ECE 382N-Sec (FA26):

L3: Side Channels in Public Clouds

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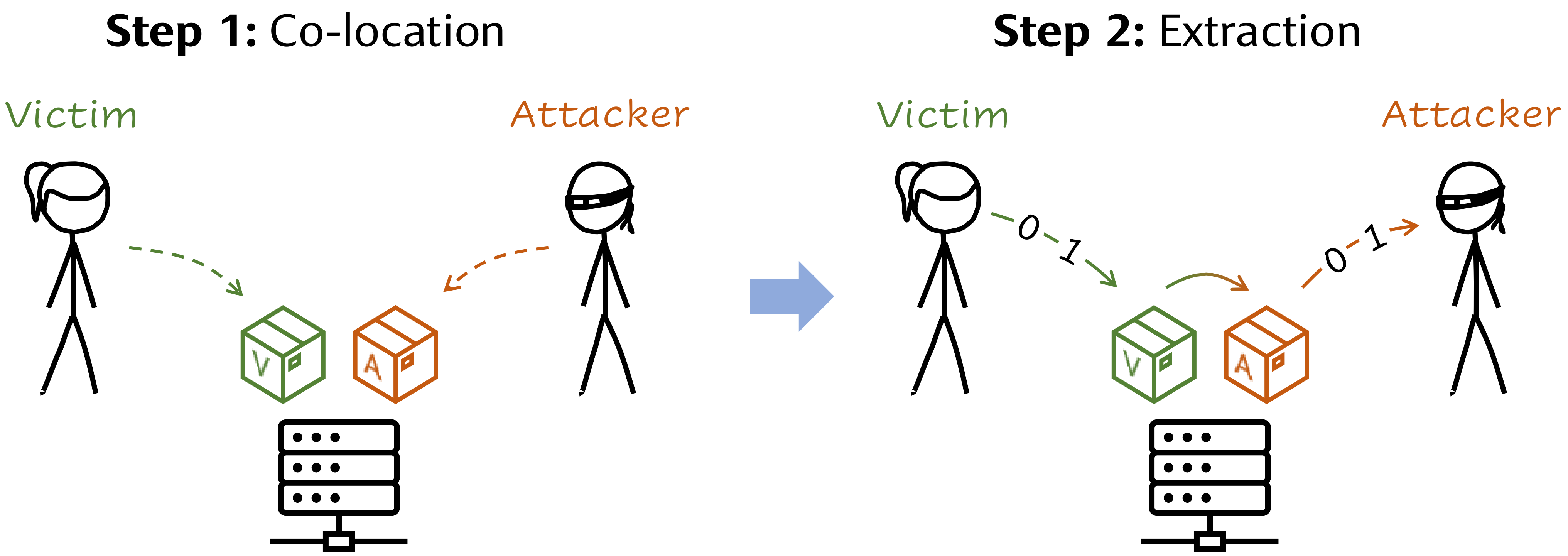
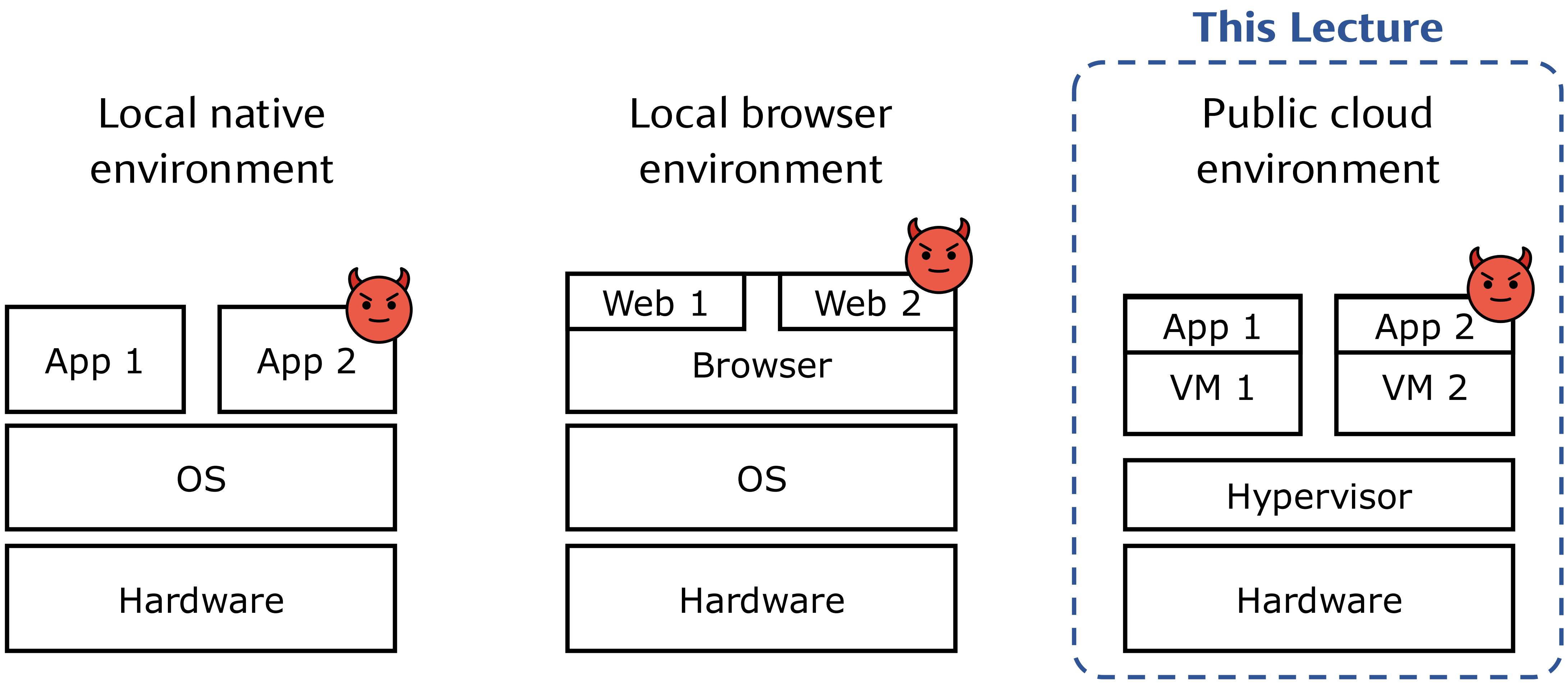
Two Steps of a Side-Channel Attack



Three Common Co-location Scenarios



Why Public Cloud?

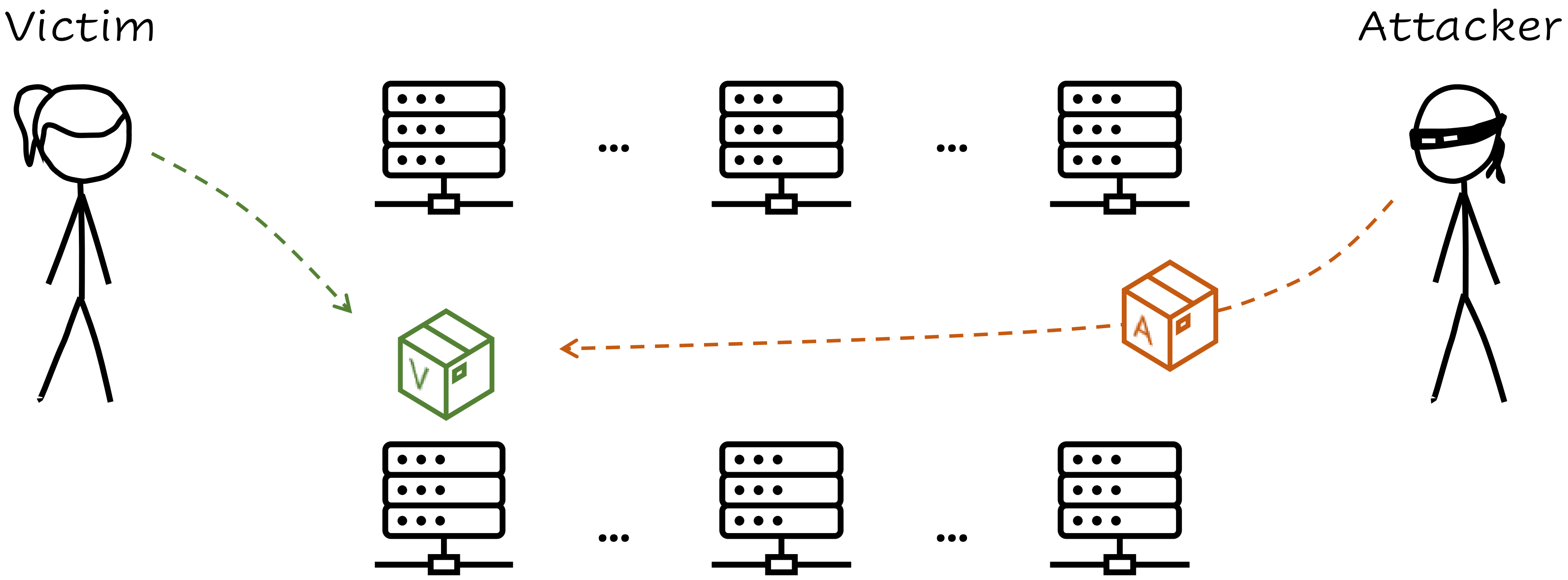
- Public cloud fundamentally relies sharing hardware resources among tenants

- Your VMs are (very likely) always co-located with someone else's VMs
  - Unlike the local setting, the attacker doesn't need to trick you to visit a malicious website or download a malicious app

- Moreover,
  - You cannot control who your "neighbors" are
  - You don't even know who your "neighbors" are

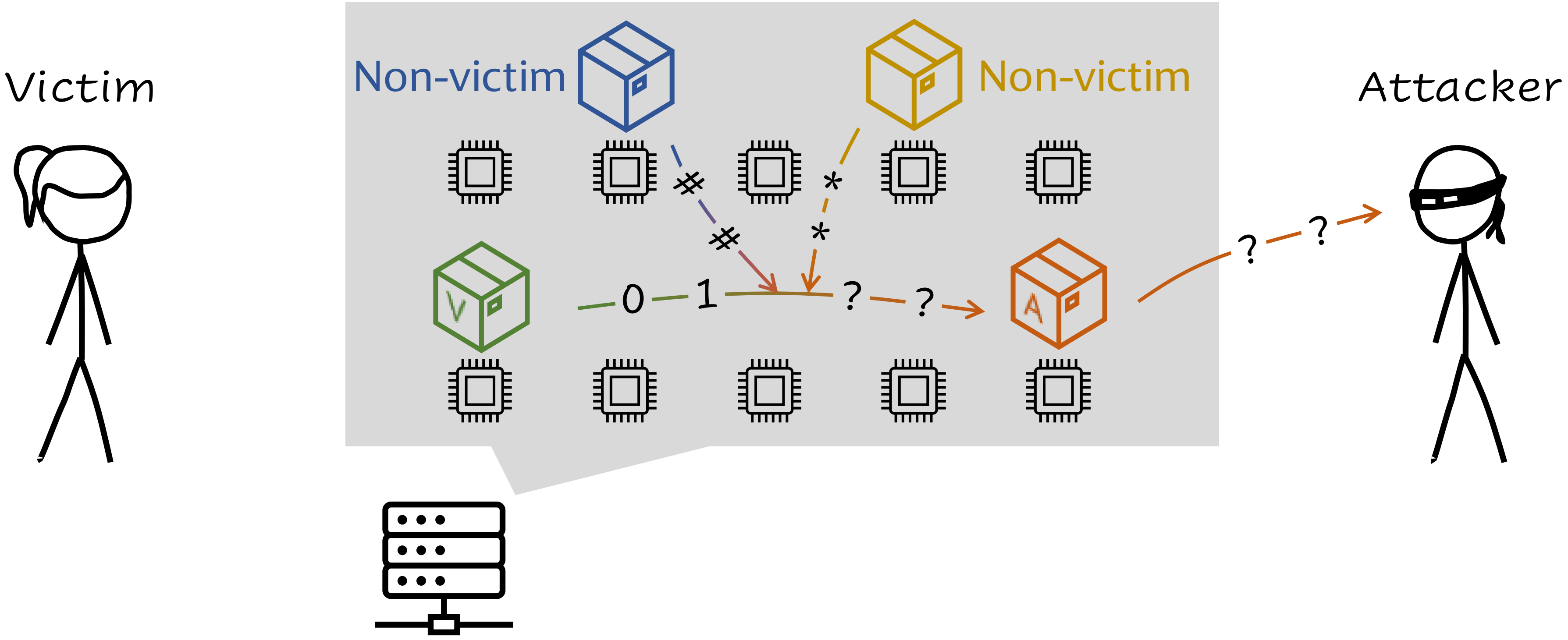
Why Side Channels in Public Cloud is Hard?

Challenge 1: Co-location with the victim in a vast datacenter



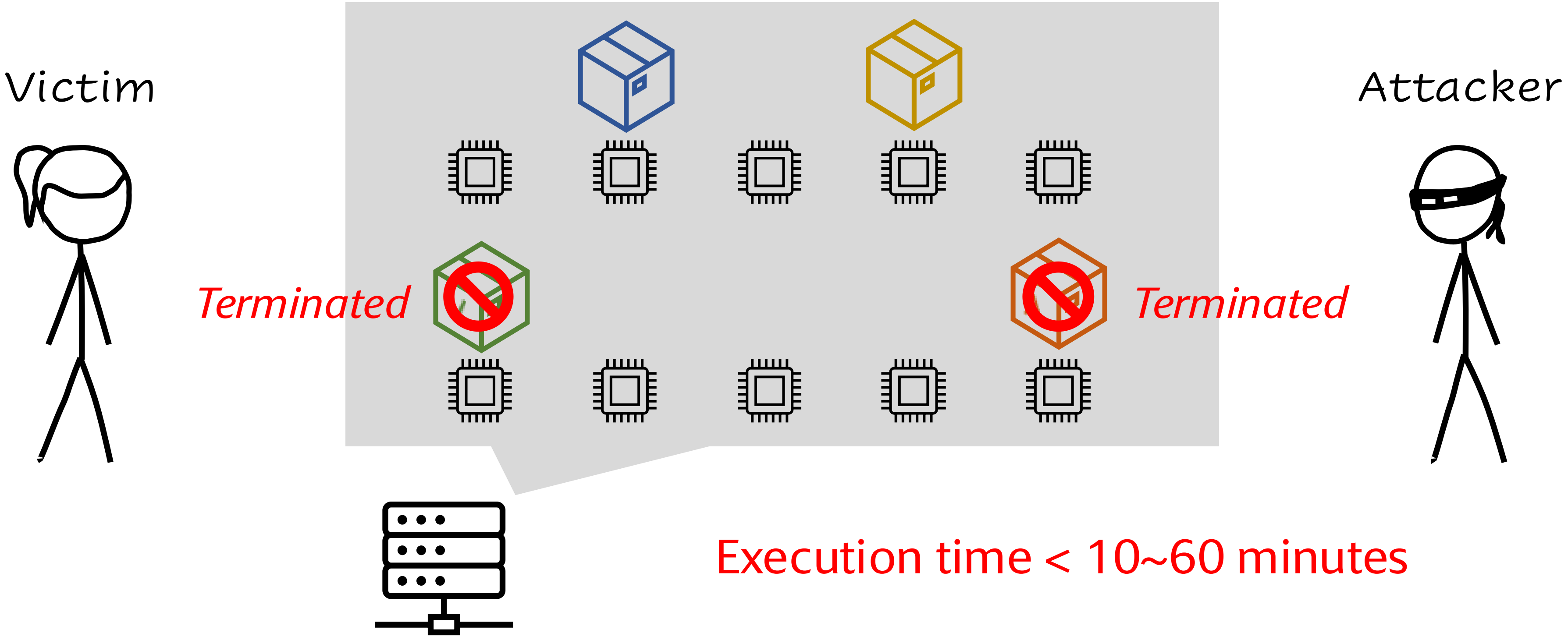
Why Side Channels in Public Cloud is Hard?

Challenge 2: Production cloud is noisy



Why Side Channels in Public Cloud is Hard?

