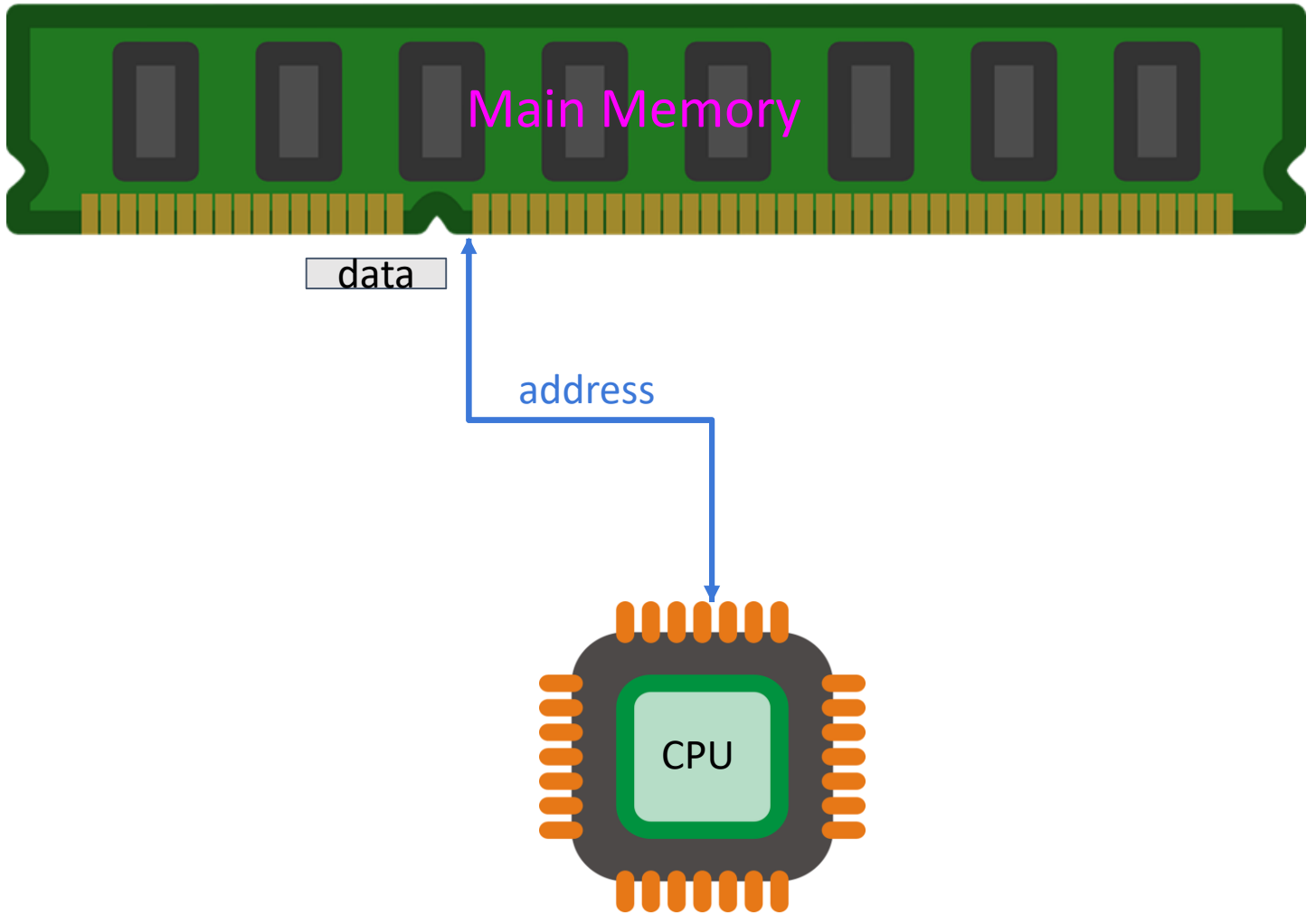
Cache Side-Channel Attacks (Brief Introduction)

Presenter: Aria Shahverdi

9/31/2019

How do we load data from Main Memory?



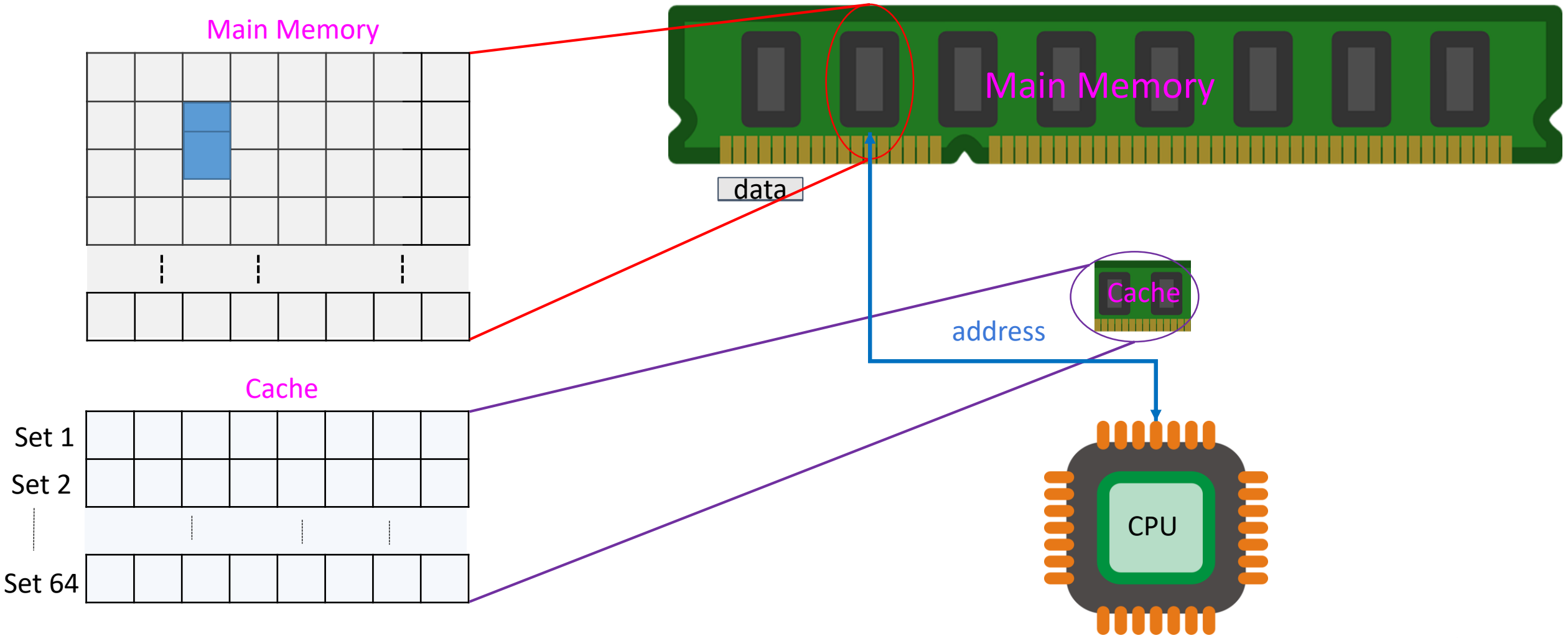
Memory Locality

- Future memory accesses are near past memory accesses
- Memories take advantages of two locality
  - **Temporal Locality**: near in time
    - We will often access the same data again very soon
  - **Spatial Locality**: near in space/distance
    - Our next access is often very close to our last access (or recent accesses)

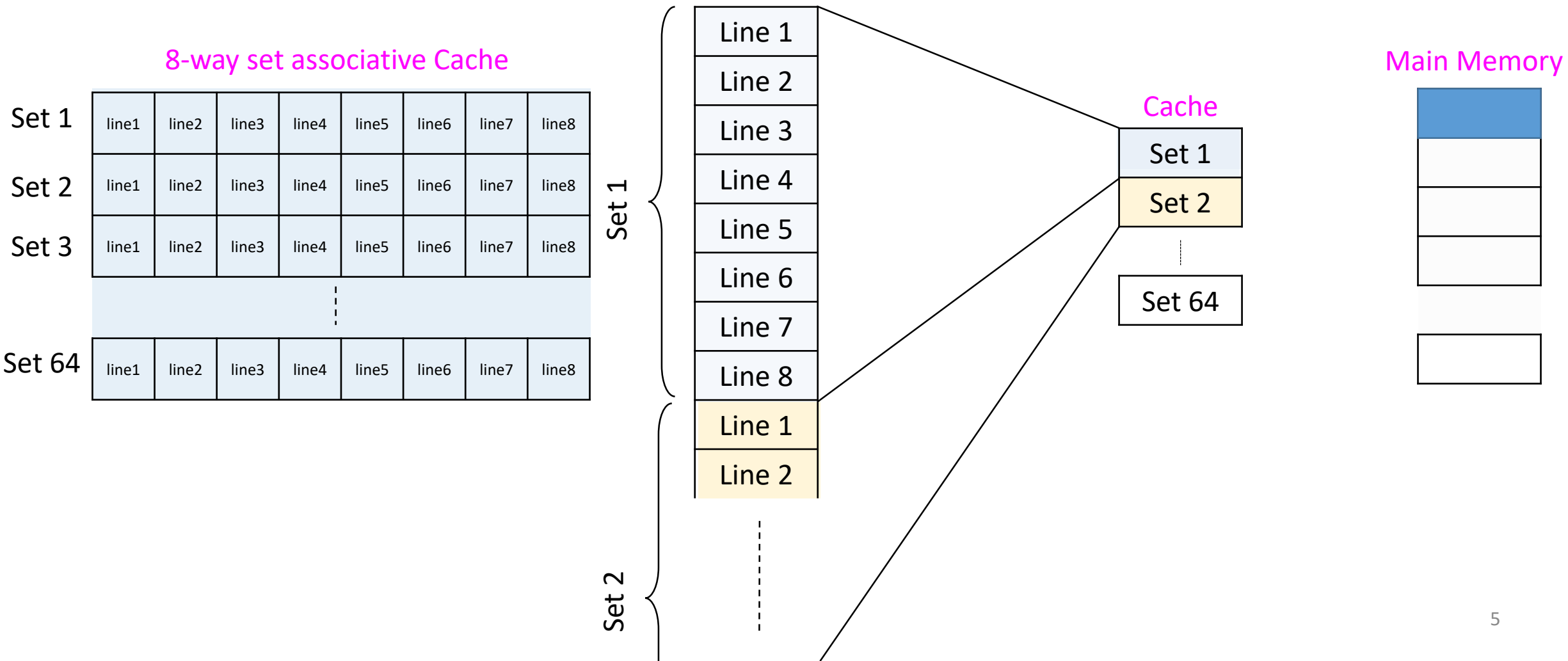
```
for(i = 0; i < 20; i++)
  a[i] = a[i]*2;
```

```
a[0]
a[1]
a[2]
…
```

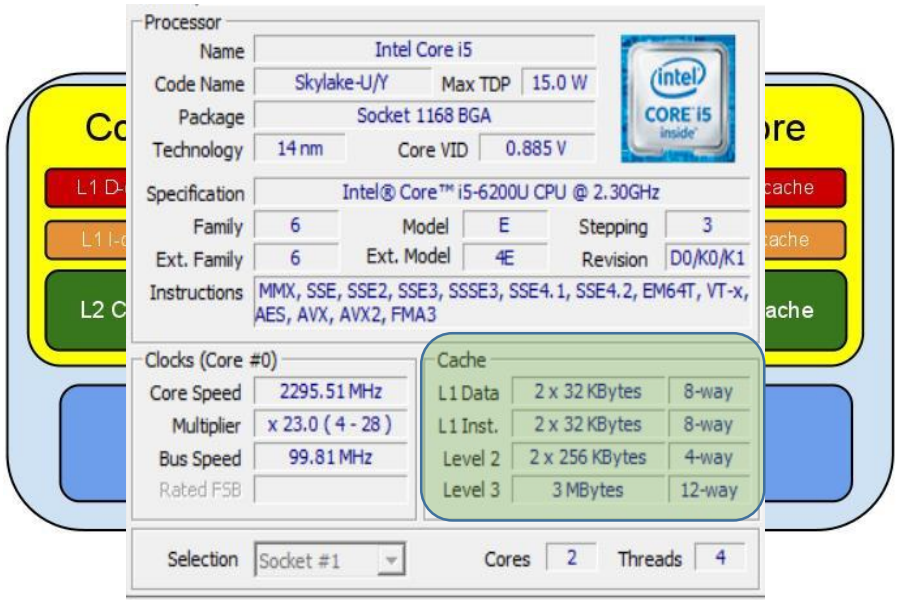
Cache Architecture High Level

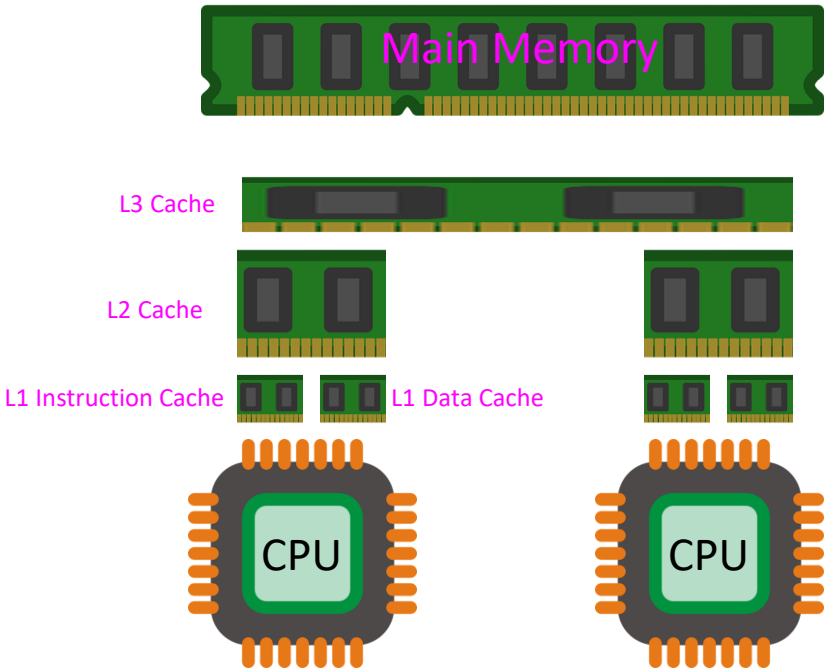


Set Associative Cache Architecture



Introduction to Cache Architecture

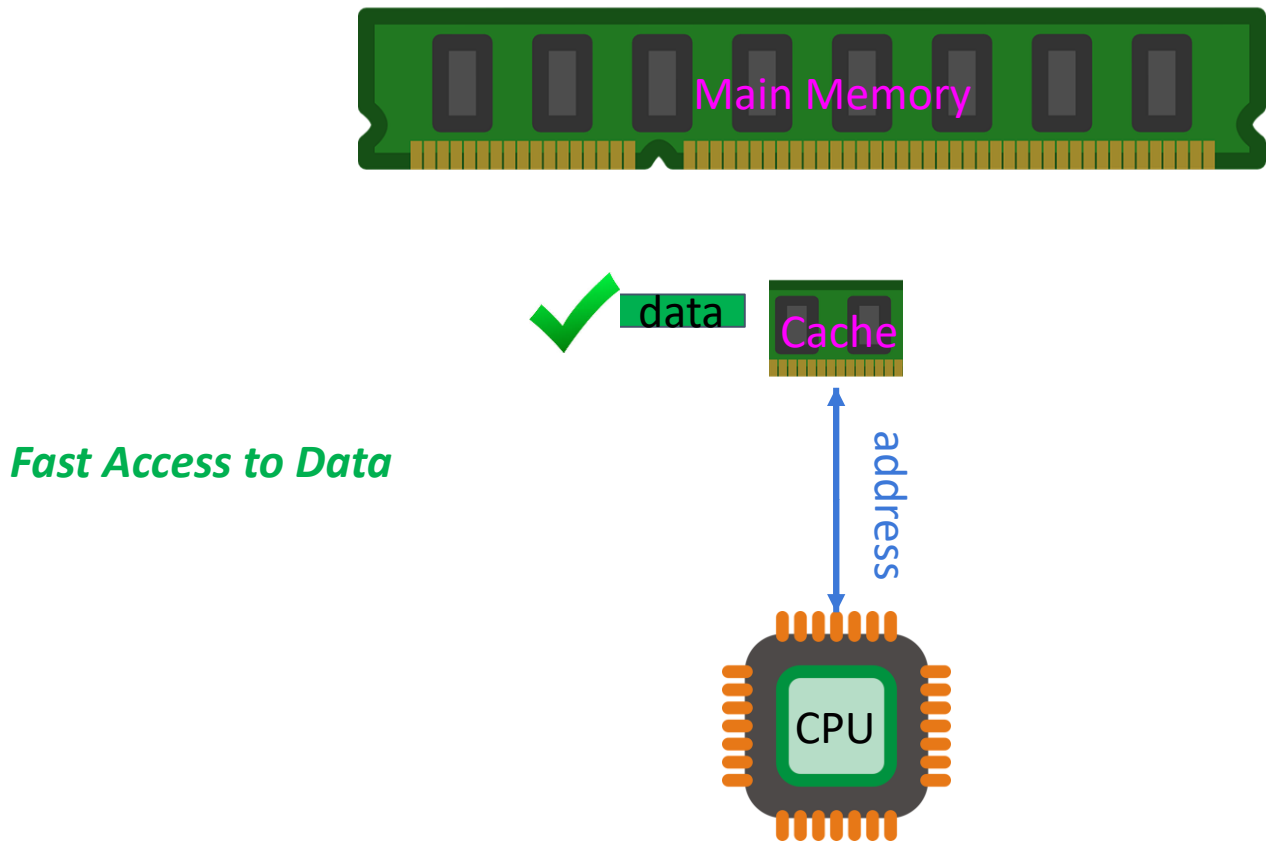




Cache Architecture (Summary)

