Concurrent programming: From theory to practice

Concurrent Algorithms 2018

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From theory to practice

Theoretical (design)	Practical (design)	Practical (implementation)

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- Impossibilities
- Upper/Lower bounds
- Techniques
- System models
- Correctness proofs

Design (pseudo-code)

From theory to practice

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Design (pseudo-code)

- System models
  - shared memory
  - message passing
- **Finite memory**
- Practicality issues
  - re-usable objects
- **Performance**

Design (pseudo-code, prototype)

From theory to practice

Theoretical (design)	Practical (design)	Practical (implementation)

• Impossibilities
• Upper/Lower bounds
• Techniques
• System models
• Correctness proofs
	• System models
	  • shared memory
	  • message passing
	• **Finite memory**
	• Practicality issues
	  • re-usable objects
	• **Performance**
		• **Hardware**
		• Which atomic ops
		• Memory consistency
		• Cache coherence
		• Locality
		• **Performance**
		• **Scalability**

		
Design (pseudo-code)	**Design (pseudo-code, prototype)**	**Implementation (code)**

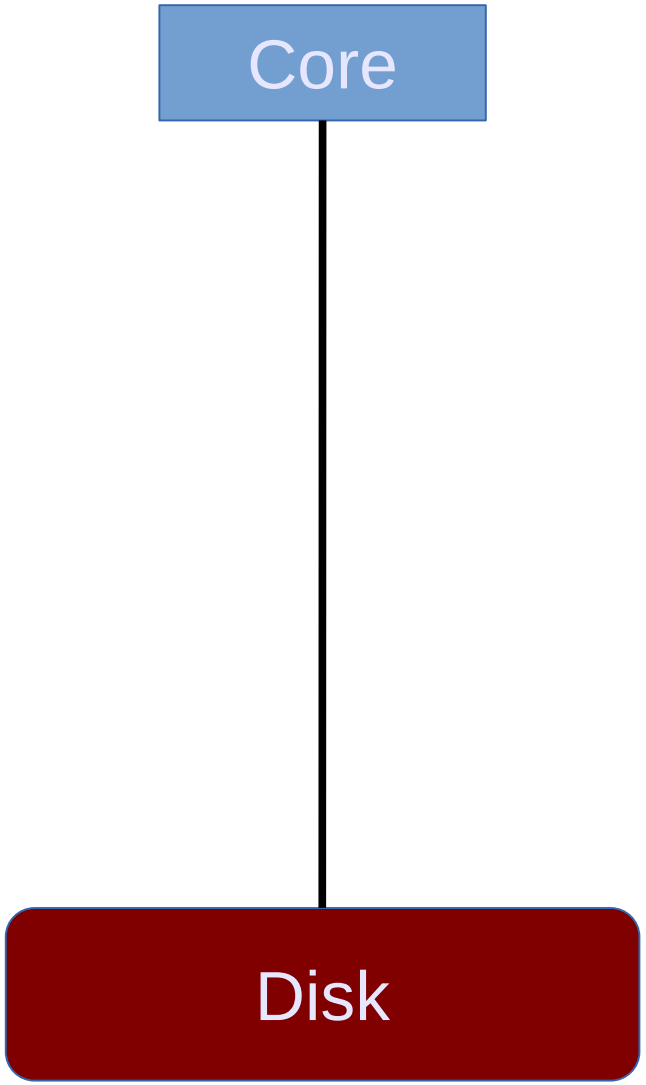
Outline

- CPU caches
- Cache coherence
- Placement of data
- Graph processing: Concurrent data structures

Outline

- **CPU caches**
- Cache coherence
- Placement of data
- Graph processing: Concurrent data structures

Why do we use caching?



- Core freq: 2GHz = 0.5 ns / instr
- Core → Disk = ~ms

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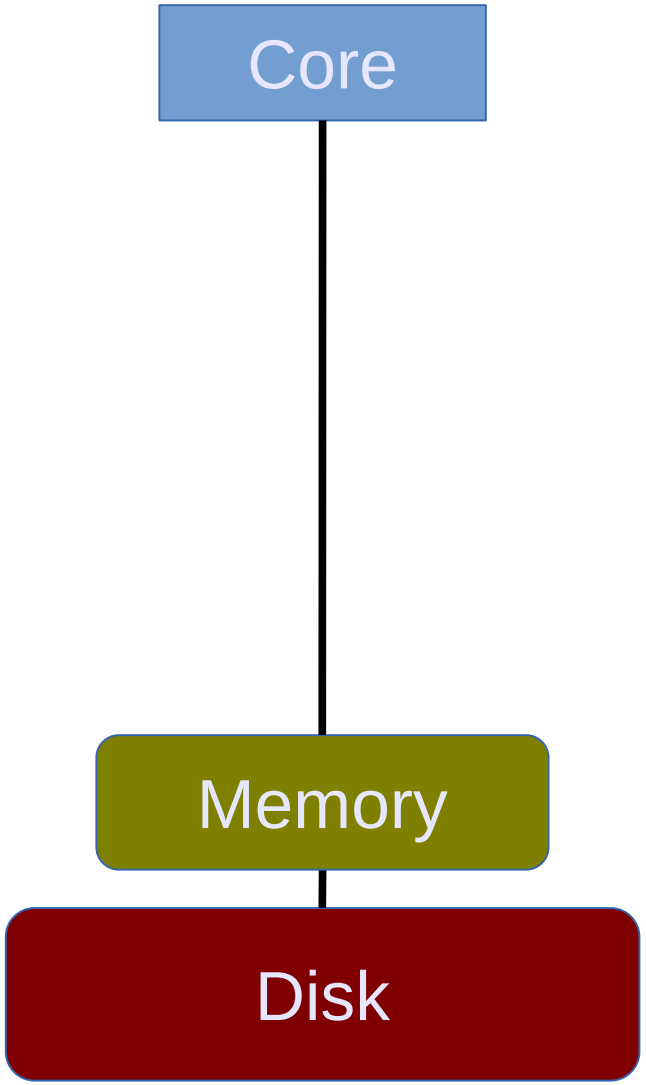