Challenge 3: Modern clouds (e.g., FaaS) are dynamic



Execution time < 10~60 minutes

Cloud Vendors Claim Side-Channel Attacks are Impractical

Example: AWS Whitepaper – The Security Design of the AWS Nitro System (Nov. 2022)

Paraphrased:

"Last-level cache (LLC) Prime+Probe is impractical due to the noise; therefore, our side-channel mitigations are very strong even if we do not protect VMs against LLC Prime+Probe"

Let's Start with Co-location

CCS '09

Hey, You, Get Off of My Cloud: Exploring Information Leakage in Third-Party Compute Clouds

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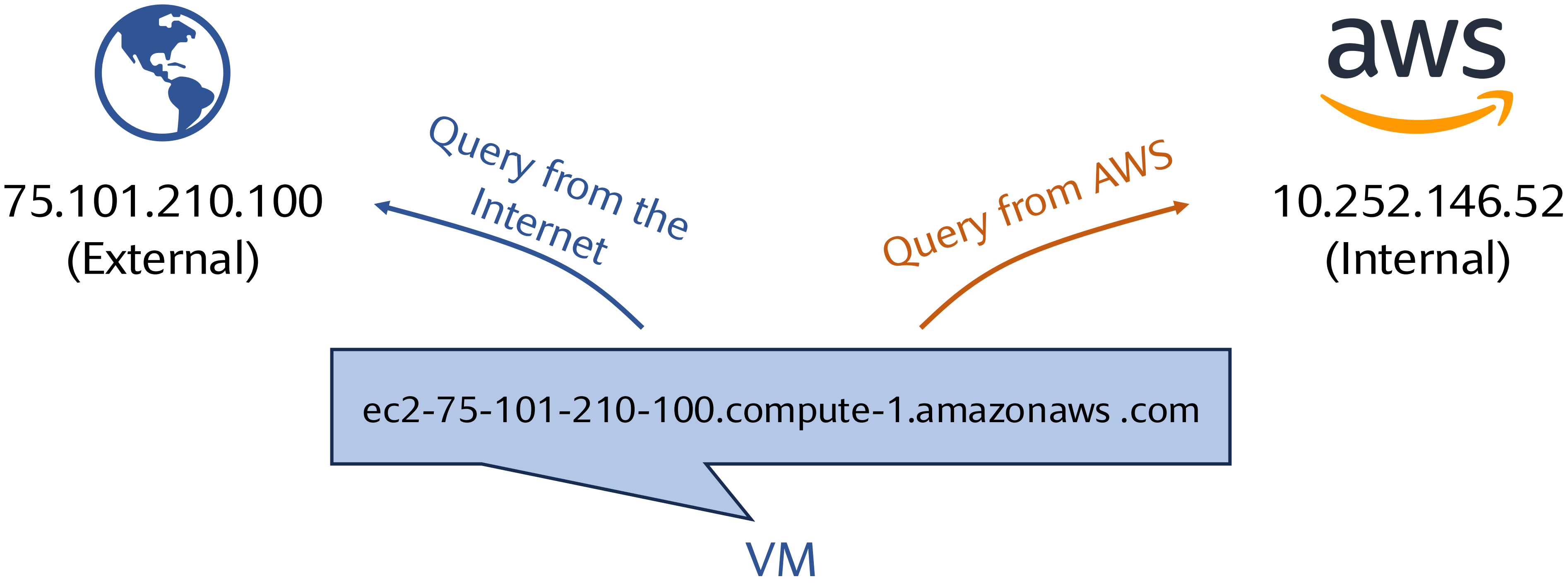
tromer@csail.mit.edu

3085 citations to date

Tips:

- Be the first
- Find a catchy title
- Form a strong team

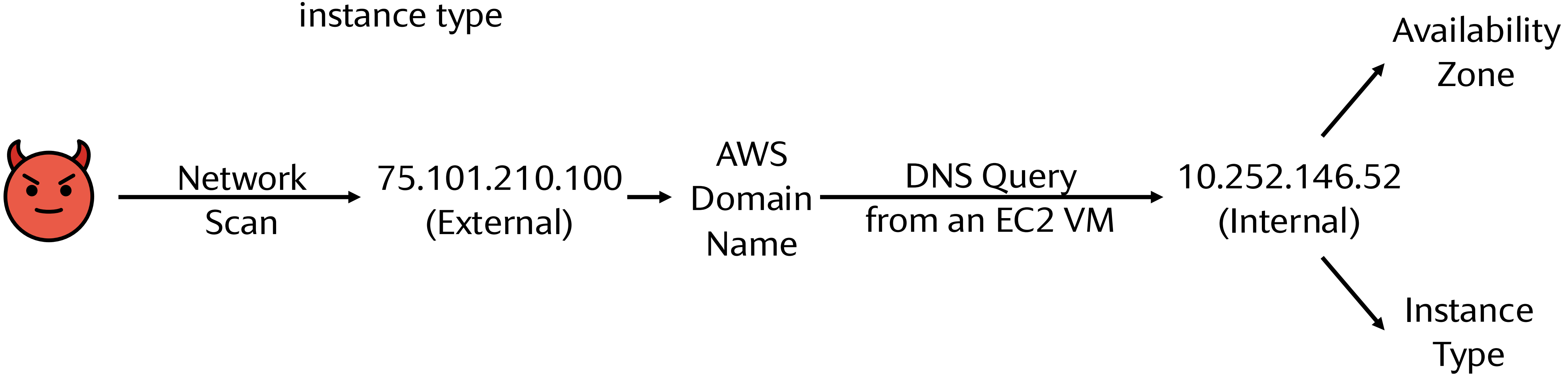
Networking of VMs in AWS (in 2009)



Hypothesis: a VM’s internal IP depends on its where the VM is placed

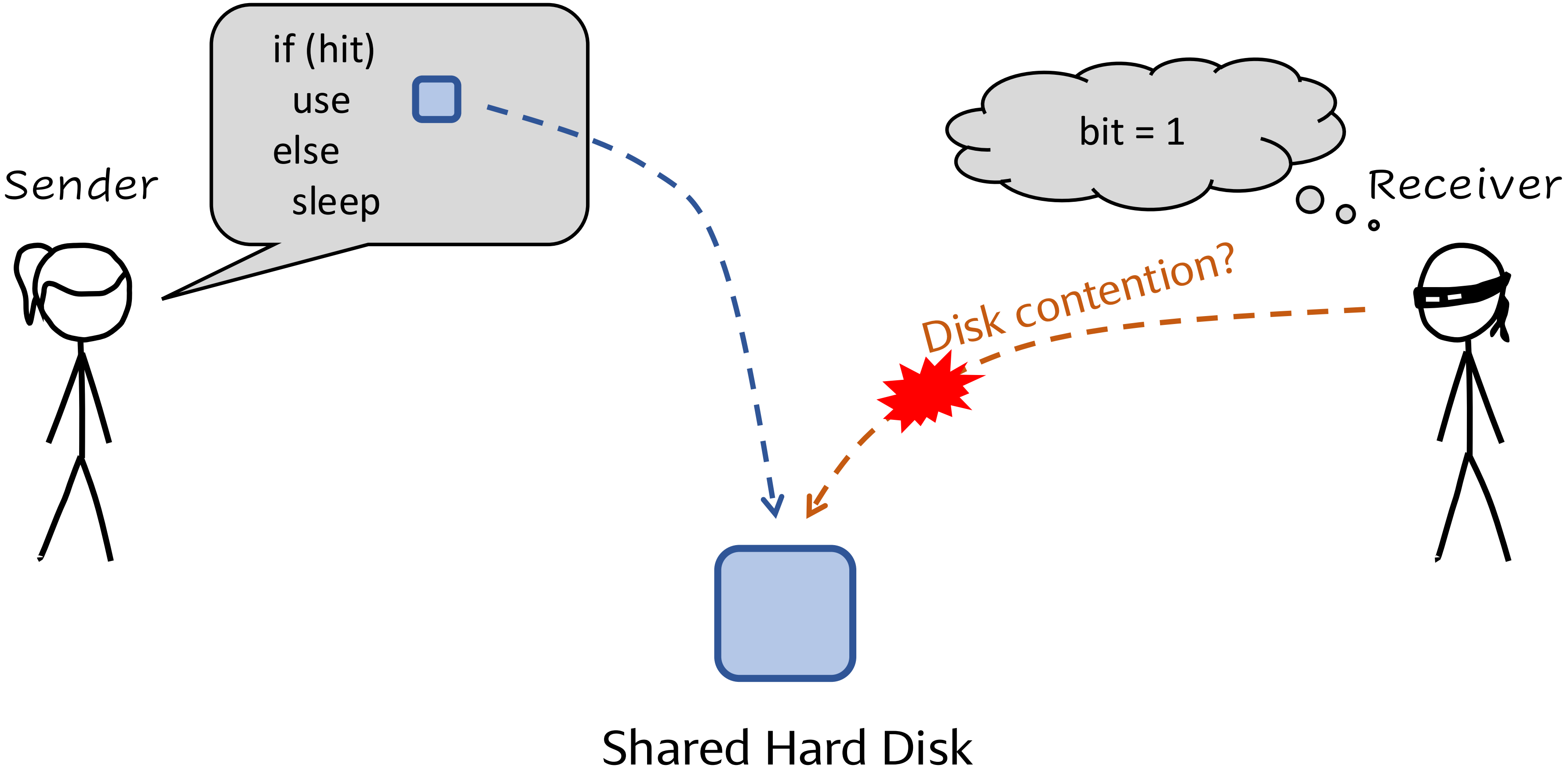
Cloud Cartography

- **Method:** Launch VMs with different instance types in different zones, record their internal IPs
- **Overall findings:**
  - Different zones use distinct ranges of internal IP addresses
  - An IP /24 prefix (e.g., 10.252.10.*) mostly corresponds to a specific instance type

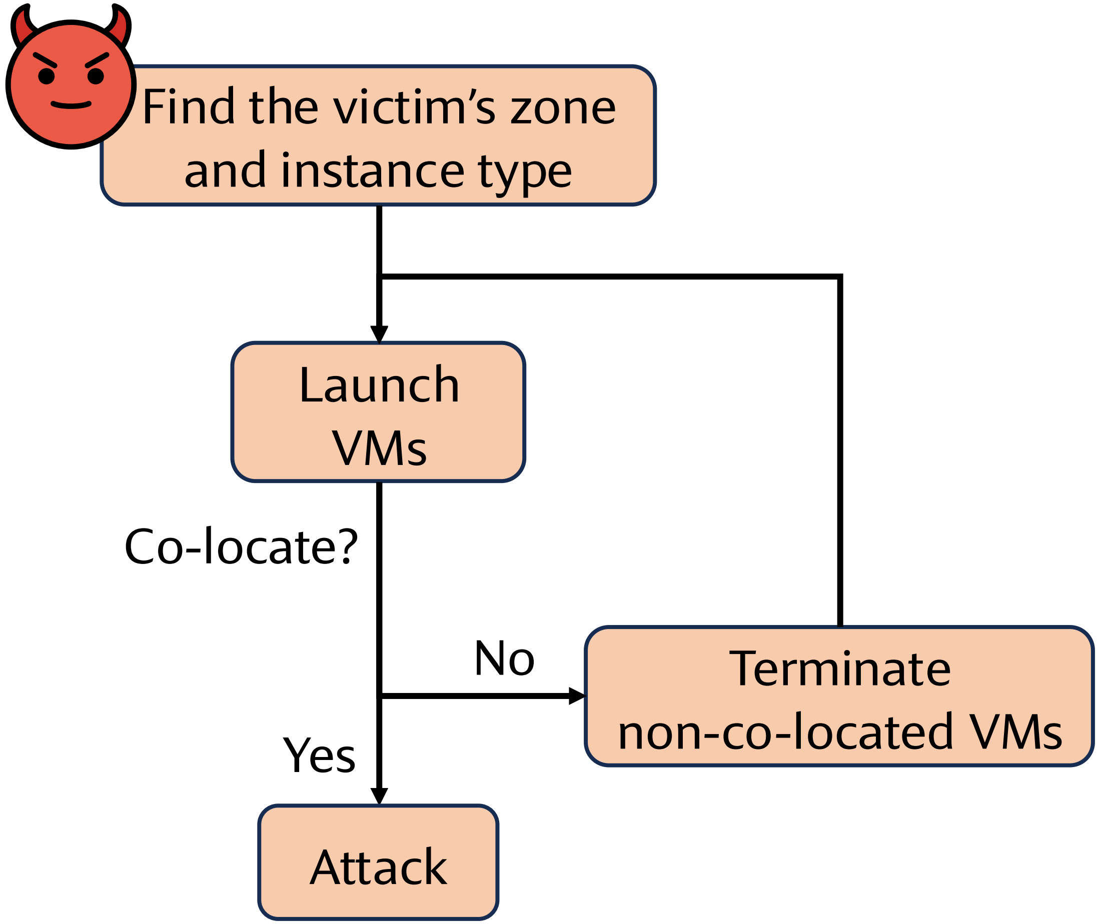


Verifying Co-location With a Covert Channel

Send a random 5-bit message



Brute-Force Placement

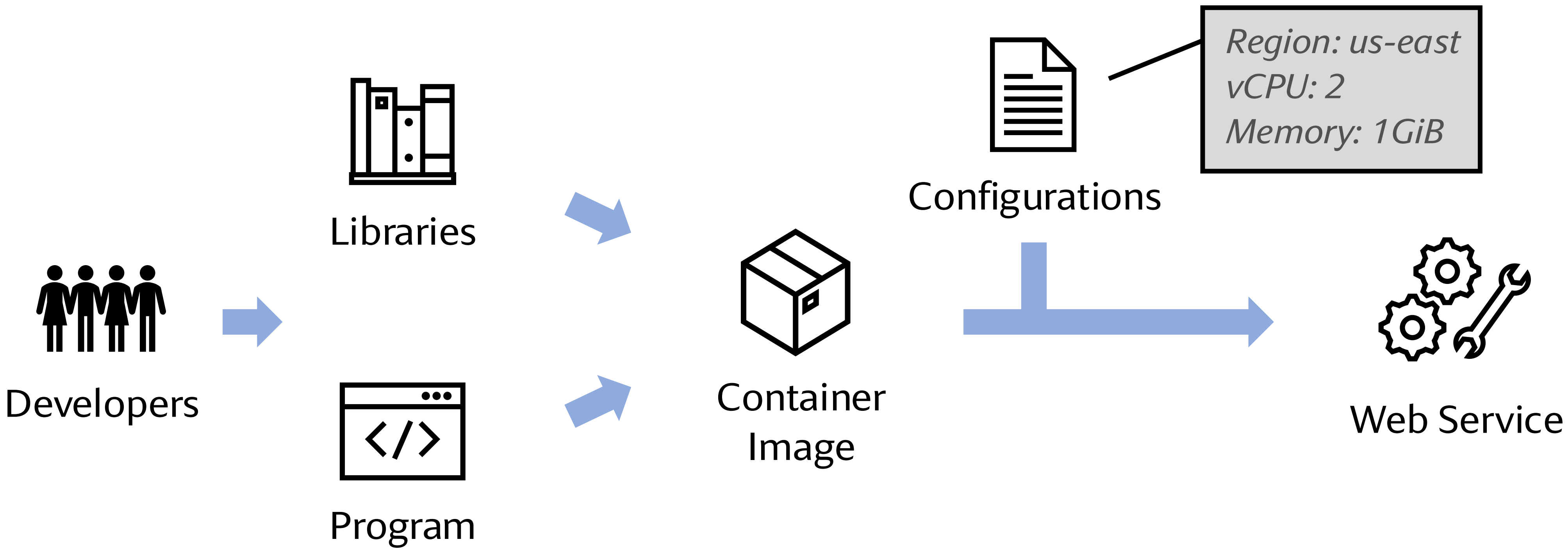


8.4% victim coverage
(over 18 days)

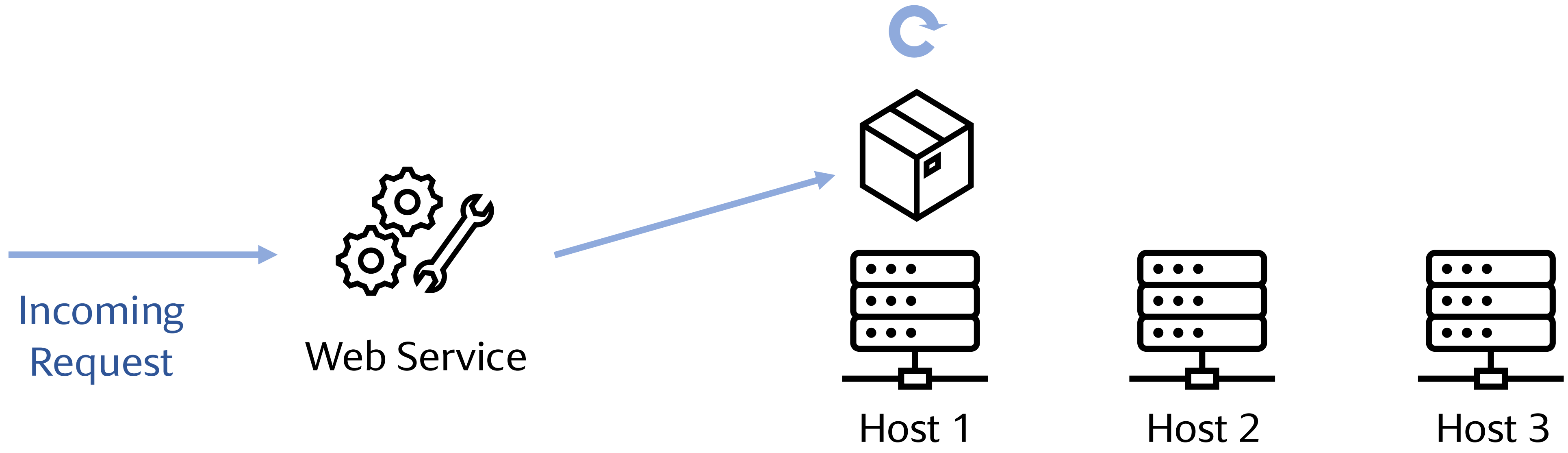
What Changed from 2009

- Virtual private cloud ⇒ network isolation between tenants
- More servers ⇒ Harder to co-located
- More powerful hardware ⇒ More tenants on the same node and thus more noise
- The widespread of non-inclusive LLC
- Container + Function-as-a-Service (FaaS)
  - Short lifetime
  - High background noise

Background: Fully-Managed Containerized Environment



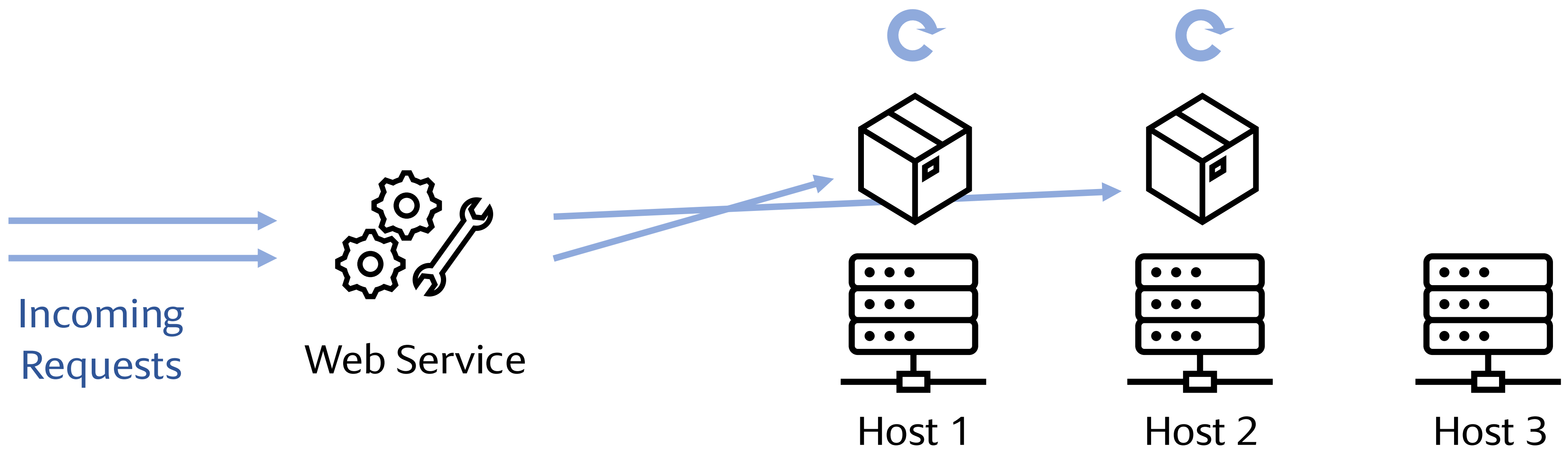
Background: Fully-Managed Containerized Environment