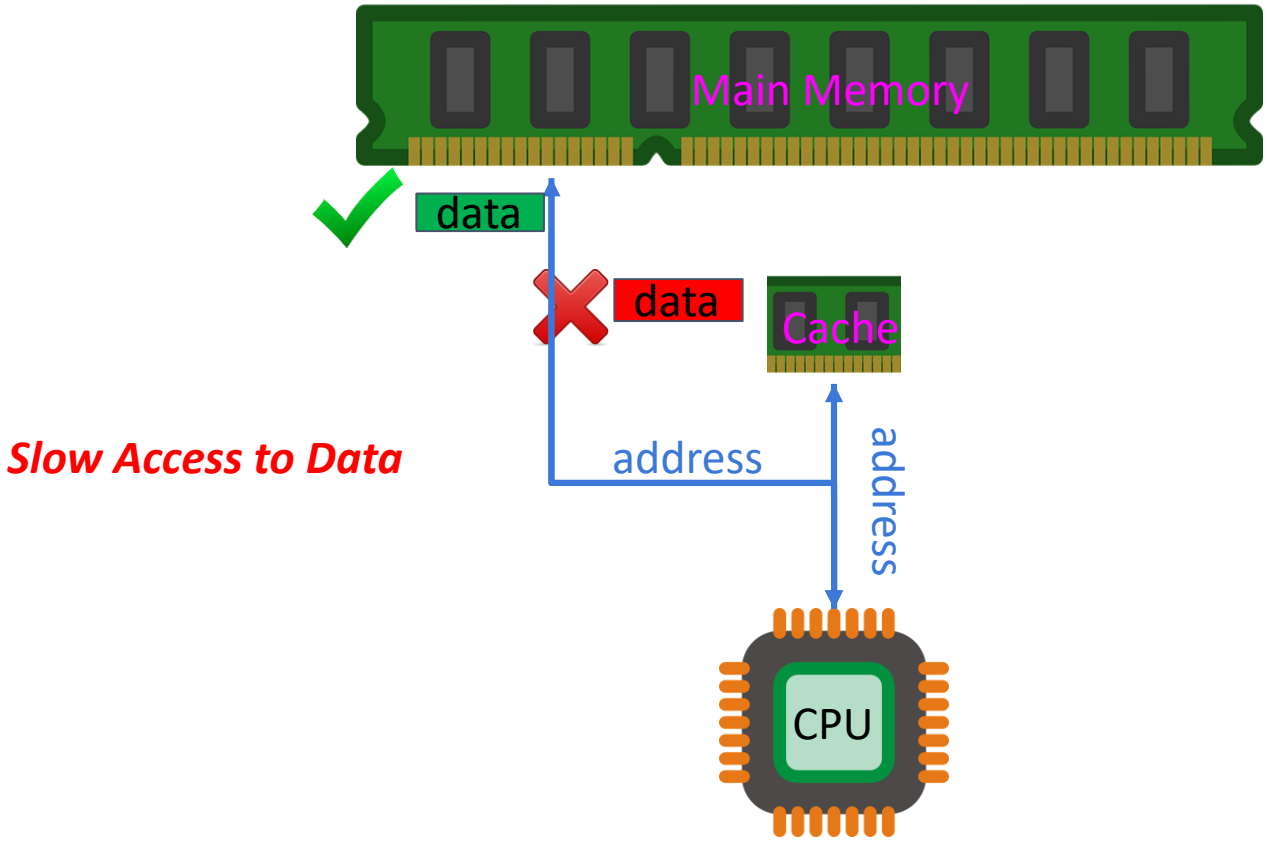
- Unit of Memory in cache is a line
- A cache consists of multiple sets which stores fixed number of lines
- The number of lines in a set is called associativity
  - L1 is 8-way, L2 is 4-way, L3 is 12-way
- Last Level Cache (LLC) is inclusive
  - LLC contains copies of all of the data in the lower cache level
  - Evicting data from LLC remove that data from all other cache levels

Accessing Memory (Cache Hit)



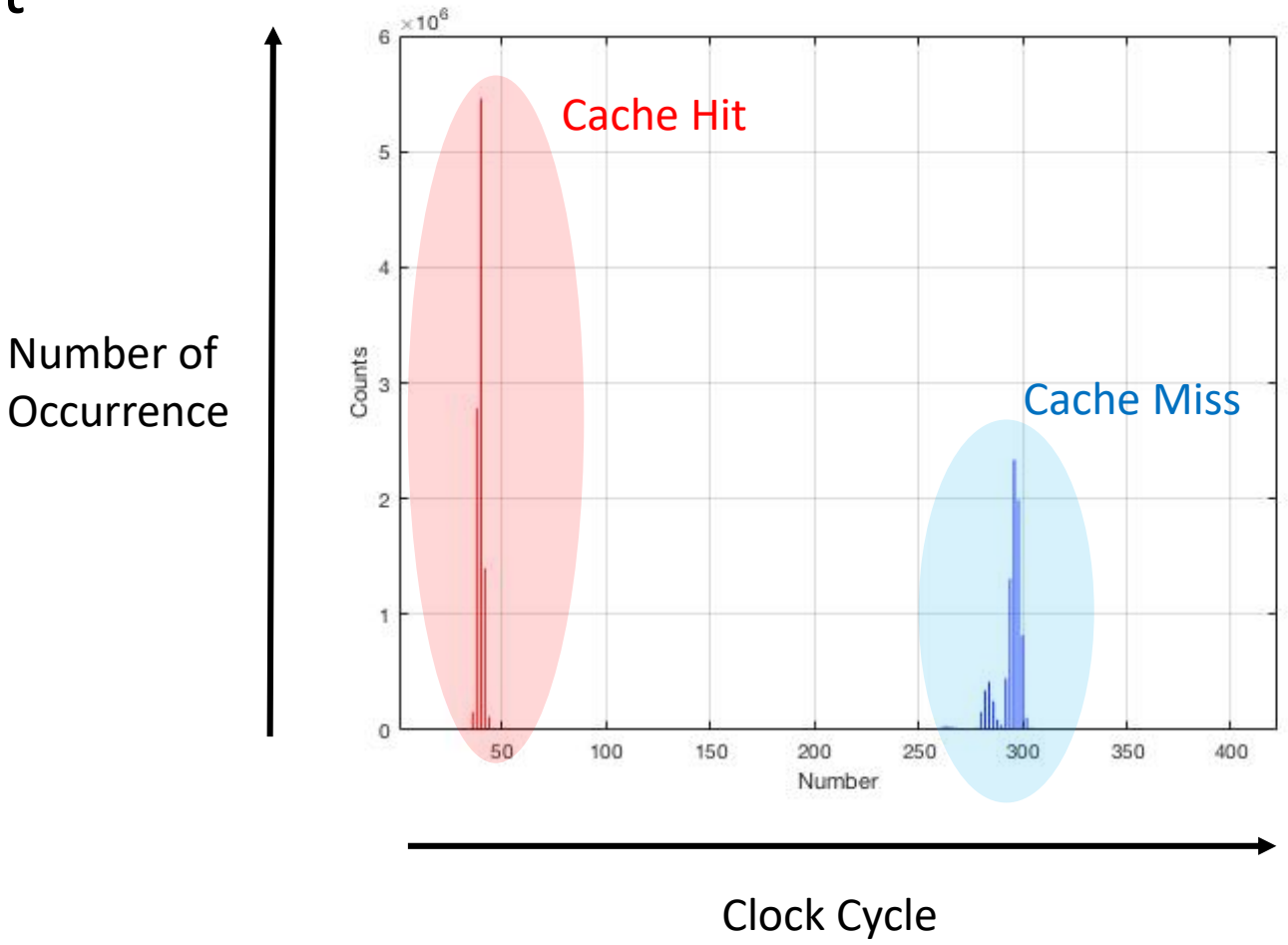
Fast Access to Data

Accessing Memory (Cache Miss)