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- Core → Memory = ~100ns

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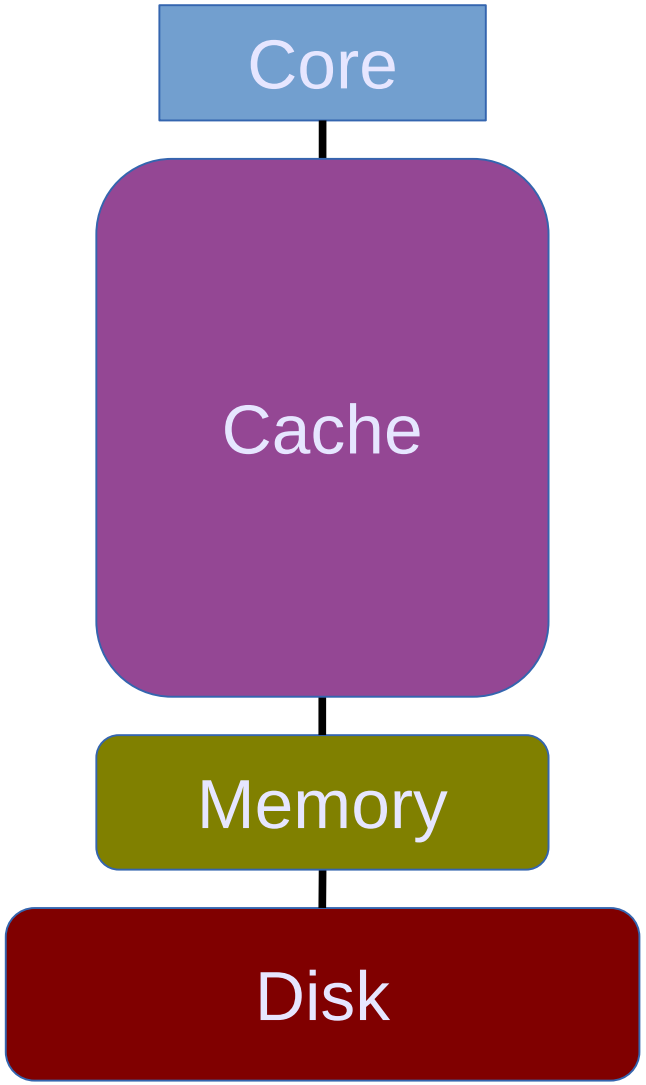
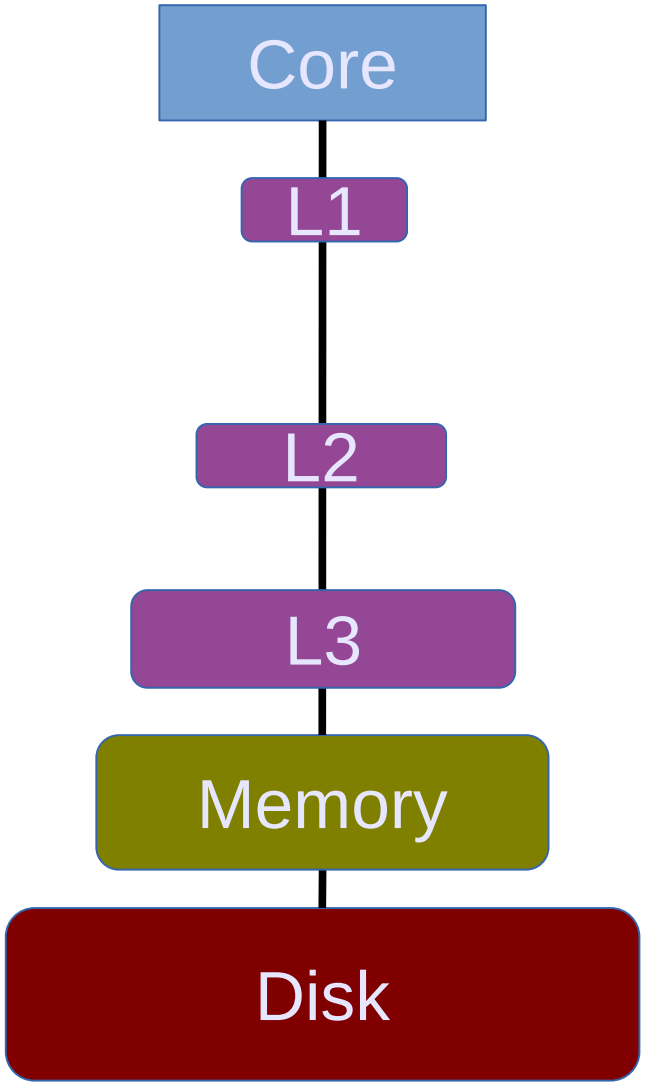


