

Hello from the Other Side: SSH over Robust Cache Covert Channels in the Cloud

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Outline

- cache covert channels
- how do we get a covert channel working in the **cloud**?
- how do we get a covert channel working in a **noisy environment**?
- what are the **applications** of such covert channel?

CPU cache

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CPU cache

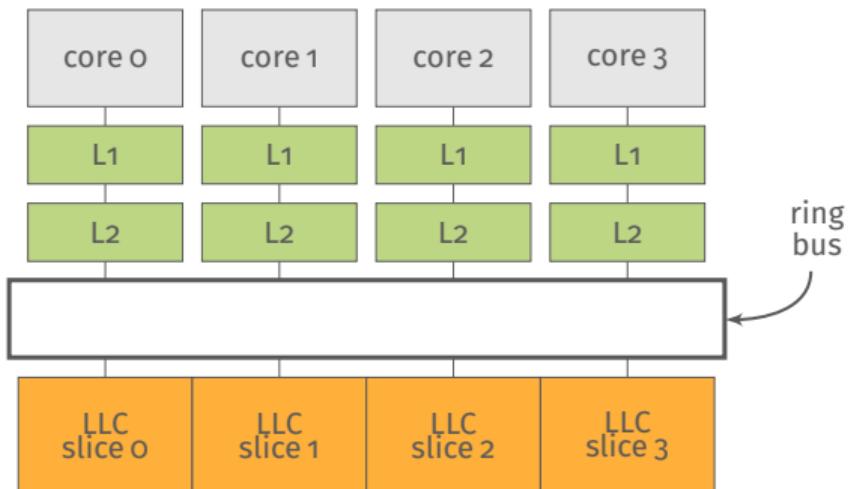
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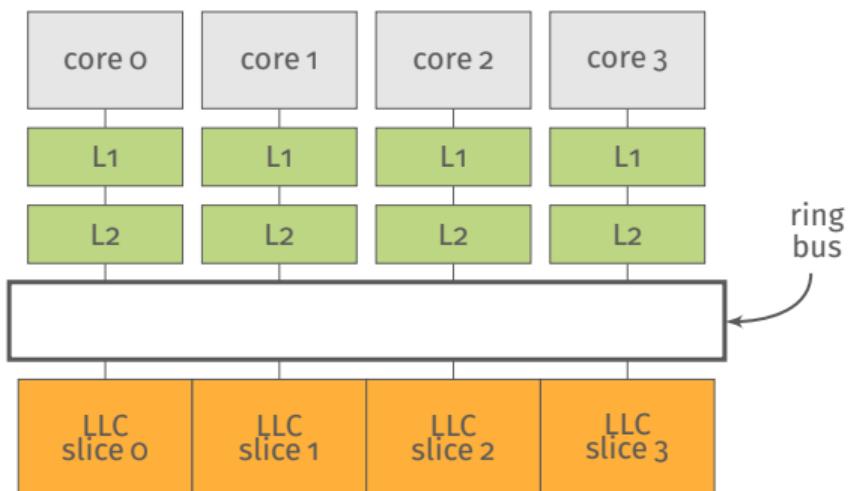
- main memory is slow compared to the CPU
- caches buffer frequently used data
- every data access goes through the cache
- caches are transparent to the OS and the software

Caches on Intel CPUs

- L1 and L2 are private

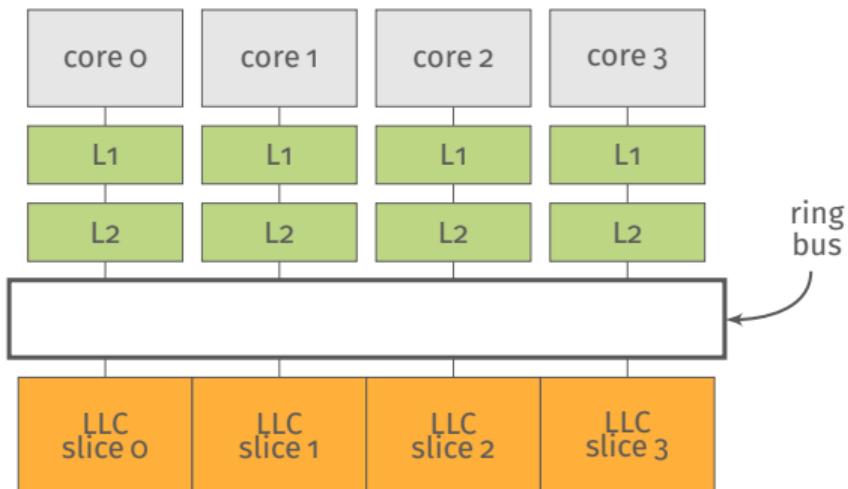


Caches on Intel CPUs



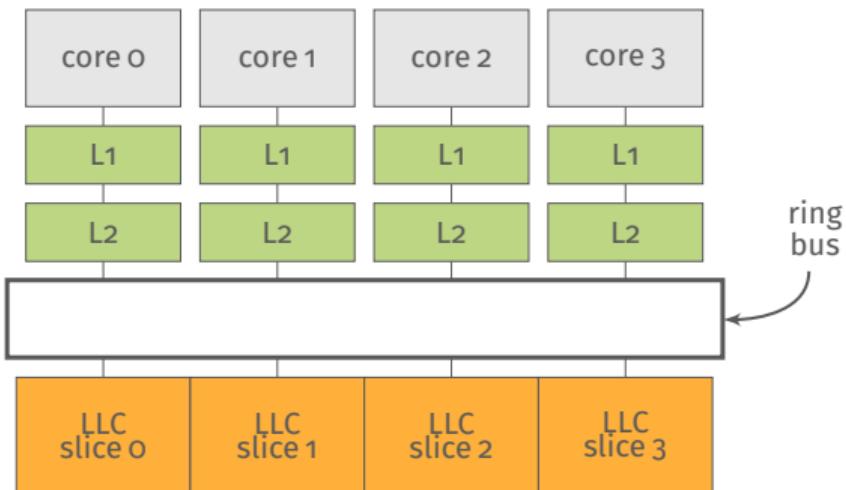
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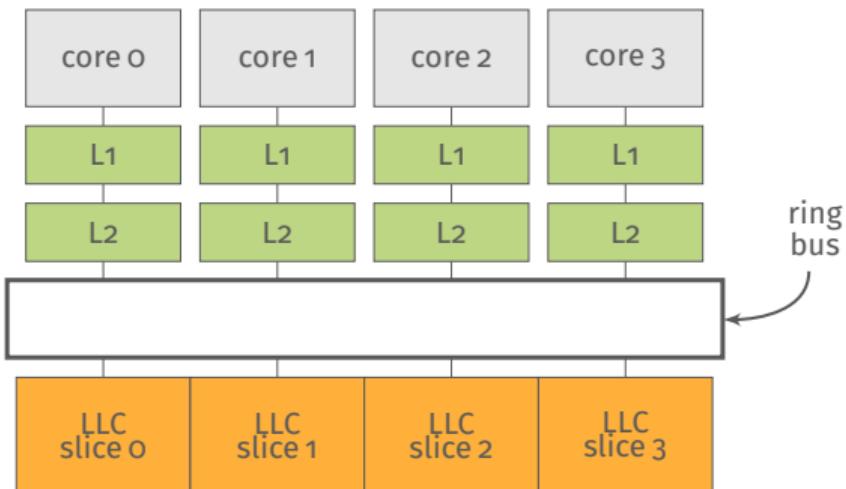
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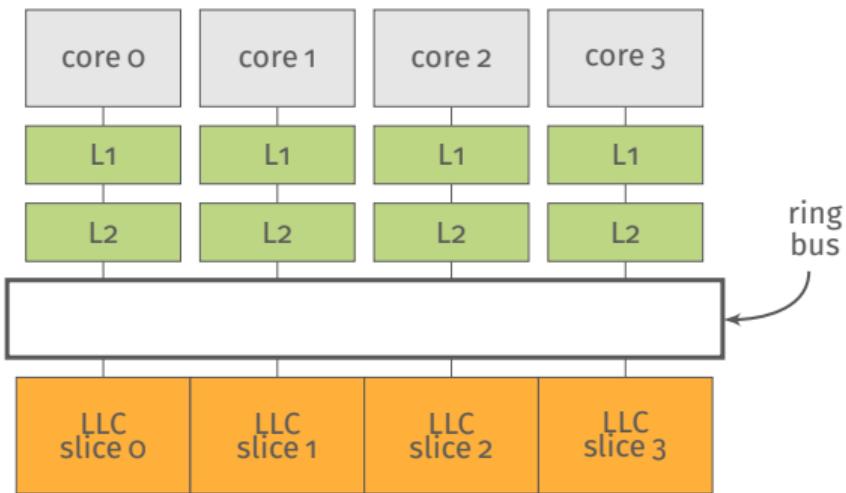
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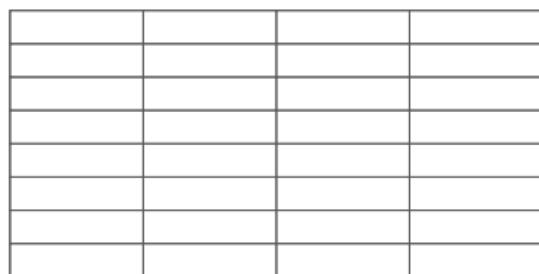
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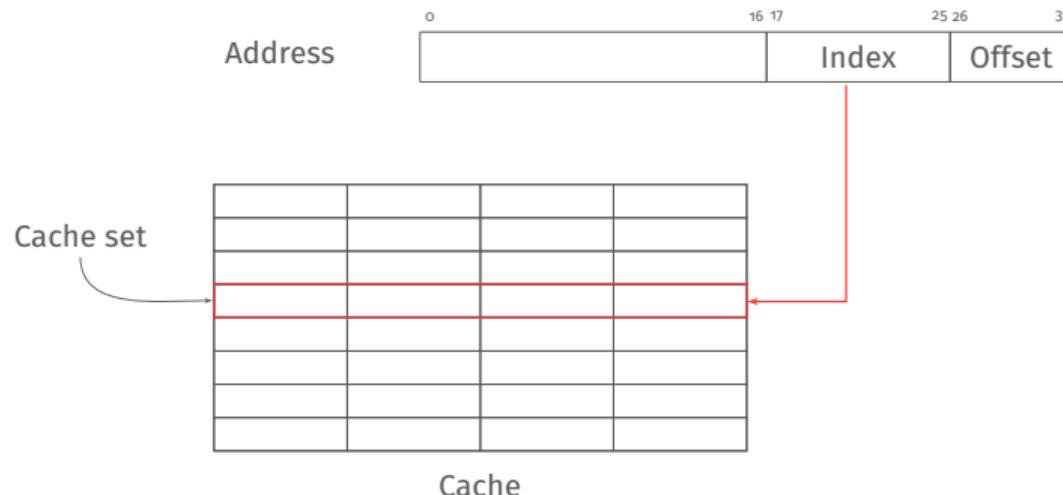
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 - **shared** across cores
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 - hash function maps a physical address to a slice

Set-associative caches



Cache

Set-associative caches



Data loaded in a specific **set** depending on its address

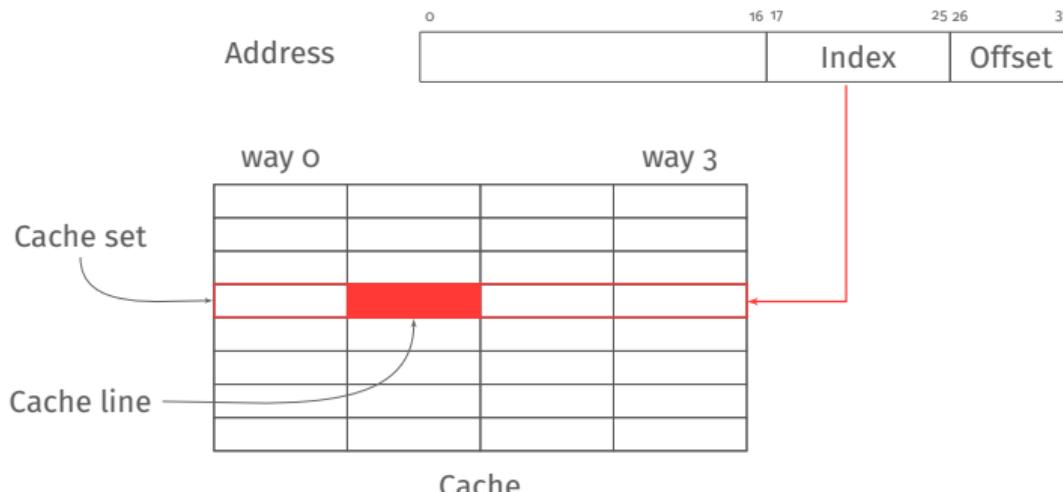
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Several **ways** per set