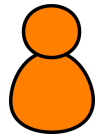
Cache Hit vs. Miss Time Difference

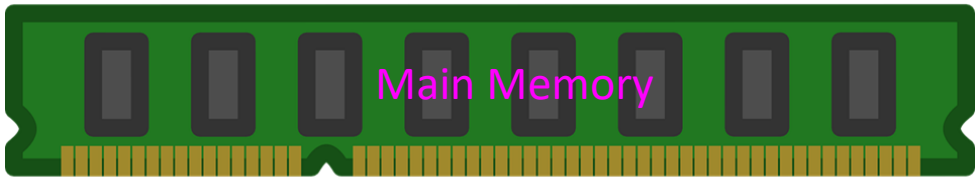
- ≈10 Million measurement

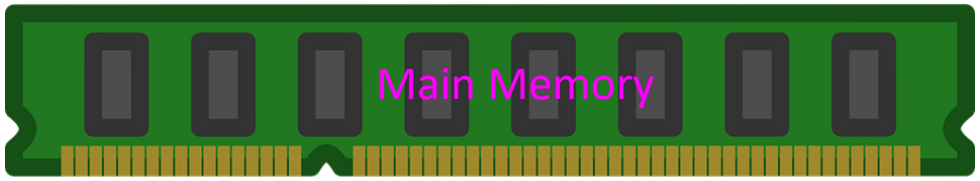


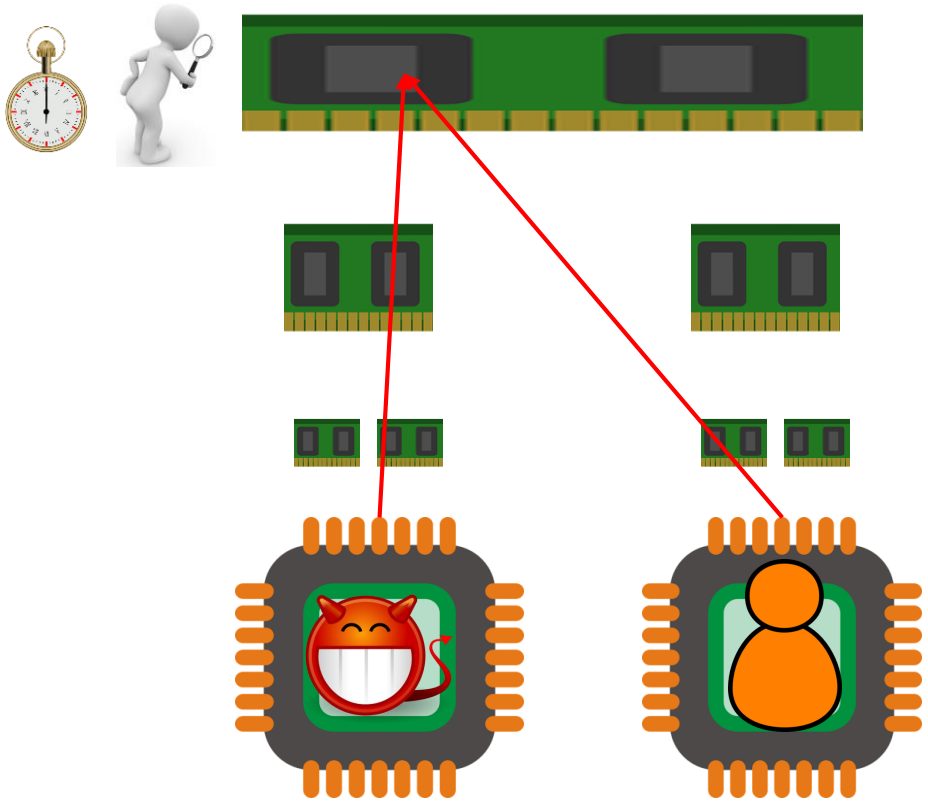
Cache Attack Model

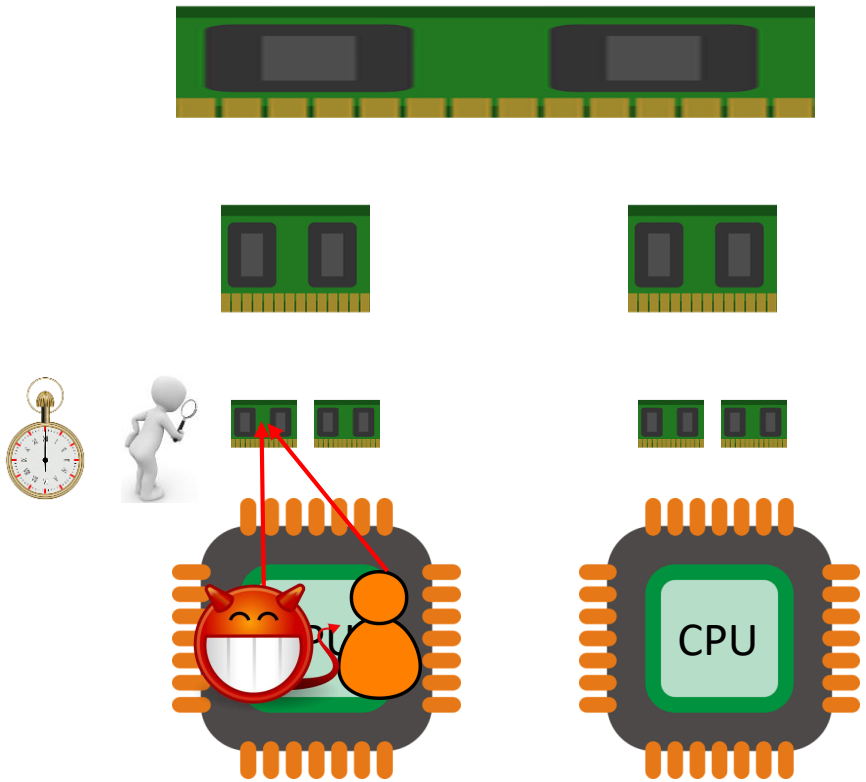

: Attacker


: Victim



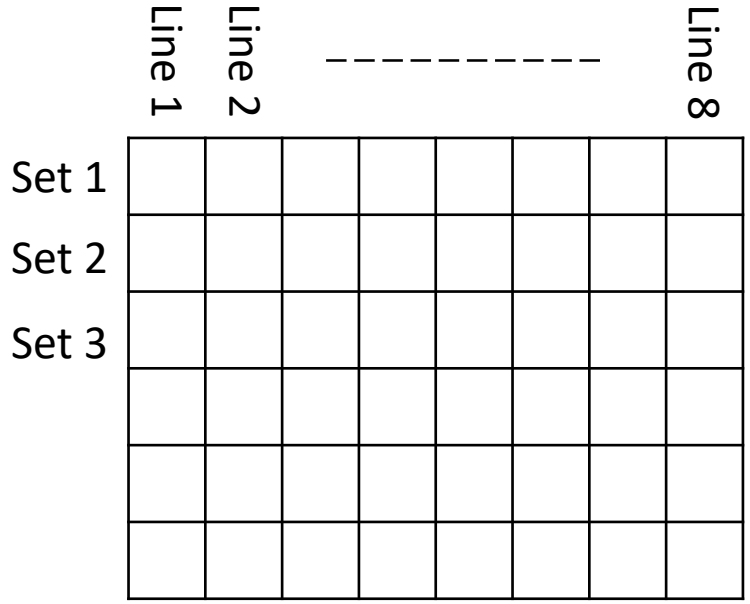






Some Cache Attack Technique

- Evict and Time
- Flush and Reload
- Prime and Probe



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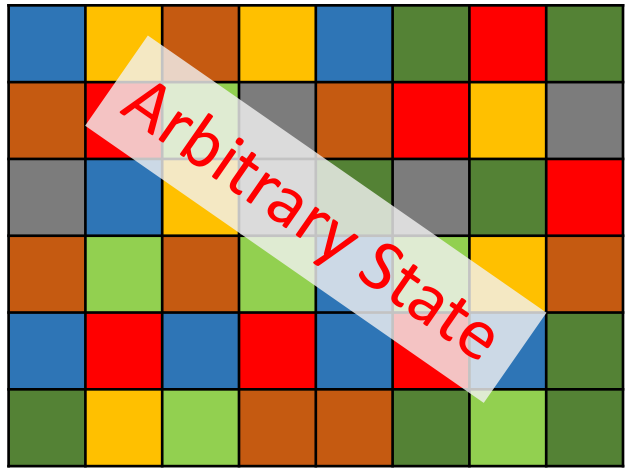
Evict and Time

1. Trigger encryption
2. Selectively manipulate the state of the cache (e.g. evict a full cache set)
3. Trigger encryption
4. Measure how long it took
5. Deduce what cache sets it accessed
6. Repeat step 1-4 to gain information on all the set the encryption accessed



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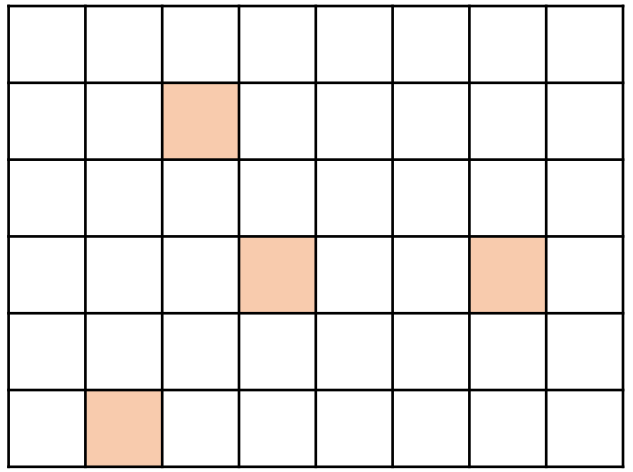

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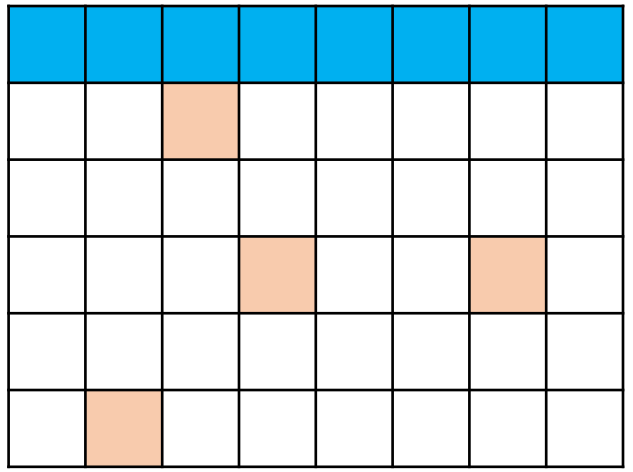
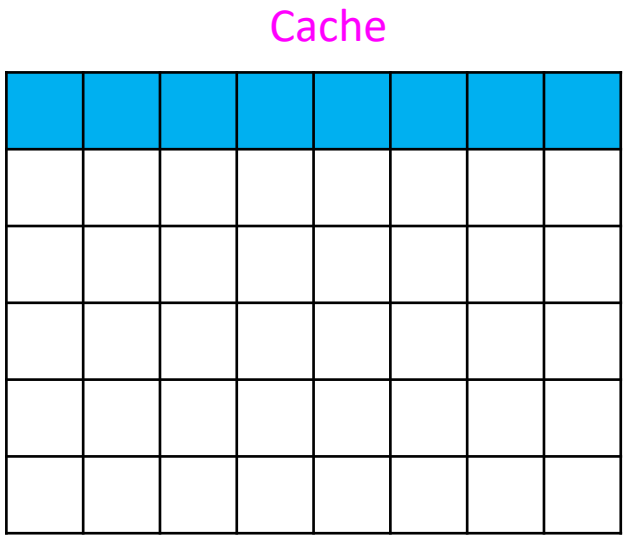
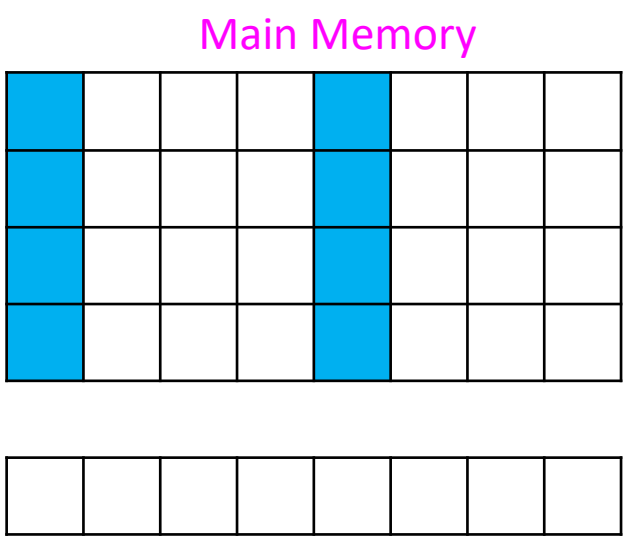


How do we fill a cache set?

- By Accessing some of the memory locations the corresponding locations in the cache is going to be filled.
- Main Challenge: which lines to access?





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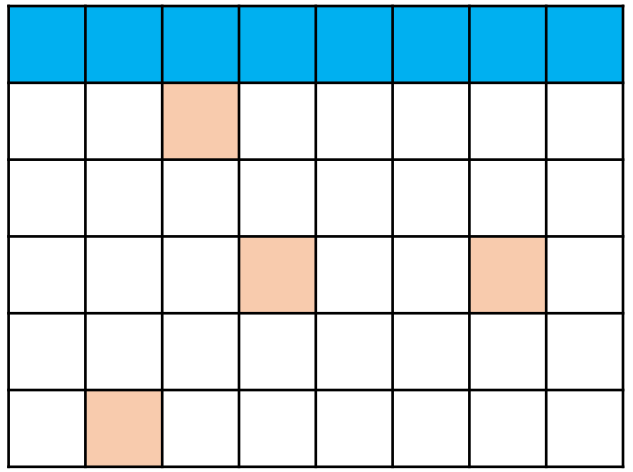

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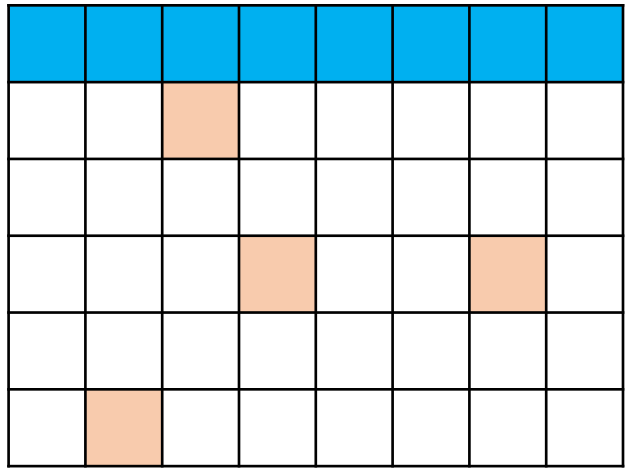

It took almost the same amount time

Evict and Time

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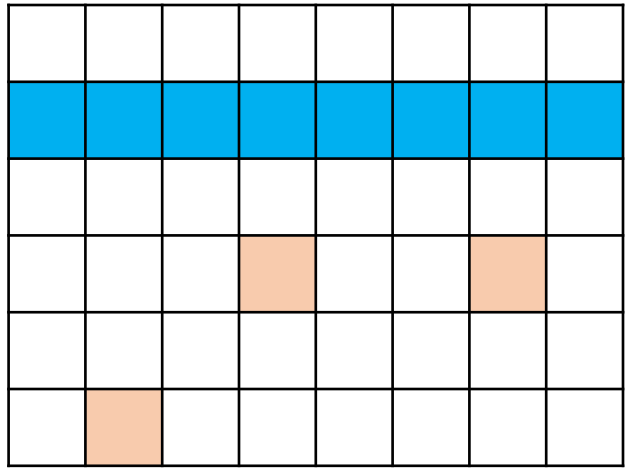

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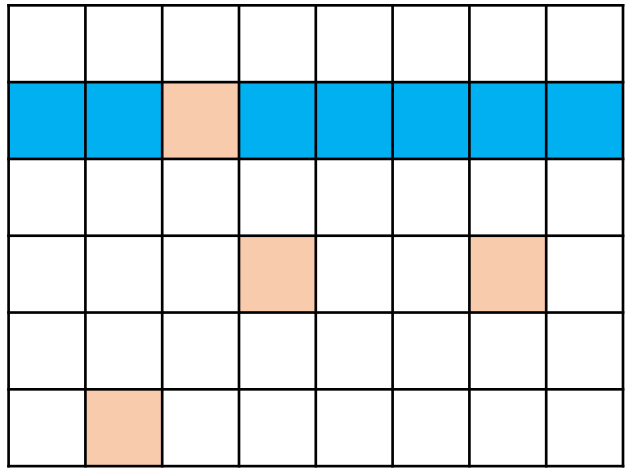

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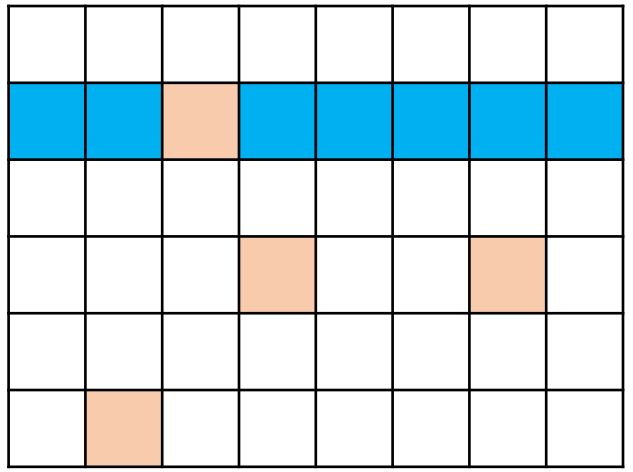

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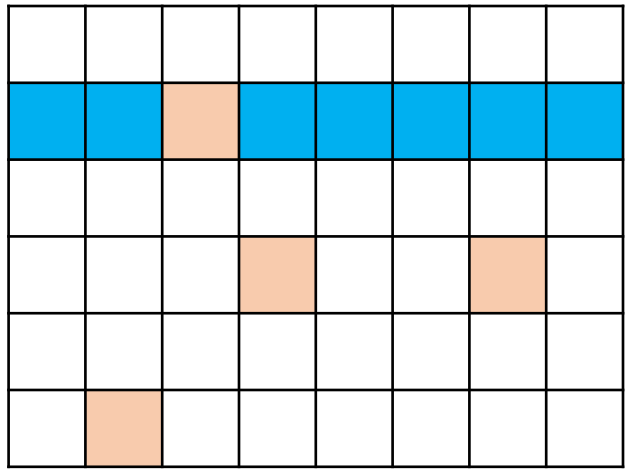


Set 2 was accessed!!

Some Cache Attack Technique

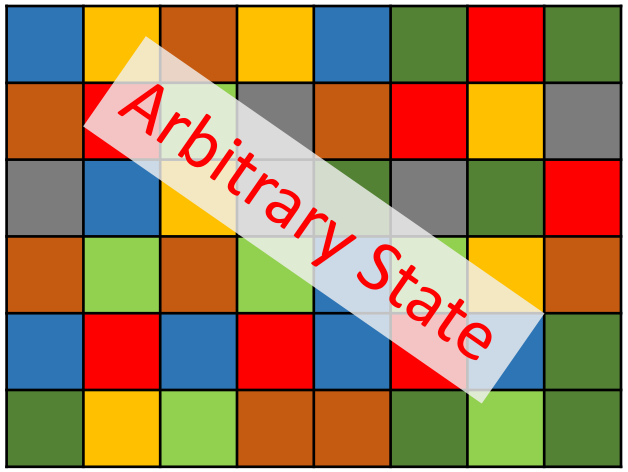
- Evict and Time
- Flush and Reload
- Prime and Probe

Flush and Reload

- Exploits cache behavior to leak information on victim access to shared memory.
  - Shared libraries
  - Memory de-duplication
- Spy monitors victim’s access to shared code
  - Spy can determine what victim does
  - Spy can infer the data the victim operates on