Cloud vendor automatically launches a container instance

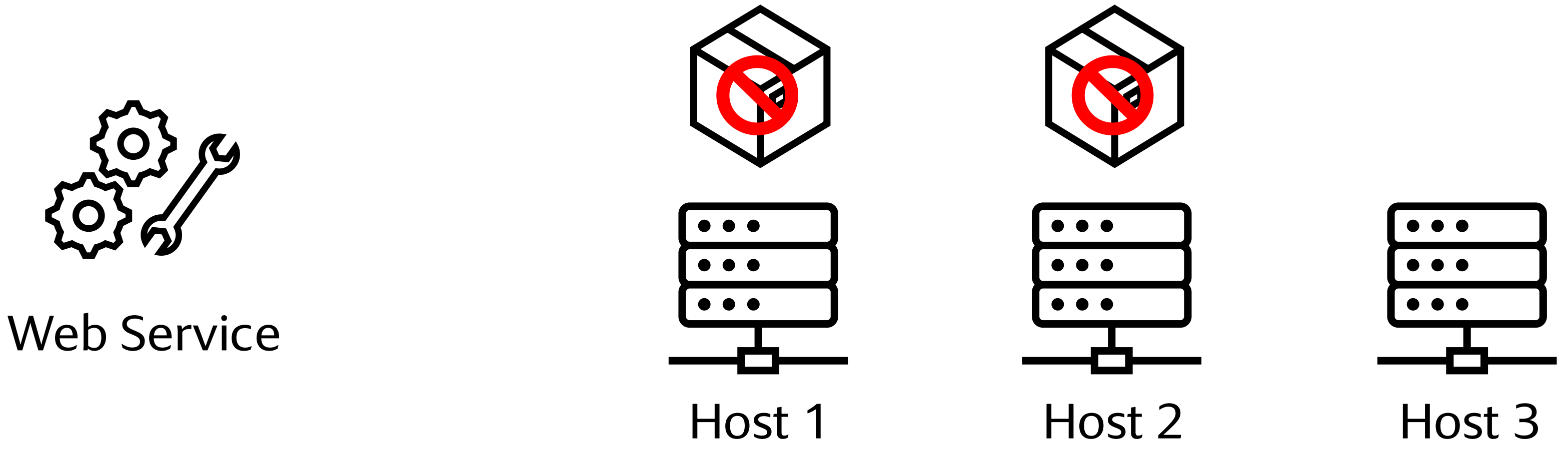
(The instance placement is managed by the vendor)

Background: Fully-Managed Containerized Environment



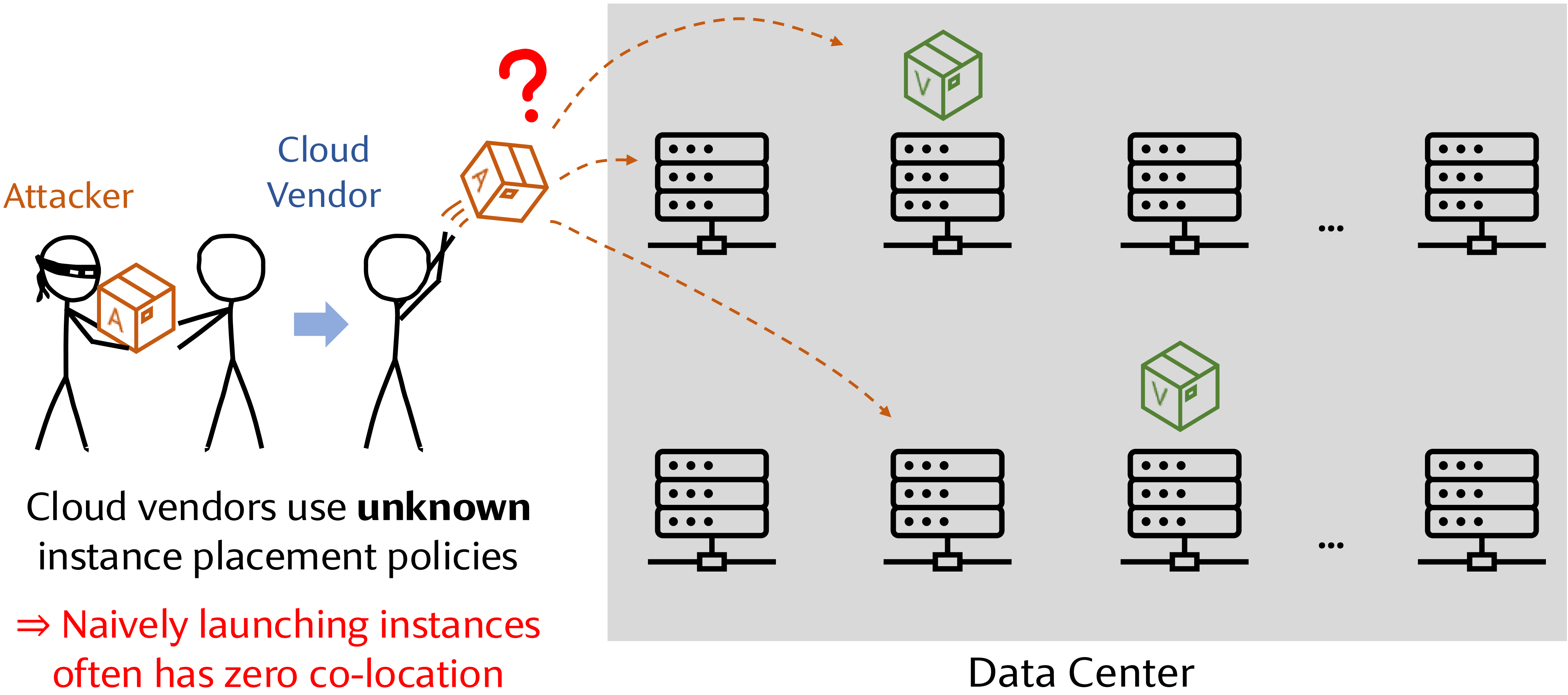
Cloud vendor launches more instances to handle traffic increases

Background: Fully-Managed Containerized Environment



Cloud vendor automatically terminates idle instances

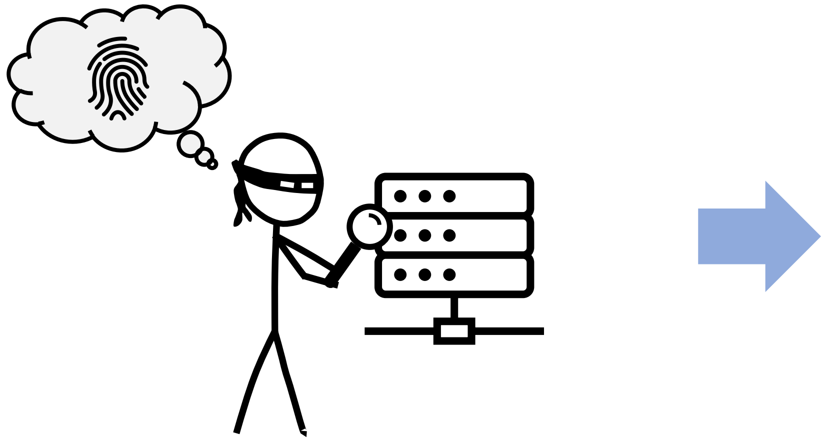
Fog of War: Container Instance Placement



Cloud vendors use **unknown** instance placement policies

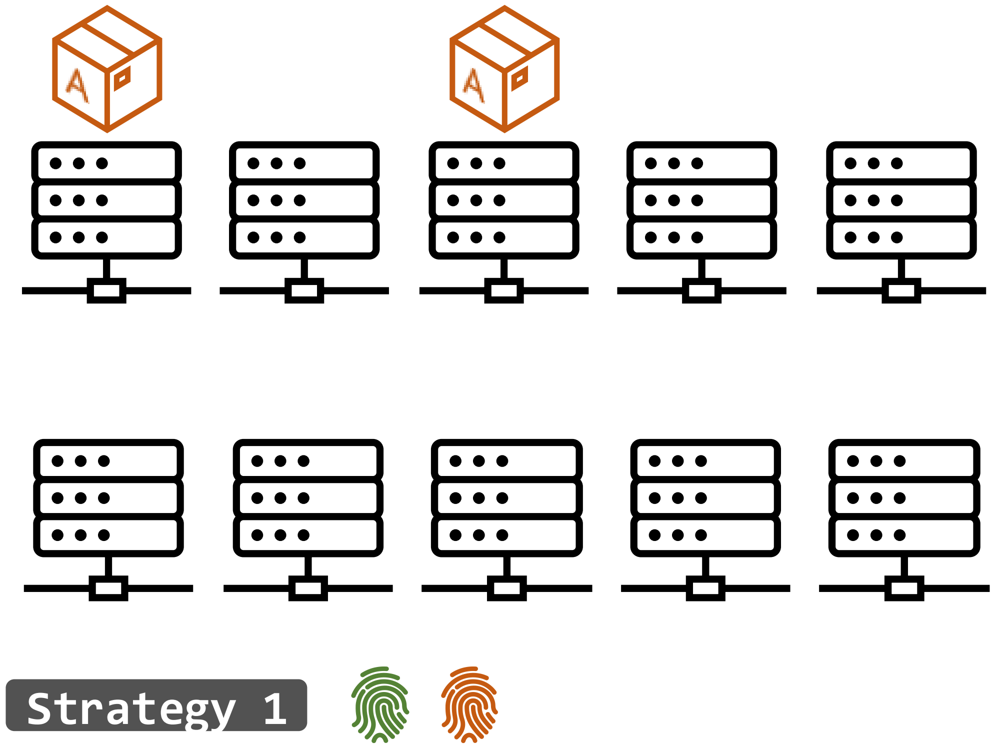
⇒ Naively launching instances often has zero co-location

Idea: Fingerprint Host → Reverse Engineer Placement Behavior



Accurate host fingerprinting

Understand container placement



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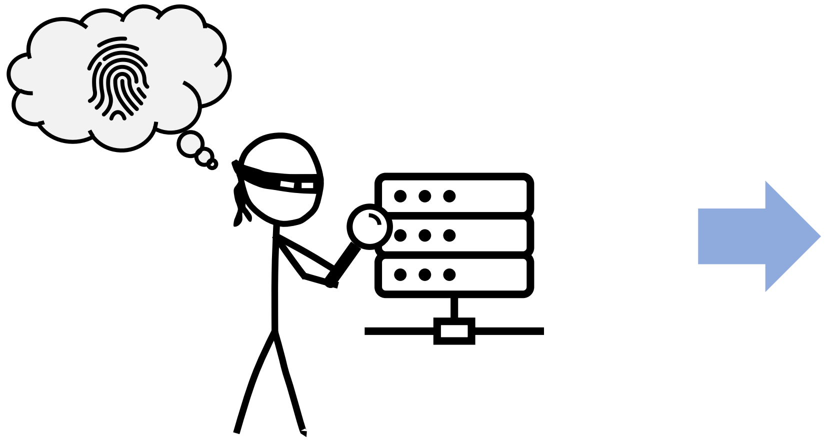
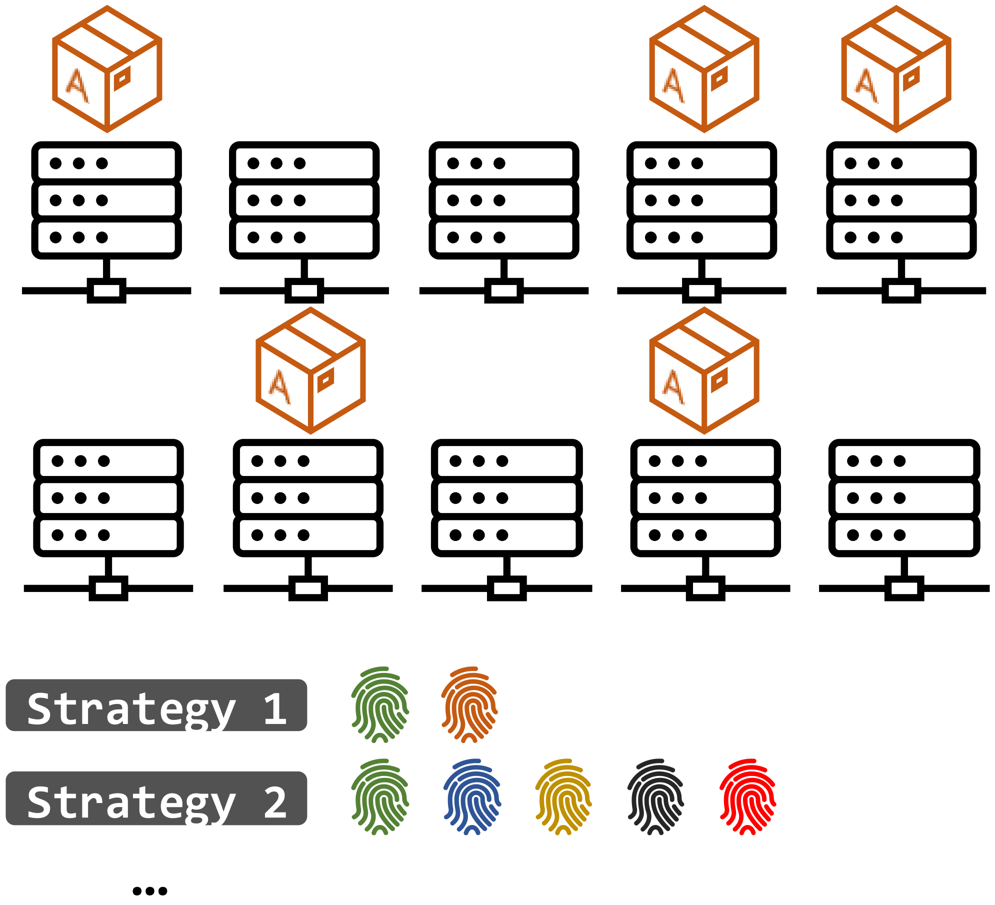


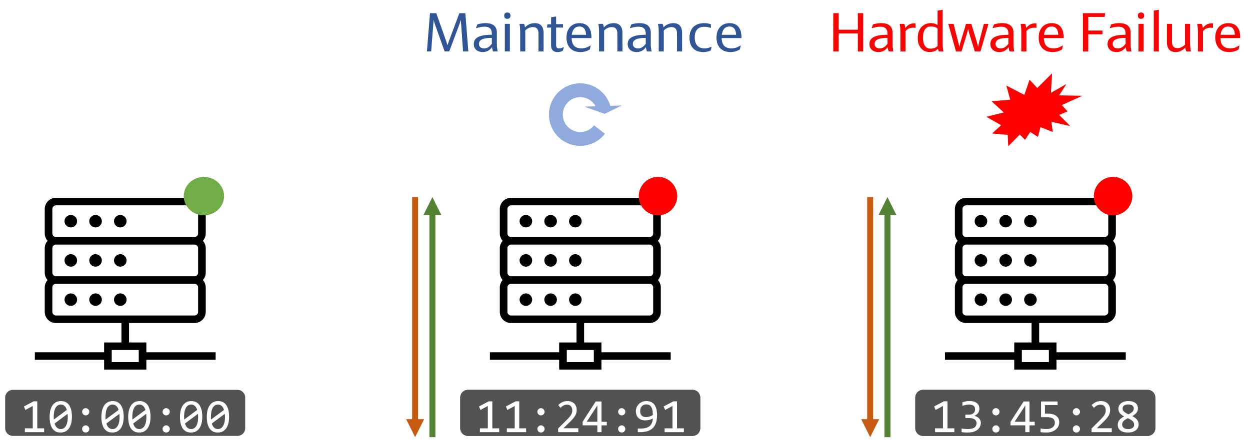
Accurate host fingerprinting

Understand container placement



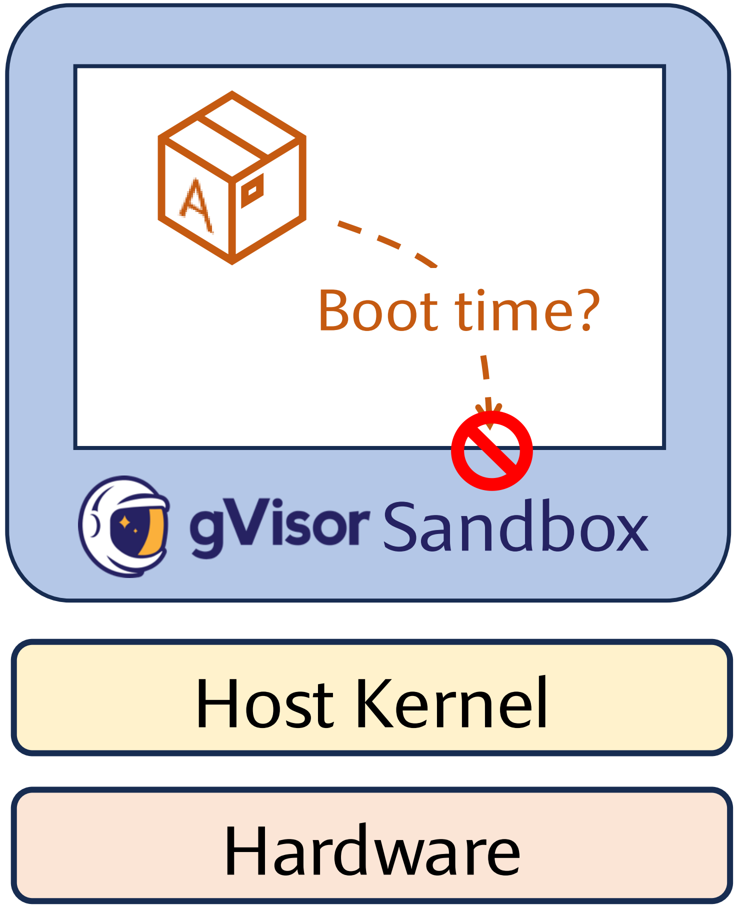
Insight 1: Physical Host’s Boot Time as Fingerprint