Set-associative caches

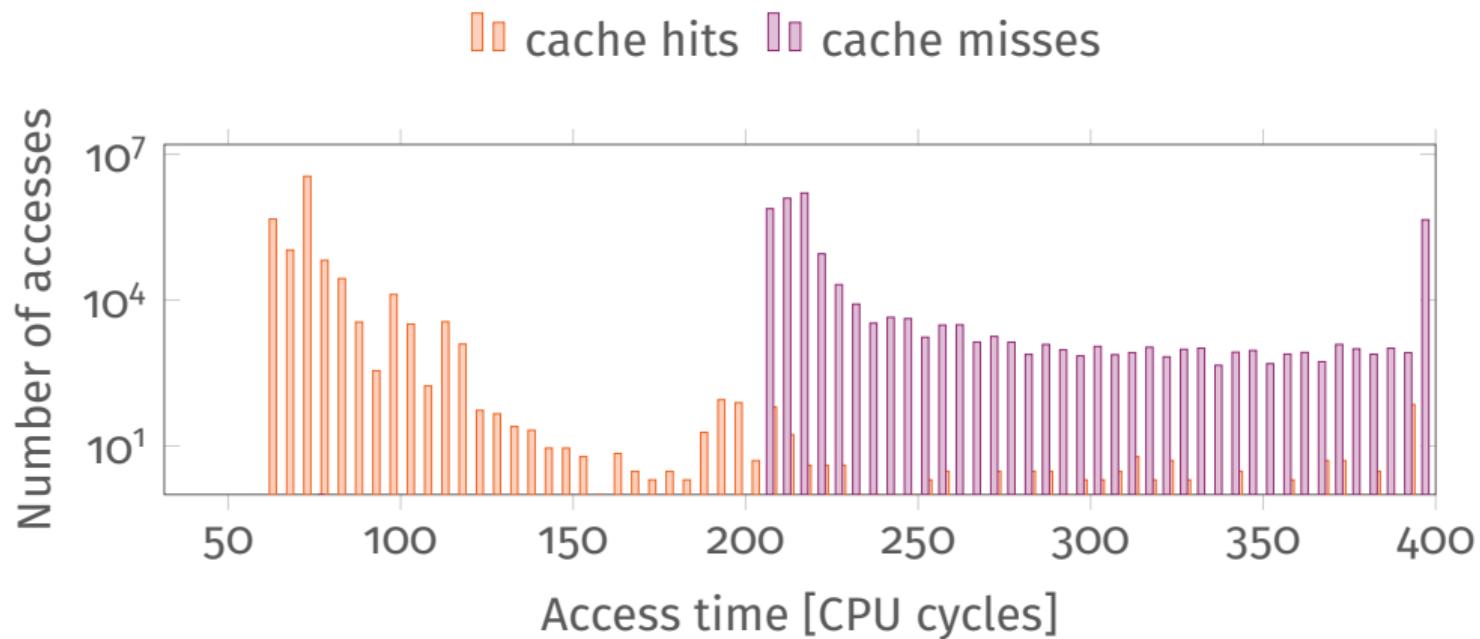


Data loaded in a specific **set** depending on its address

Several **ways** per set

Cache line loaded in a specific way depending on the replacement policy

Timing differences



Cache-based covert channels

- cache attacks → exploit timing differences of memory accesses

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Cache-based covert channels

- cache attacks → exploit timing differences of memory accesses
- covert channel: two processes **communicating** with each other
 - **not allowed** to do so, e.g., across VMs
- literature: stops working with **noise** on the machine
- solution? “Just use error-correcting codes”

Prime+Probe

- attacker knows which **cache set** the victim **accessed**, not the content

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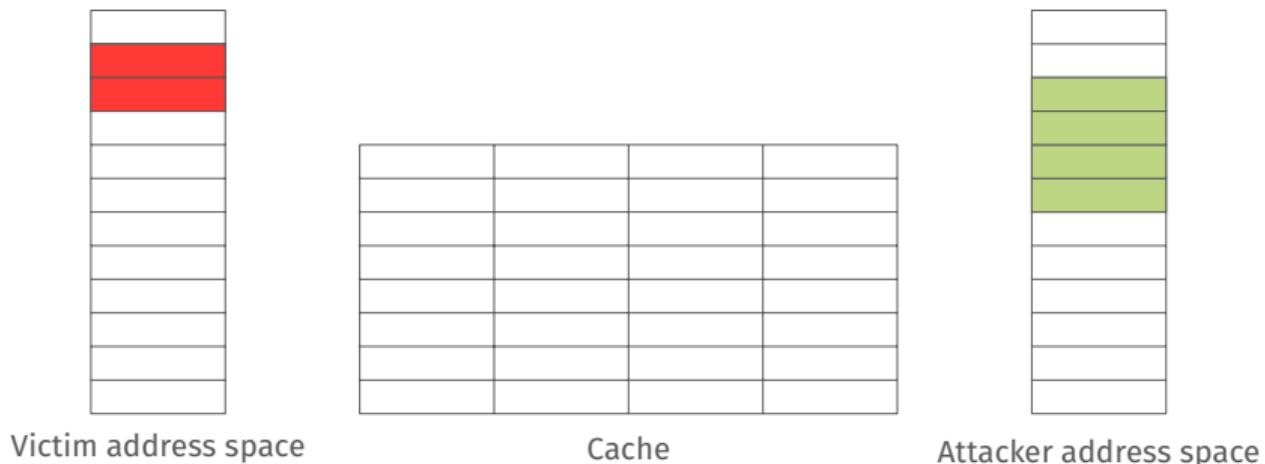
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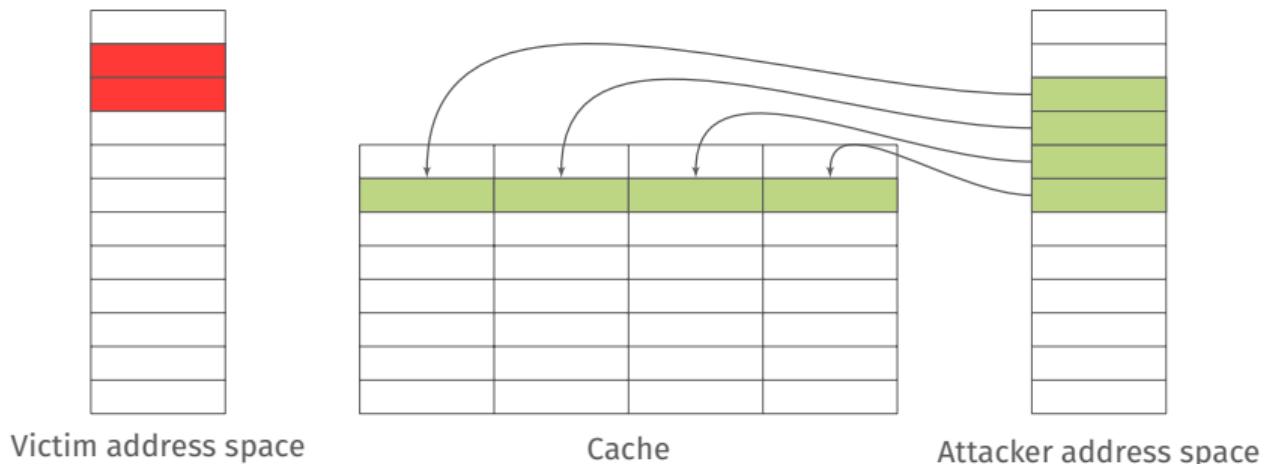
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- attacker knows which **cache set** the victim **accessed**, not the content
 - works **across CPU cores** as the last-level cache is shared
 - does not need shared memory, e.g., memory de-deduplication
- works **across VM in the cloud**, e.g., on Amazon EC2

Prime+Probe

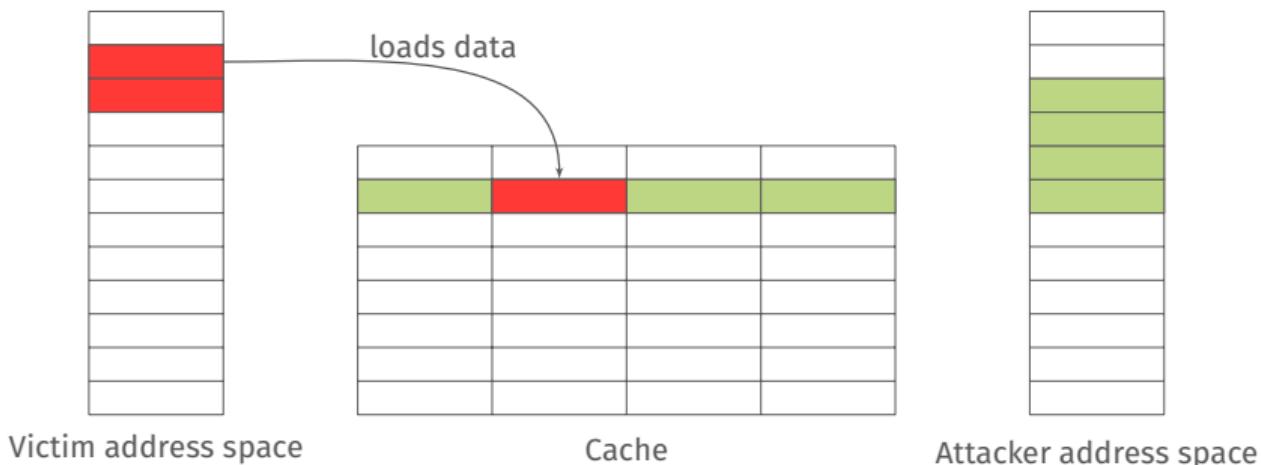


Prime+Probe



Step 1: Attacker **primes**, i.e., fills, the cache (no shared memory)

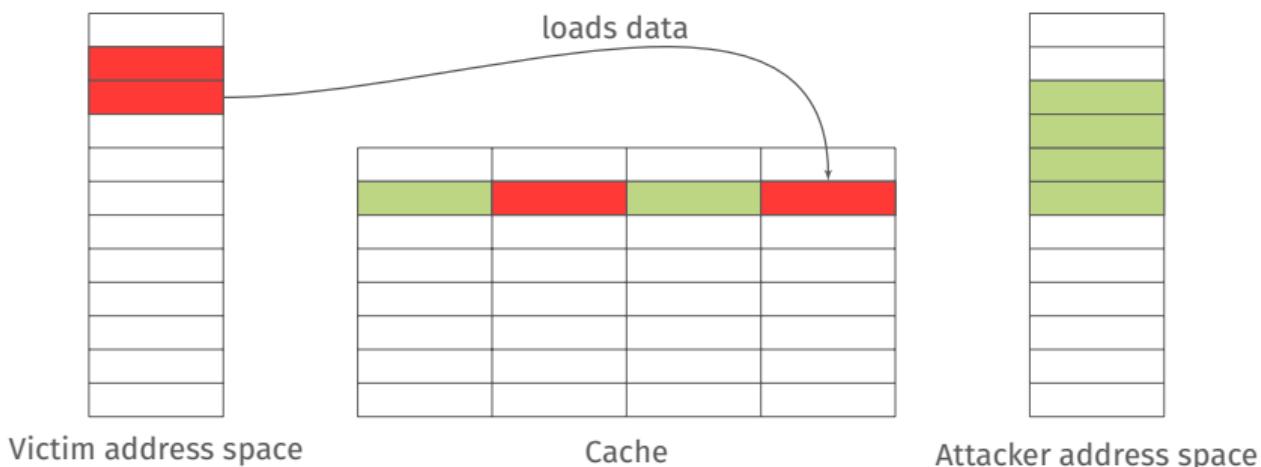
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Step 1: Attacker **primes**, i.e., fills, the cache (no shared memory)