Flush and Reload

1. Flush memory line
2. Wait a bit
3. Measure time to Reload line
4. Repeat



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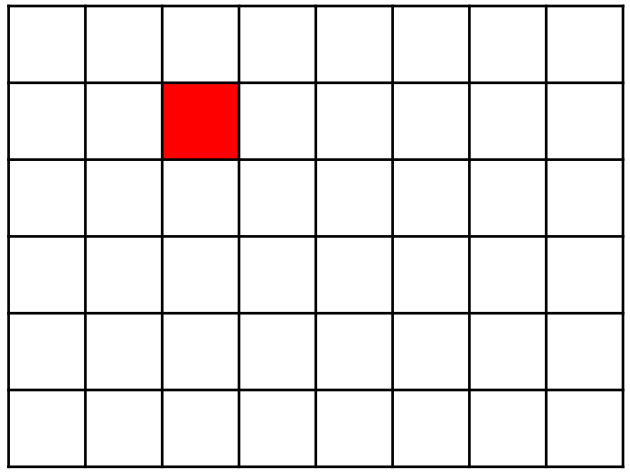
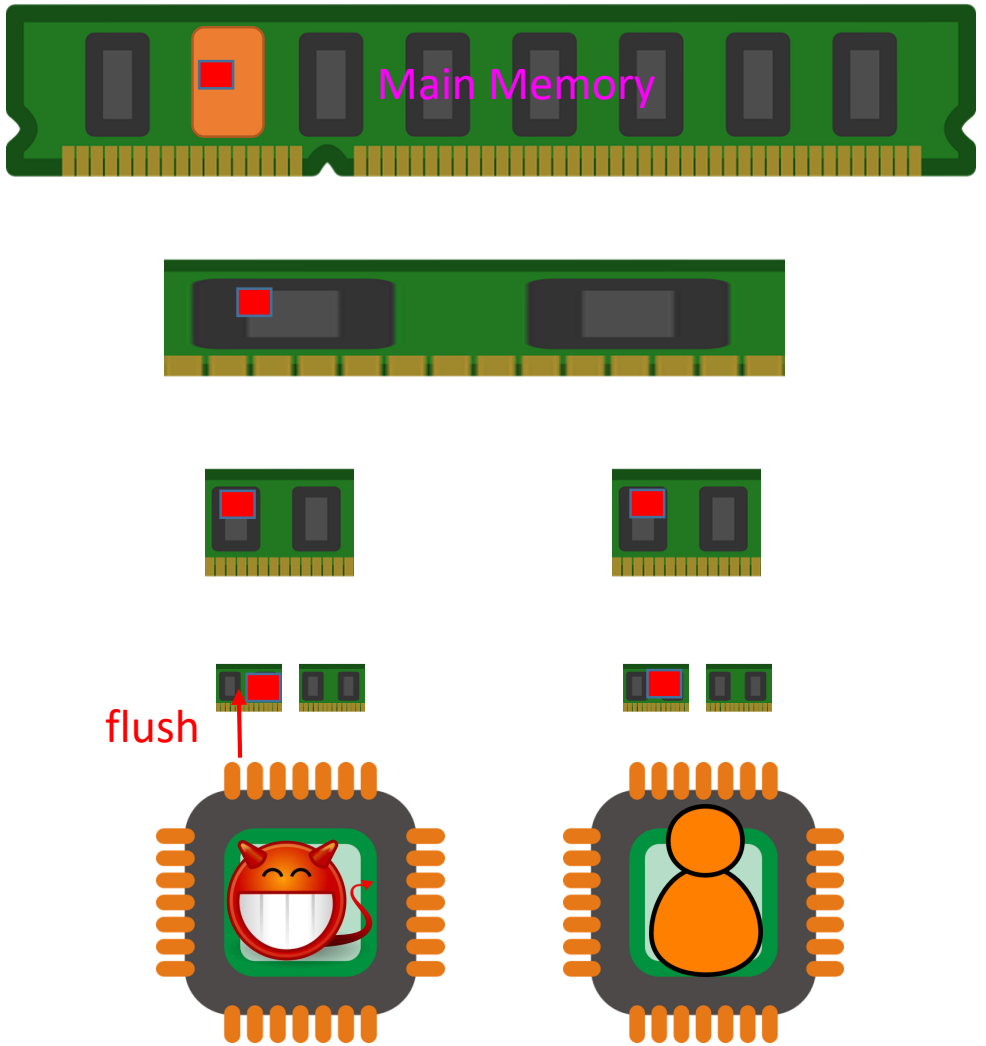


Flush a Line From Cache



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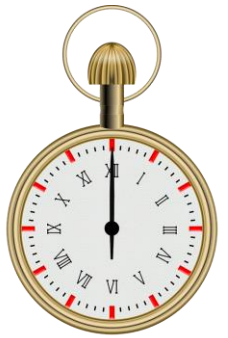
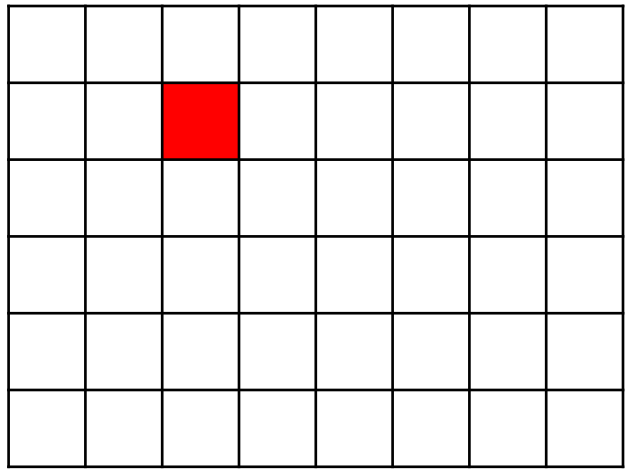
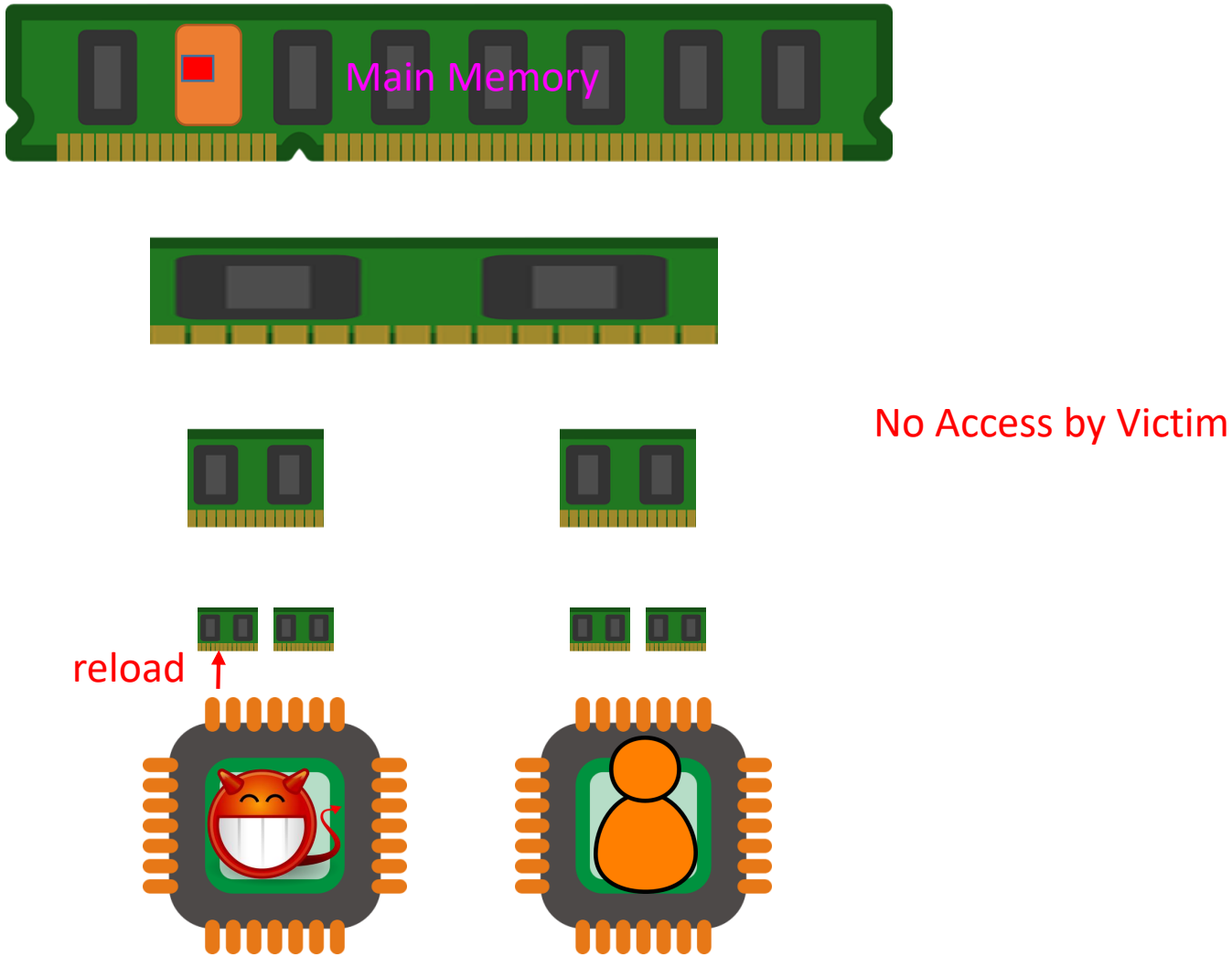




Reload a Line From Cache



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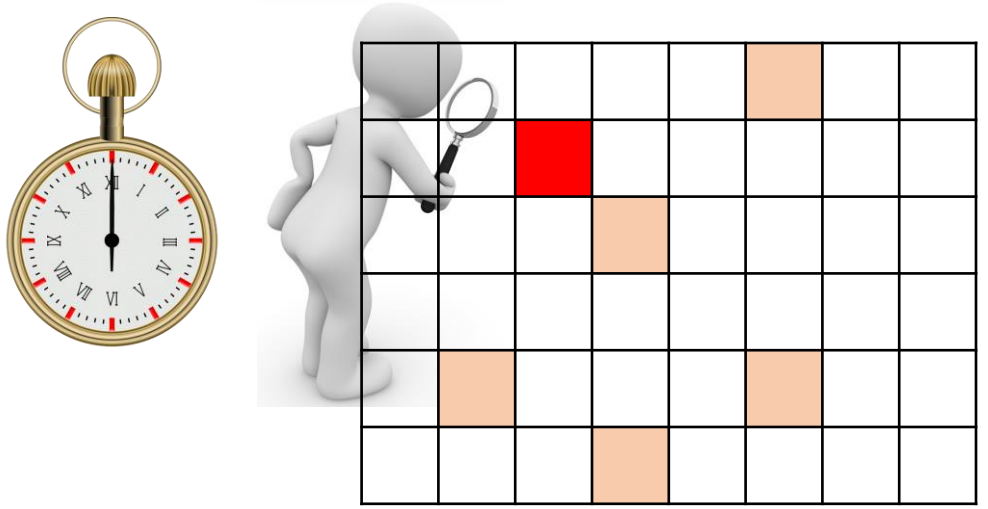
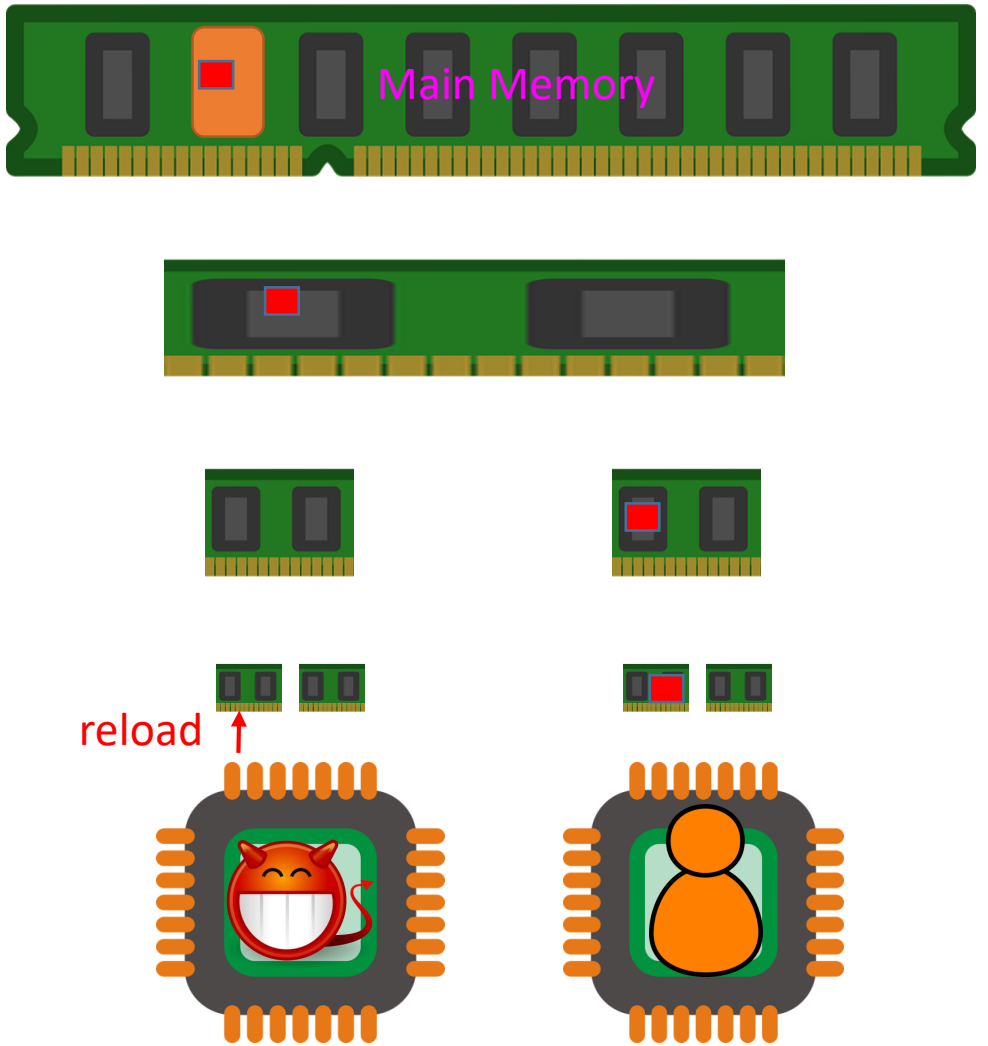


Slow means no access by victim

Reload a Line From Cache



Flush and Reload

1. Flush memory line
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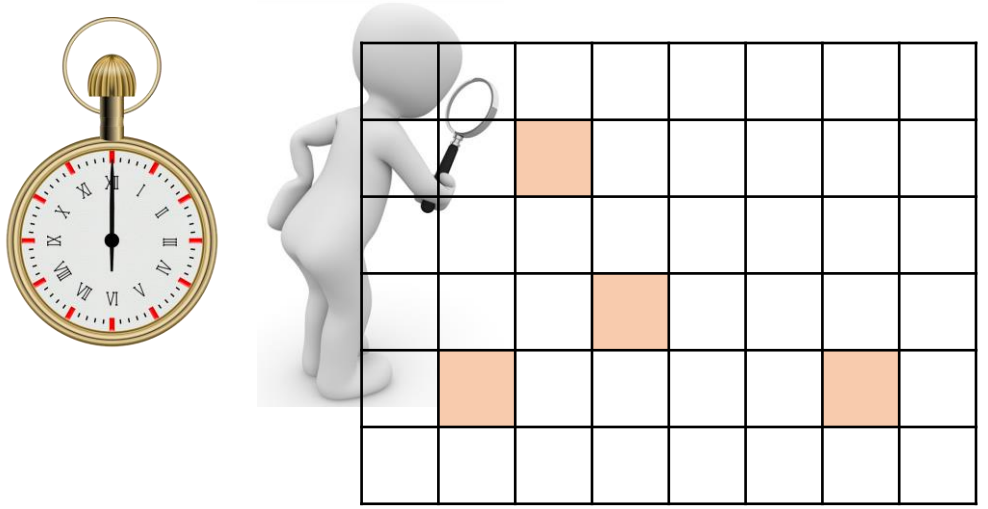


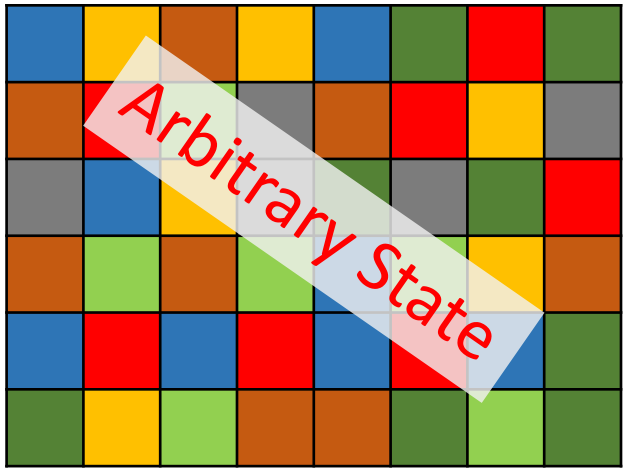
Fast means that victim accessed

Some Cache Attack Technique

- Evict and Time
- Flush and Reload
- Prime and Probe

Prime and Probe

1. Attacker fills a set with its own data by accessing some locations in memory
2. Victim Executes and evicts some of the cache lines
3. Attacker accesses those cache line and measure time