Boot times:



Likely unique within a data center

Challenge: Host Information is Hidden Due to Sandboxing

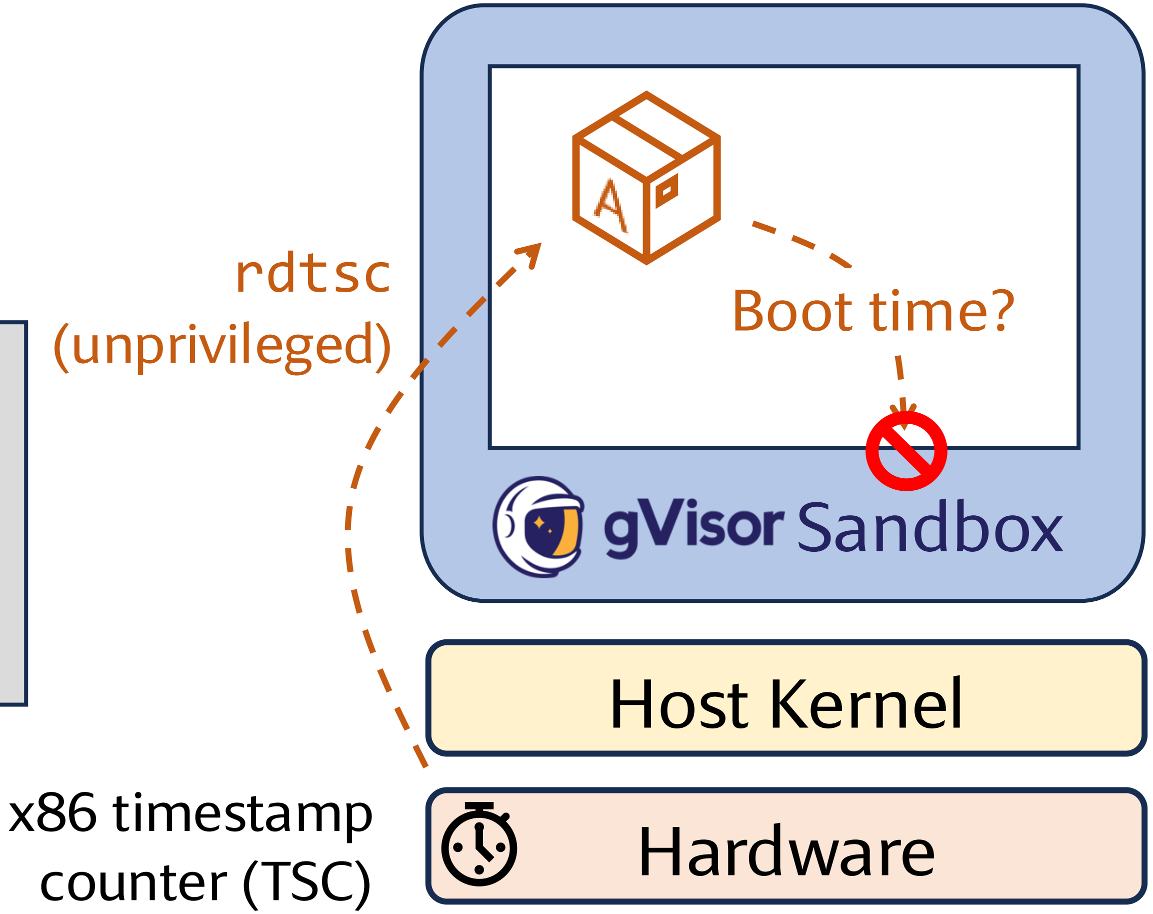


Insight 2: Bypassing Software Protection by Asking the Hardware

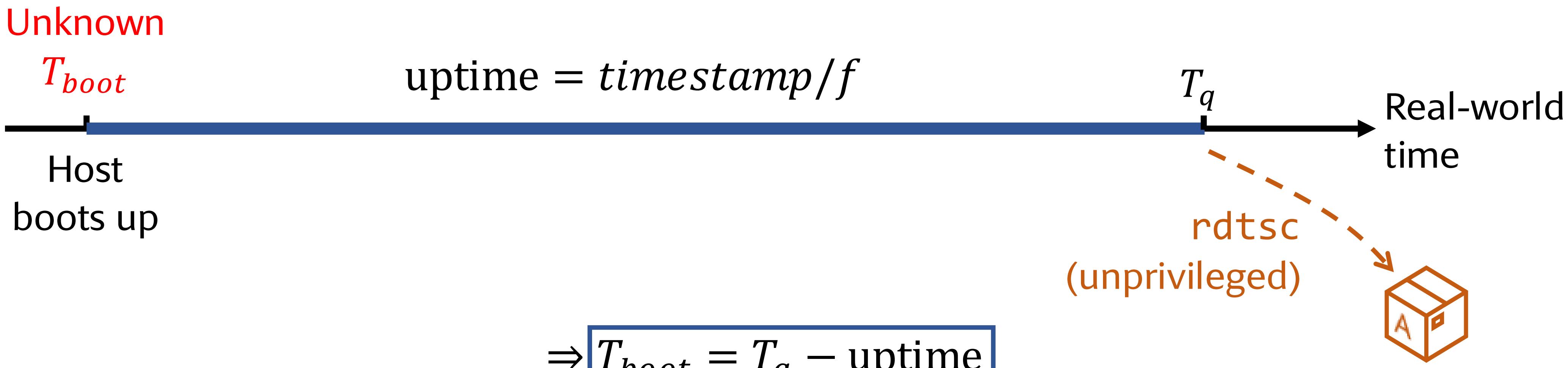
Useful properties:

1. Reset to **0** when the physical host boots
2. Increments at a **known** fixed rate f

Not affected by CPU frequency scaling and power state



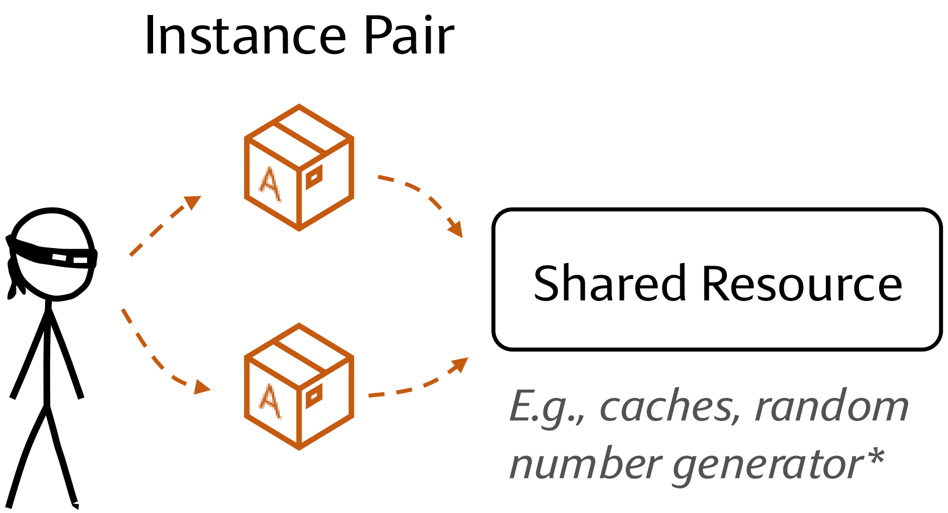
Derive Boot Time From Timestamp Counter

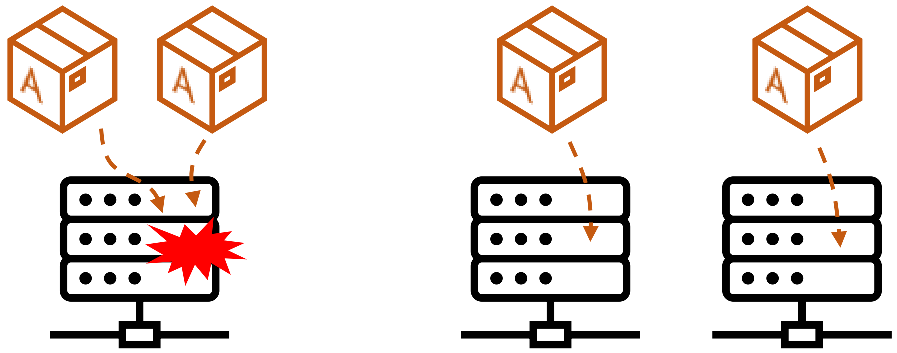


$$\Rightarrow \boxed{T_{boot} = T_q - \text{uptime}}$$

Fingerprint

Verifying Co-Location





Contention!
⇒ Co-Located

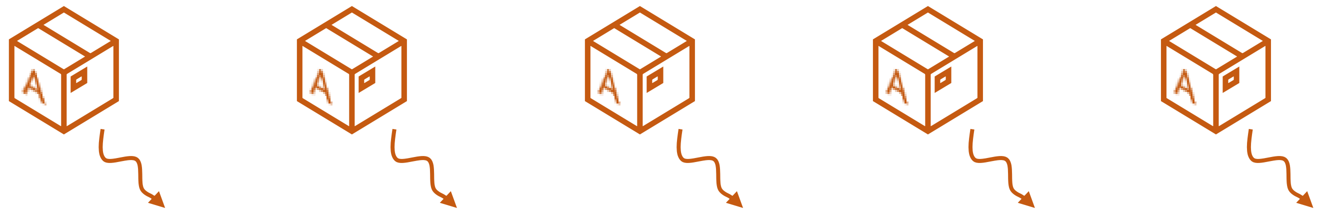
No Contention
⇒ Not Co-Located

Scalability issue: it requires $O(N^2)$ pairwise tests to verify N containers

* Evtyushkin et al., Covert Channels through Random Number Generator: Mechanisms, Capacity Estimation and Mitigations (CCS '16)

Go Beyond Pairwise Testing – Batch Testing

	A_1	A_2	A_3	A_4	A_5



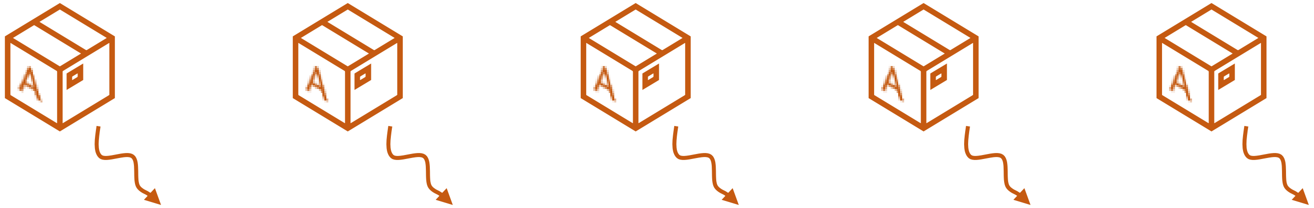
Contention?	✗	✗	✗	✓	✓

A_1, A_2, A_3 do not co-locate with any other instance (i.e., they are *single instances*)

A_4 and A_5 are co-located

Go Beyond Pairwise Testing – Batch Testing

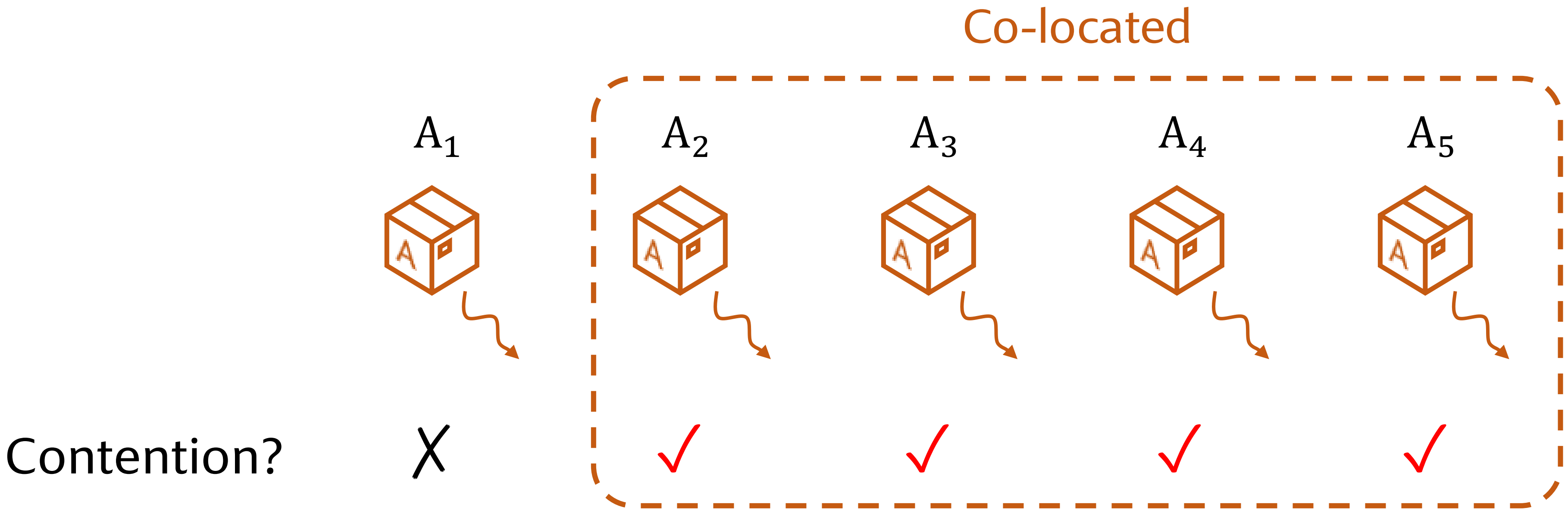
	A_1	A_2	A_3	A_4	A_5



Contention?	✗	✗	✓	✓	✓

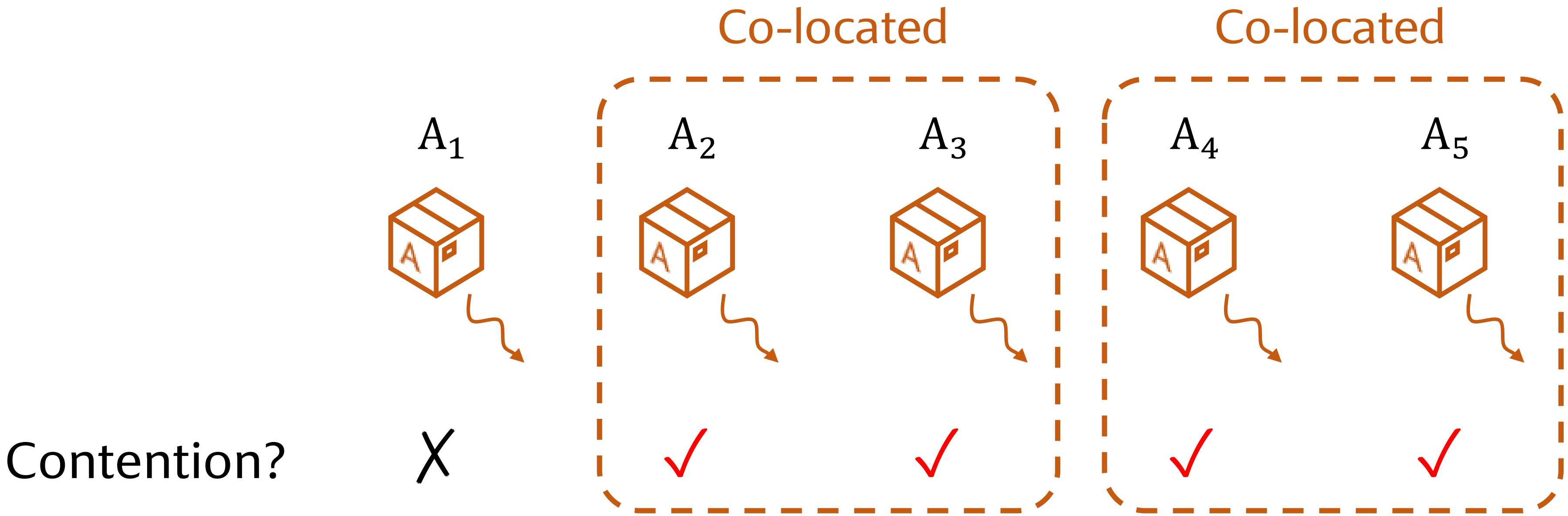
A_3, A_4, A_5 are co-located

Go Beyond Pairwise Testing – Batch Testing



A_2, A_3, A_4, A_5 are co-located? Not sure!