Step 2: Victim evicts cache lines while running

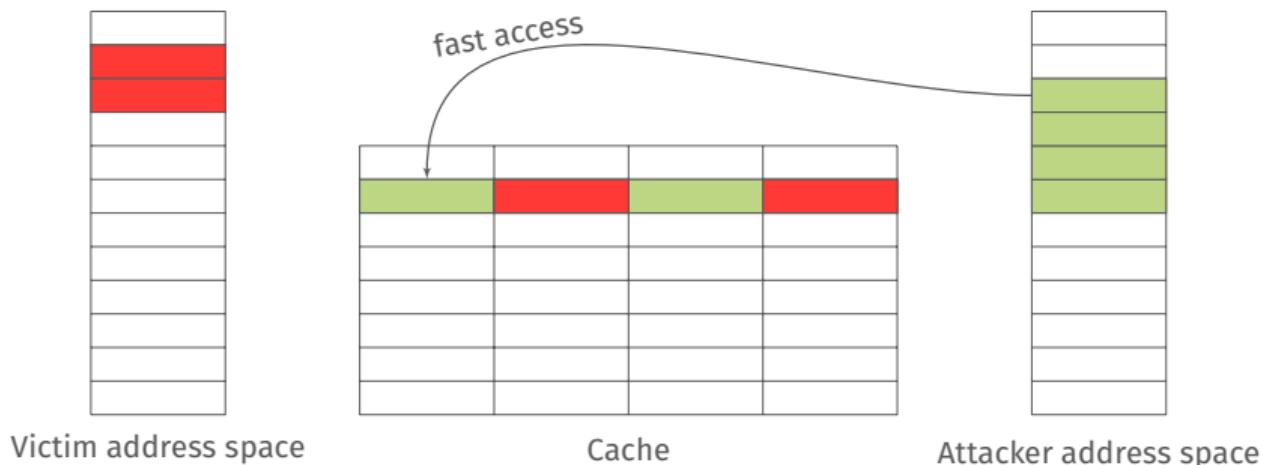
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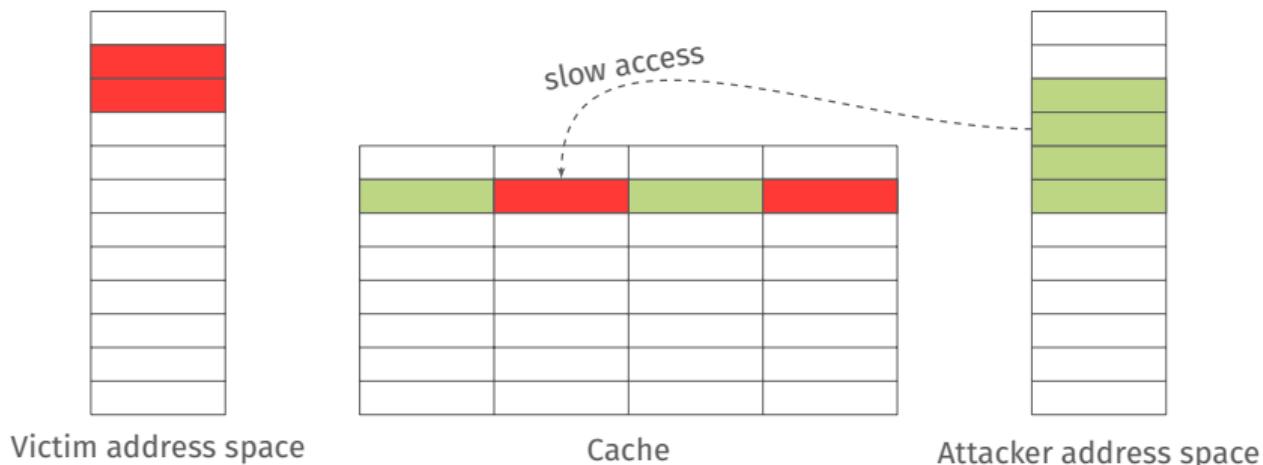


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Why can't we just use error correcting codes?

Sender

1	0	0	1	1	0
---	---	---	---	---	---



Receiver

1	0	0	1	1	0
---	---	---	---	---	---



(a) Transmission without errors

Why can't we just use error correcting codes?

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(a) Transmission without errors

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(b) Noise: **substitution** error

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(b) Noise: **substitution** error

Sender

1	0	██████	0	1	1	0
---	---	--------	---	---	---	---



Receiver

1	0	0	0	0	0	1	1	0
---	---	---	---	---	---	---	---	---



(c) Sender descheduled: **insertions**

Why can't we just use error correcting codes?

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Receiver

1	0	██████	0
---	---	--------	---



(d) Receiver descheduled: **deletions**

Our robust covert channel

- **physical** layer:
 - transmits words as a sequence of '0's and '1's
 - deals with synchronization errors
- **data-link** layer:
 - divides data to transmit into packets
 - corrects the remaining errors

Physical layer: Sending '0's and '1's

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Physical layer: Sending '0's and '1's

- sender and receiver agree on one set
- receiver probes the set continuously
- sender **transmits '0'** doing nothing
 - lines of the receiver still in cache → **fast access**
- sender **transmits '1'** accessing addresses in the set
 - evicts lines of the receiver → **slow access**

Eviction set generation

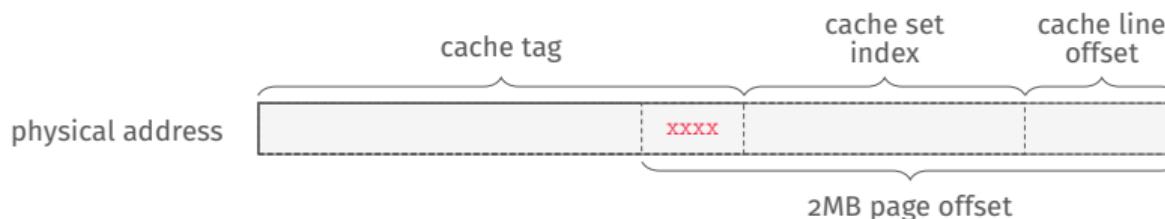
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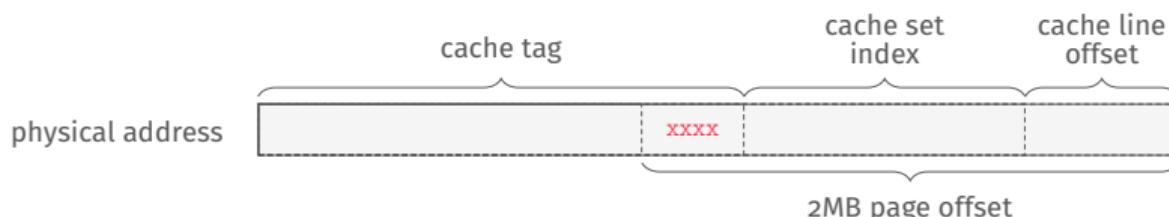
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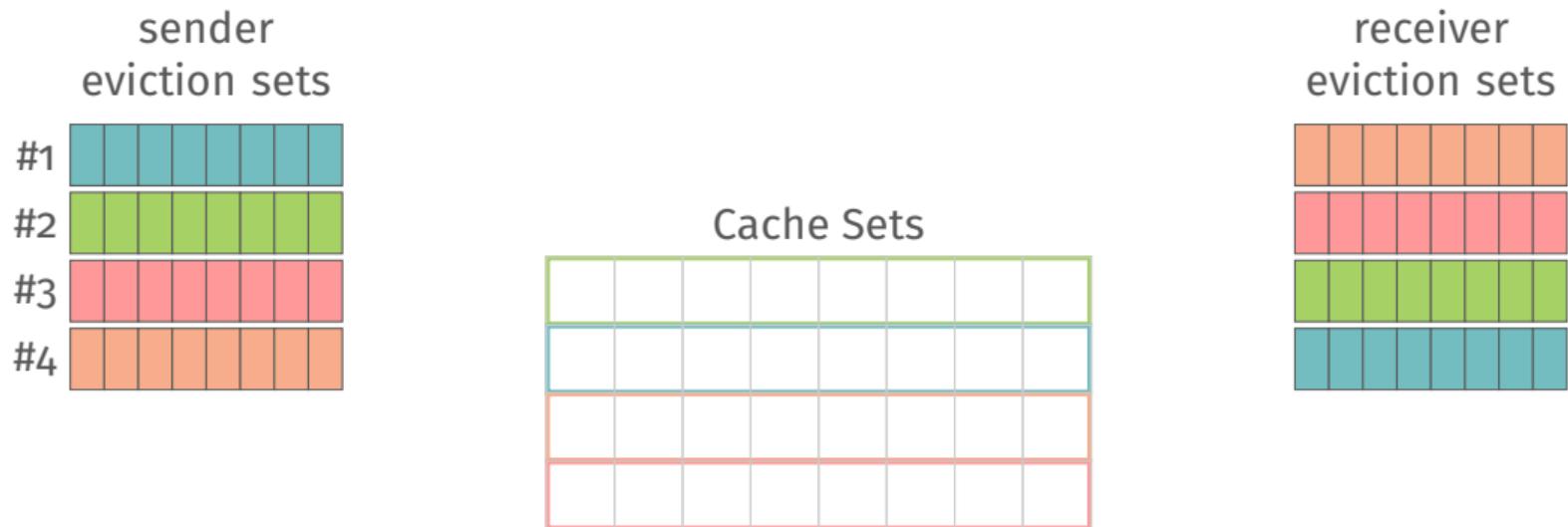
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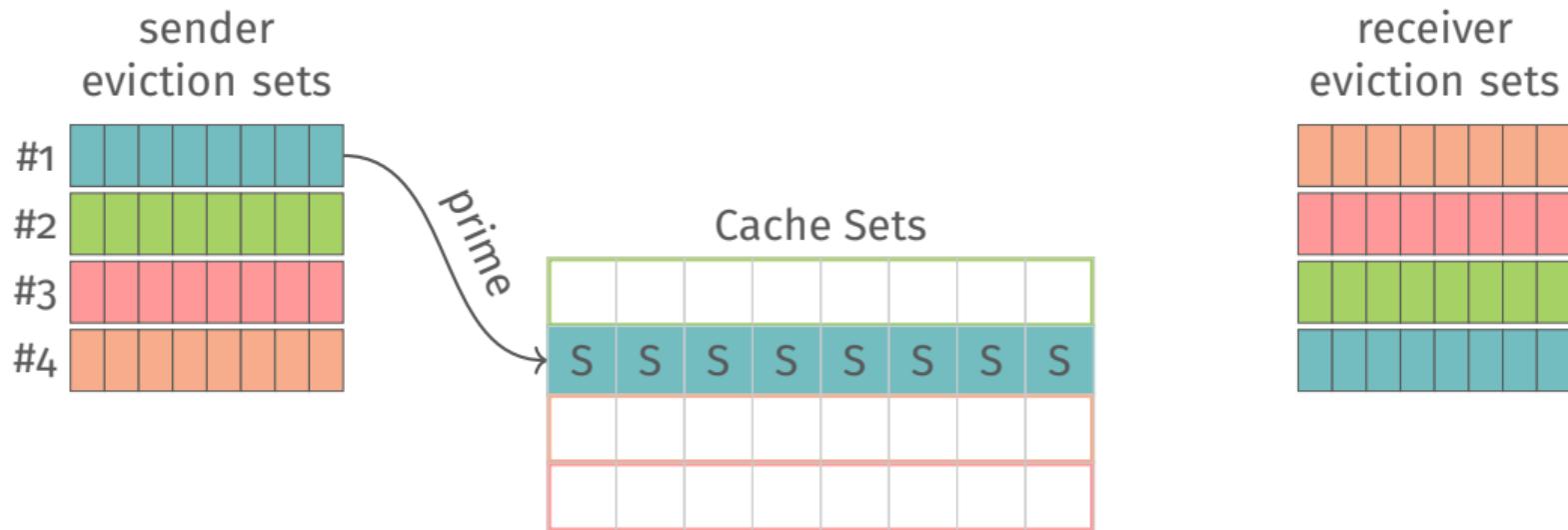