- Core freq: 2GHz = 0.5 ns / instr
- Core → Disk = ~ms
- Core → Memory = ~100ns
- Cache
  - Large = slow
  - Medium = medium
  - Small = fast

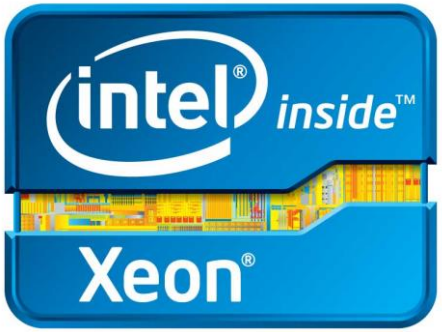
Why do we use caching?



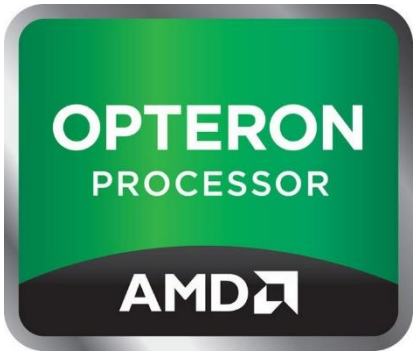
- Core freq: 2GHz = 0.5 ns / instr
- Core → Disk = ~ms
- Core → Memory = ~100ns
- Cache
  - Core → L3 = ~20ns
  - Core → L2 = ~7ns
  - Core → L1 = ~1ns

Typical server configurations

- **Intel Xeon**
  - 12 cores @ 2.4GHz
  - L1: 32KB
  - L2: 256KB
  - L3: 40MB
  - Memory: 128GB



- **AMD Opteron**
  - 12 cores @ 2.4GHz
  - L1: 64KB
  - L2: 512KB
  - L3: 20MB
  - Memory: 128GB