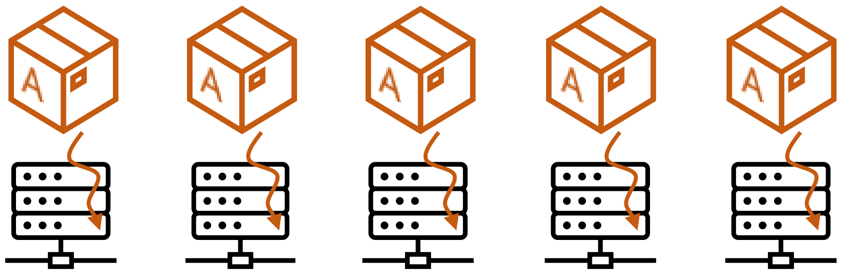
Go Beyond Pairwise Testing – Batch Testing



A_2, A_3, A_4, A_5 are co-located? Not sure!

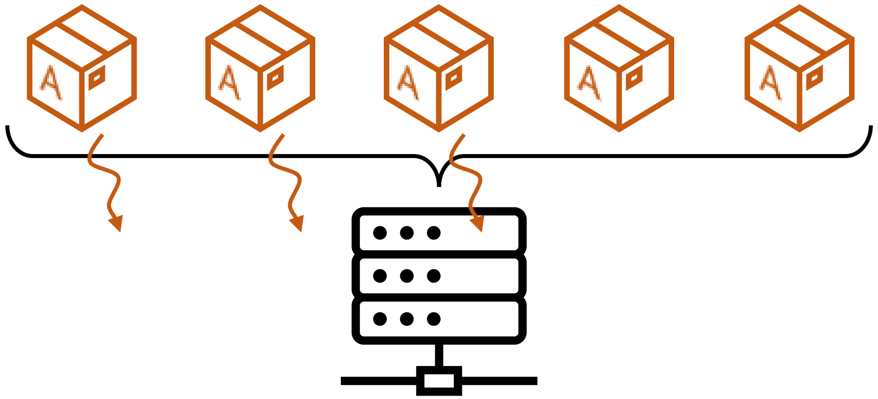
Batch Testing Strategies

Truly not co-located



Batch test all instances at once

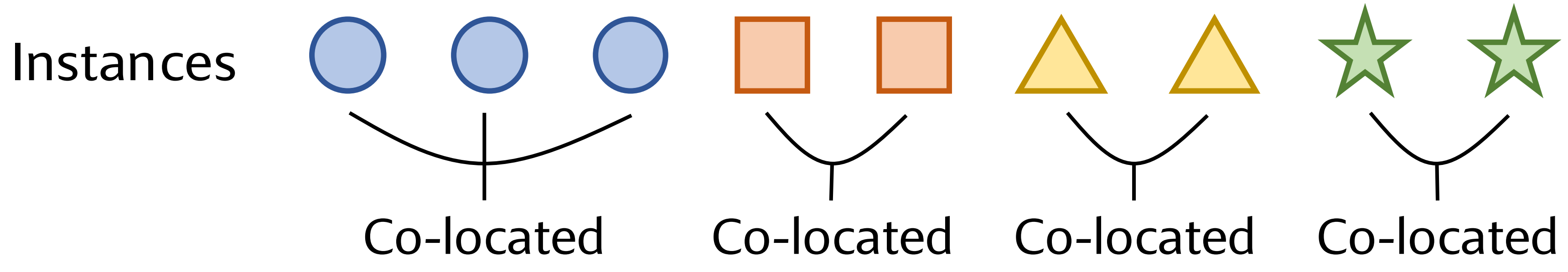
Truly co-located



Batch test 3 instances at once

If fingerprints are accurate, they can provide hints on which instances are likely co-located

Fingerprint-Assisted Co-Location Verification



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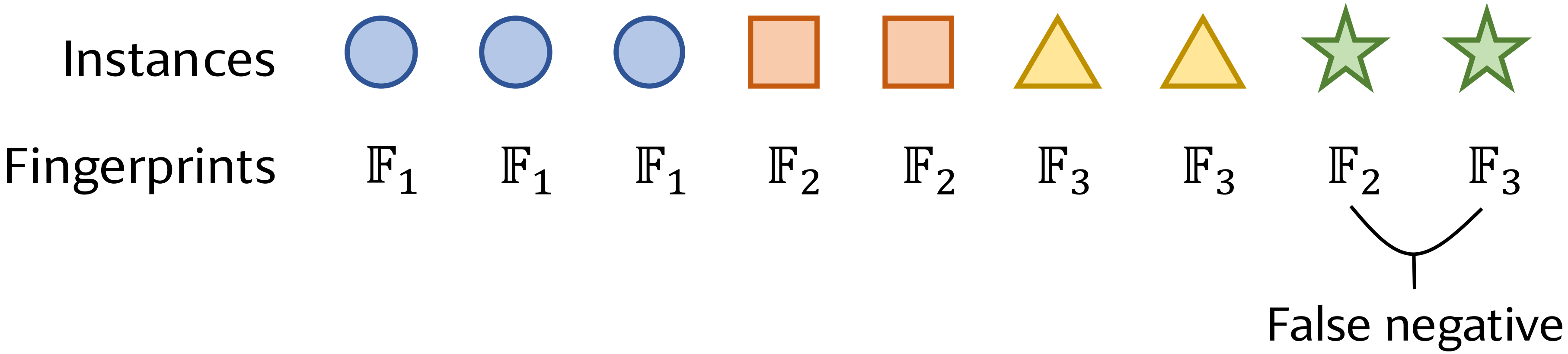

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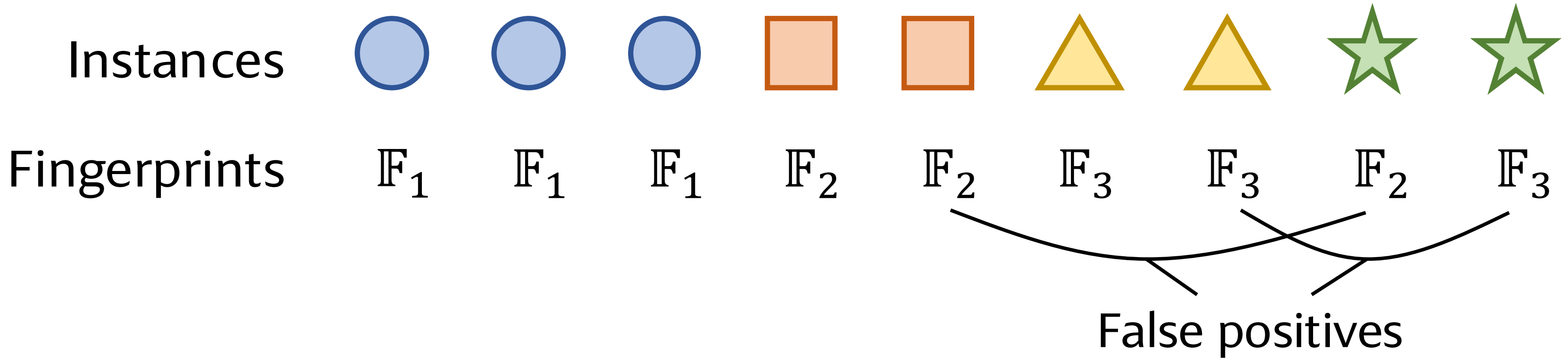

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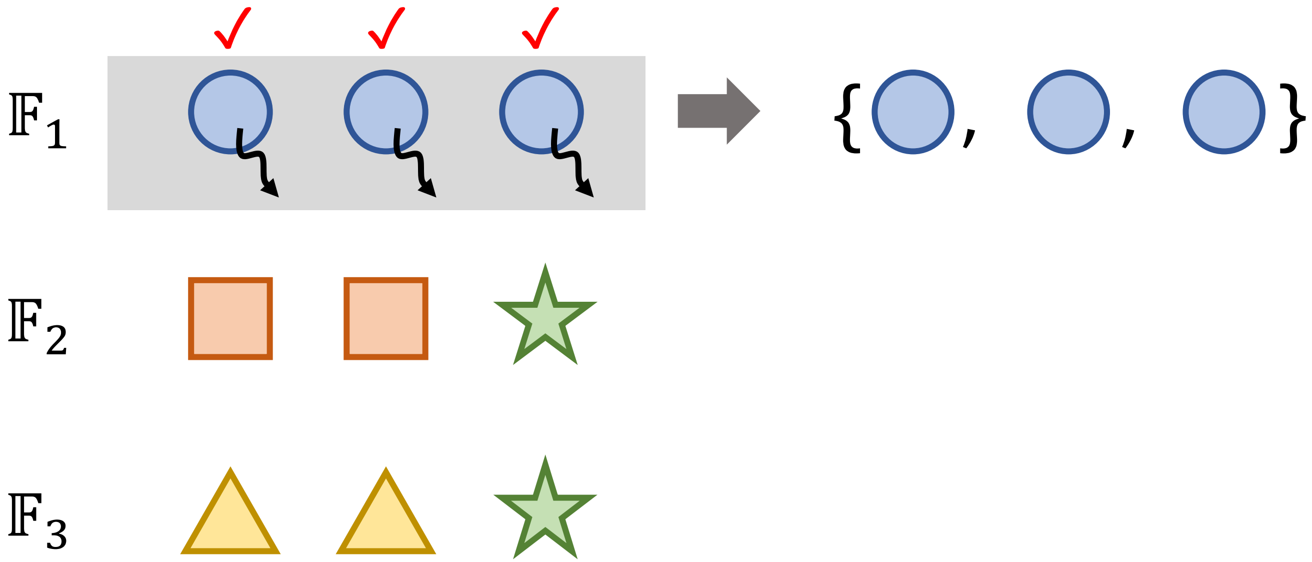

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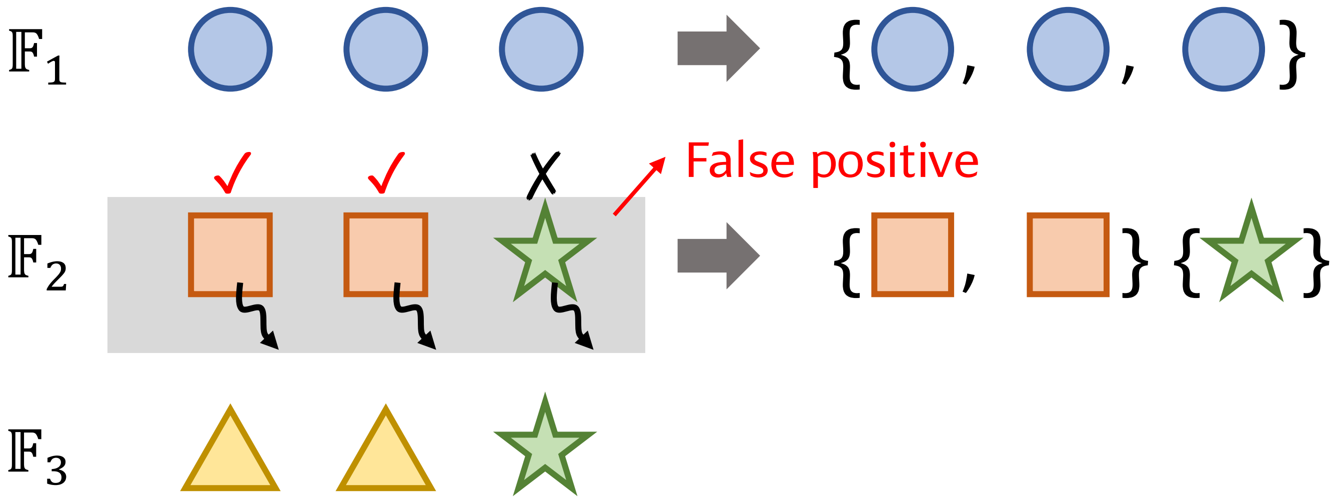

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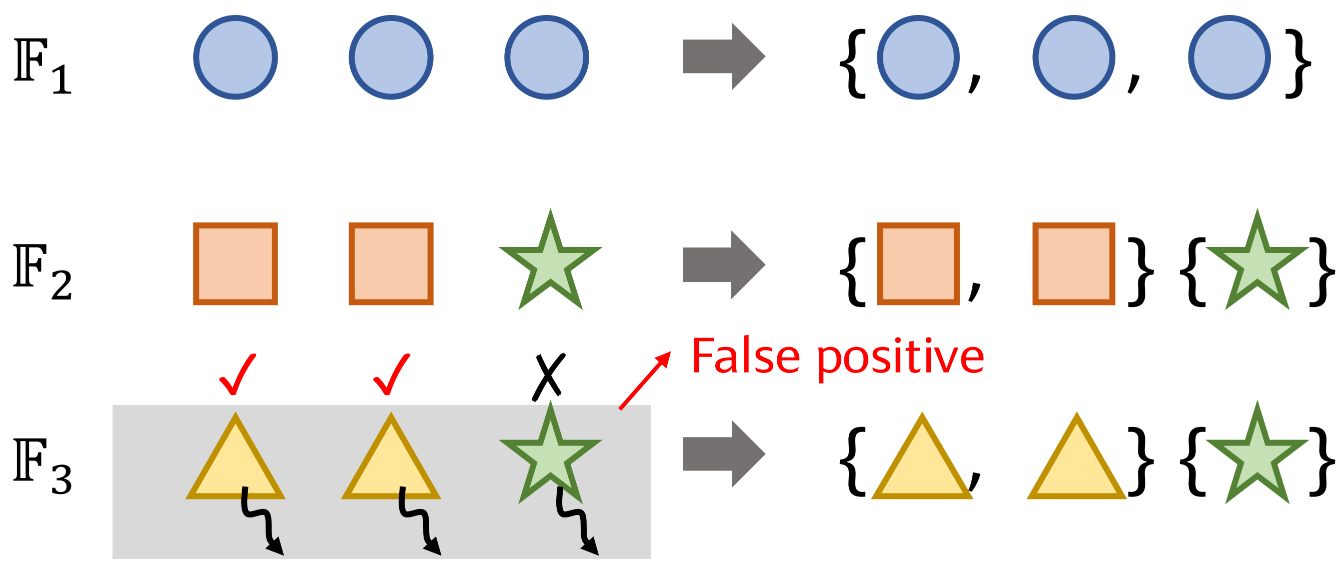

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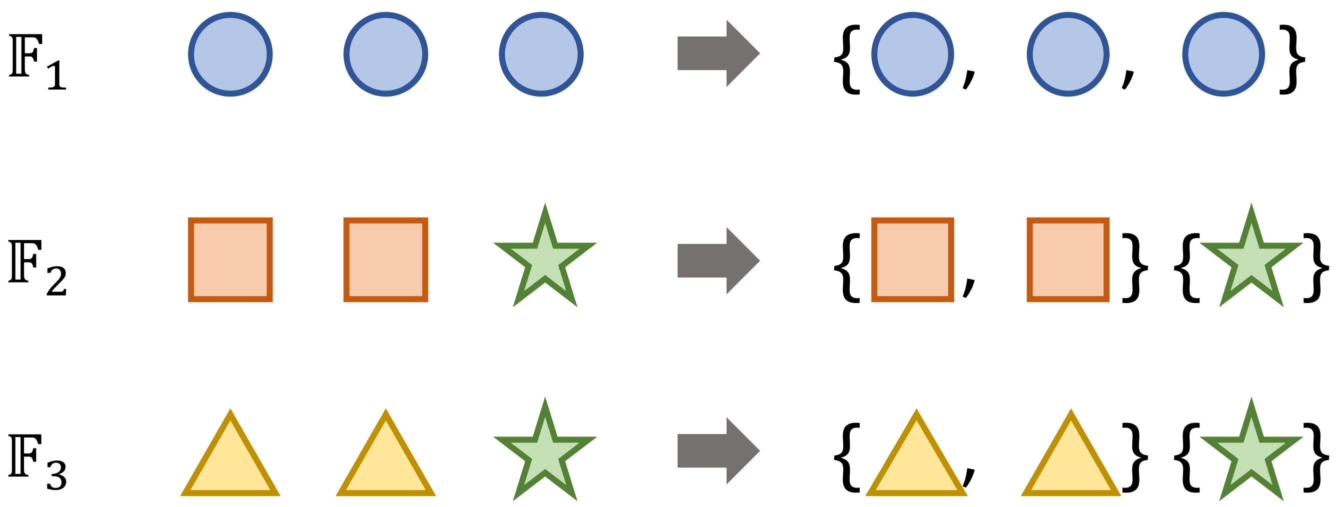
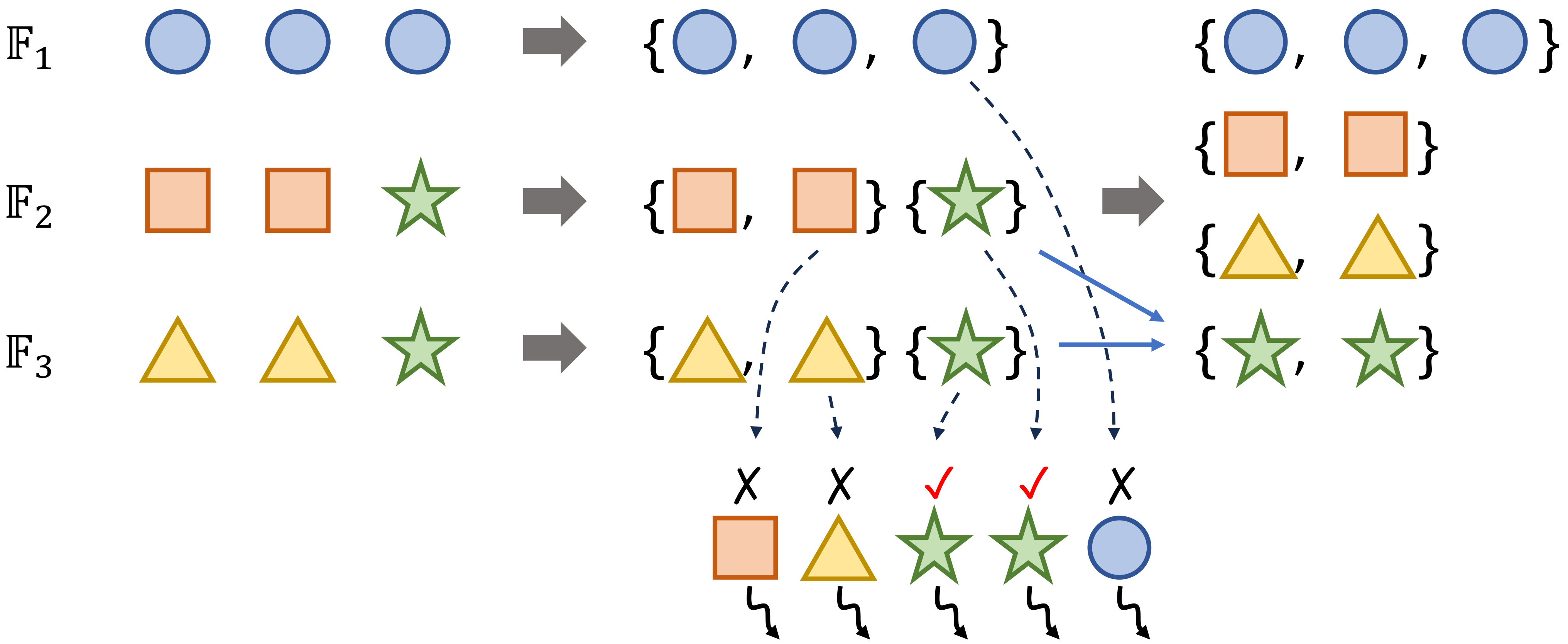