- we can build a set of addresses in the **same cache set** and **same slice**
- without knowing **which slice**

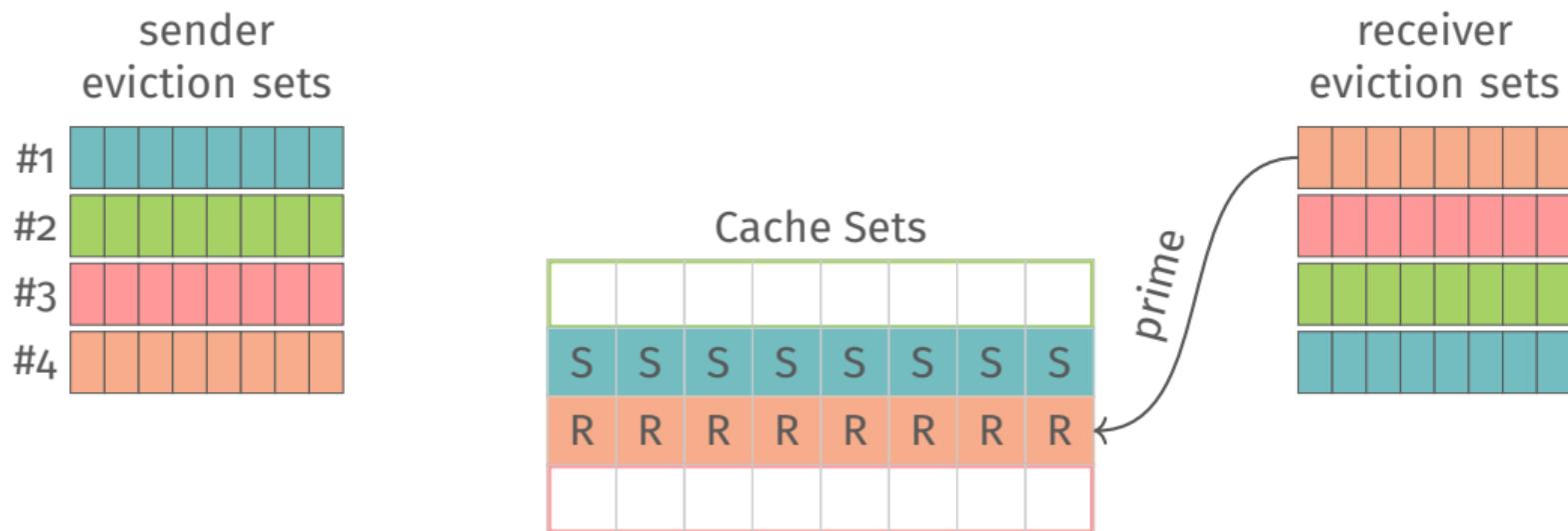
Jamming agreement



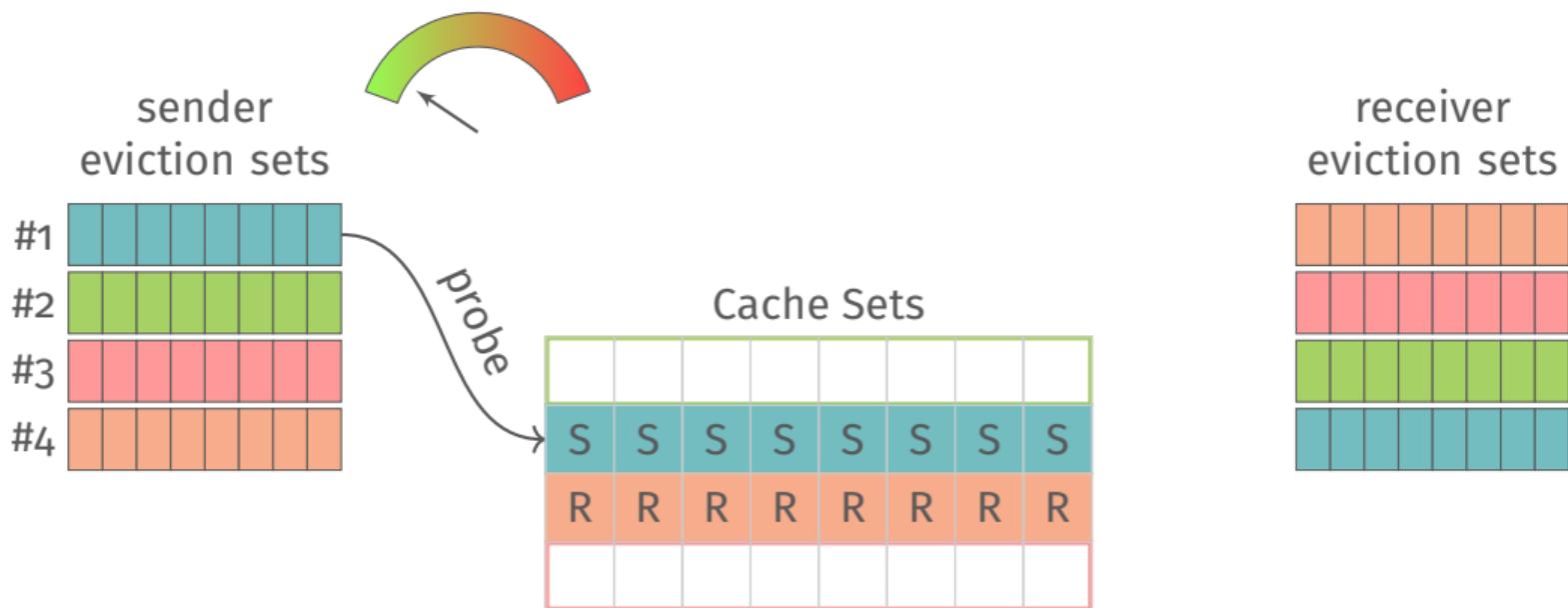
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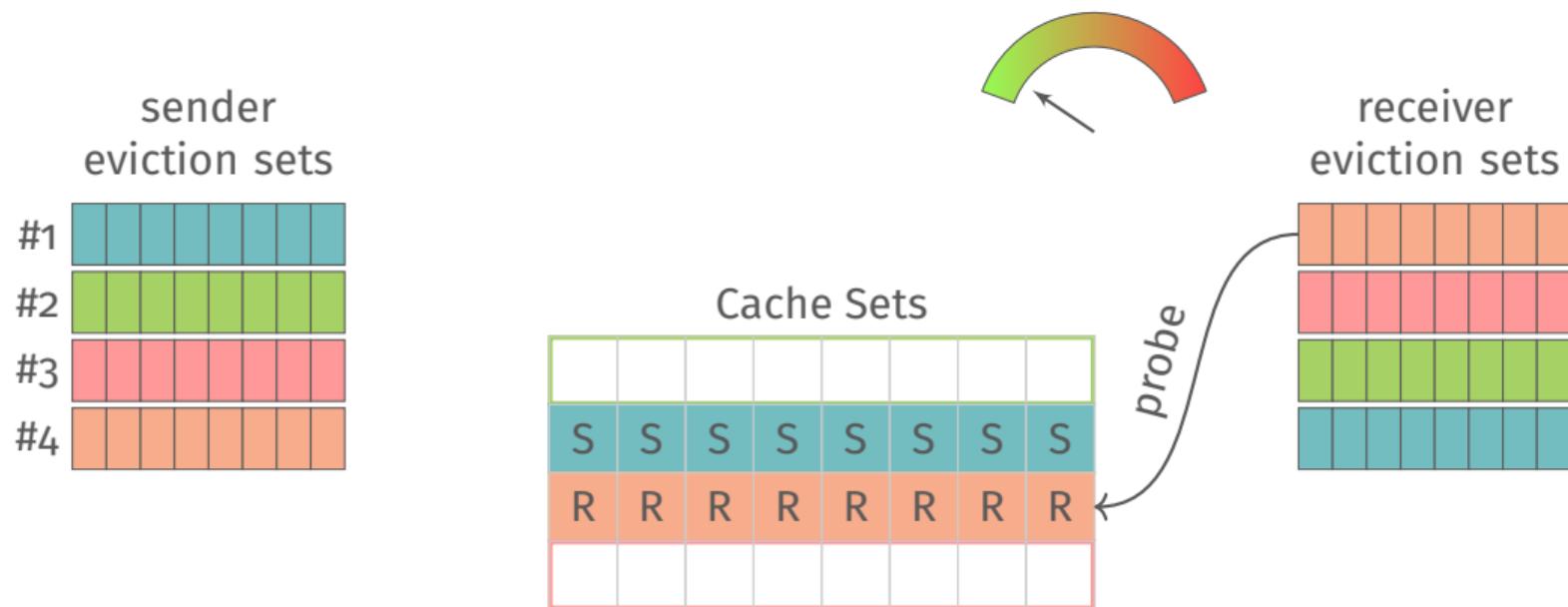
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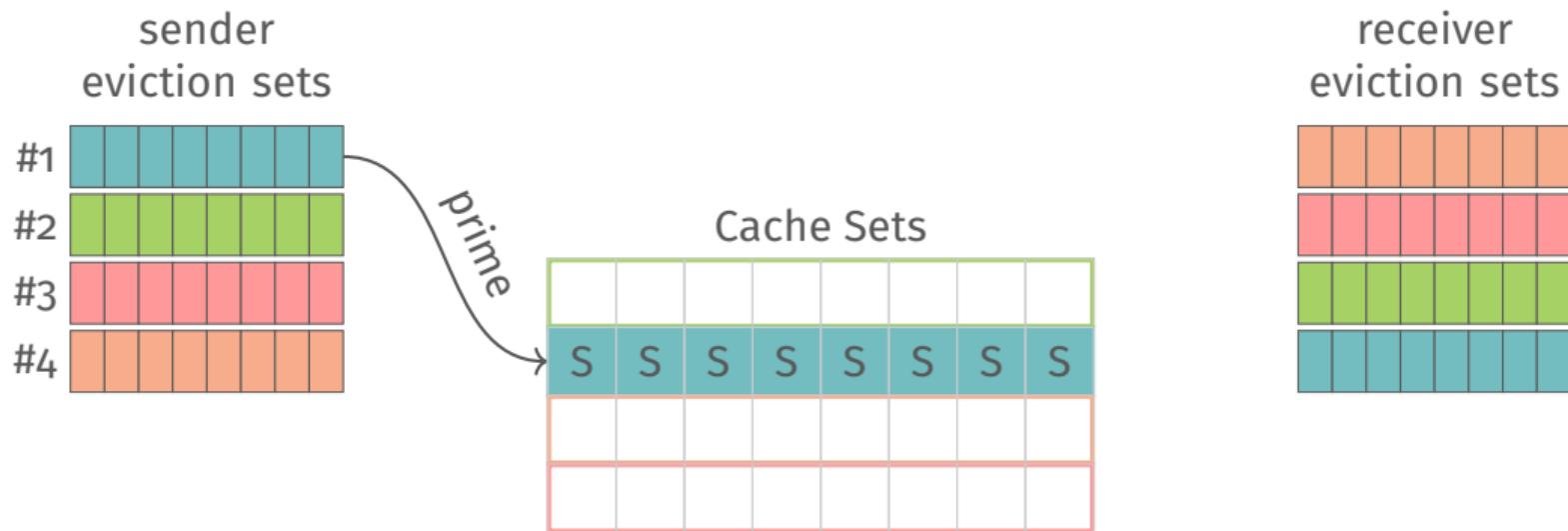
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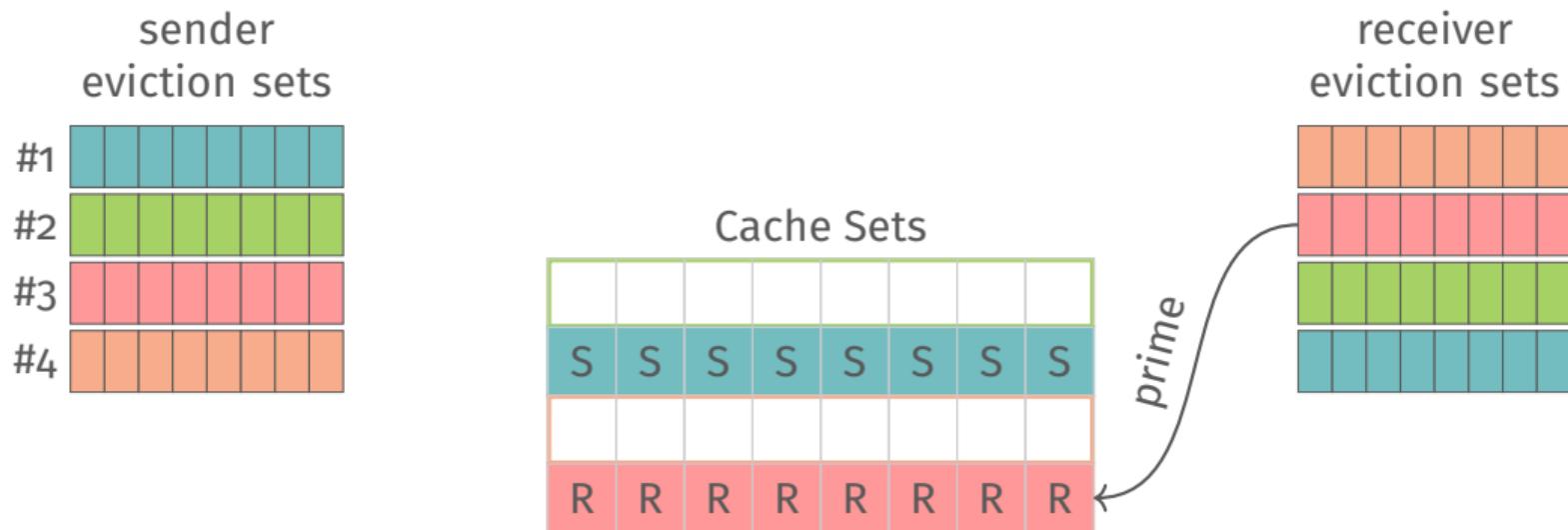