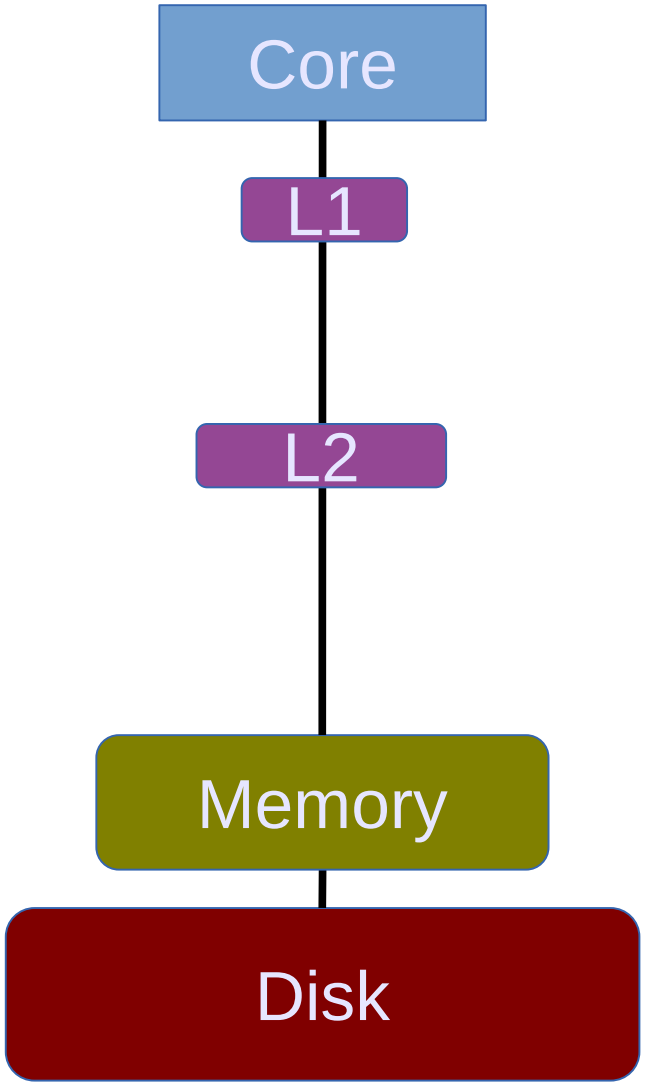
Experiment

Throughput of accessing some memory, depending on the memory size

Outline

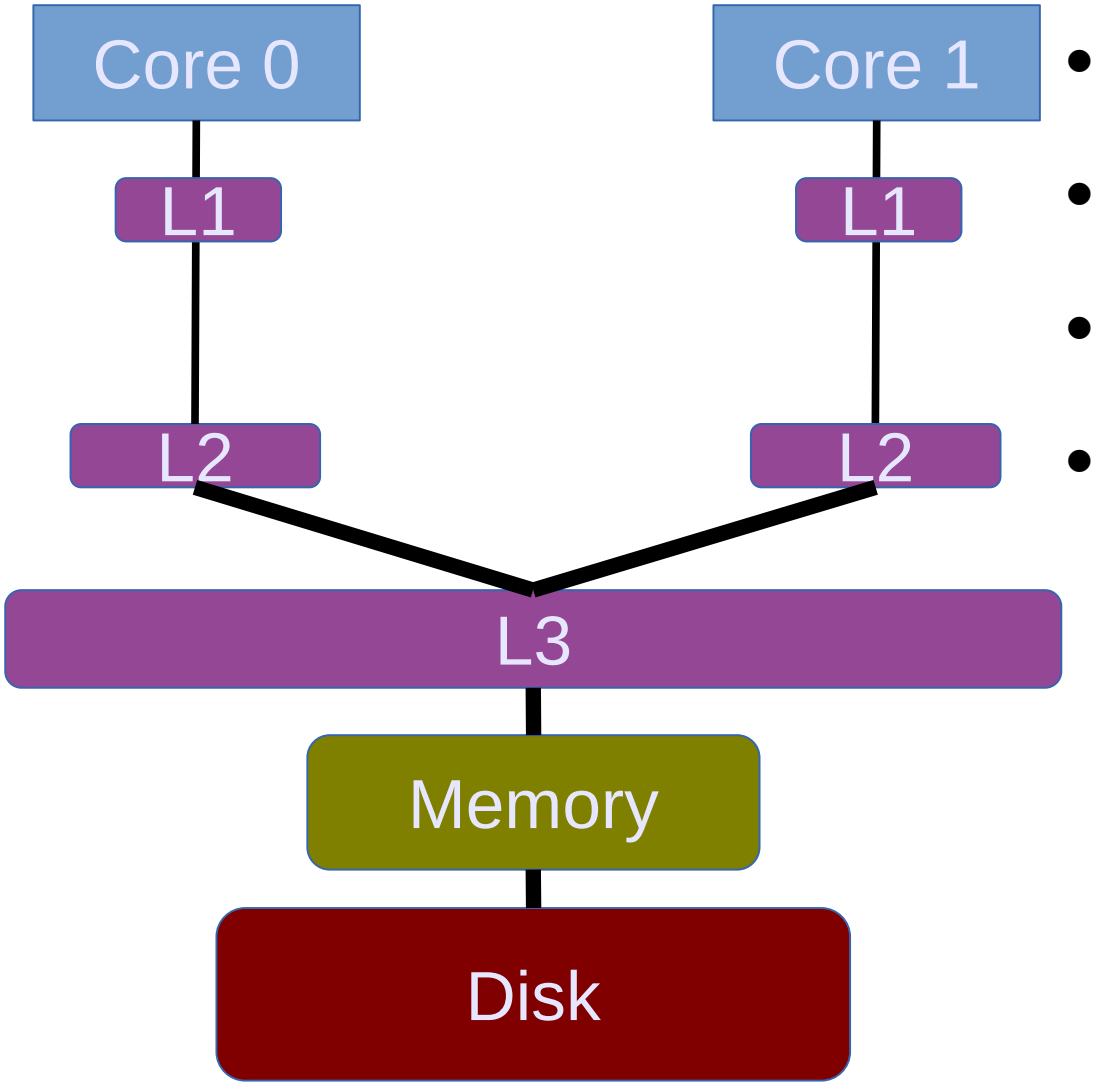
- CPU caches
- **Cache coherence**
- Placement of data
- Graph processing: Concurrent data structures