All false positives are identified, proceed to find false negatives

Fingerprint-Assisted Co-Location Verification



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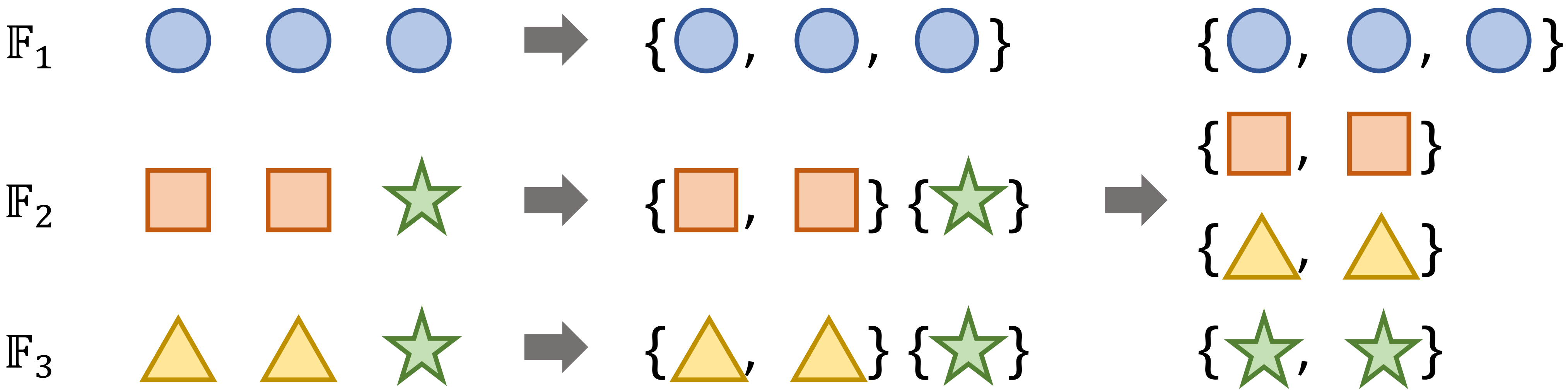

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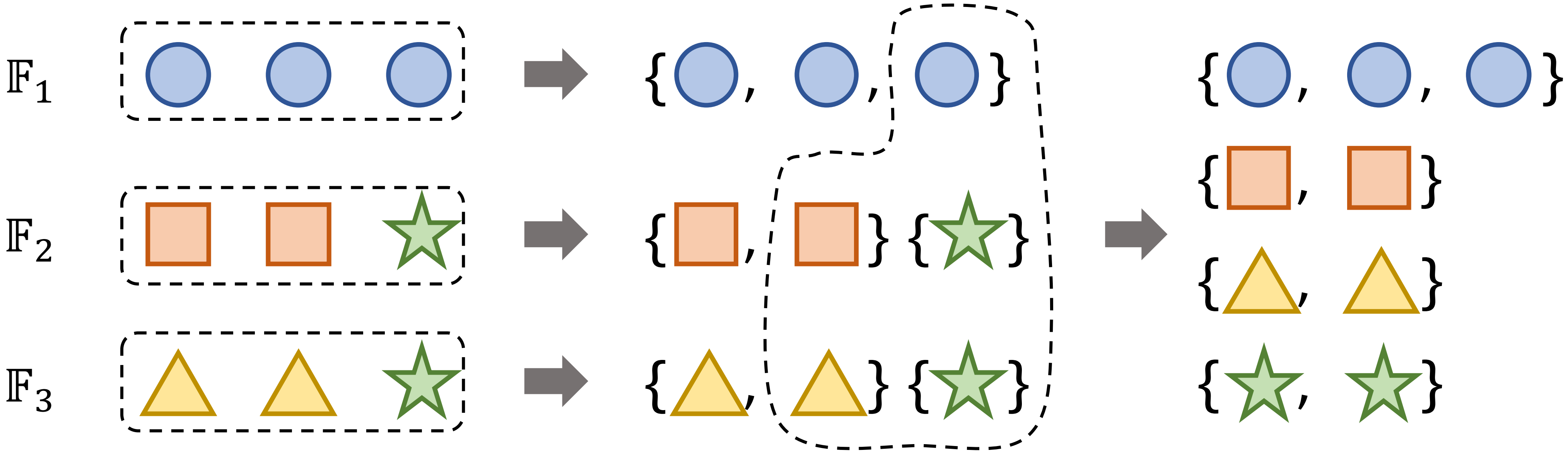


4 batch tests instead of $9 \times 8/2 = 36$ pairwise tests

More discussion in the optional reading

Host Fingerprints are Highly Accurate

For each pair of container instances

- **False positive (FP):** same fingerprints but not co-located
- **False negative (FN):** different fingerprints but co-located

- Measure accuracy in three data center regions (us-central1/east1/west1)
- Repeat measurements five times in each data center region

Average FN rate: 0.00%
Average FP rate: 0.02%

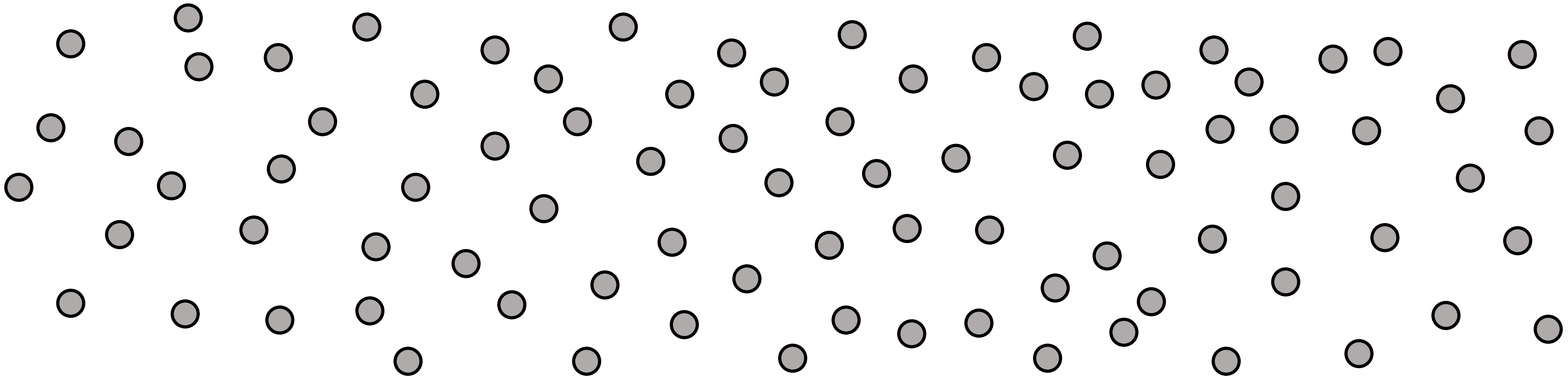
☺ 14 out of 15 measurements generate perfect fingerprints (no FP nor FN)

Understanding Instance Placement Policy

Method:

Google Cloud

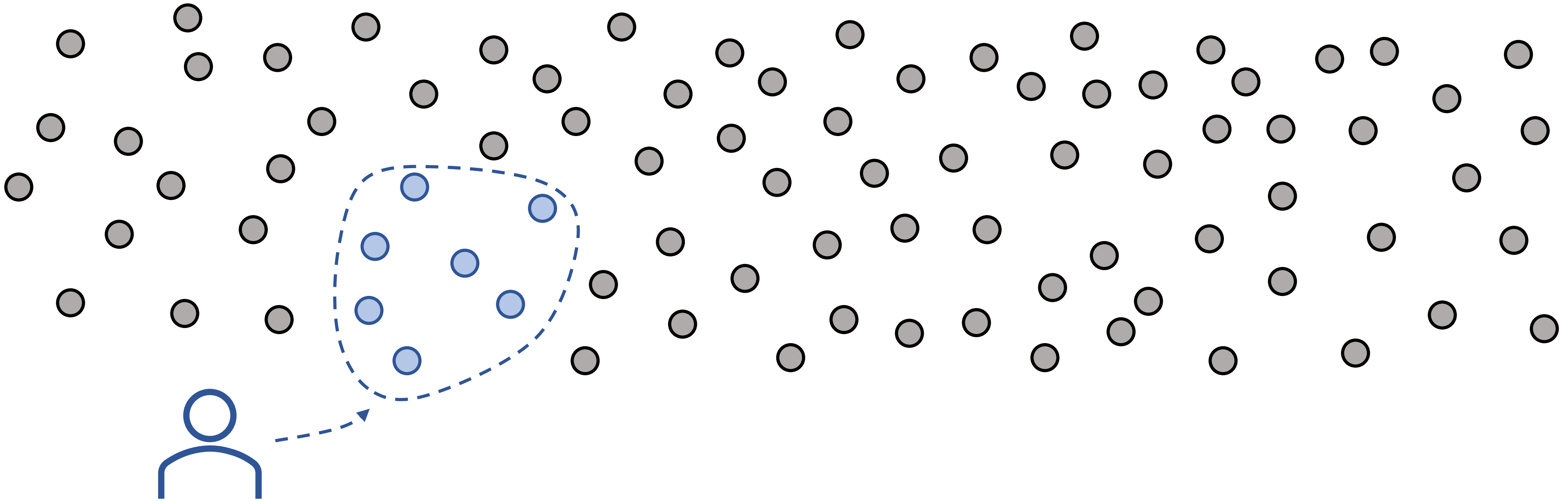
= Physical Host



Observation 1: An Account Has a Preferred Set of Hosts

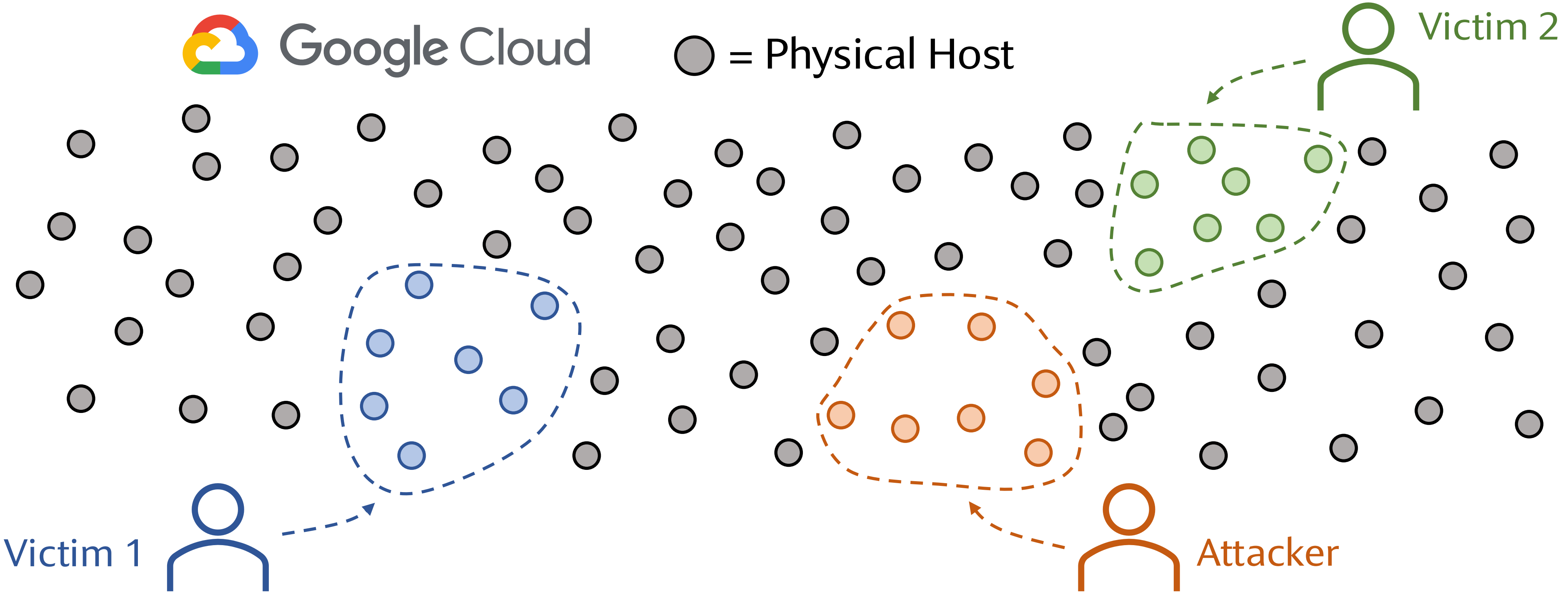
Why: Affinity scheduling to reduce communication overhead