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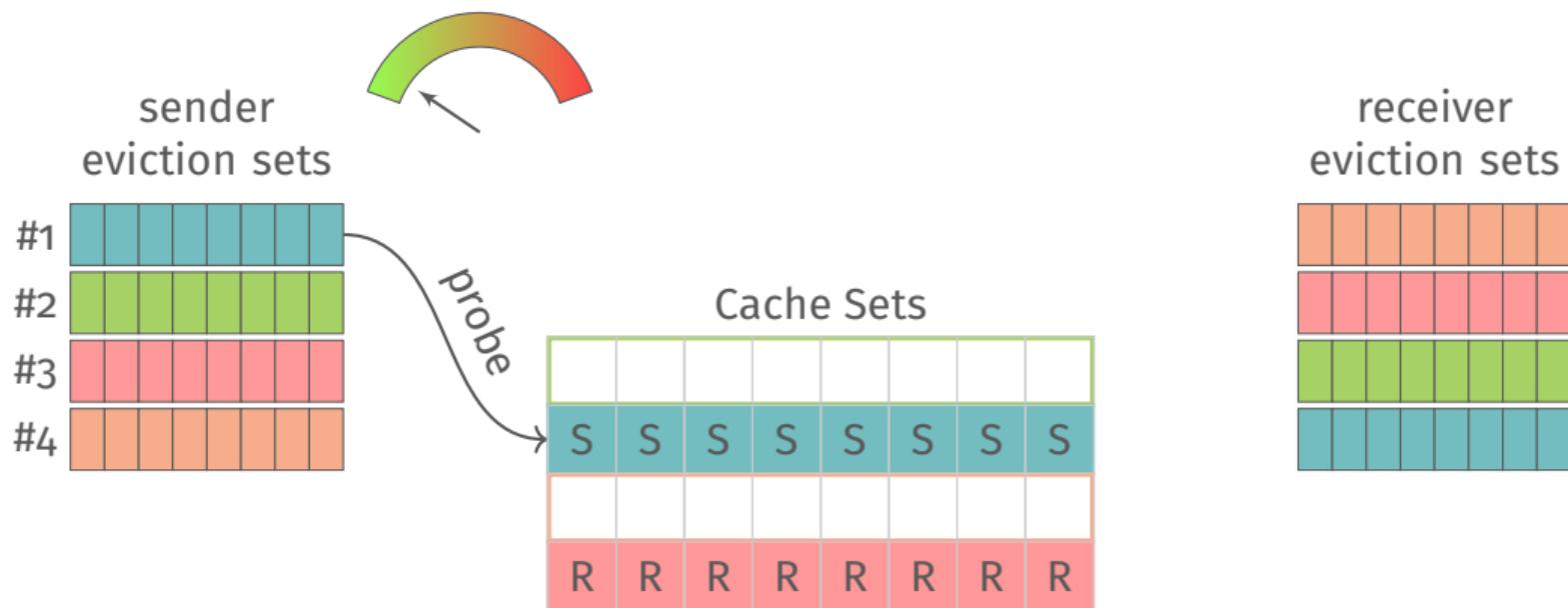
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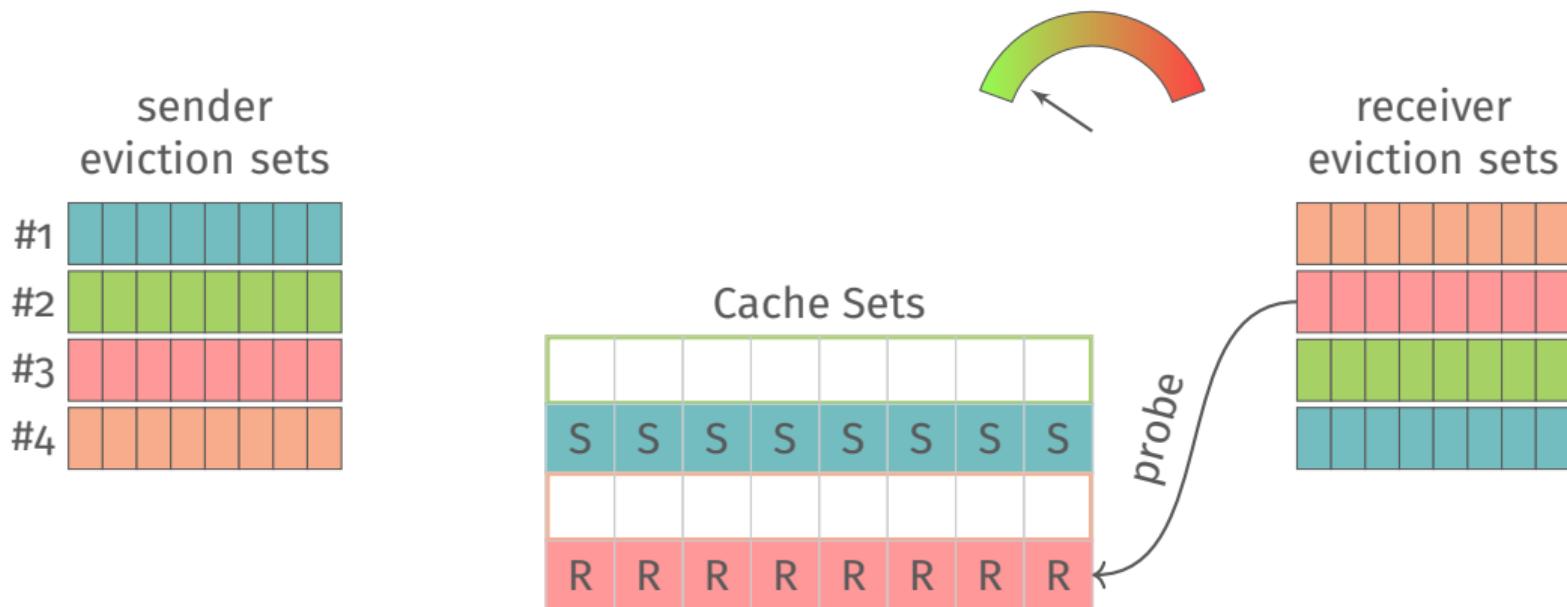
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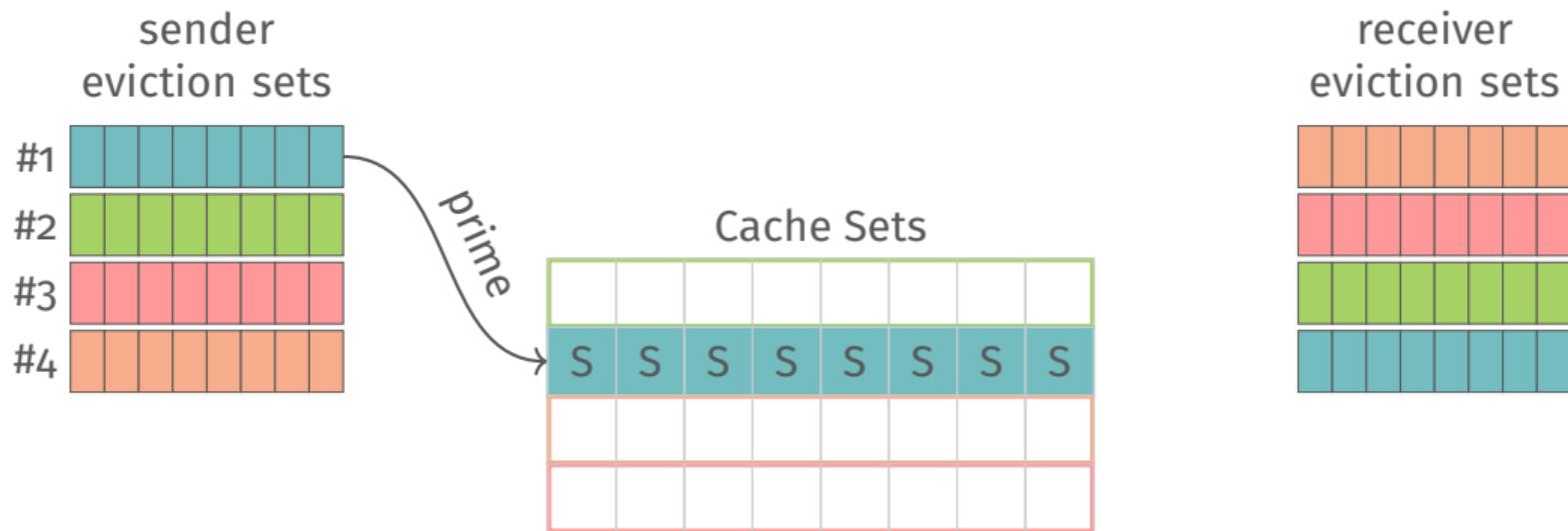
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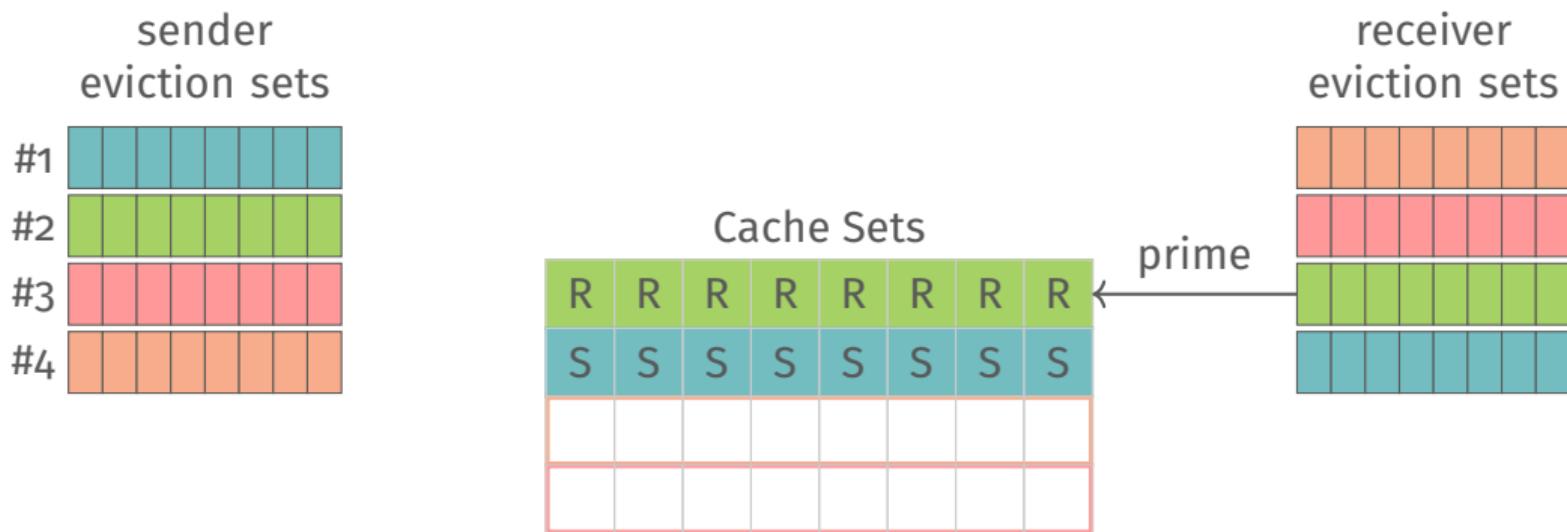
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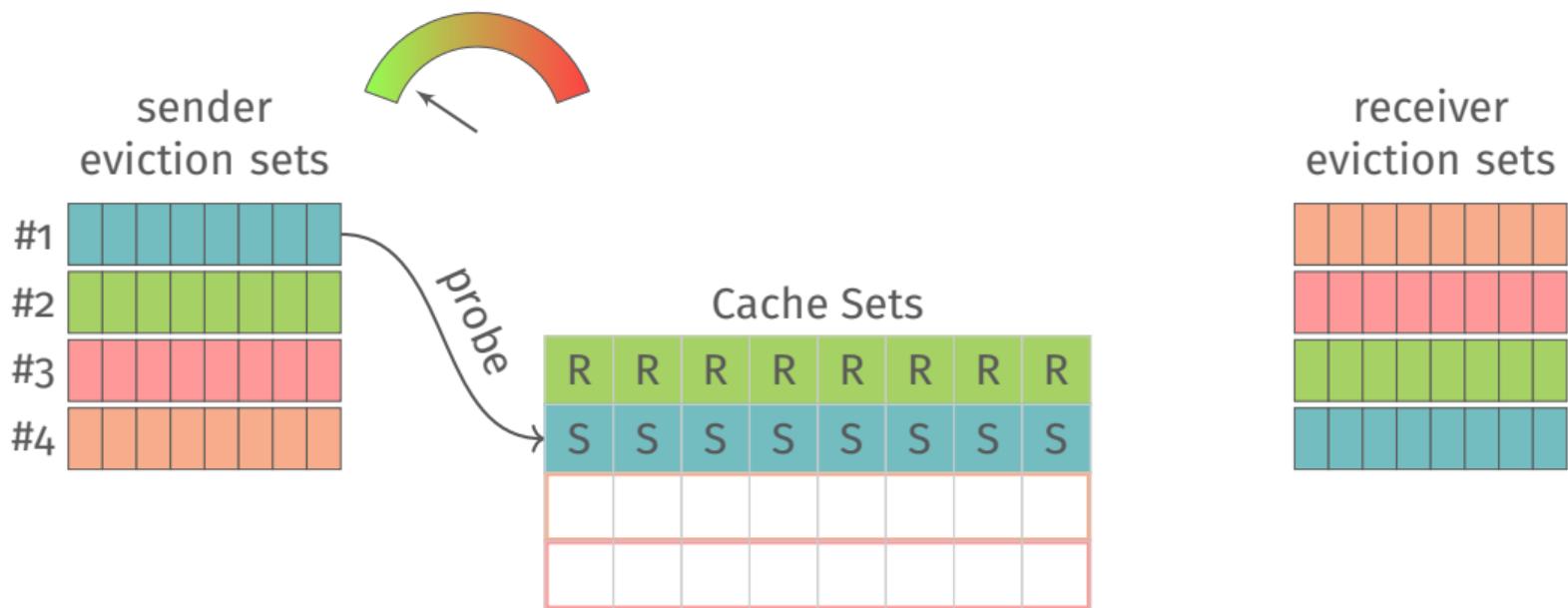
