ ...other-ops ... ⟩           ⟨ ...operation ... ⟩
```

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```
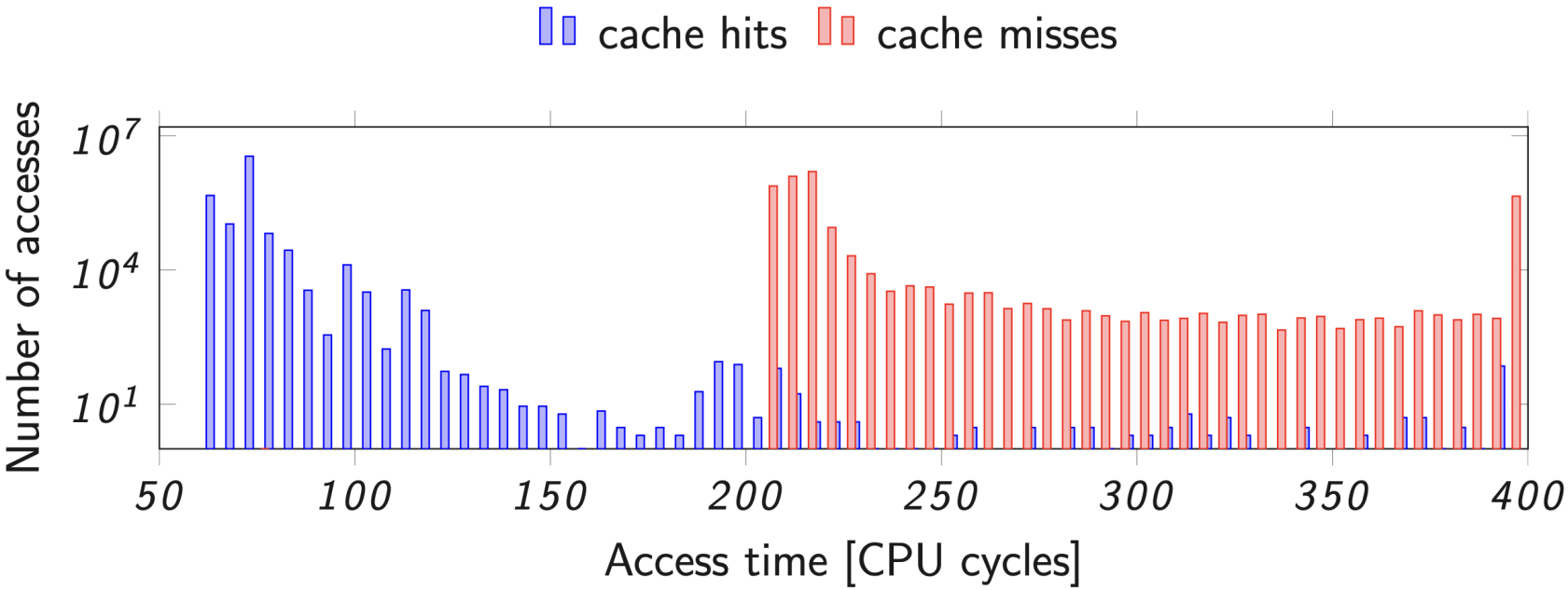

Side note: how to measure timing accurately?

- use pseudo-serializing instruction `rdtscp` (recent CPUs)
- and/or use serializing instructions like `cpuid`
- and/or use fences like `mfence`

How to Benchmark Code Execution Times on Intel IA-32 and IA-64 Instruction Set Architectures White Paper, December 2010.