Google Cloud = Physical Host

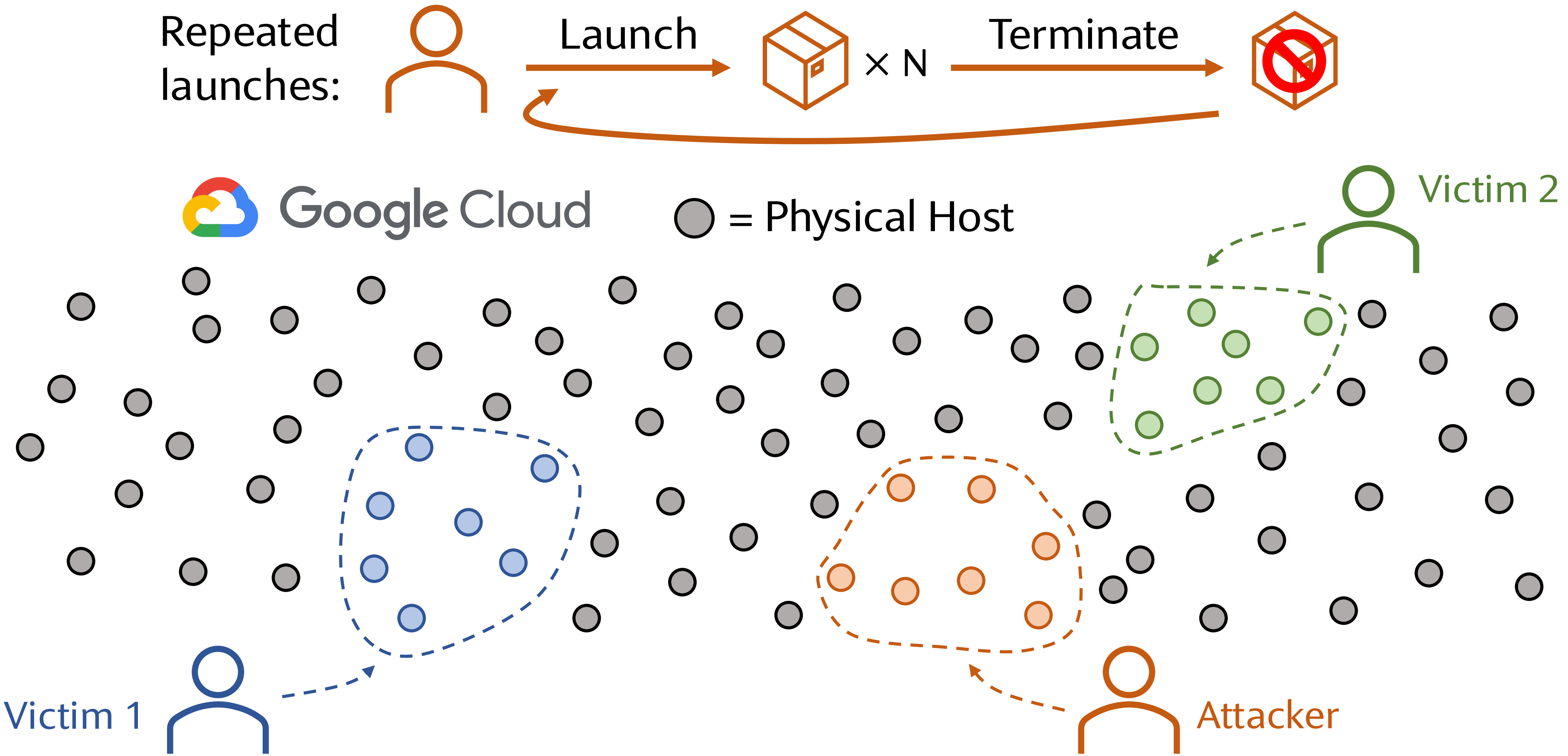


Observation 2: Different Accounts Have Different Preferred Hosts

Implication: Low chance of co-location with a target user



Observation 3: Repeated Launches Spread Instances



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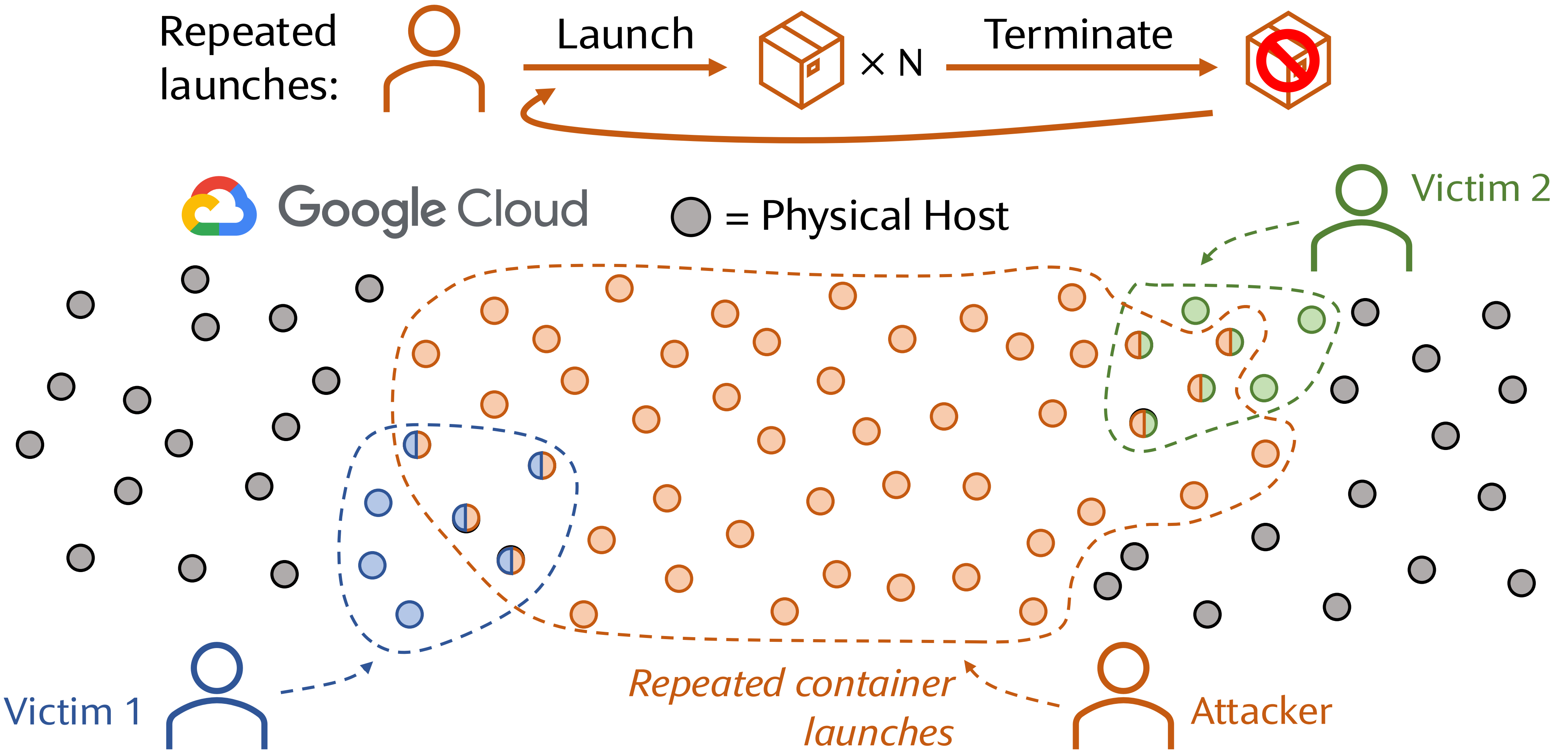
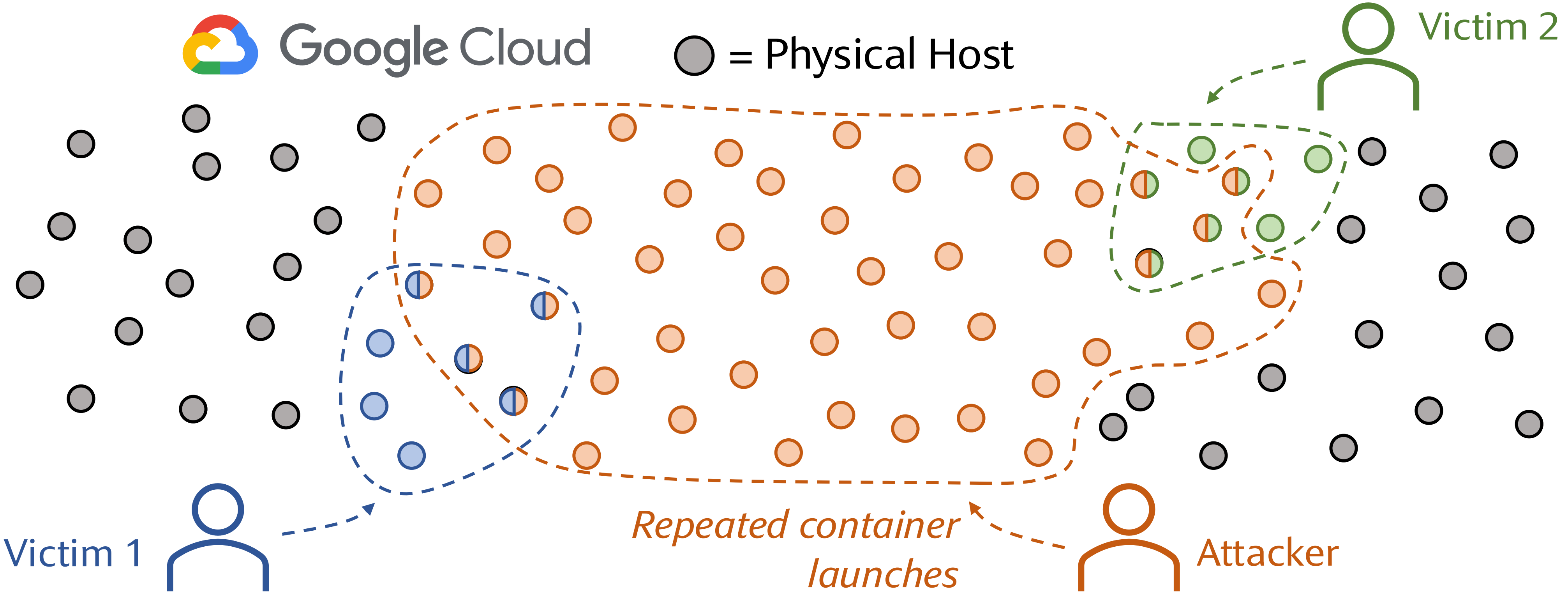
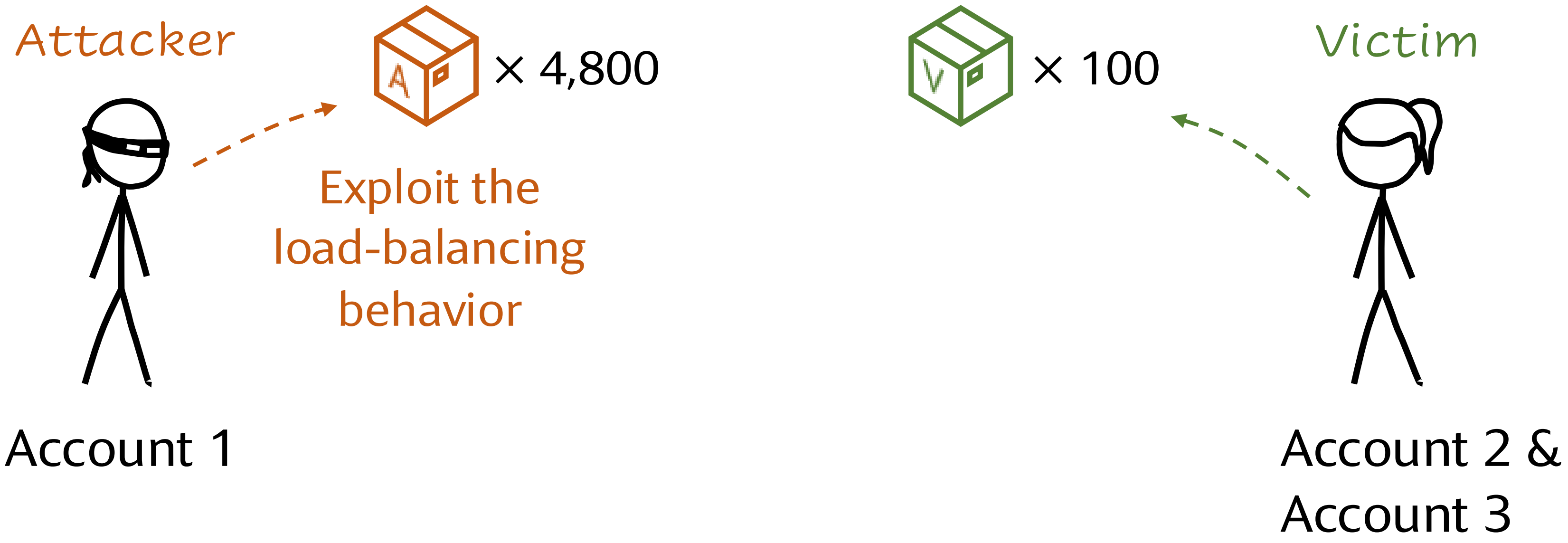


Observation 3: Repeated Launches Spread Instances

Why: Repeated launches ⇒ User has high demand ⇒ Load balance



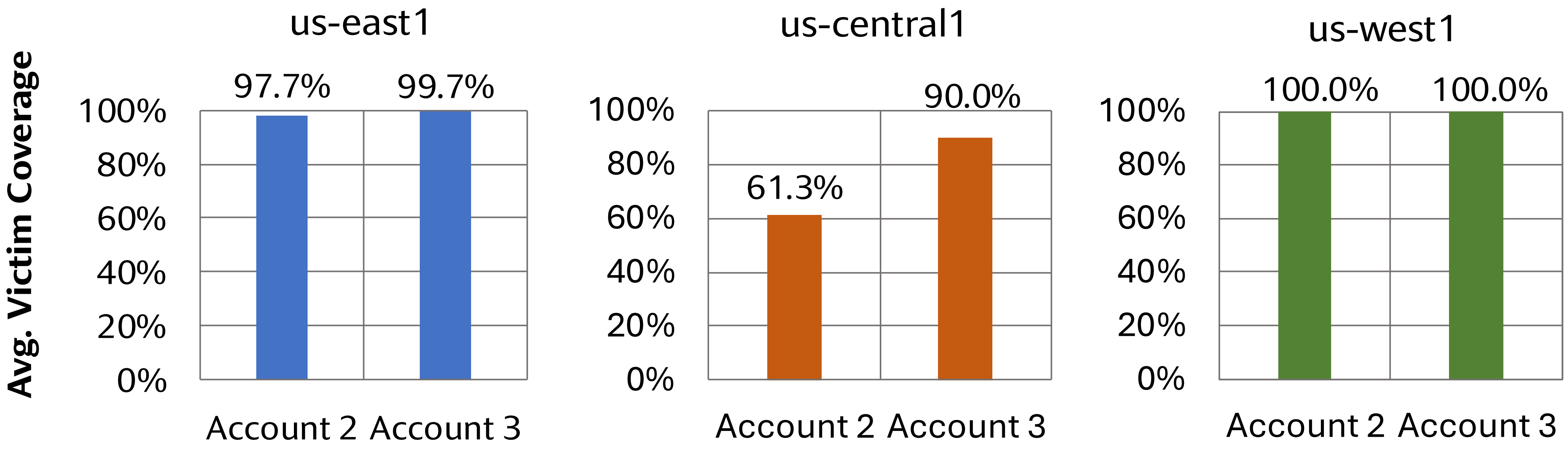
Evaluation: Co-Location with Victims



Victim coverage: Percentage of victim instances that are co-located with the attacker

High Victim Coverage and Low Attack Cost

Average Victim Instance Coverage (3 repetitions in each region)

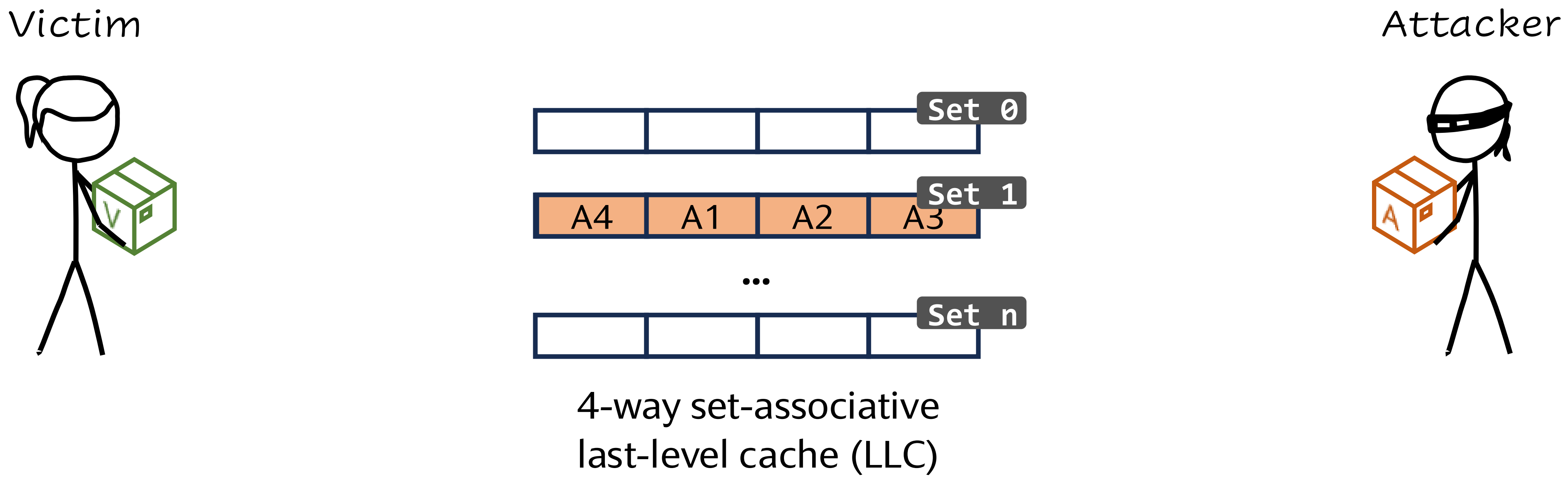


Avg. Attack Cost: 24 USD 23 USD 27 USD

Takeaway: High victim coverage and low attack cost

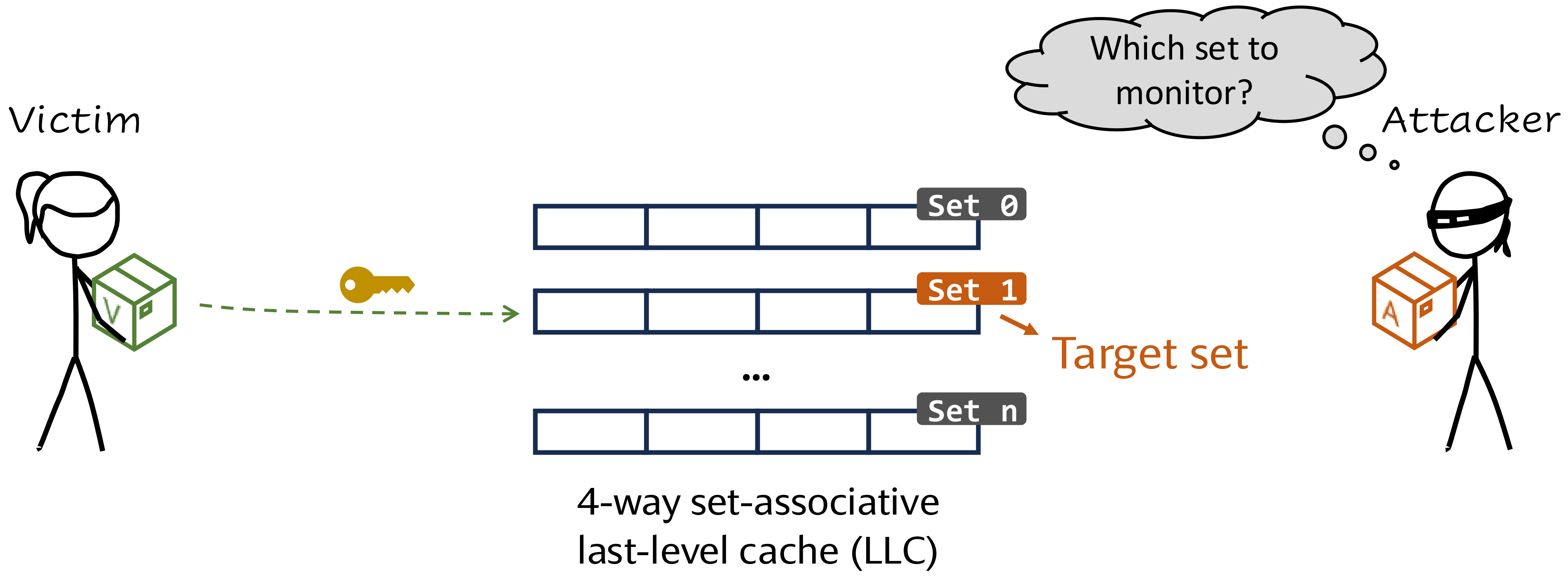
LLC Prime+Probe Attack with an Eviction Set