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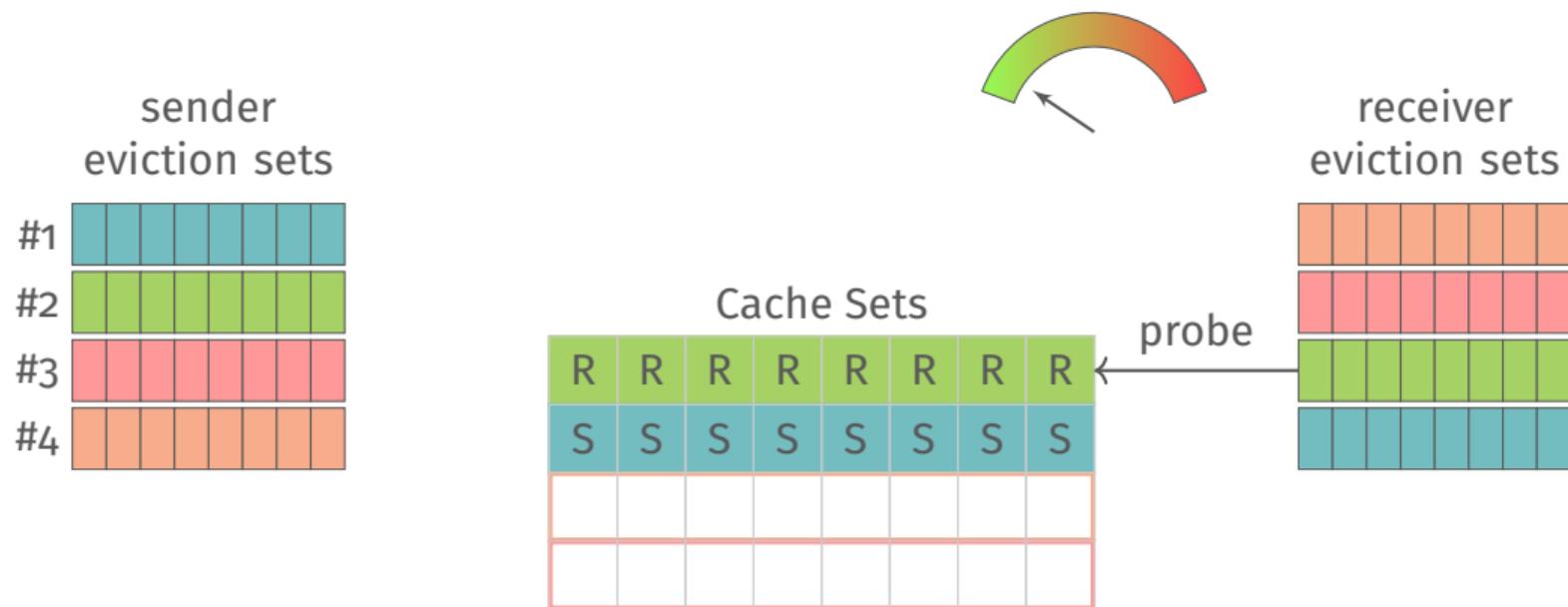
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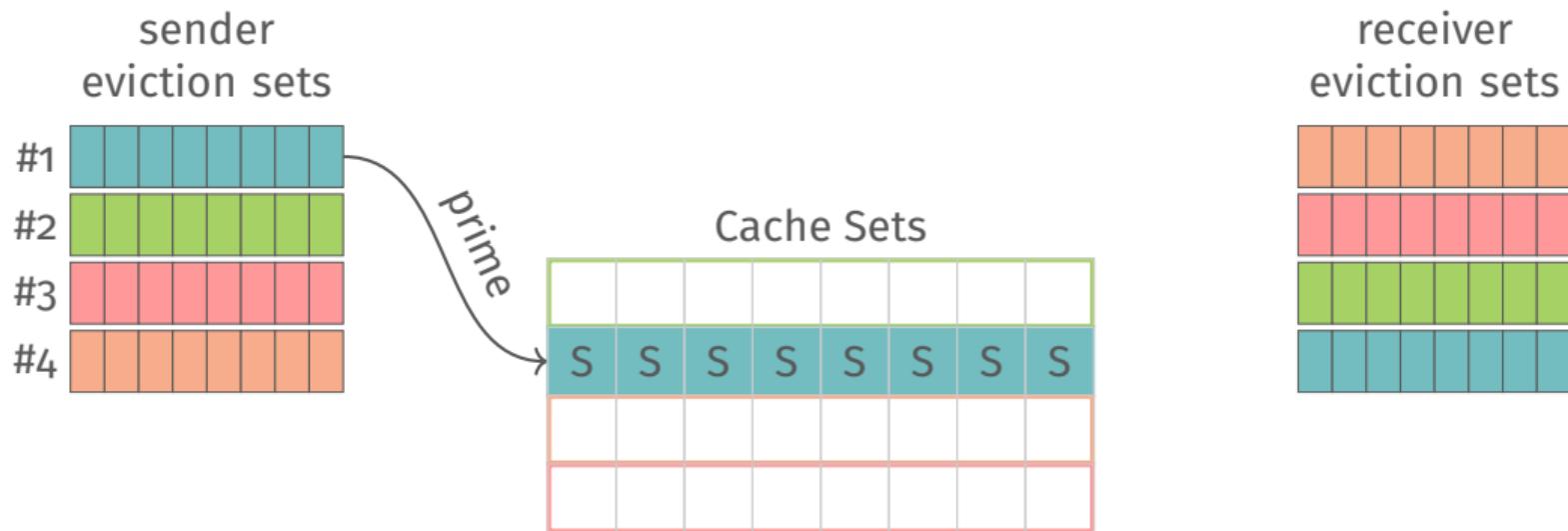
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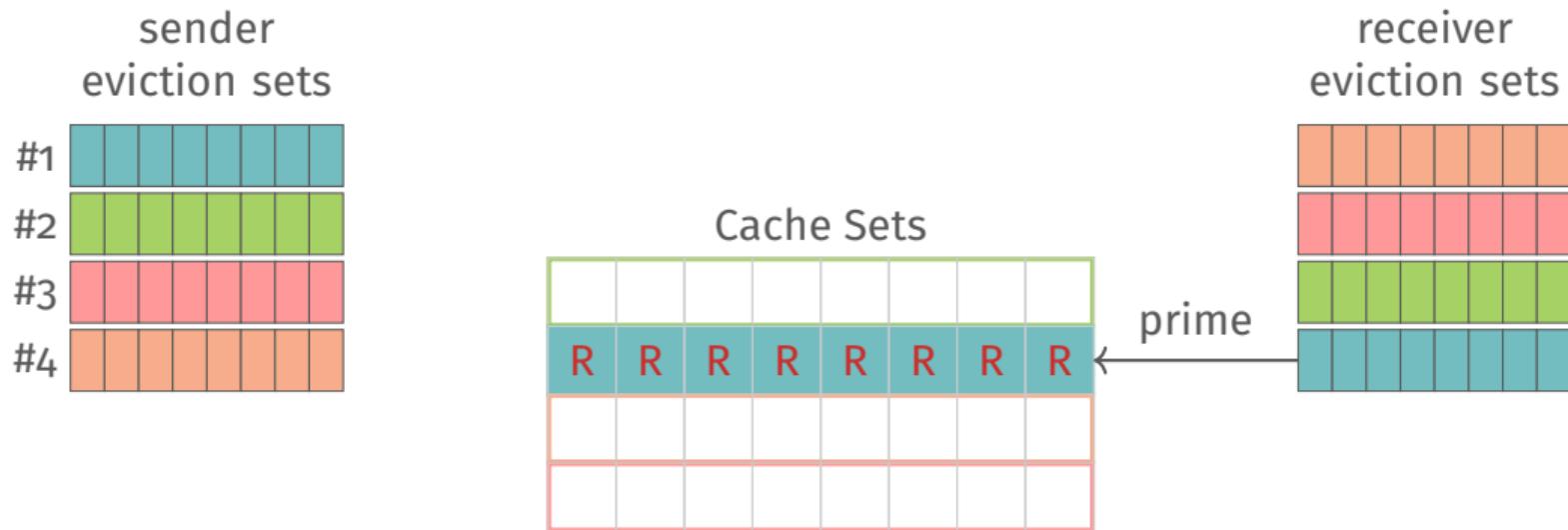
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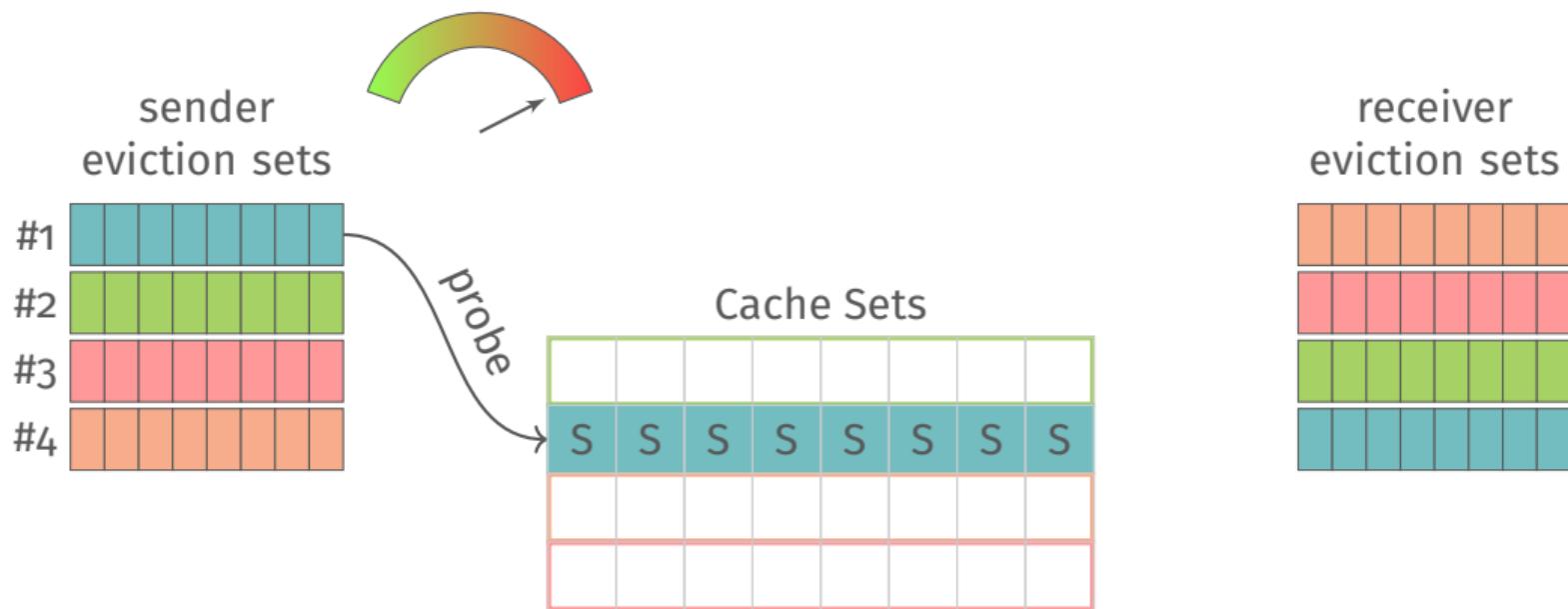
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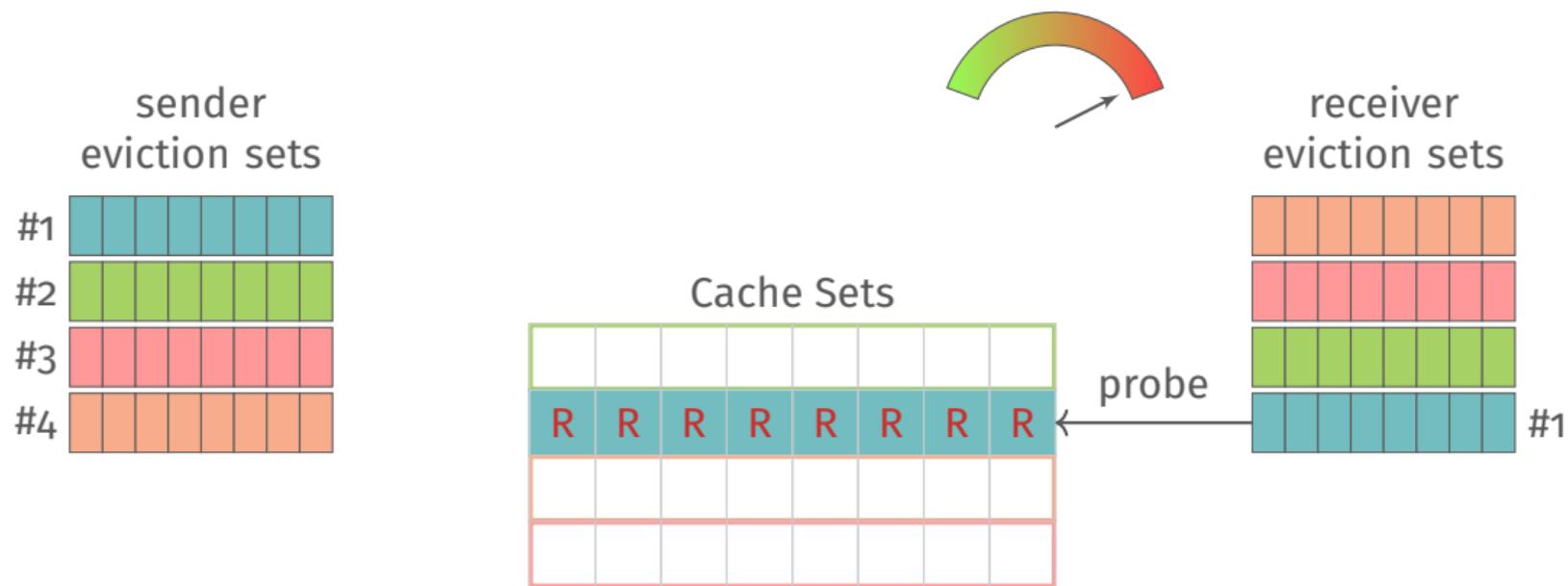