Until ~2004: single-cores



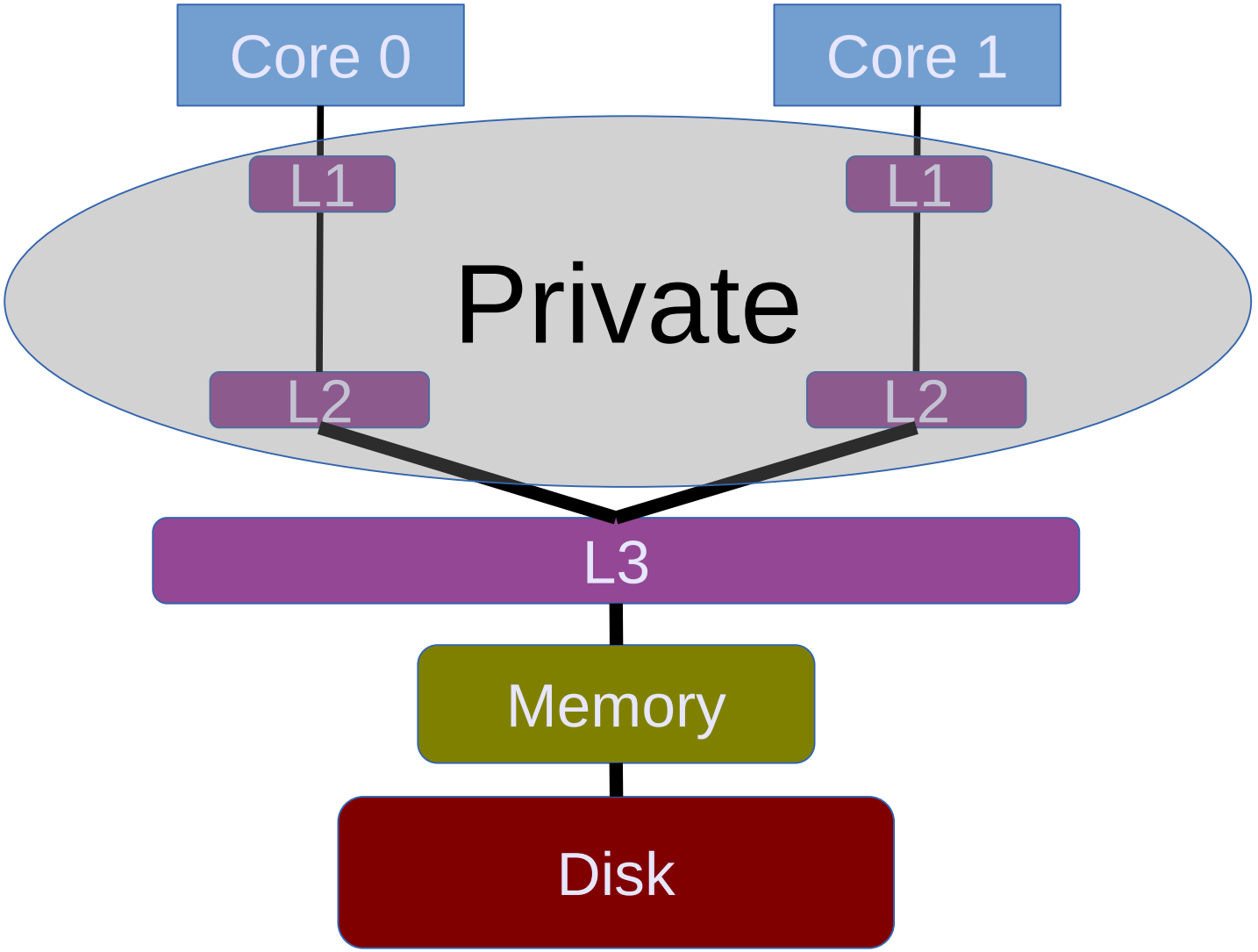
- Core freq: 3+GHz
- Core → Disk
- Core → Memory
- Cache
  - Core → L3
  - Core → L2
  - Core → L1

After ~2004: multi-cores



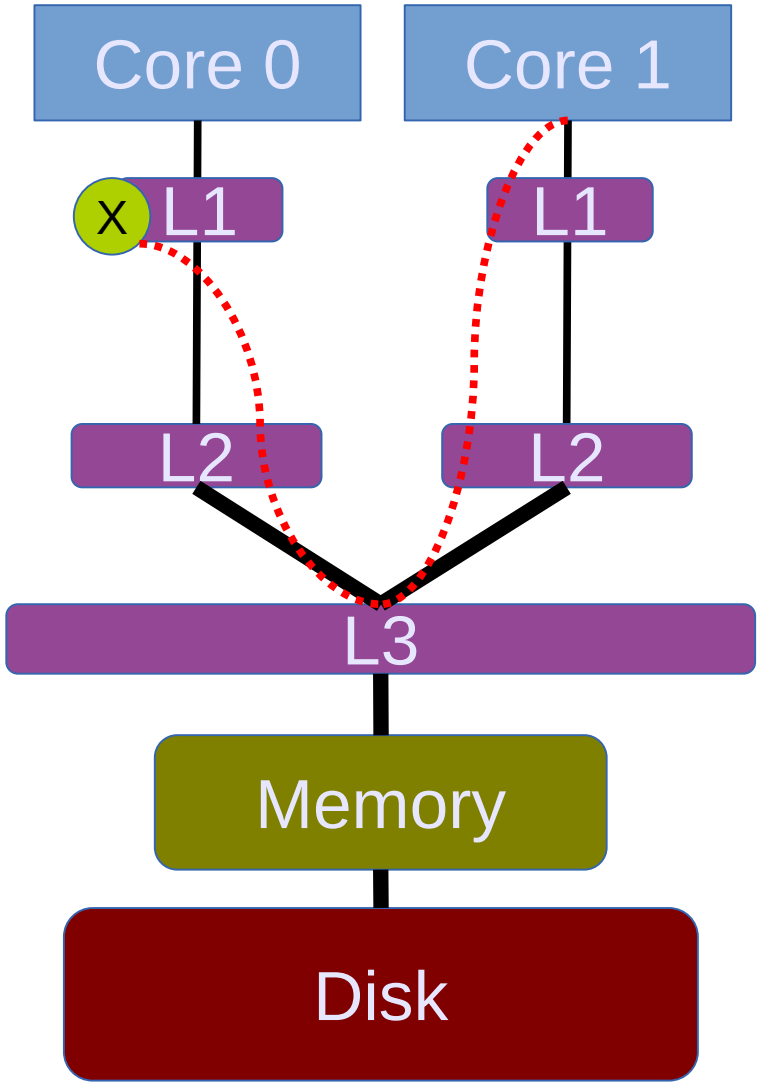
- Core freq: ~2GHz
- Core → Disk
- Core → Memory
- Cache
  - Core → **shared** L3
  - Core → L2
  - Core → L1