Timing difference on cache hit/miss



Cycle difference on cache hit/miss

On current Intel CPUs:

- L1 cache: 4 cycles
- L2 cache: 12 cycles
- L3 cache: 26-31 cycles
- DRAM memory: $>$ 120 cycles

(Unprivileged) cache maintenance

User programs can (voluntarily) optimize cache usage:

- `prefetch`: suggest CPU to load data into cache
- `clflush`: throw out data from all caches

. . . based on virtual addresses

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This is the enabler of any cache-based attack:
Attacker monitors its own activity to find cache accessed by victim.

A concrete scenario

- You run a secret program on machine, and the program does one of two things
  - `encrypt()`
  - `decrypt()`
- You do not want anyone to know whether your program is encrypting a message or decrypting a message.
  - assuming trust in operating system and hardware
- The binary of your program is available.

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- Attackers can run their programs on the same machine.
- Their goal is to infer which operation your program is running.

Access-driven attacks

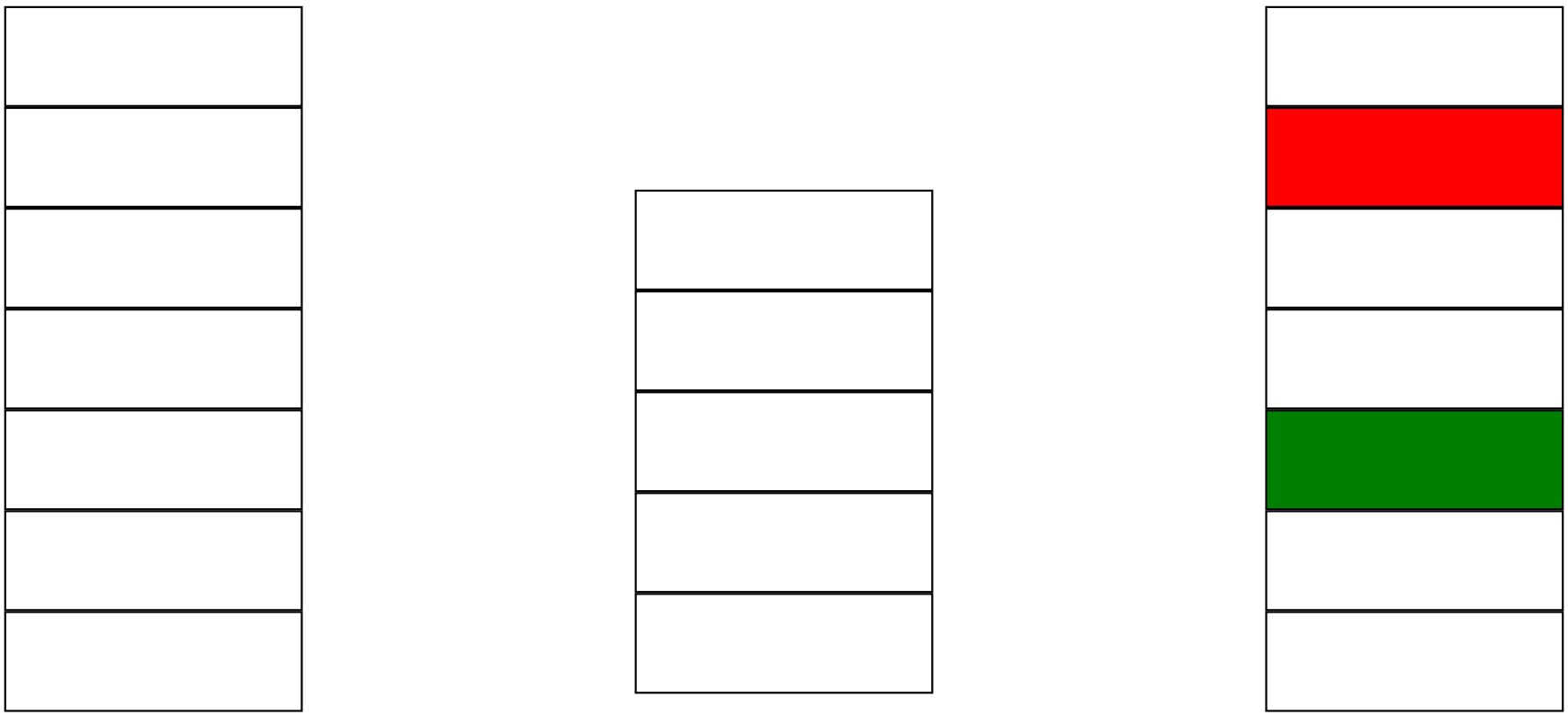
- **Flush+Reload**
- **Prime+Probe**

Flush+Reload

Attacker address space

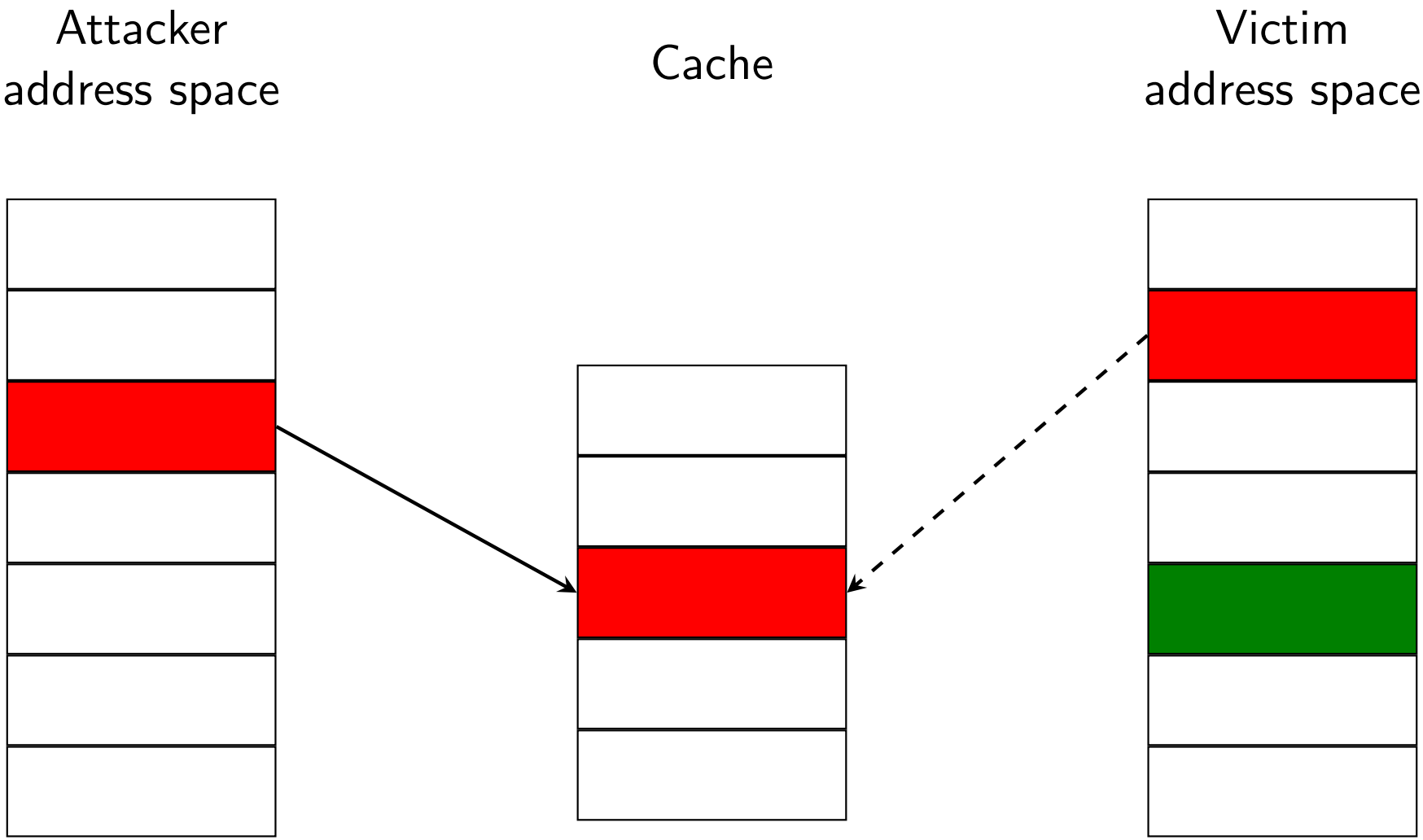
Cache

Victim address space



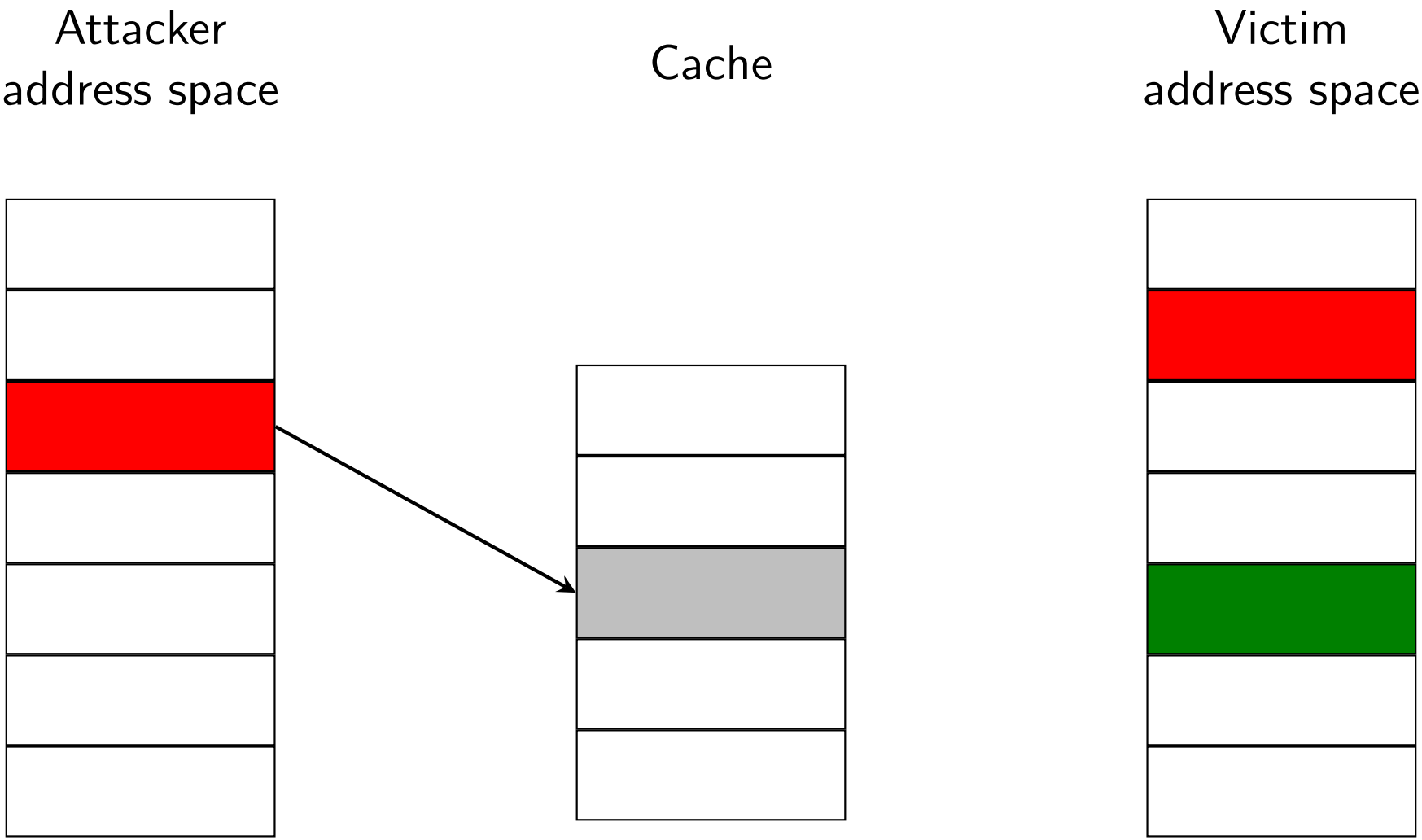
Init: victim program loaded while cache is empty

Flush+Reload



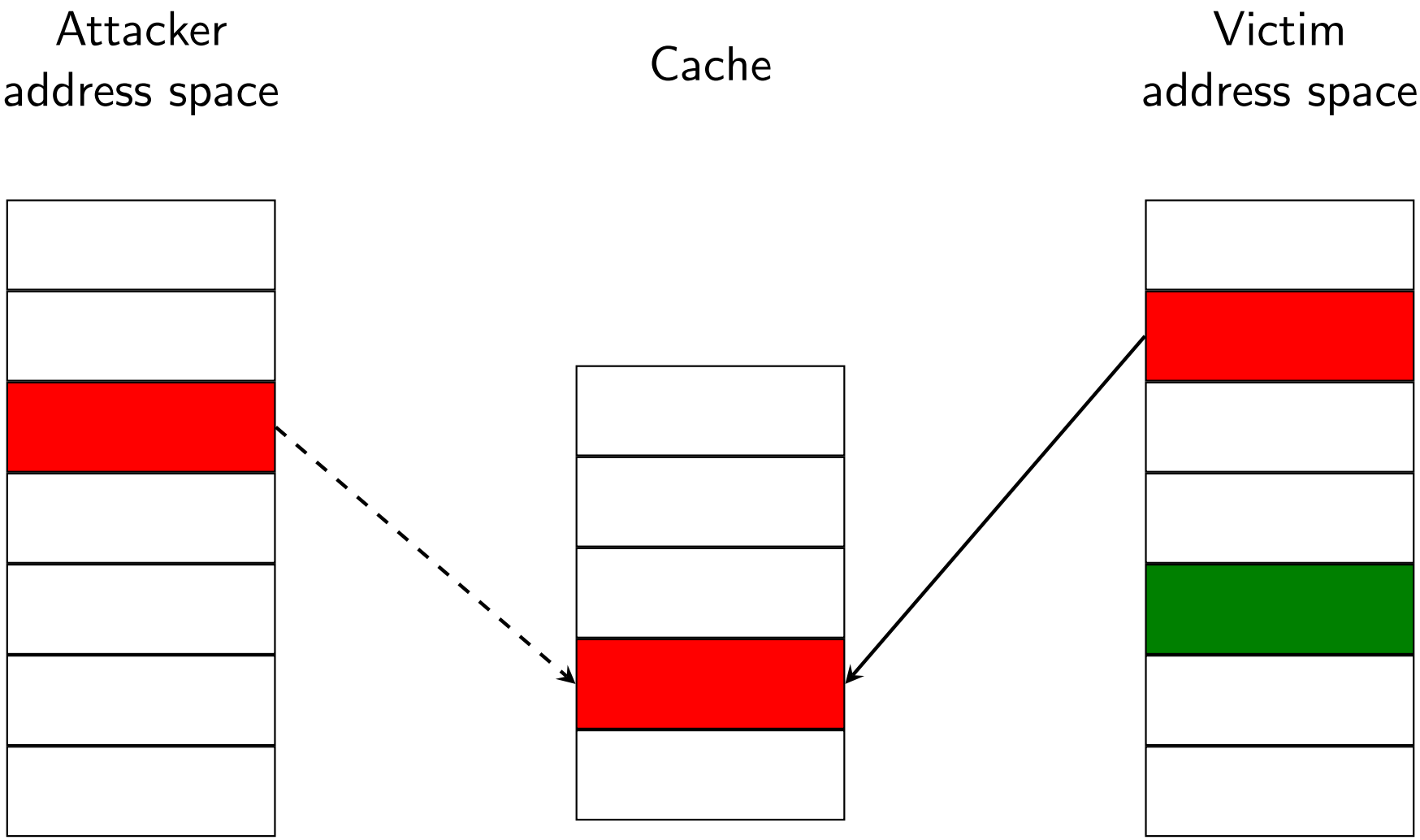