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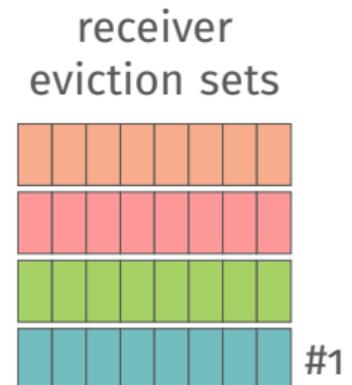
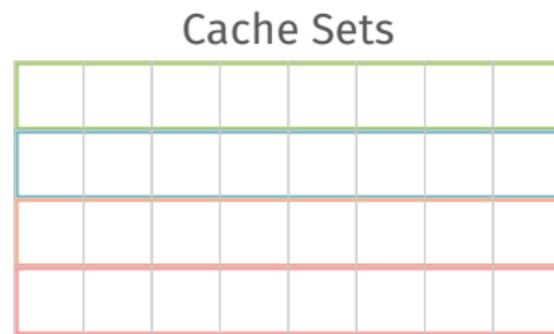
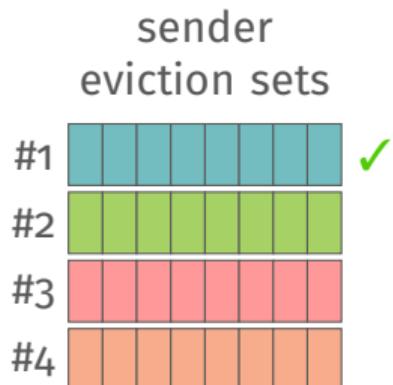
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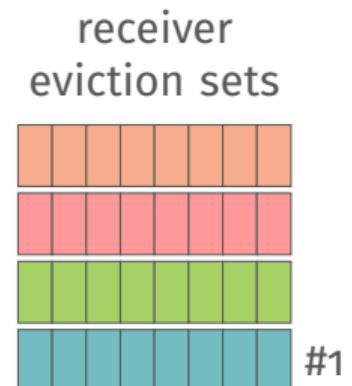
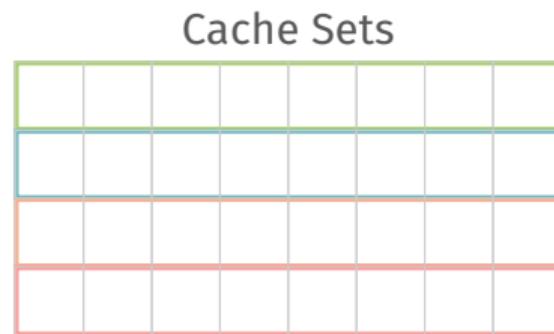
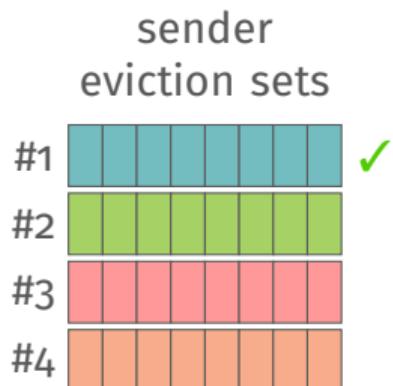
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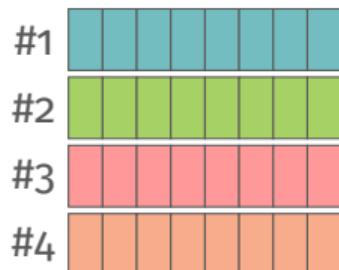