Multi-cores with private caches



= multiple copies

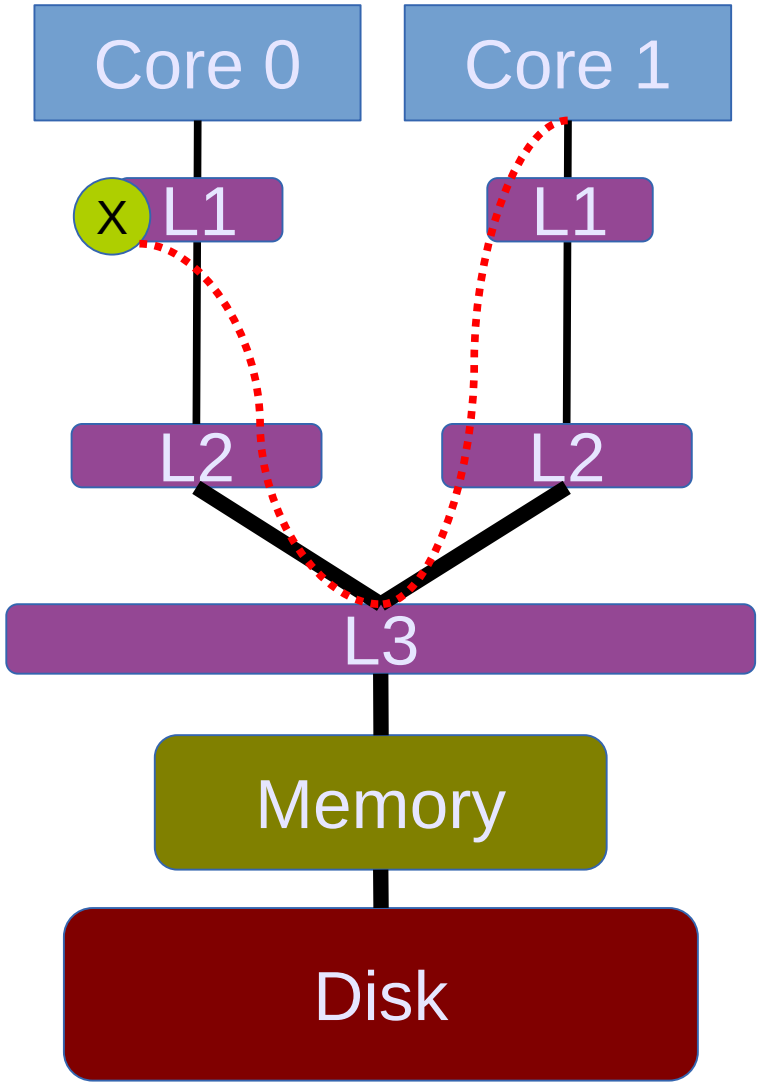
Cache coherence for consistency



Core 0 has X and Core 1

- wants to write on X
- wants to read X
- did Core 0 write or read X?

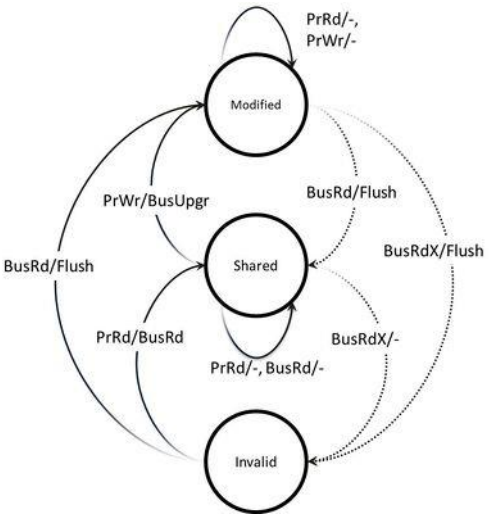
Cache coherence principles



- To perform a write
  - invalidate all readers, or
  - previous writer
- To perform a read
  - find the latest copy

Cache coherence with MESI

- A state diagram
- State (per cache line)
  - **M**odified: the only dirty copy
  - **E**xclusive: the only clean copy
  - **S**hared: a clean copy
  - **I**nvalid: useless data



The ultimate goal for scalability

- Possible states
  - **M**odified: the only dirty copy
  - **E**xclusive: the only clean copy
  - **S**hared: a clean copy
  - **I**nvalid: useless data

- **Which state is our “favorite”?**

The ultimate goal for scalability

- Possible states
  - **M**odified: the only dirty copy
  - **E**xclusive: the only clean copy
  - **S**hared: a clean copy
  - **I**nvalid: useless data

= threads can keep the data close (L1 cache)