Step 1: attacker loads the `encrypt()` code into its address space

Flush+Reload



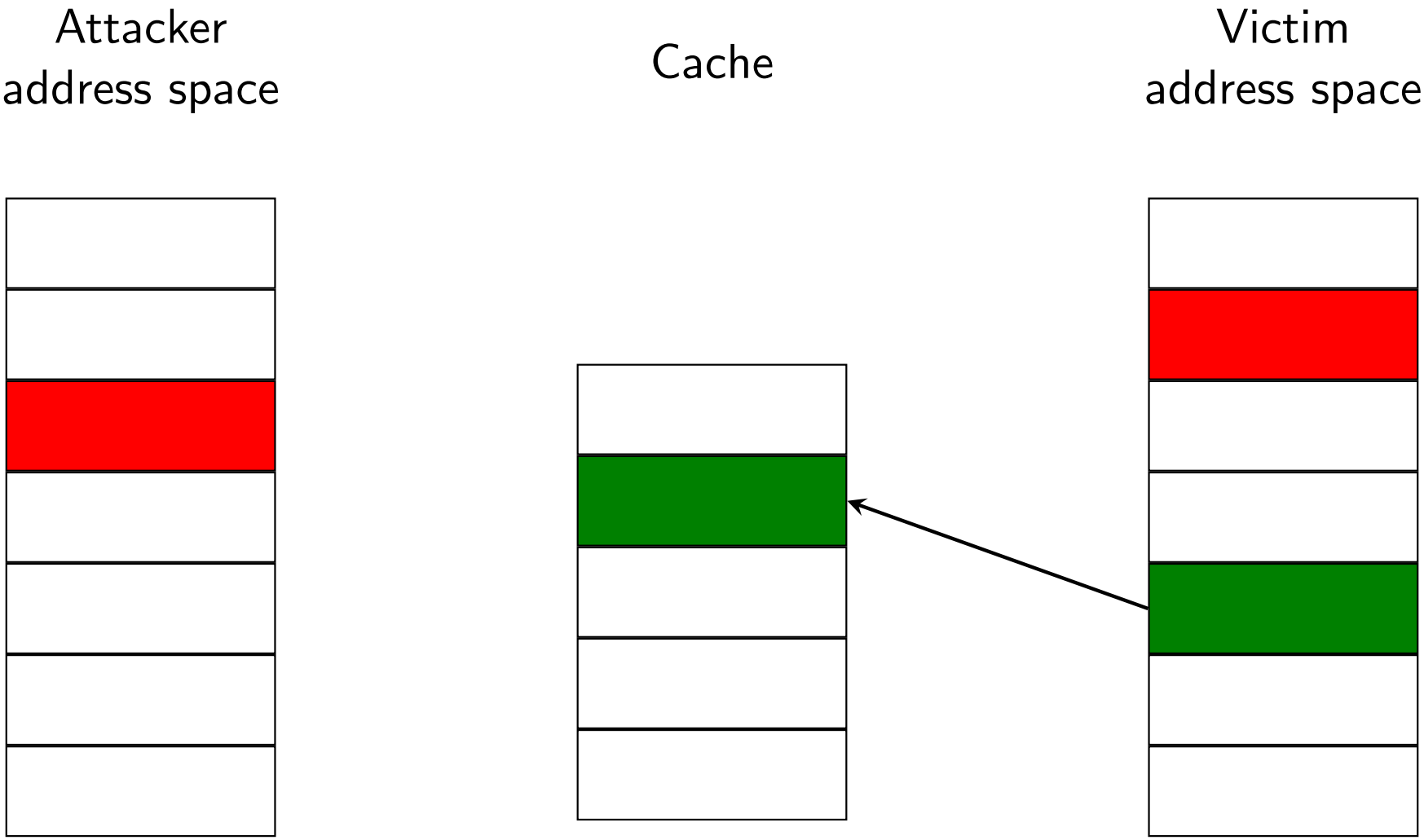
Step 2: attacker flushes the shared cache

Flush+Reload



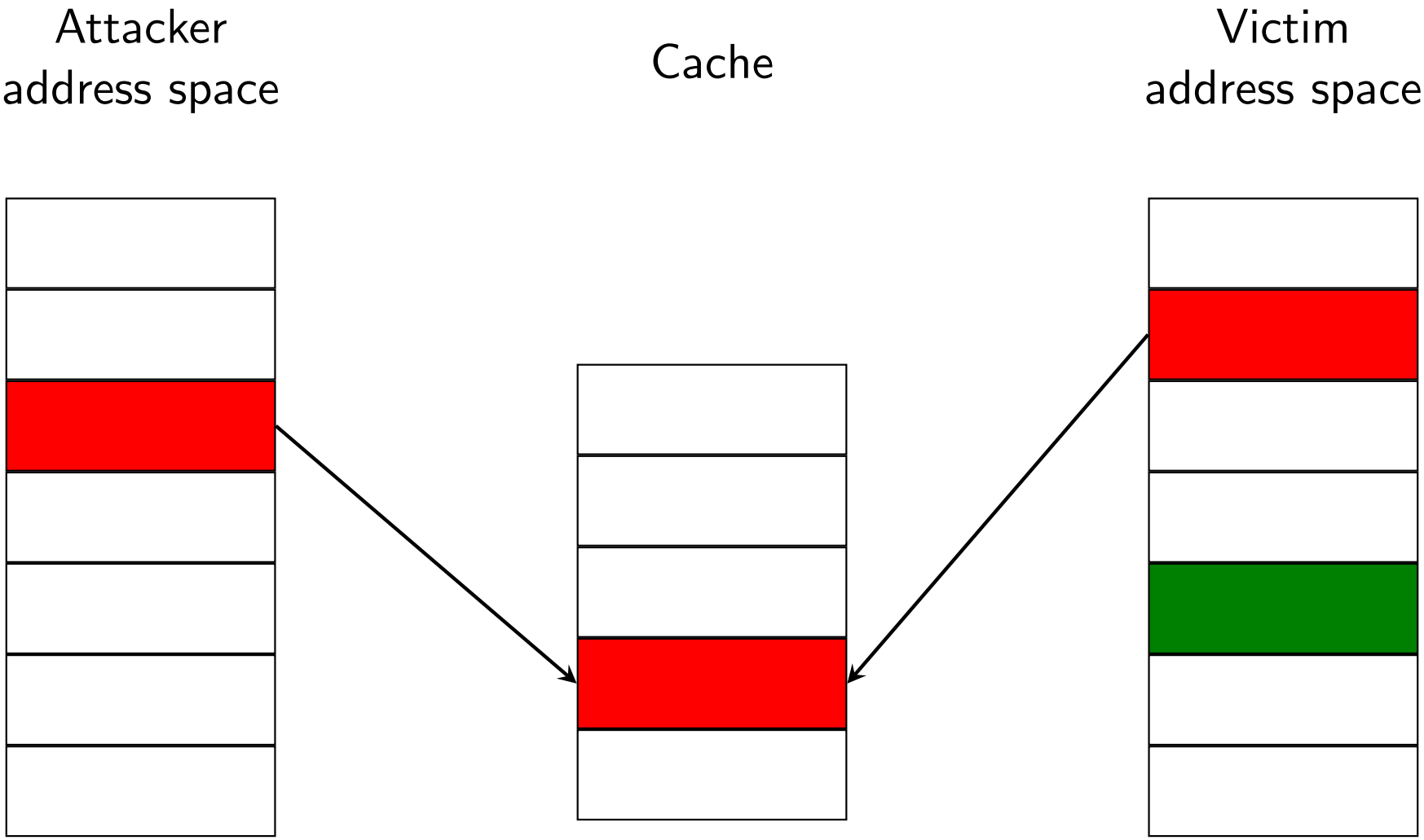
Step 3(a): victim performs operation `encrypt()`

Flush+Reload



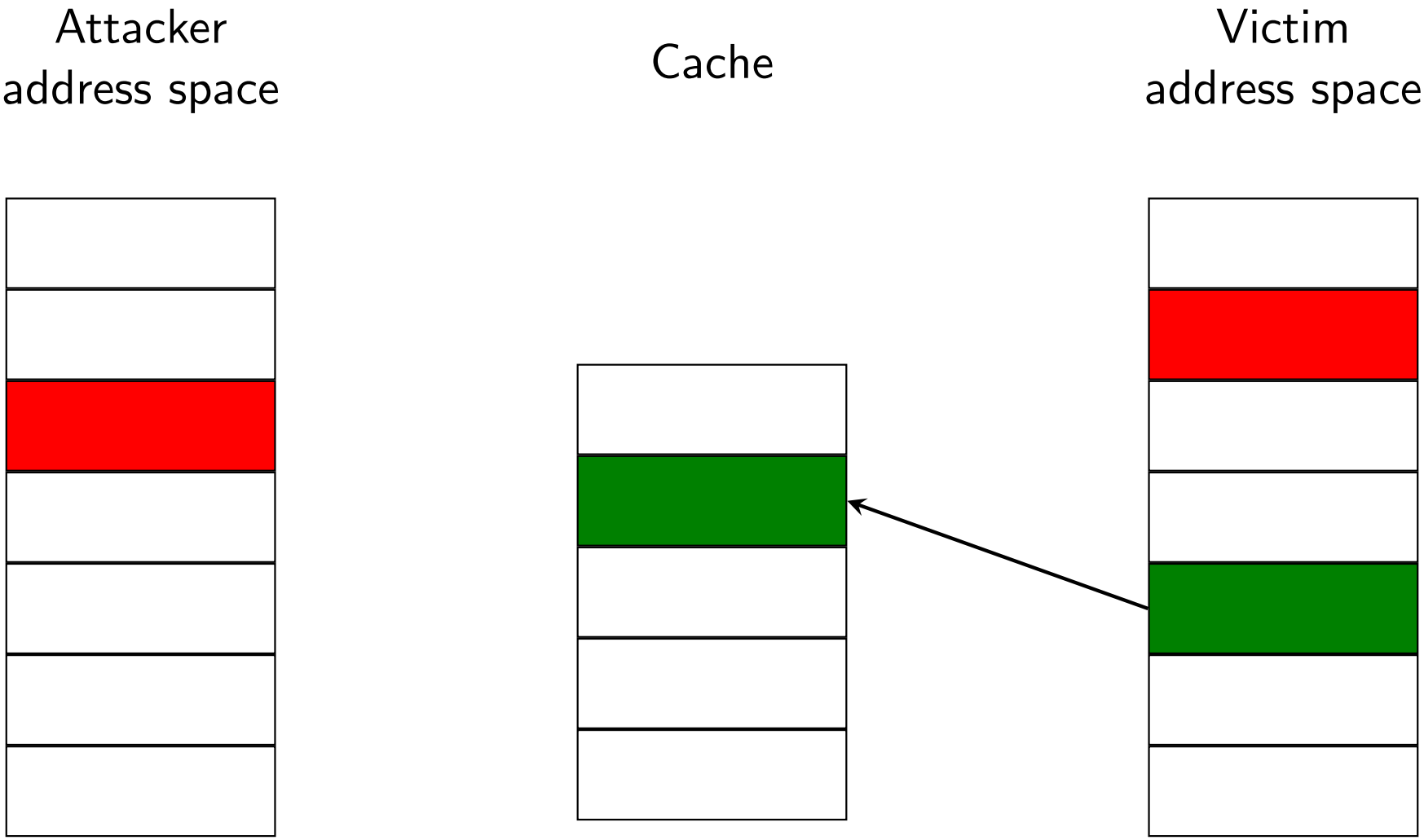
Step 3(b): victim performs operation `decrypt()`

Flush+Reload



Step 4: attacker calls `encrypt()` after **step 3(a)** $\Longrightarrow$ fast!

Flush+Reload