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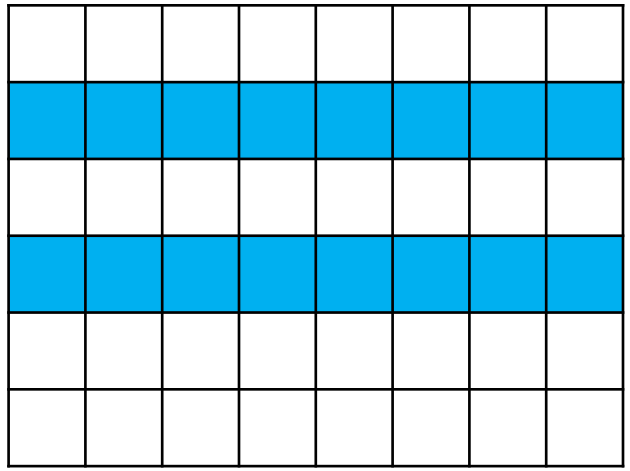
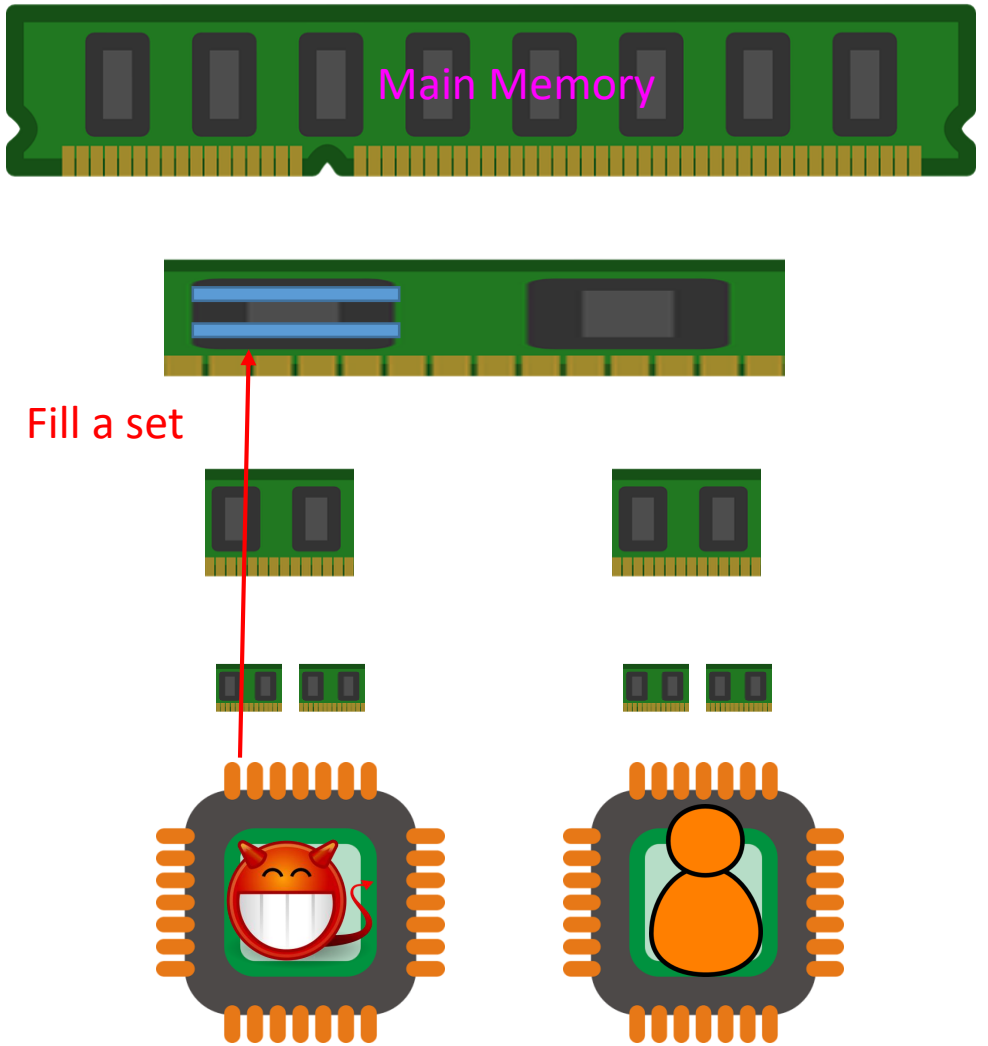


Fill a cache set (In this example 2 sets)



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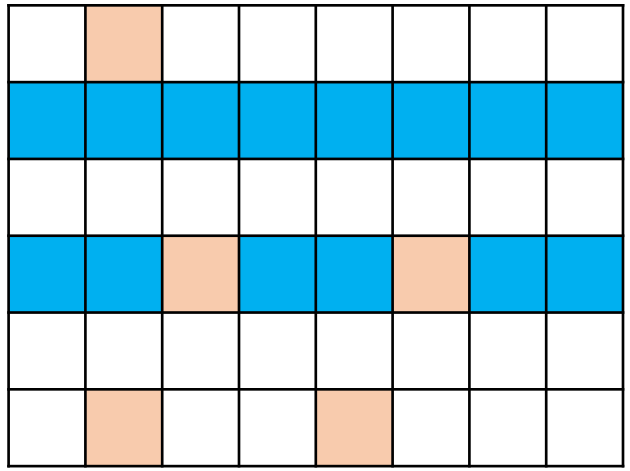
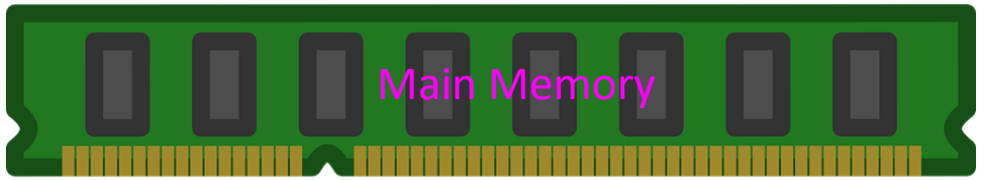
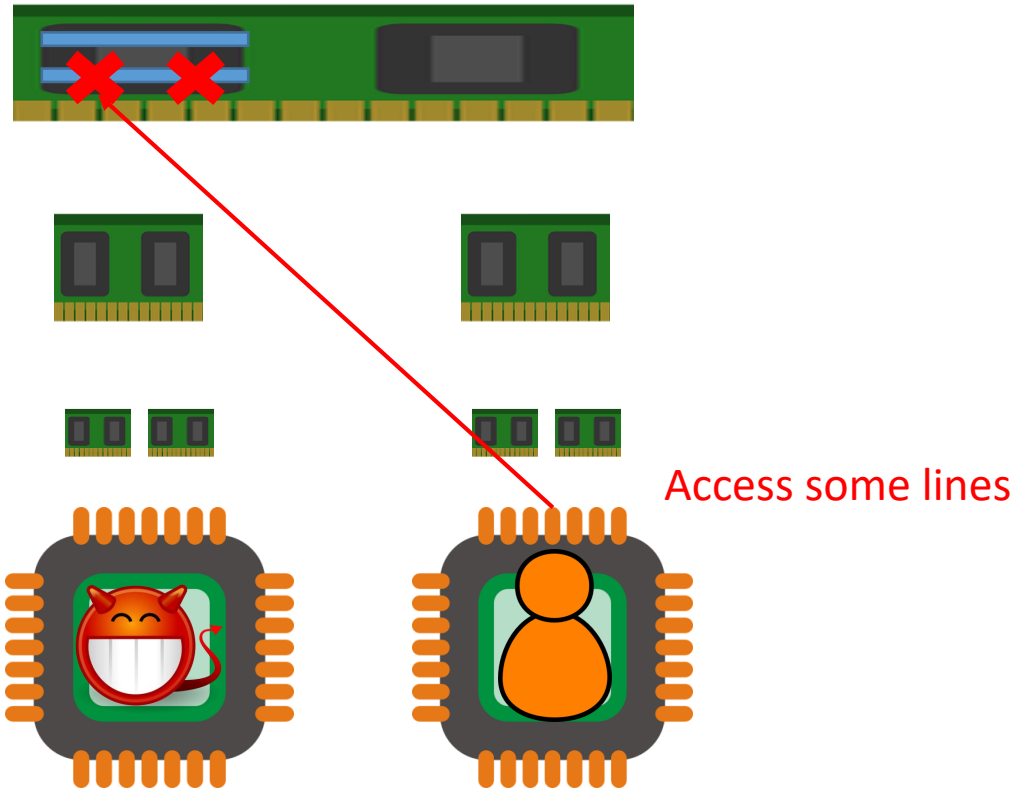


Victim Execution



: Attacker's data

: Victim's data



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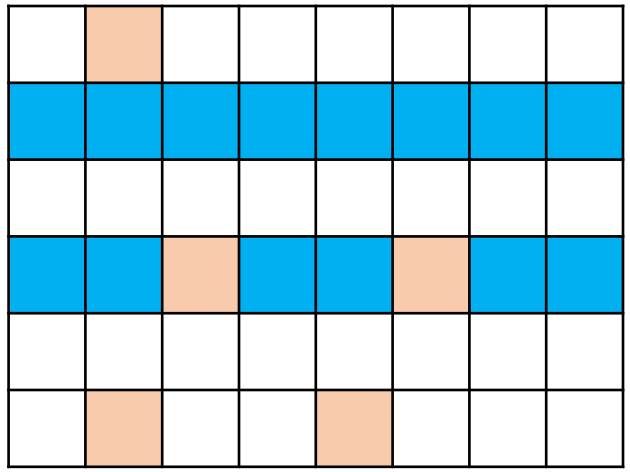
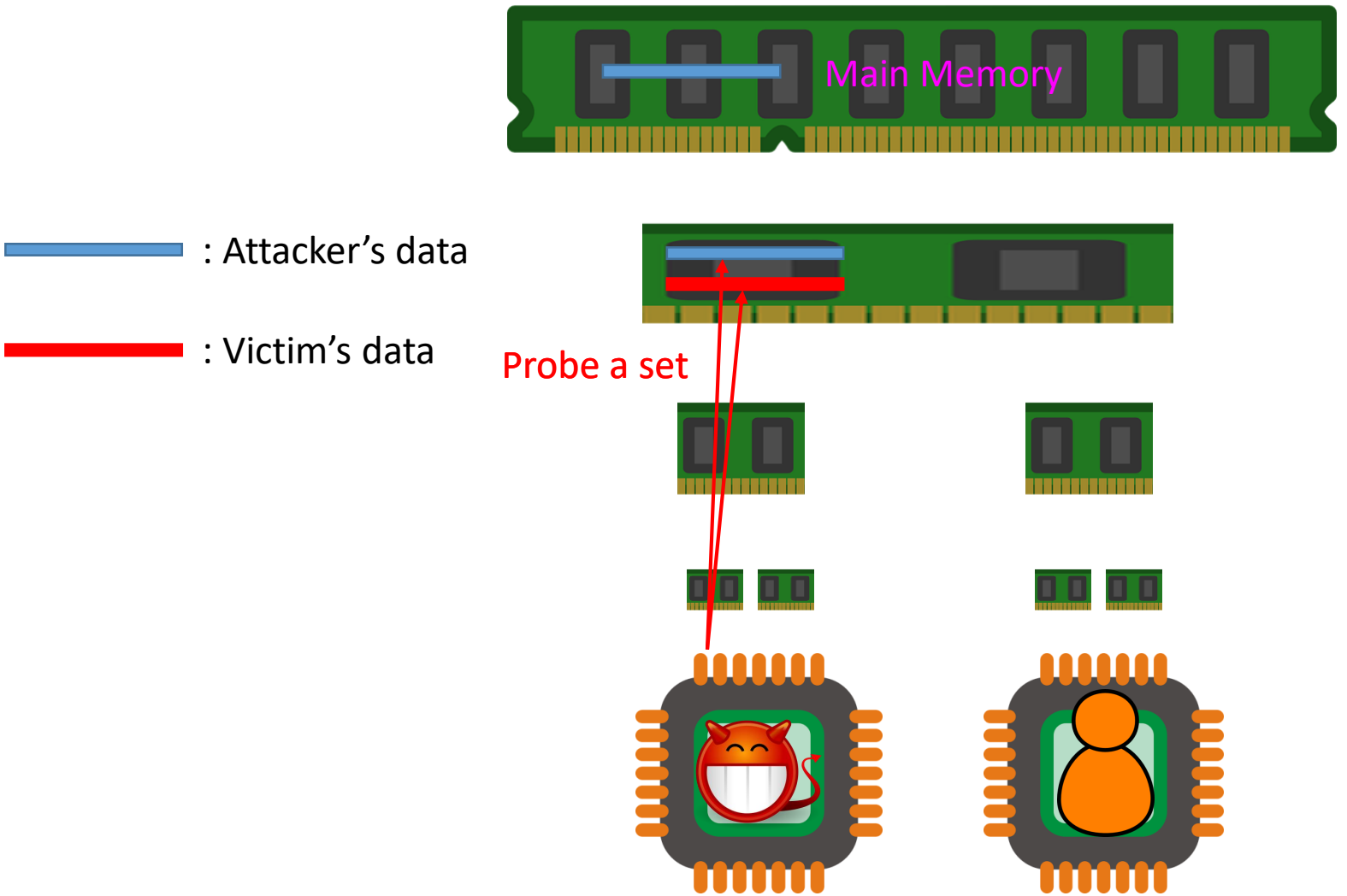


Probe



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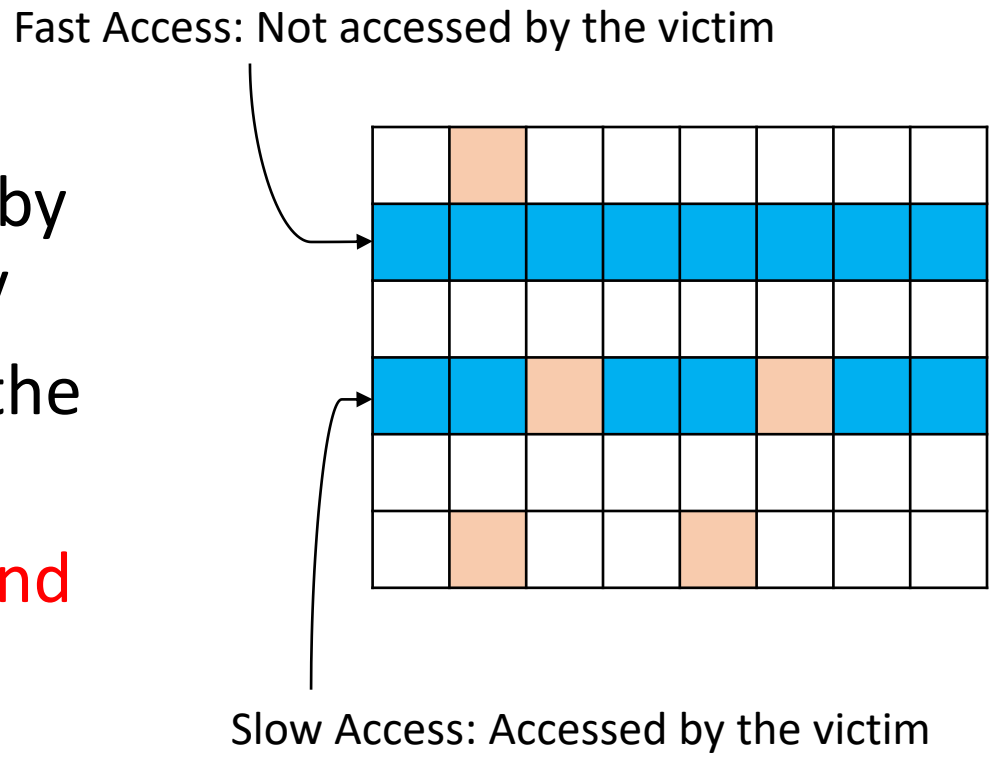


How To Recover Secret Key?