Eviction set ⇒ Monitor memory accesses to an LLC set with **Prime+Probe**



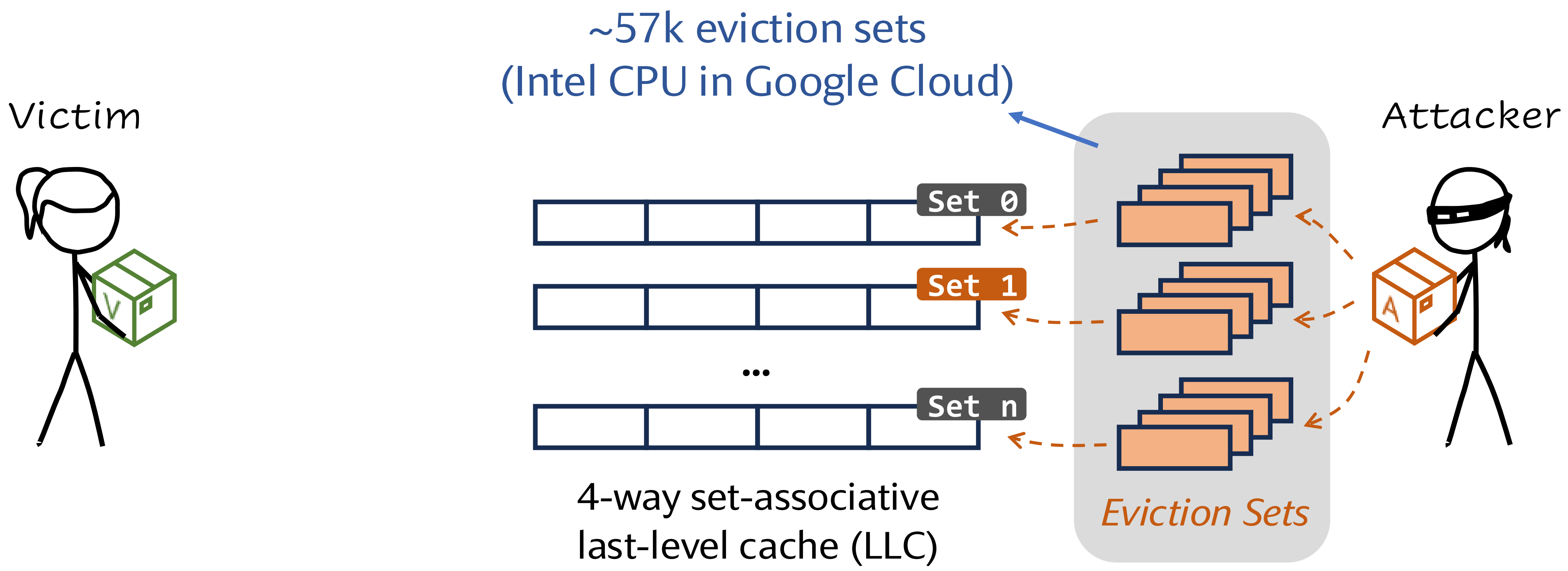
An Unprivileged Attacker Does Not Know the Target Set

Target set: An LLC set accessed by the victim in a secret-dependent manner



Step 1: Build Many Eviction Sets

Attacker needs an eviction set for every LLC set in the system



Step 2: Identify Target LLC Set to Monitor

Attacker collects an access trace from *each* LLC set
⇒ Checks whether the access trace matches victim's access behavior

4-way set-associative
last-level cache (LLC)

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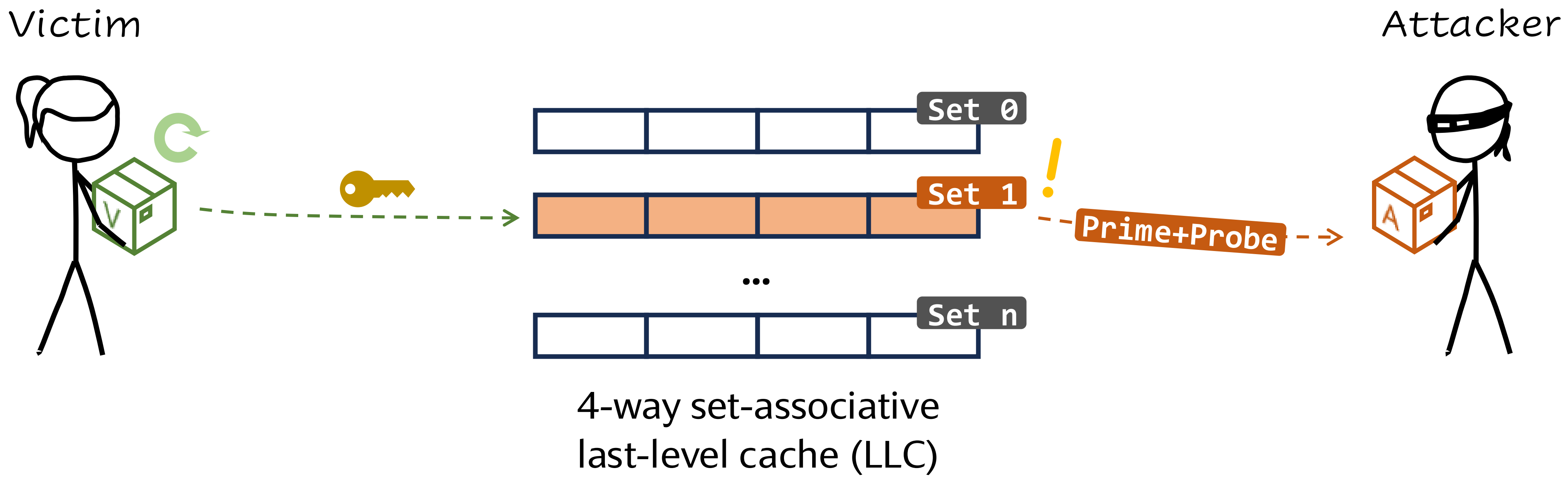
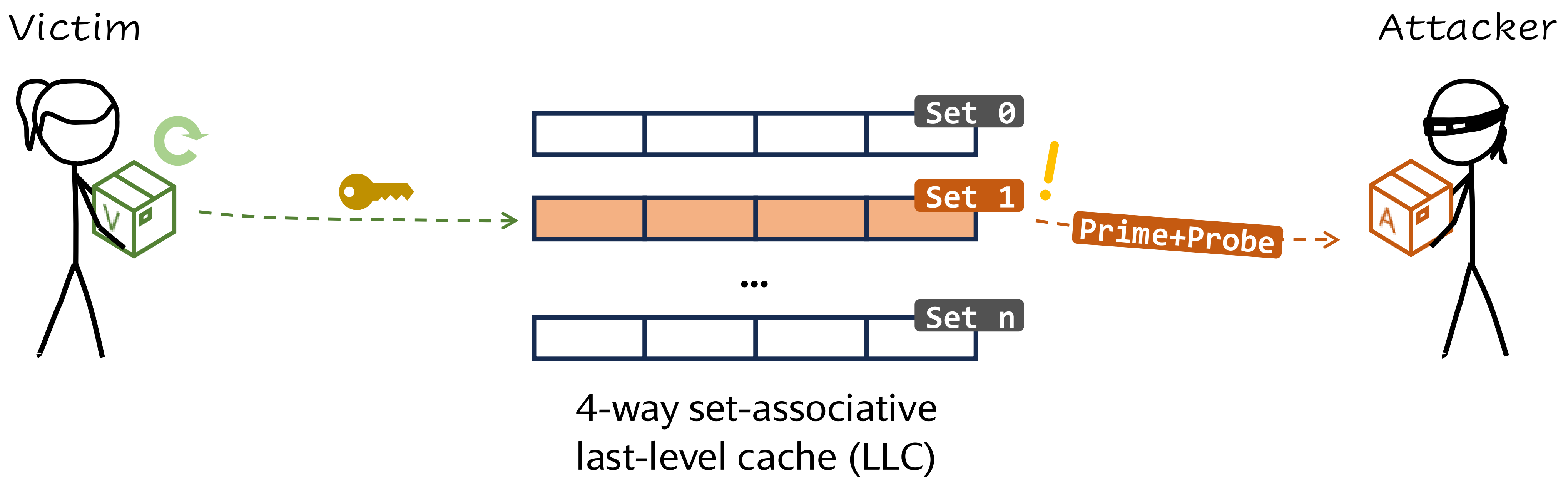


Step 3: Extract Information from the Victim

Attacker monitors the target set and extracts the sensitive information



Victim: Elliptic Curve Digital Signature Algorithm (ECDSA)

Target victim: A vulnerable ECDSA program from OpenSSL 1.0.1e

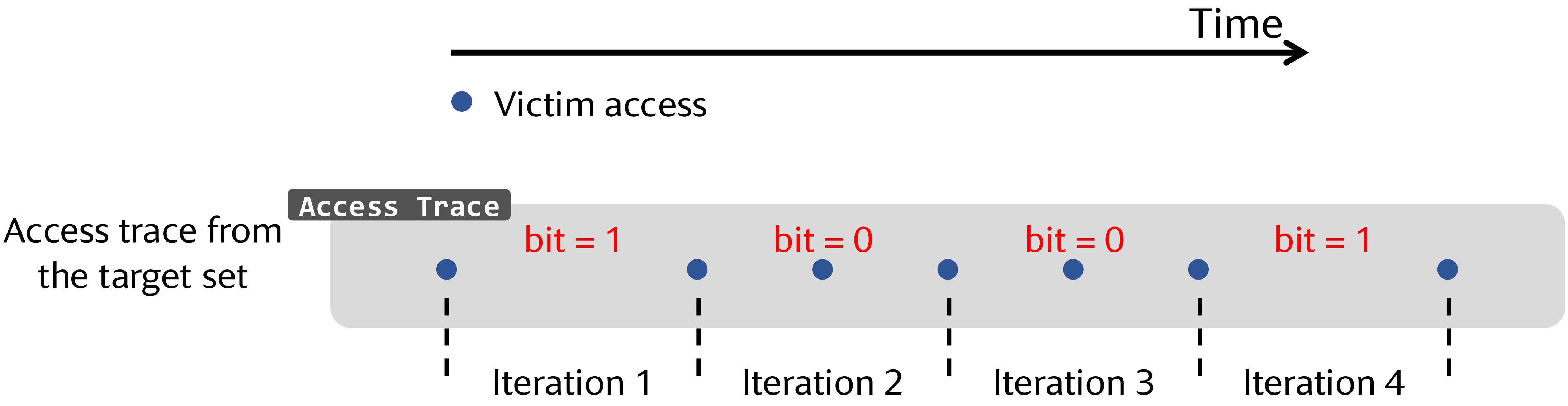
Setup: The victim runs in a container owned by a different Google account

Simplified victim code

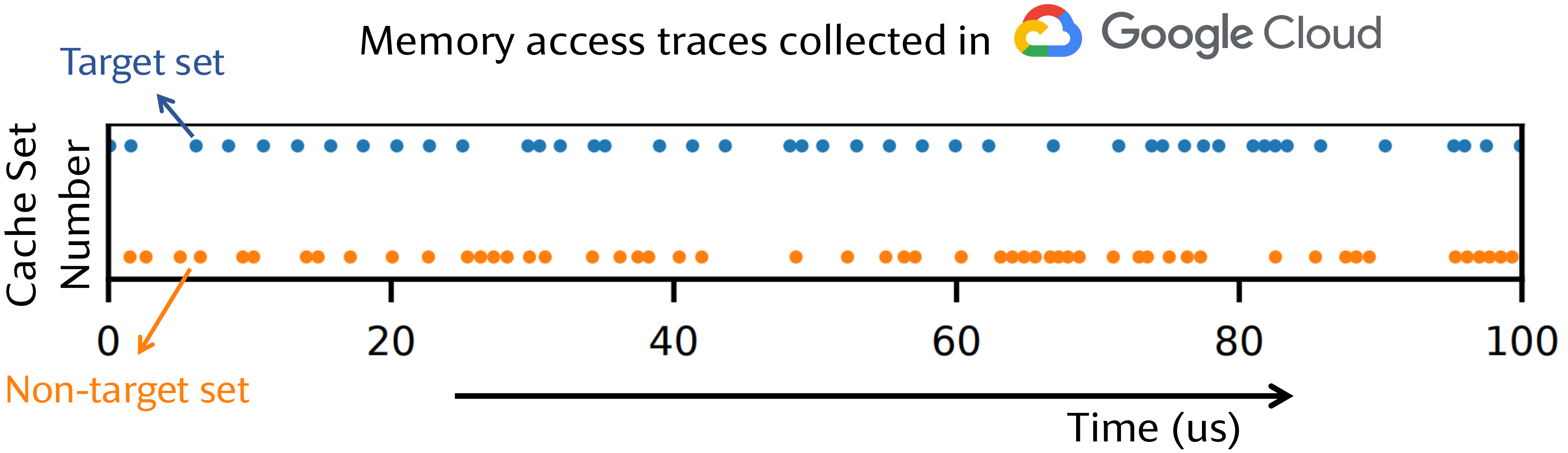
```
for bit in secret_nonce {
  // ...
  if (!bit) {
    Fetch Victim Address;
  }
  // ...
  Fetch Victim Address;
}
```

Can be derive the private key

Expected Access Trace from the Target Set

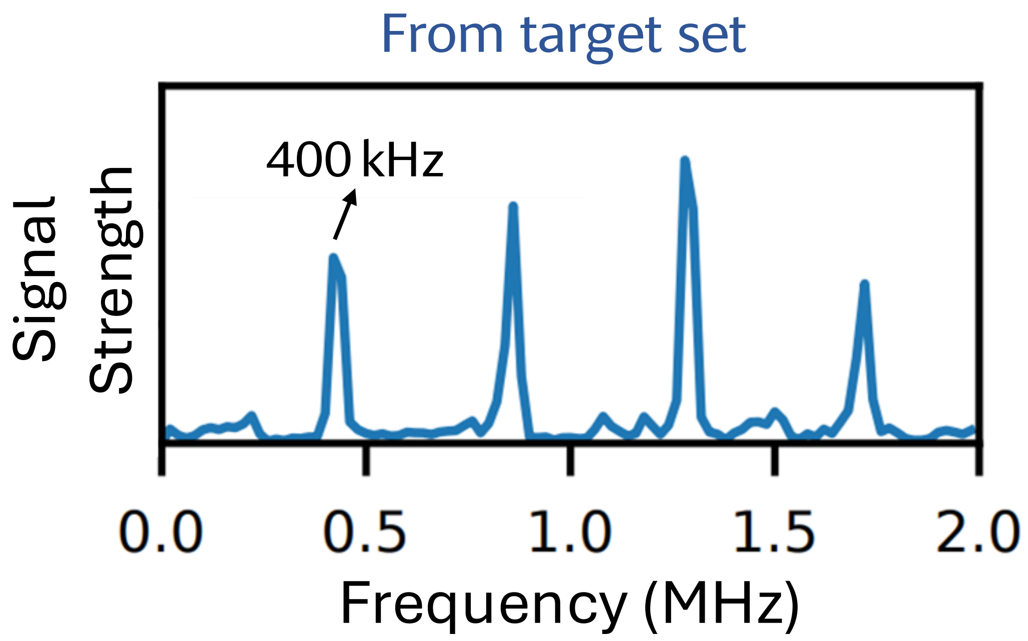


Actual Access Traces Collected in Google Cloud



New Technique: Identify Target Set via Spectral Analysis

Intuition: Victim accesses are periodic ⇒ Spectral analysis



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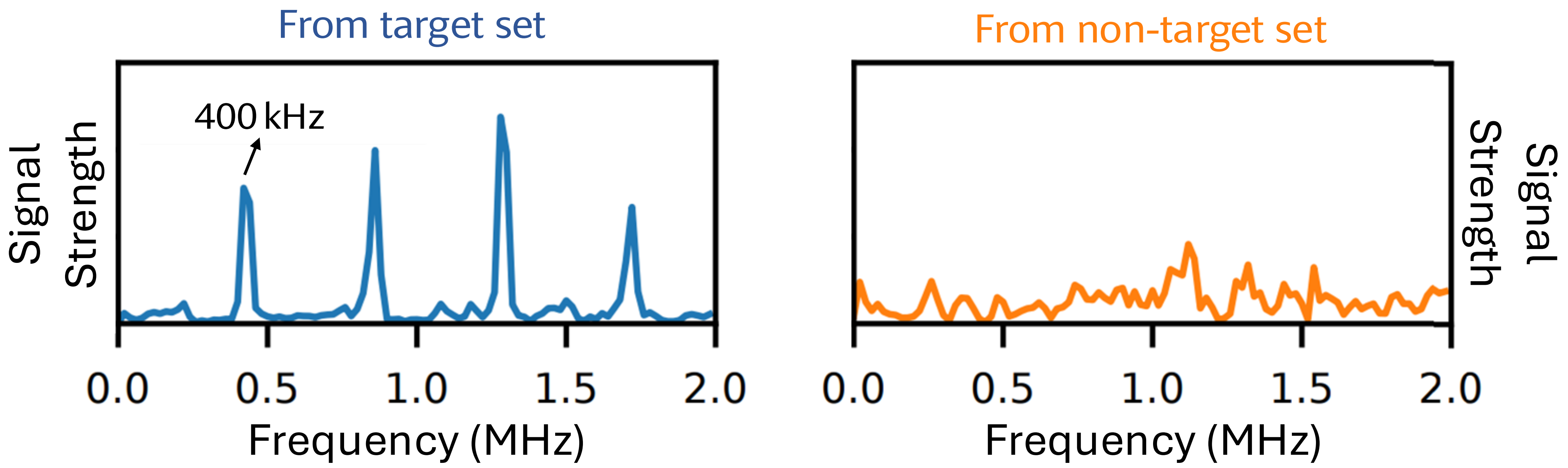

Result: Find the target set in ~3 minutes, 74% success rate

Google Cloud

Legends

- Attacker Container
- Victim Container
- Task Running
- Task Completed
- Task Failed
- Victim Found

Attack stage:

Not Started

Preflight | Next | Repeat | Reset

Running Time: 0.0s

Attacker Count: 0

Server Count: 0

Cost: $0

Attack Traces:

WebSocket Status: Connected

Mode: Live Switch

Extracted Traces

Percentage of Secret Bits Extracted: 88.4%; Error rate: 2.8%;