Step 4: attacker calls `encrypt()` after **step 3(b)** $\Longrightarrow$ slow!

Prime+Probe

Attacker address space

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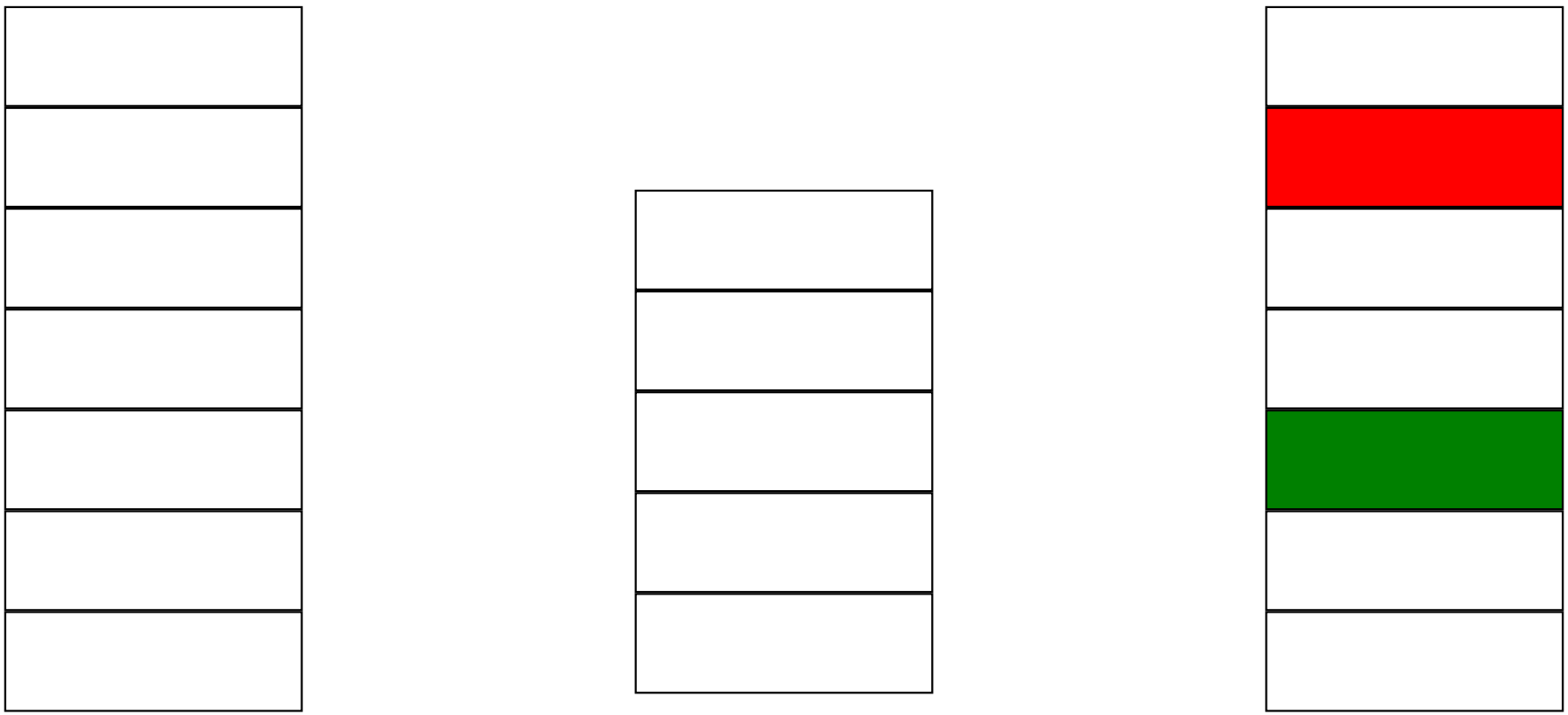

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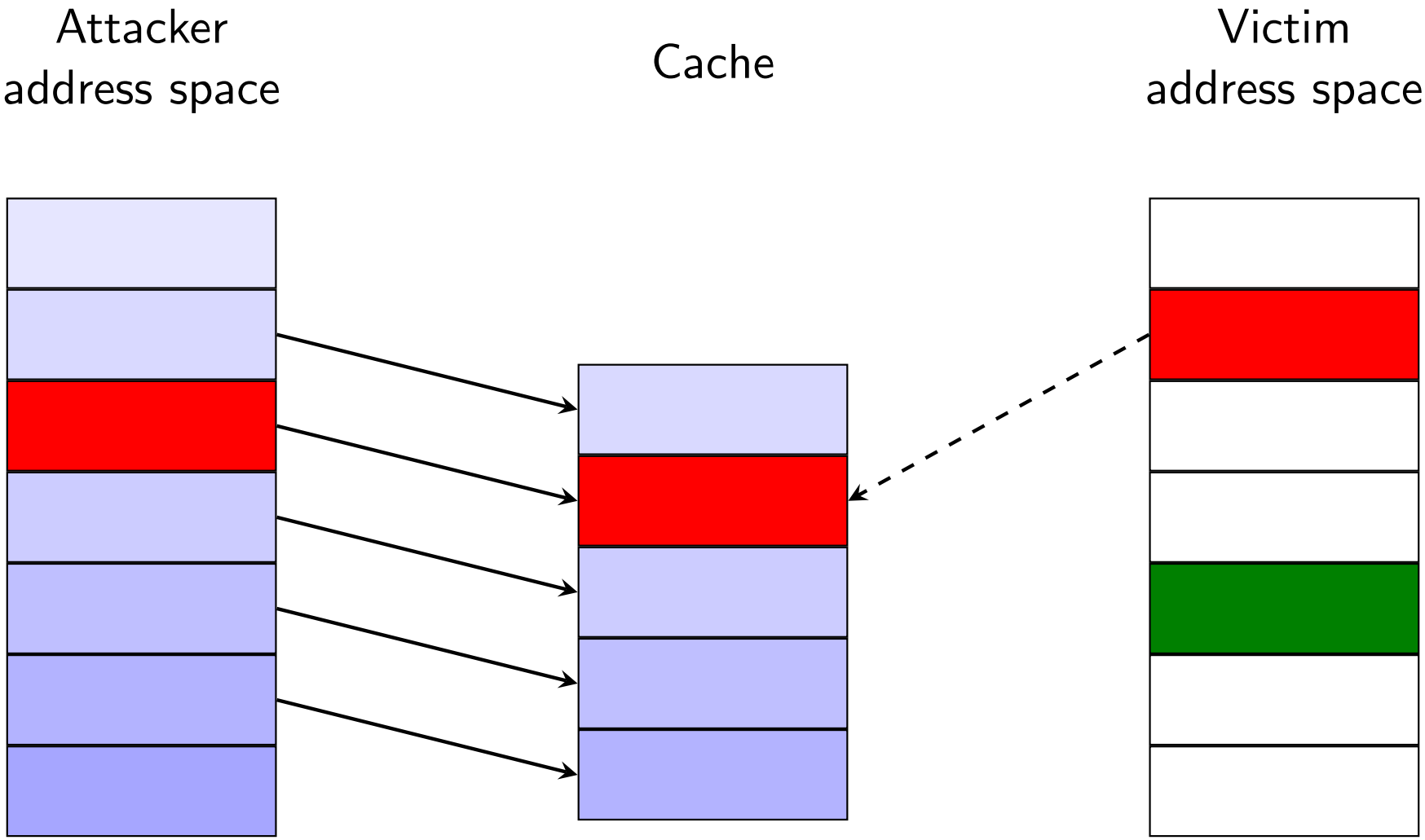
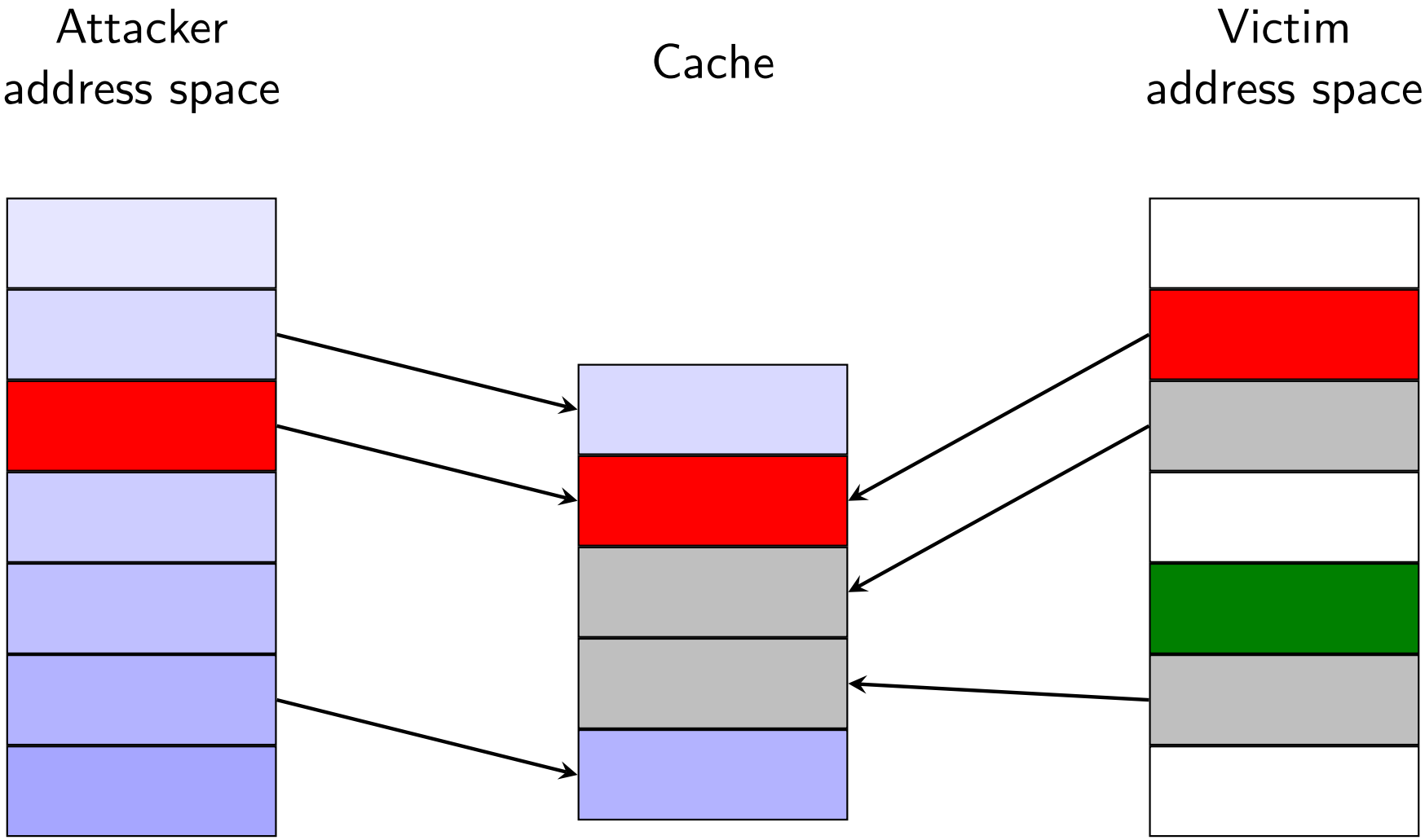


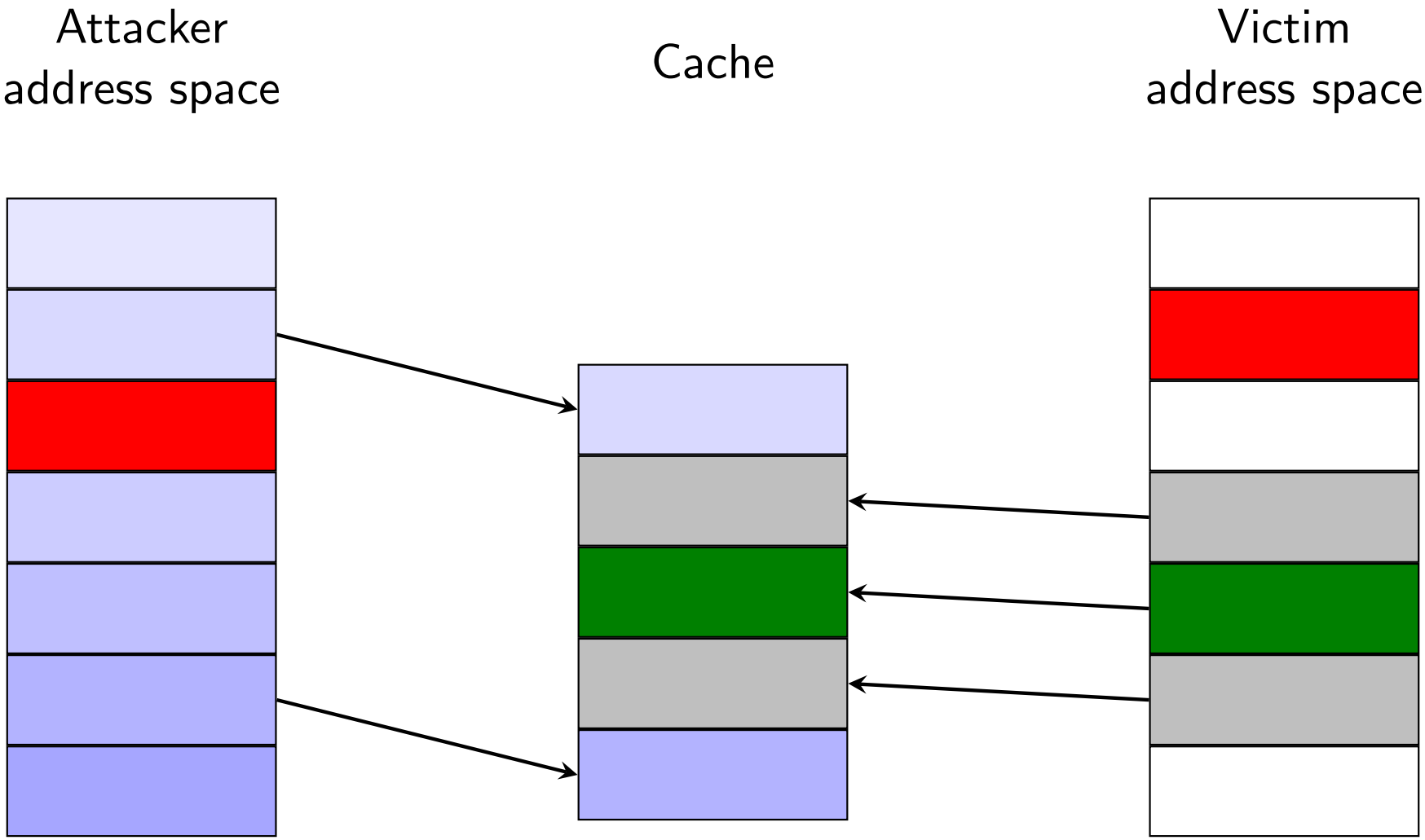
Step 1: attacker fills *all* available cache (prime)

Prime+Probe



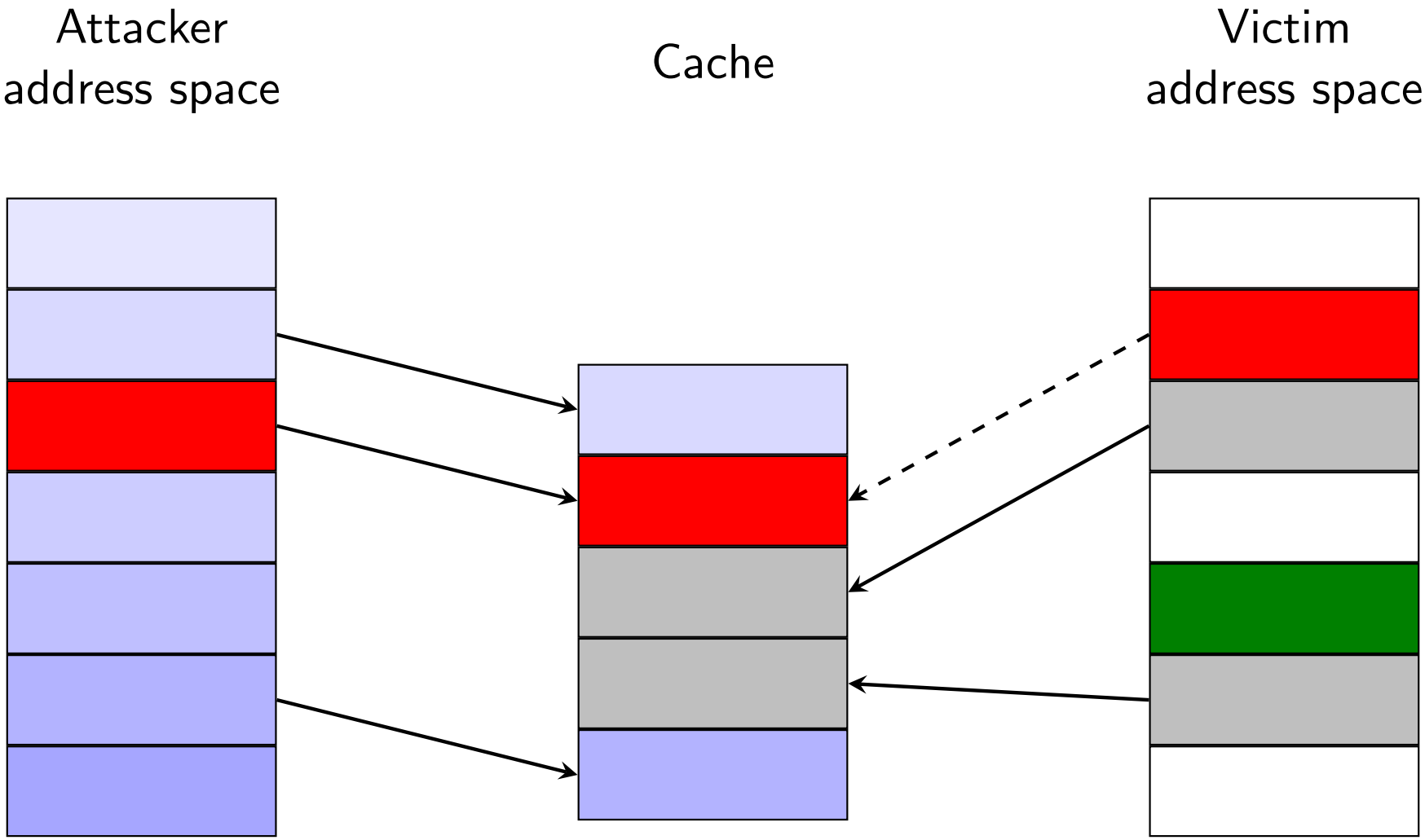