SM S S SM SM S S

1 0 0 1 1 0 0

- How do we compute $b^e mod\ n$?
  - Assume e is secret information we want to recover.
- Bit = 0 : Square
- Bit = 1 : Square + Multiply

✓The Sequence of operation will reveal the secret information.

$x \leftarrow 1$

for $i \leftarrow |e|\text{-}1$ **downto** 0 do

  $x \leftarrow x^2 \bmod n$

  if $(e_i = 1)$ **then**

    $x = xb \bmod n$

  endif

done

return x

A Sample Measurement (Flush and Reload)

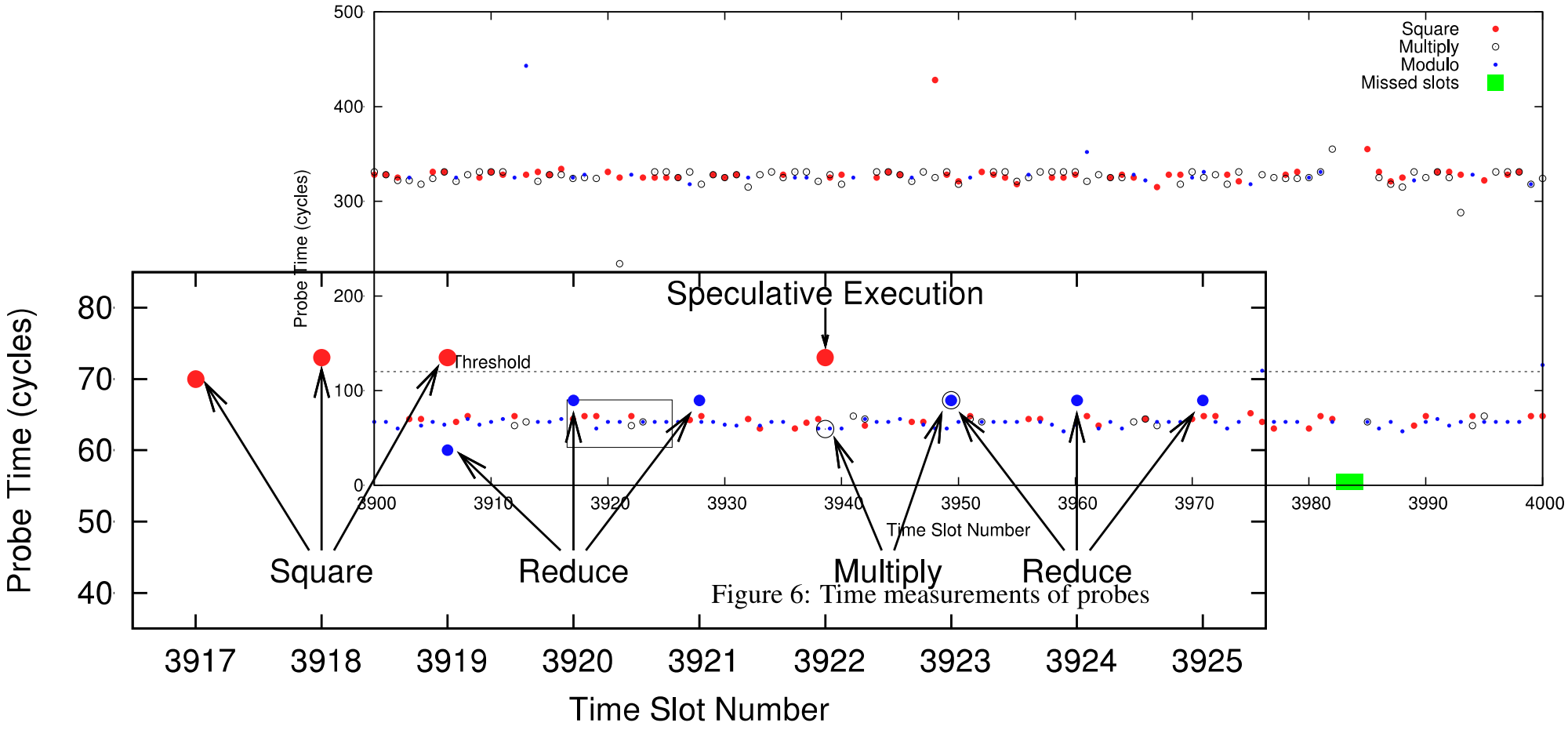
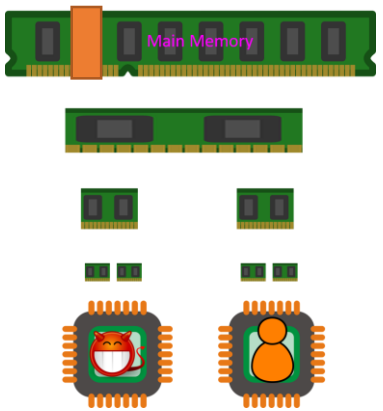
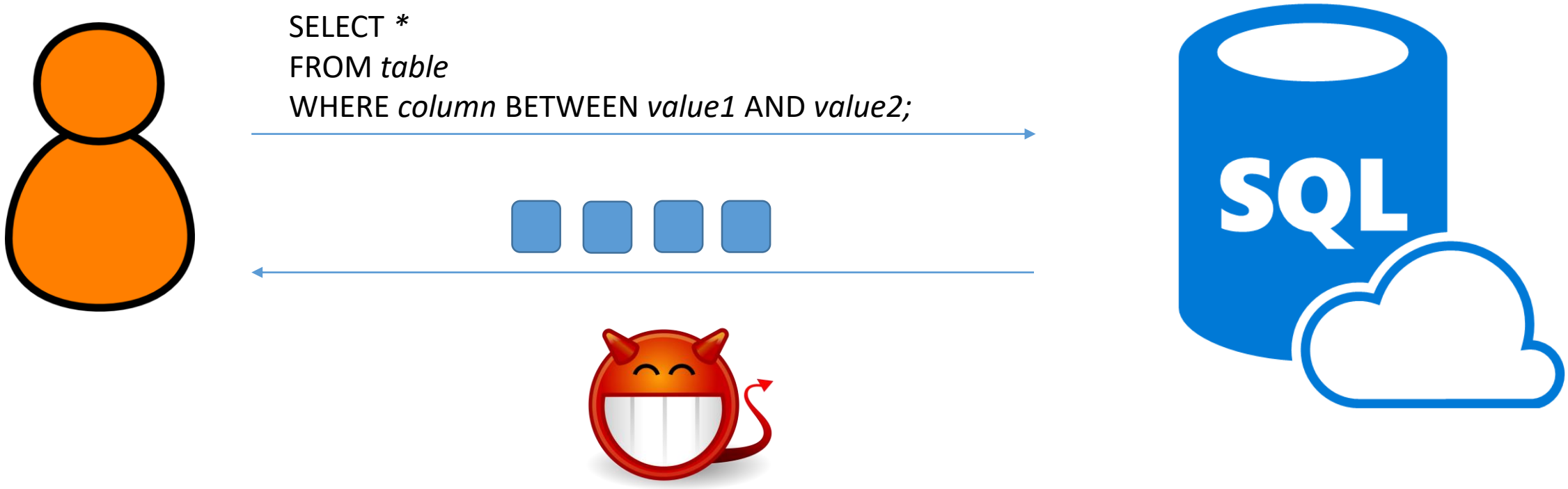


Figure 6: Time measurements of probes



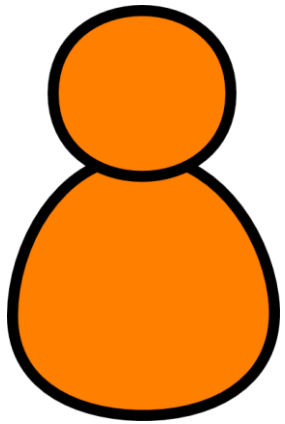
Cache Attack on Database

- User execute queries in the form of range queries
  - Asks for entries with column value between value1 and value 2
- Attacker sees the volume of the responses



Cache Attack on Database

Students	Grade
A	1
B	2
C	2
D	2
E	3
F	3
G	3
H	4
I	4



SELECT * FROM *table* WHERE *Grade* BETWEEN *1* AND *1*

A

SELECT * FROM *table* WHERE *Grade* BETWEEN *1* AND *2*

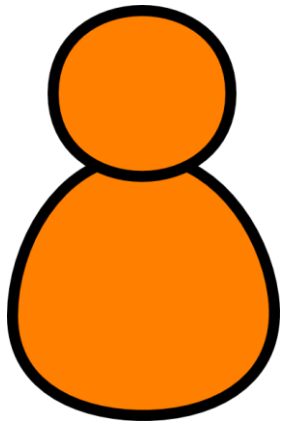
A B C D

SELECT * FROM *table* WHERE *Grade* BETWEEN *3* AND *4*

E F G H I

Cache Attack on Database

Students	Grade
A	1
B	2
C	2
D	2
E	3
F	3
G	3
H	4
I	4

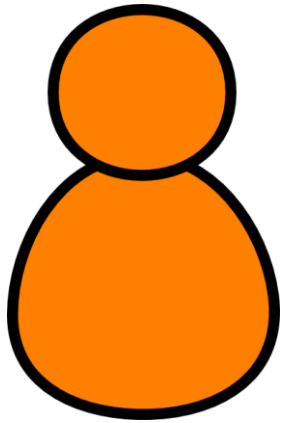


SELECT * FROM *table* WHERE *Grade* BETWEEN *1* AND *1*

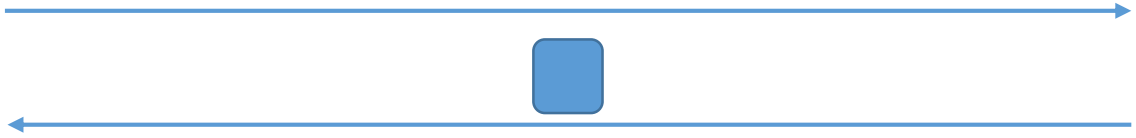
SELECT * FROM *table* WHERE *Grade* BETWEEN *1* AND *2*

SELECT * FROM *table* WHERE *Grade* BETWEEN *3* AND *4*

Cache Attack on Database



SELECT * FROM *table* WHERE *Grade* BETWEEN *1* AND *1*

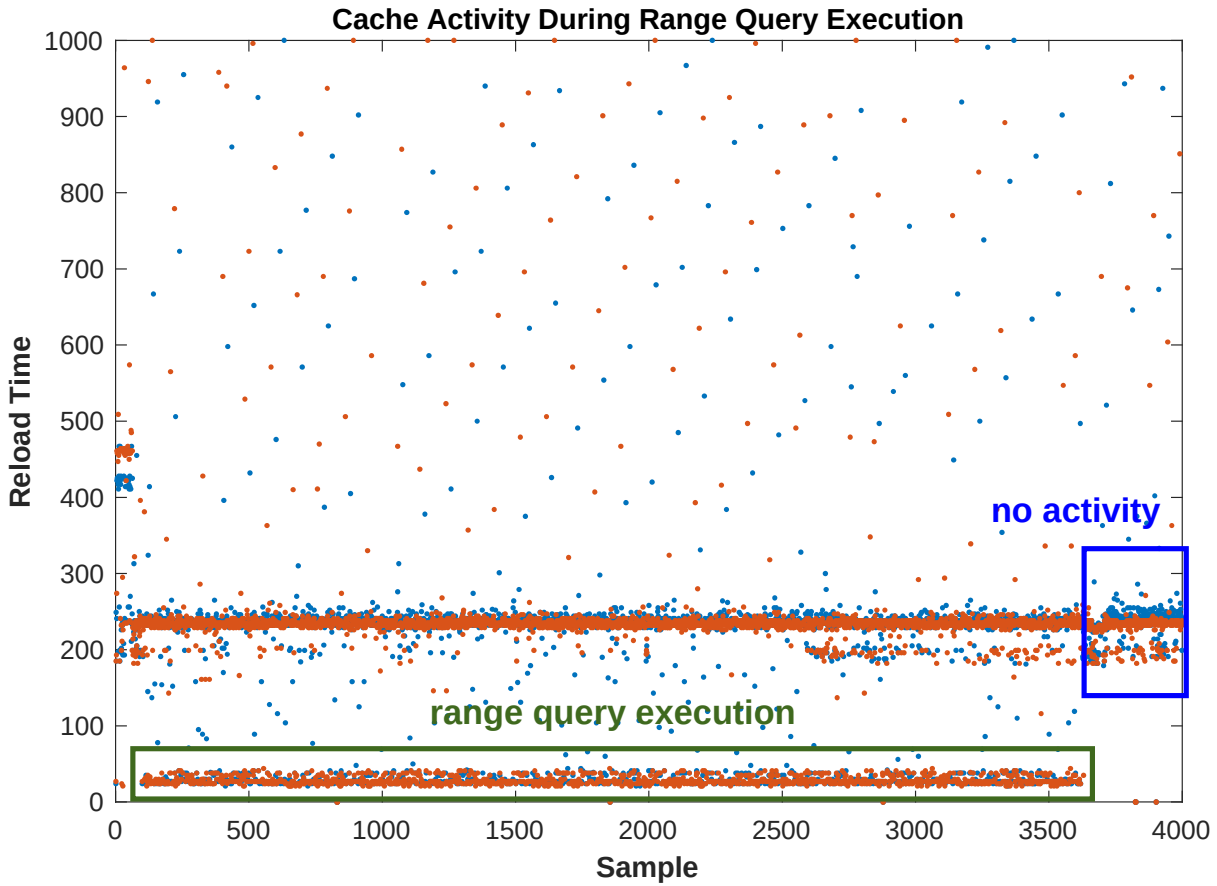


SELECT * FROM *table* WHERE *Grade* BETWEEN *1* AND *2*

SELECT * FROM *table* WHERE *Grade* BETWEEN *3* AND *4*

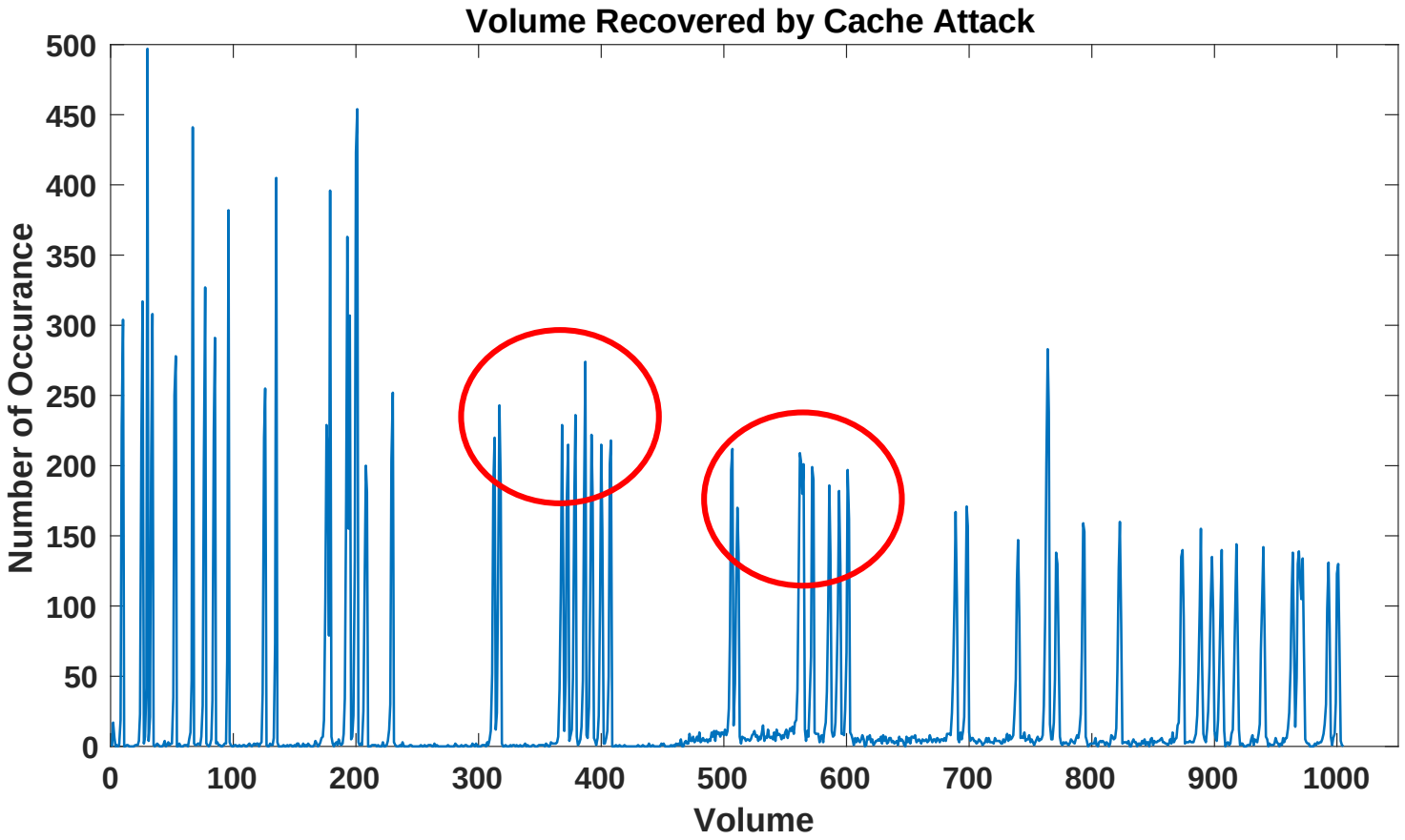
Students	Grade
A	1
B	2
C	2
D	2
E	3
F	3
G	3
H	4
I	4