= faster

Experiment

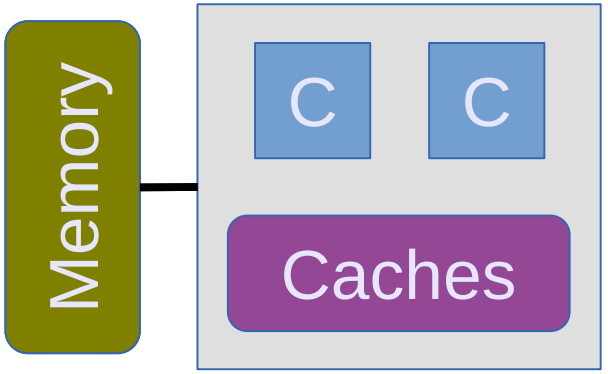
The effects of false sharing

Outline

- CPU caches
- Cache coherence
- **Placement of data**
- Graph processing: Concurrent data structures

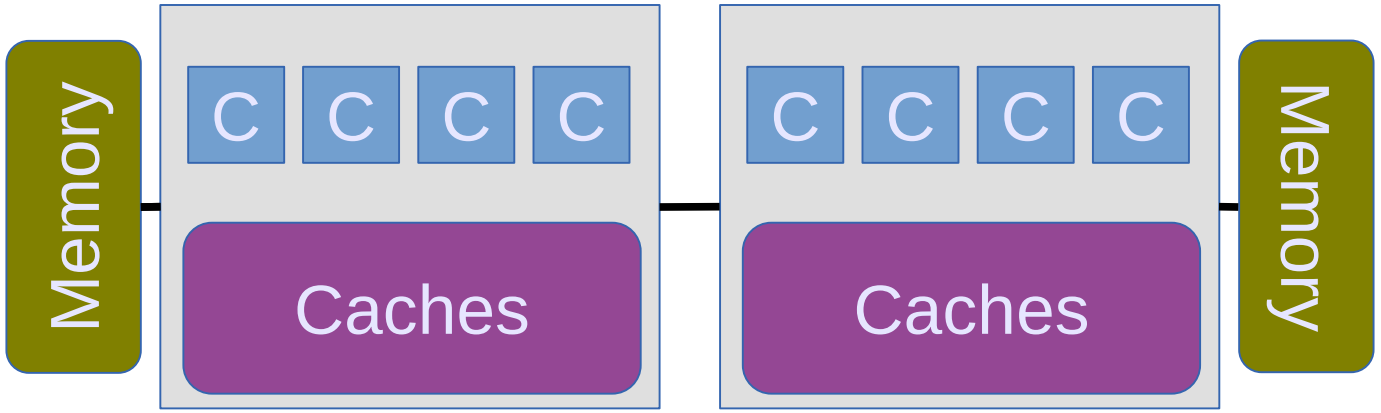
Uniformity vs. non-uniformity

- Typical **desktop** machine