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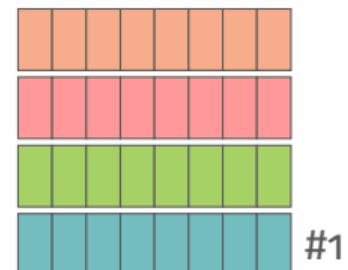
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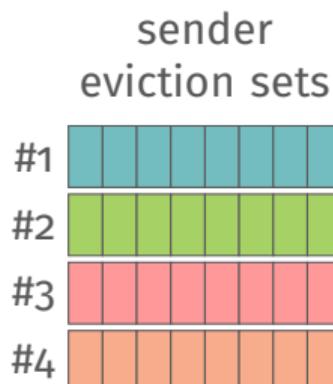


repeat!

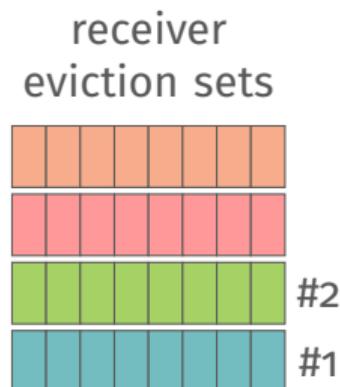
receiver
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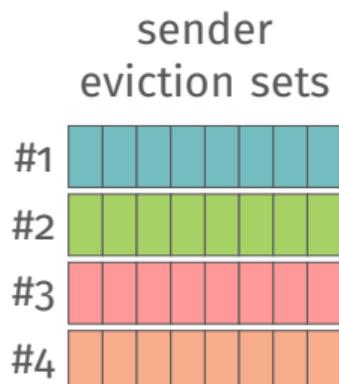
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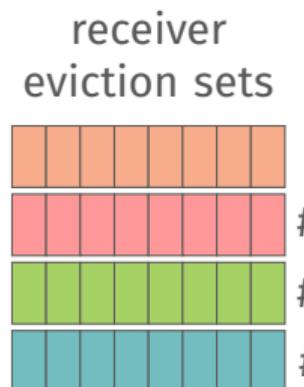
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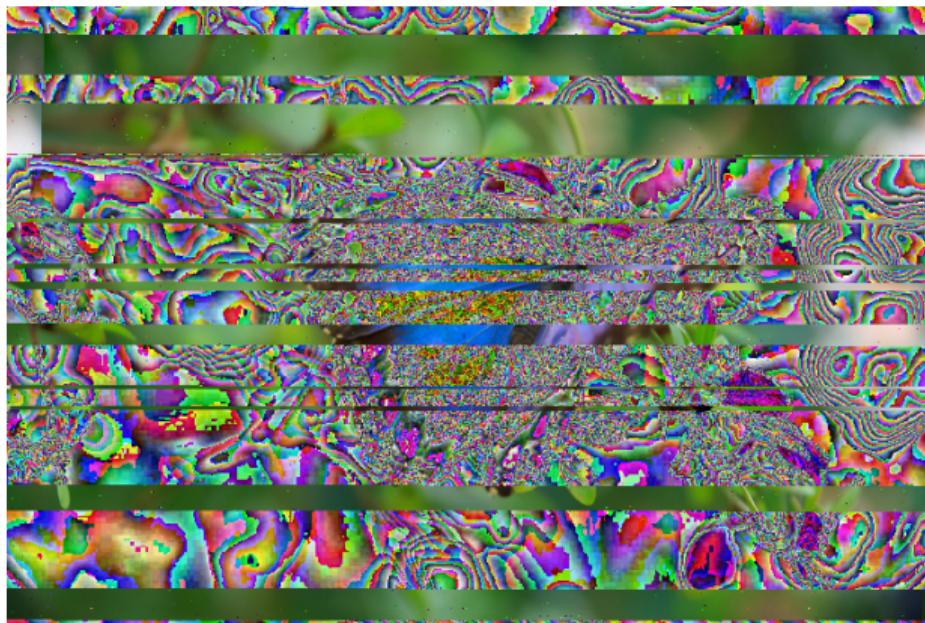
(repeat!)



Jamming agreement



Sending the first image



Handling synchronization errors



Handling synchronization errors

- deletion errors: **request-to-send scheme** that also serves as ack
 - 3-bit sequence number
 - request: encoded sequence number (7 bits)

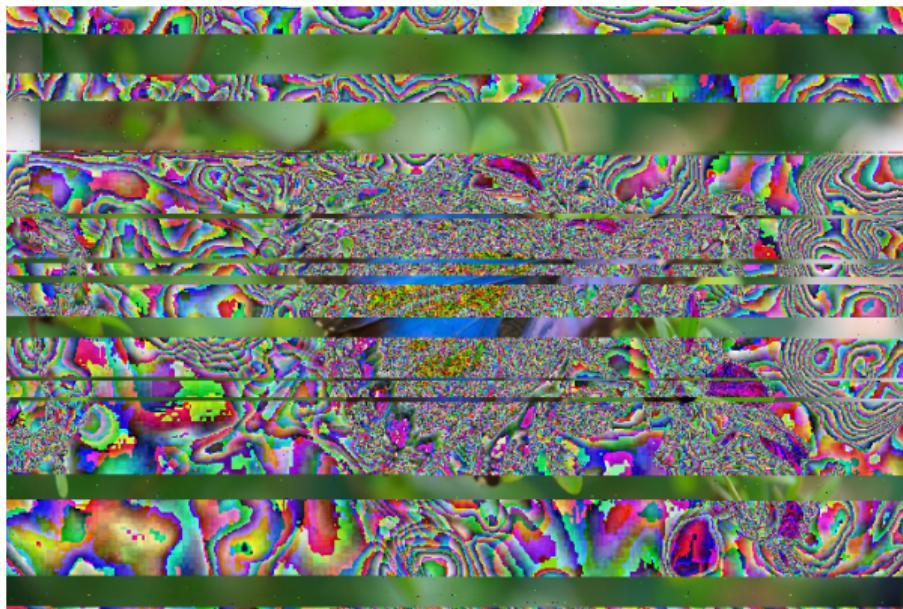


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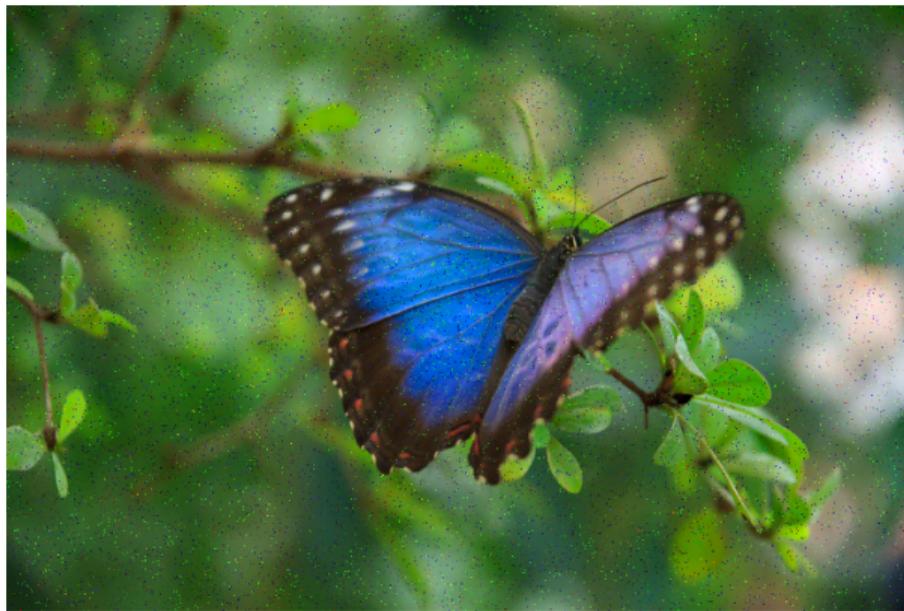
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- 'o'-insertion errors: **error detection code** → Berger codes
 - appending the number of 'o's in the word to itself
 - property: a word cannot consist solely of 'o's



Synchronization (before)



Synchronization (after)



Synchronization (after)



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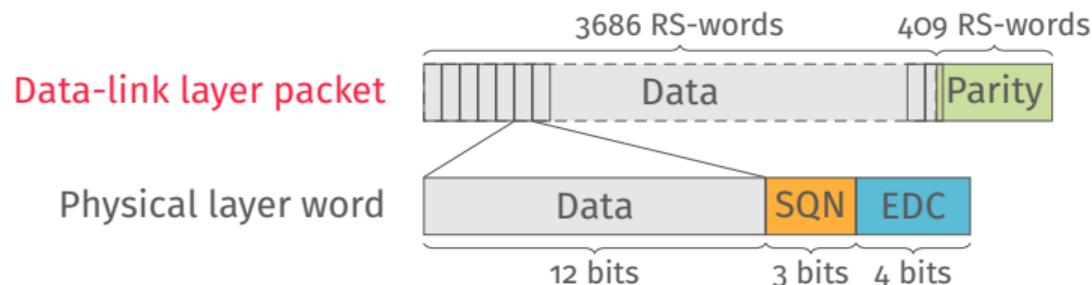


Data-link layer: Error correction

- Reed-Solomon codes to correct the remaining errors

Data-link layer: Error correction

- Reed-Solomon codes to correct the remaining errors
- RS word size = physical layer word size = 12 bits
- packet size = $2^{12} - 1 = 4095$ RS words
- 10% error-correcting code: 409 parity and 3686 data RS words



Error correction (after)



Evaluation

Environment	Bit rate	Error rate	Noise
Native	75.10 KBps	0.00%	-

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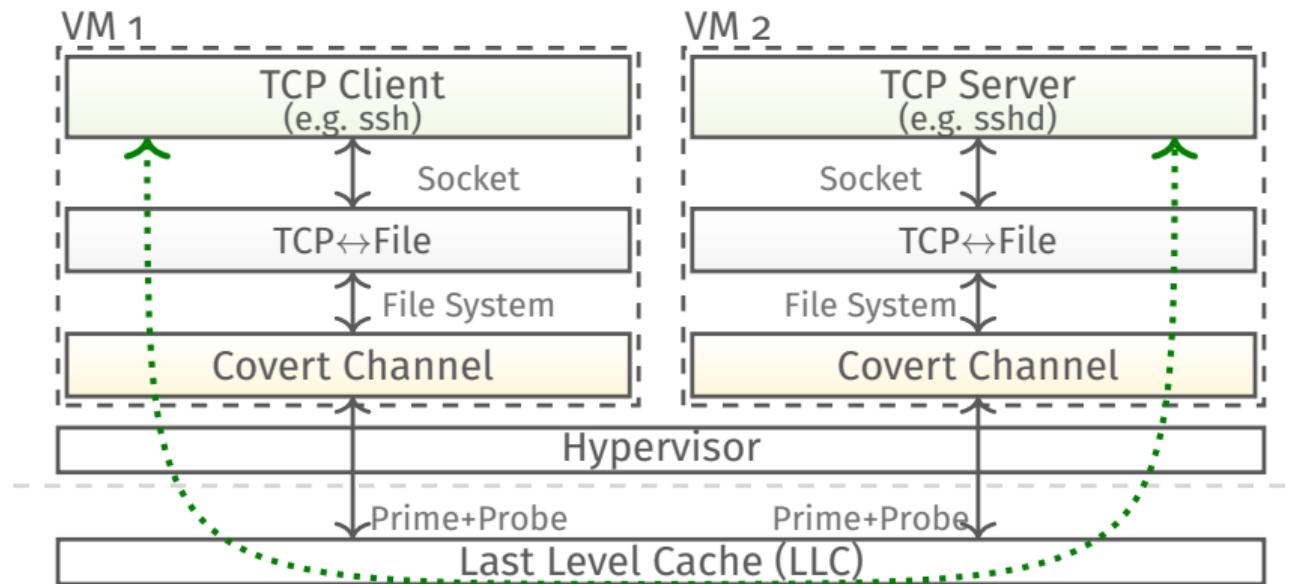
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Environment	Bit rate	Error rate	Noise
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Native	36.03 KBps	0.00%	stress -m 1
Amazon EC2	45.25 KBps	0.00%	-
Amazon EC2	45.09 KBps	0.00%	web server serving files on sender VM
Amazon EC2	42.96 KBps	0.00%	stress -m 2 on sender VM
Amazon EC2	42.26 KBps	0.00%	stress -m 1 on receiver VM
Amazon EC2	37.42 KBps	0.00%	web server on all 3 VMs, stress -m 4 on 3rd VM, stress -m 1 on sender and receiver VMs
Amazon EC2	34.27 KBps	0.00%	stress -m 8 on third VM

Building an SSH connection



SSH evaluation

Between two instances on Amazon EC2

Noise	Connection
No noise	✓
stress -m 8 on third VM	✓
Web server on third VM	✓
Web server on SSH server VM	✓
Web server on all VMs	✓
stress -m 1 on server side	unstable

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Telnet also works with occasional corrupted bytes with `stress -m 1`

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- our robust covert channel supports an SSH connection
- we extended Amazon's product portfolio :)



Hello from the Other Side: SSH over Robust Cache Covert Channels in the Cloud

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