Attacker View From Cache



- Counts how many time the server execute the line which correspond to returning an entry
- From that, the attacker figures out approximately the value of each volume

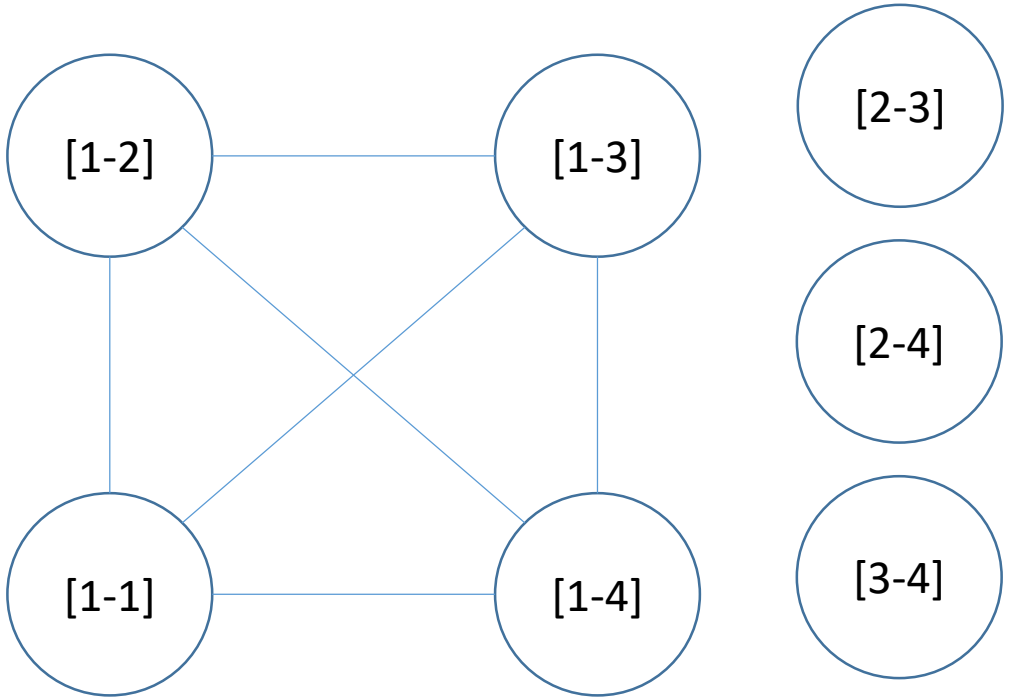
Noisy Volume Recovered

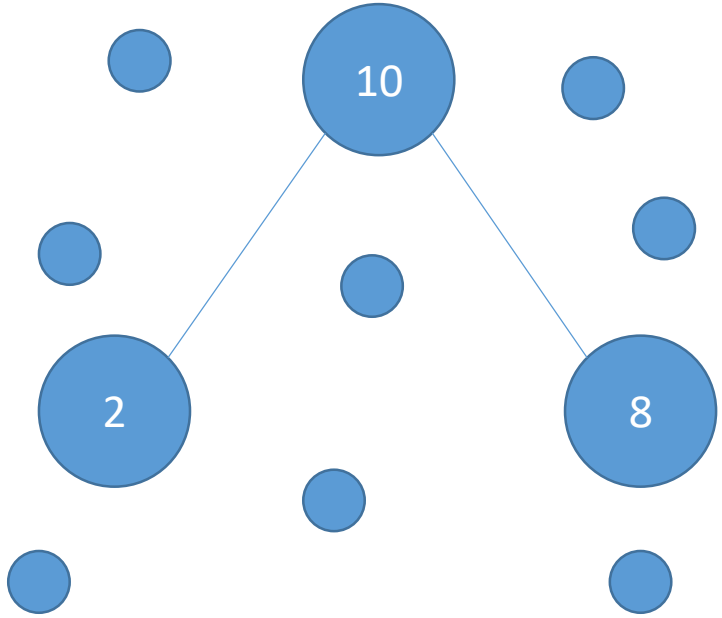


Peaks represent the Volumes

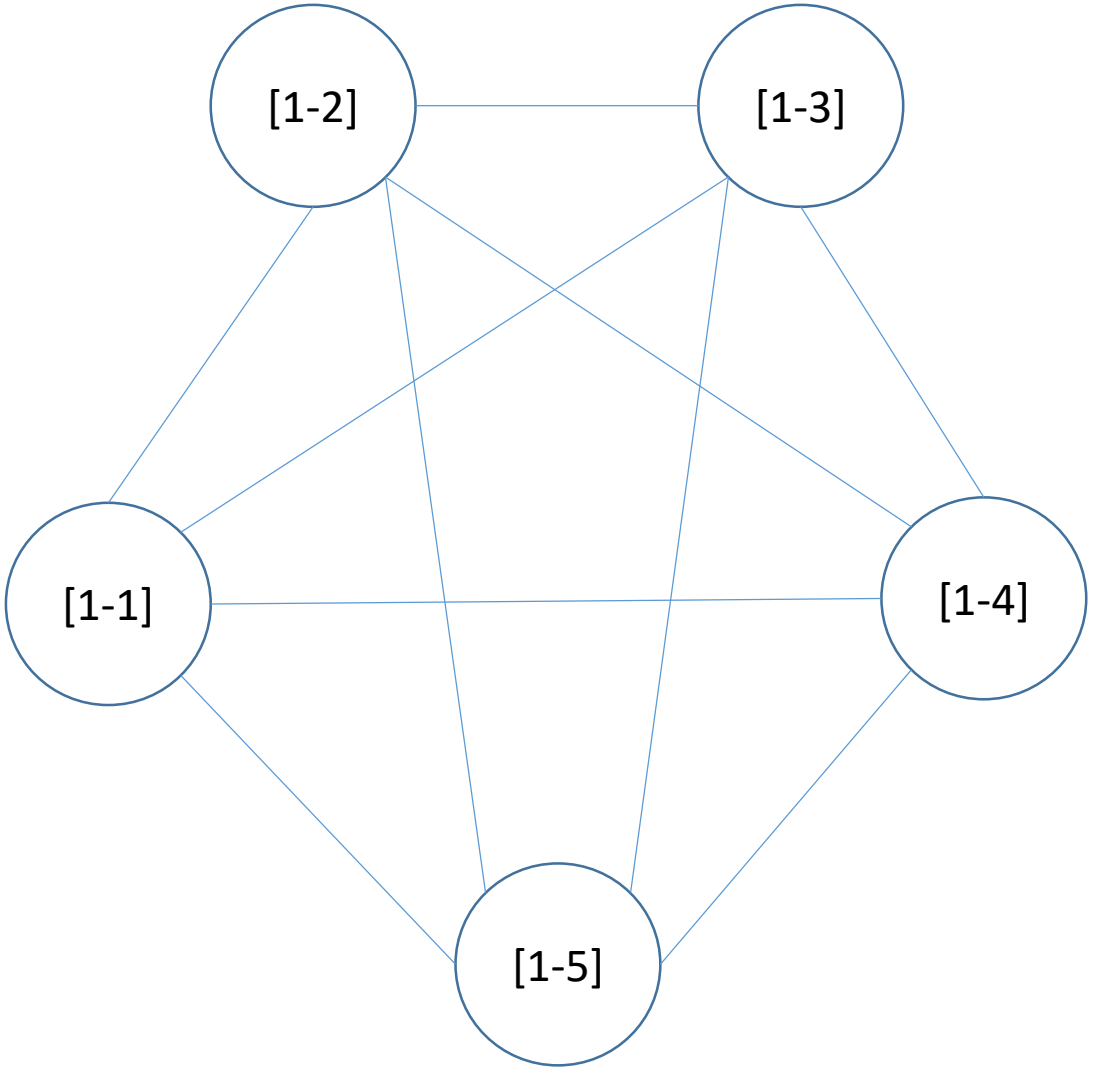
How to reconstruct the database?

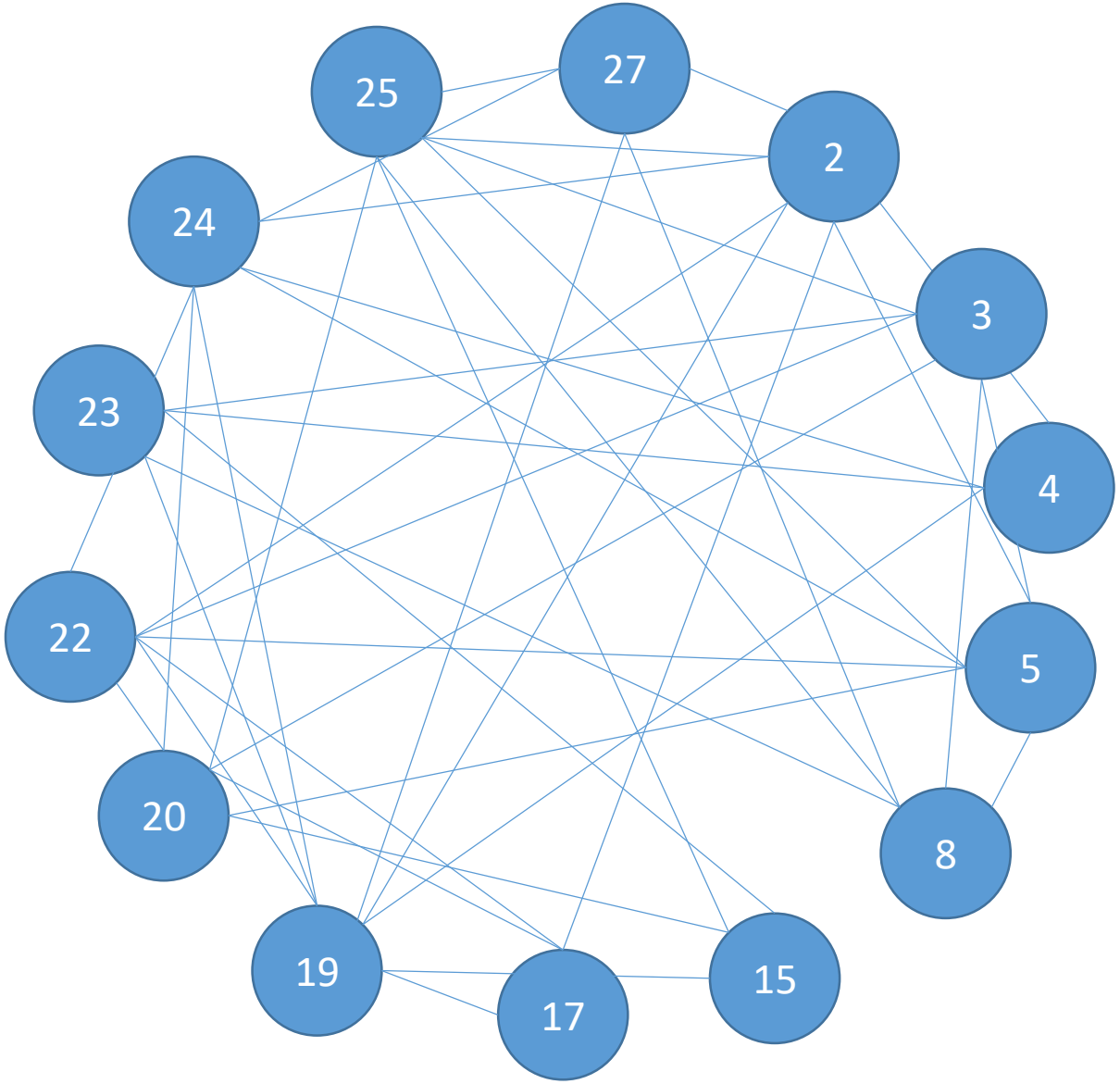
- [1-2] = [1-1] + [2-2]
- [1-3] = [1-2] + [3-3] = [1-1] + [2-3]
- [1-4] = [1-1] + [2-4] = ….