Step 2(a): victim evicts cache lines while performing operation `encrypt()`

Prime+Probe



Step 2(b): victim evicts cache lines while performing operation `decrypt()`

Prime+Probe



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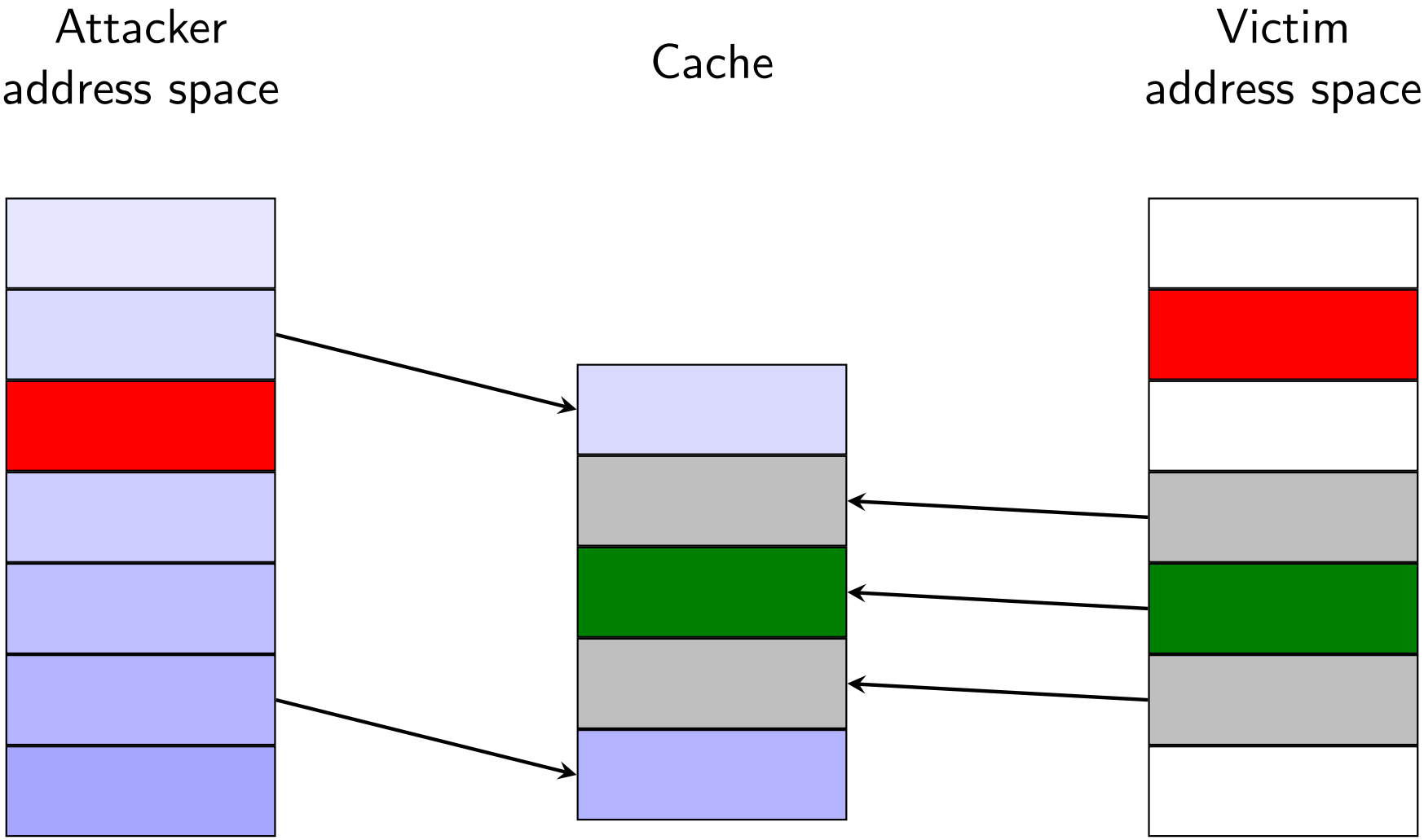

Step 3: attacker calls `encrypt()` after **step 2(b)** $\Longrightarrow$ slow!

Potential countermeasures

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- Fuse the functionalities into a single code piece