Observed Volumes


[1-2]
[1-3]
[1-1]
[1-4]
[1-5]


25
27
2
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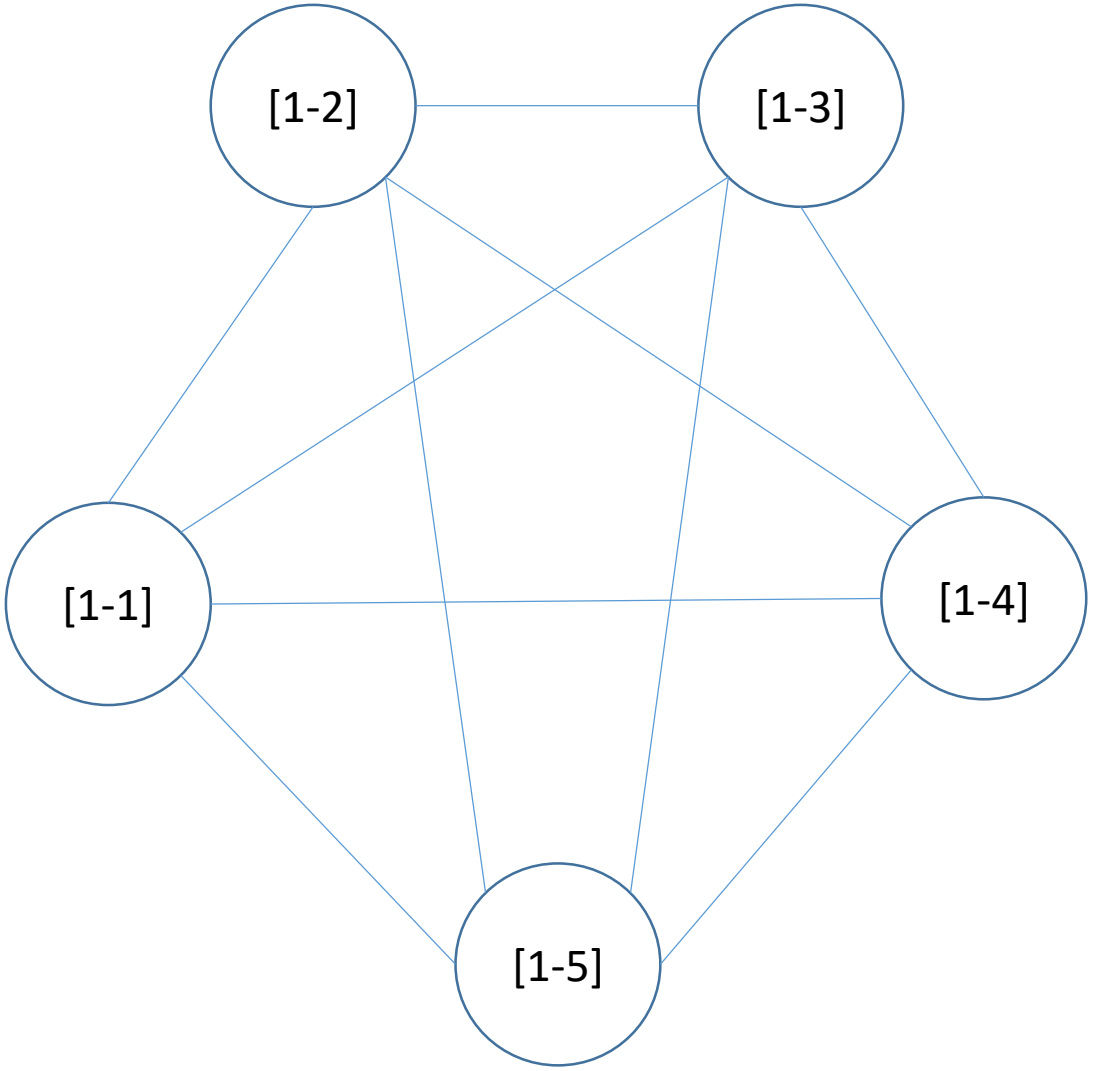
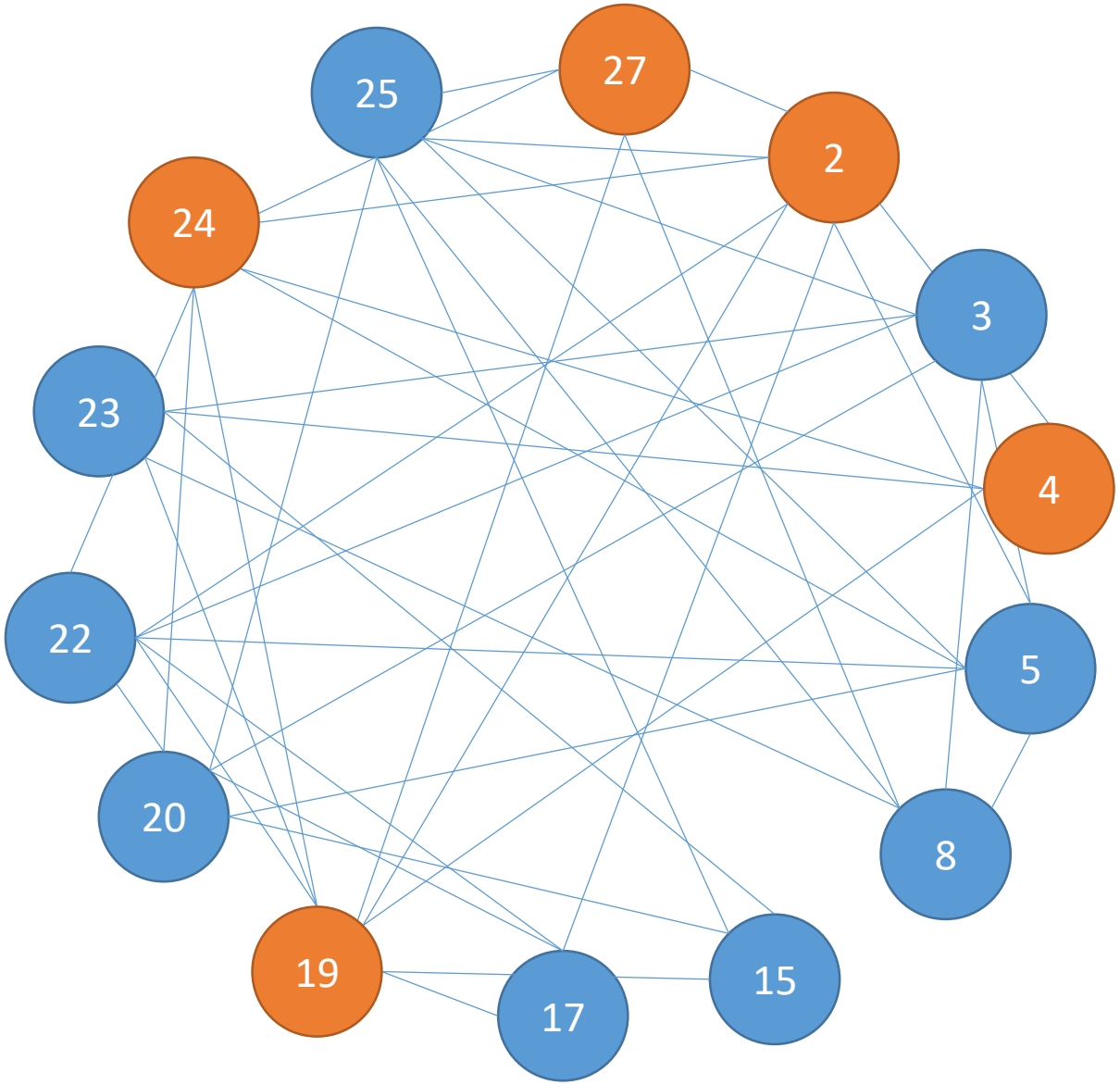
15
17


[1-2]
[1-3]
[1-1]
[1-4]
[1-5]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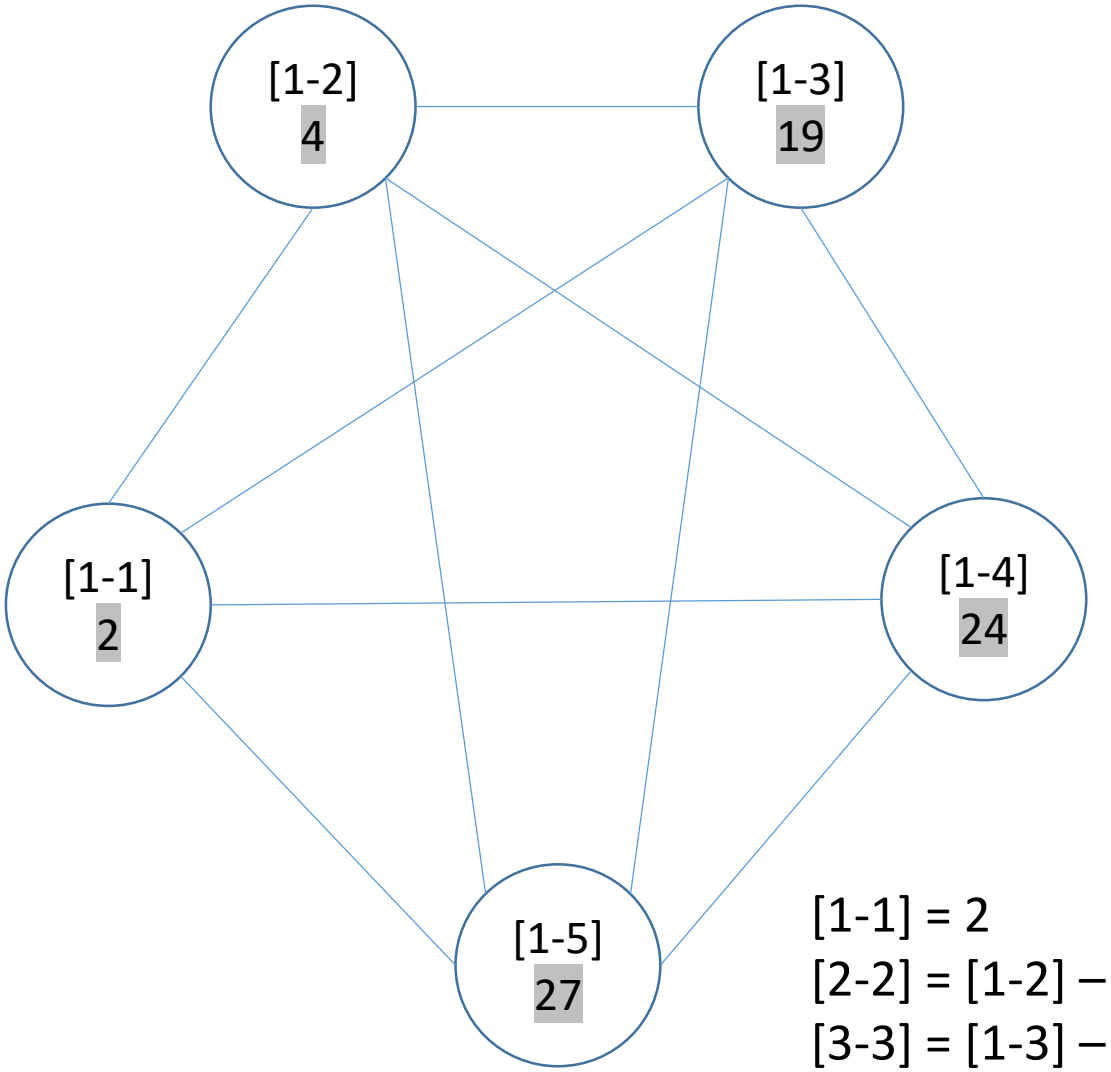
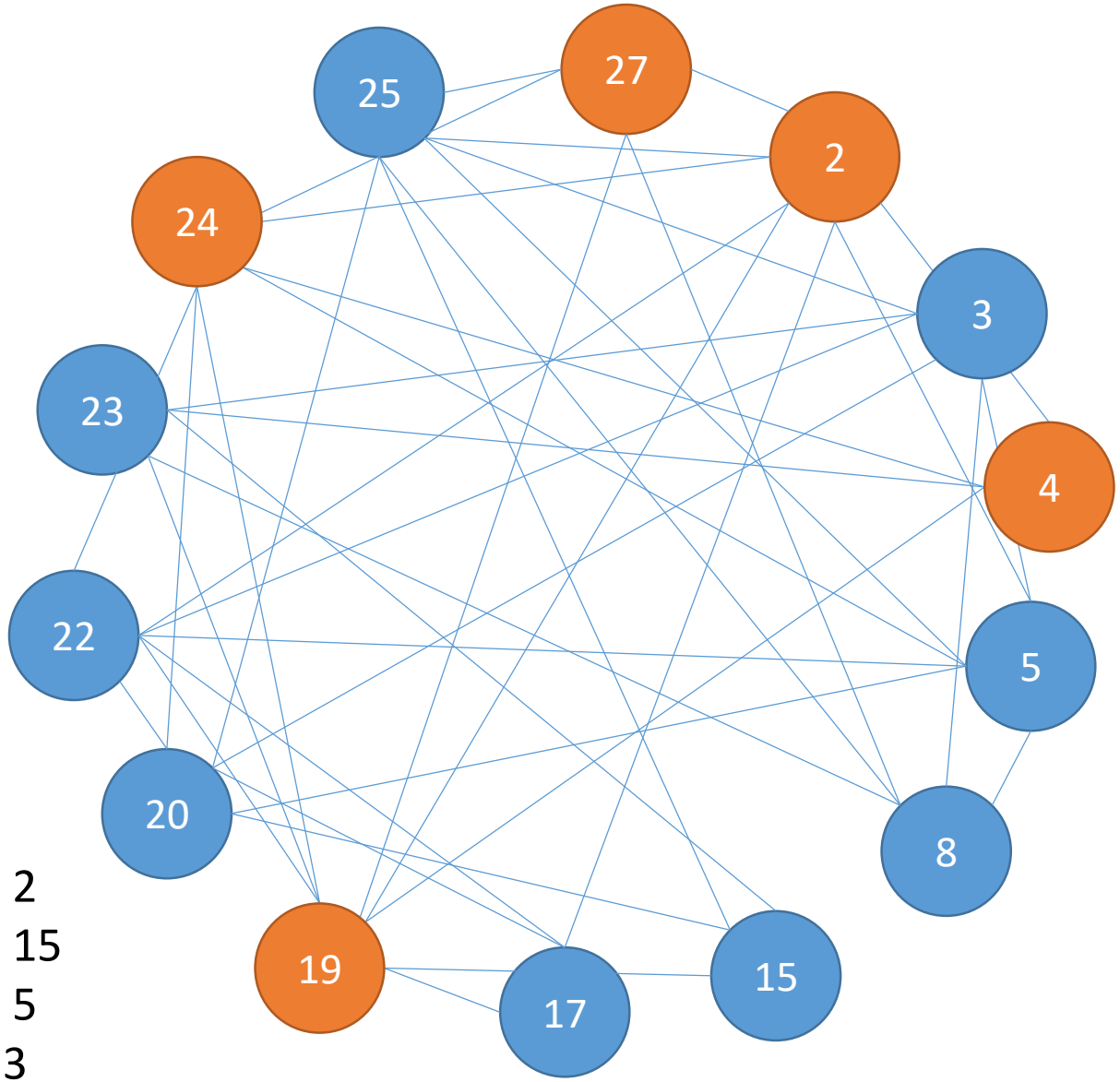


[1-1] = 2
[2-2] = [1-2] – [1-1] = 2
[3-3] = [1-3] – [1-2] = 15
[4-4] = [1-4] – [1-3] = 5
[5-5] = [1-5] – [1-4] - 3

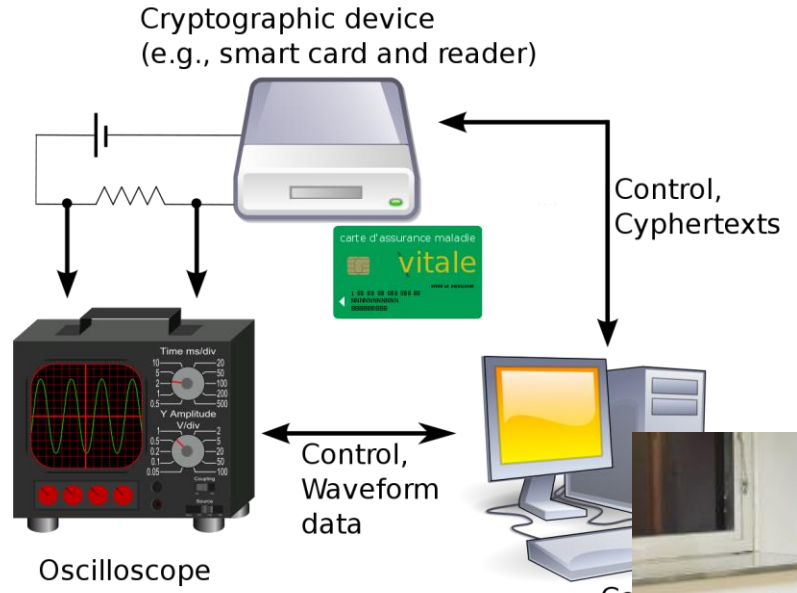


What about the case for measurements from cache

- It is harder because the measurement from cache are noisy
- Some of the volumes might be missing
  - Some of the connections ins graph is missing
- There might be some extra volumes in the graph
  - There are extra nodes in the graph which should not be there
- We still can recover the database in some of the cases

Side Channel Attacks Examples

- Timing Attacks
  - Cache Attack
- Power Analysis Attack
- Electromagnetic Emissions
- Acoustic Emission
- Fault Attacks



Thank You