```
1 if (flag) { encrypt_instruction_1(); }
2 else      { decrypt_instruction_1(); }
3 if (flag) { encrypt_instruction_2(); }
4 else      { decrypt_instruction_2(); }
5 ...
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- Voluntary cache eviction

Both at the expense of performance overhead.

More systematic countermeasures

- Use constant-time programming techniques
- Eliminate secret-dependent execution or branches
- Hide/blind inputs

Outline

Example 1: matrix multiplication

```
1  int *matrix_multiply(
2      __secret__ int *A, size_t nrow_A, size_t ncol_A,
3      __secret__ int *B, size_t nrow_B, size_t ncol_B
4  ) {
5      assert(ncol_A == nrow_B);
6      int *C = malloc(nrow_A * ncol_B * sizeof(int));
7
8      for(int i = 0; i < nrow_A; i++) {
9          for(int j = 0; j < ncol_B; j++) {
10             for(int k = 0; k < A_ncol; k++) {
11                 C[i * ncol_B + j] += A[i * ncol_A + k] * B[k * ncol_B + j];
12             }
13         }
14     }
15     return C;
16 }
```

Q: Is the above function constant-time (w.r.t secret input)?

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A: Yes

Example 1: find max

```
1 int *find_max(__secret__ int *arr, int n) {
2     int max_val = INT_MINIMUM;
3     for (int i = 0; i < n; i++) {
4         if (arr[i] > max_val) {
5             max_val = arr[i];
6         }
7     }
8     return max_val;
9 }
```

Q: Is the above function constant-time (w.r.t secret input)?

Example 1: find max (patched)

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1 int *find_max(__secret__ int *arr, int n) {
2     int max_val = INT_MINIMUM;
3     for (int i = 0; i < n; i++) {
4         int predicate = arr[i] > max_val;
5         max_val = (predicate * arr[i])
6                 | (!predicate * max_val);
7     }
8     return max_val;
9 }
```

Example 2: get element

```
1 int *get_element(
2     int *arr, int size, __secret__ int index
3 ) {
4     int element = arr[index];
5     return element;
6 }
```

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Example 2: get element (patched)

```
1  int *get_element(
2      int *arr, int size, __secret__ int index
3  ) {
4      int element = 0;
5      for (int i = 0; i < size; i++) {
6          int value = arr[i];
7          element = select(i == index, value, element);
8      }
9      return element;
10 }
```

Example 3: constant-time instructions

```
1 void foo(double x) {
2     double z, y = 1.0;
3     for (long i = 0; i < 100000000; i++) {
4         z = y * x;
5     }
6 }
```

Q: Which of the following execution is faster?

1. `foo(1.0)`
2. `foo(1.0e-323)`
3. they are the same

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A: `foo(1.0)`

Rules of thumb for constant-time programming

- Avoid variable-time instructions
- If-statements on secrets are unsafe
- Memory accesses indexed by secrets are unsafe
- There are tools to help but most constant-time code is still written by hand

Outline

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An attacker creates a capability to transfer sensitive/unauthorized information through a channel that is not supposed to transmit that information.

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What information can/cannot be transmitted through a channel may be determined by a policy/guidelines/physical limitations, etc.

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  - But Alice closely watches all Internet traffic from her computer
  - Better, she doesn't connect her computer to the Internet at all!

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- Suppose Alice publishes a weekly report summarizing some (nonsensitive) statistics

How can we create a covert channel?

- Assume that Eve can arrange for malicious code to be running on Alice's machine
  - But Alice closely watches all Internet traffic from her computer
  - Better, she doesn't connect her computer to the Internet at all!
- Suppose Alice publishes a weekly report summarizing some (nonsensitive) statistics
- Eve can "hide" the sensitive data in that report!
  - e.g., modifications to spacing, wording, or the statistics itself

⟨ End ⟩