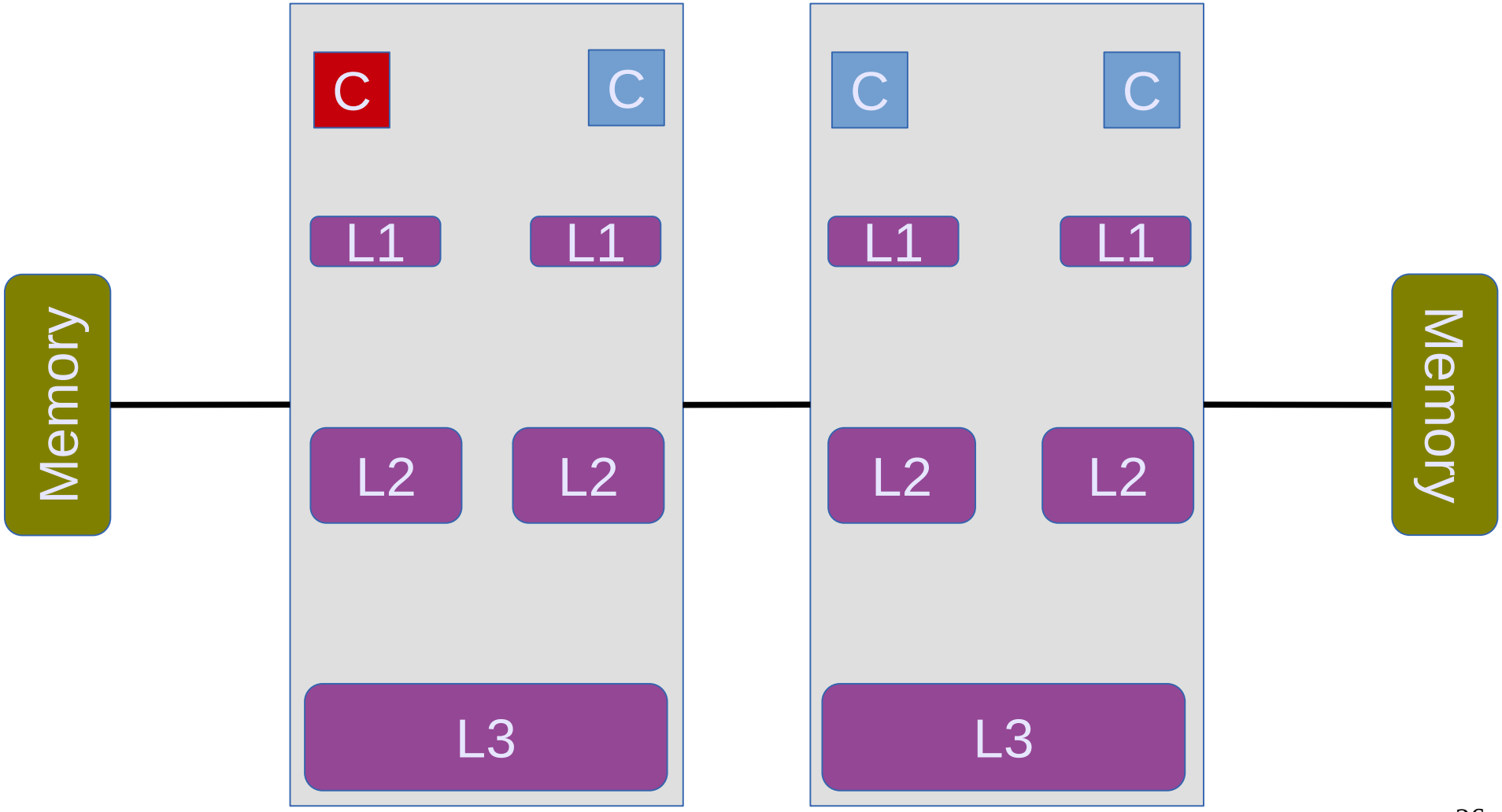
= Uniform

- Typical **server** machine



= non-Uniform

Latency (ns) to access data



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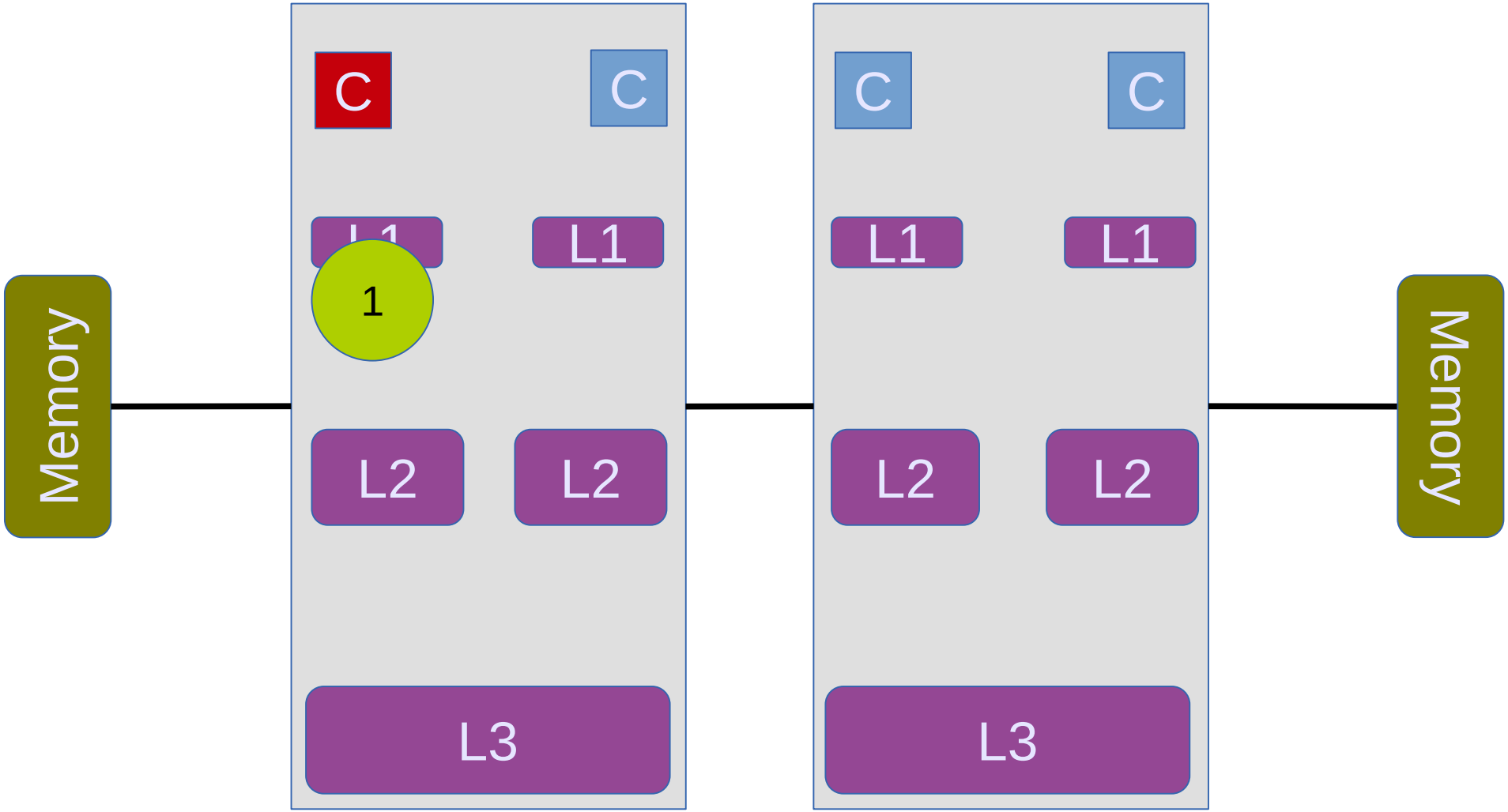

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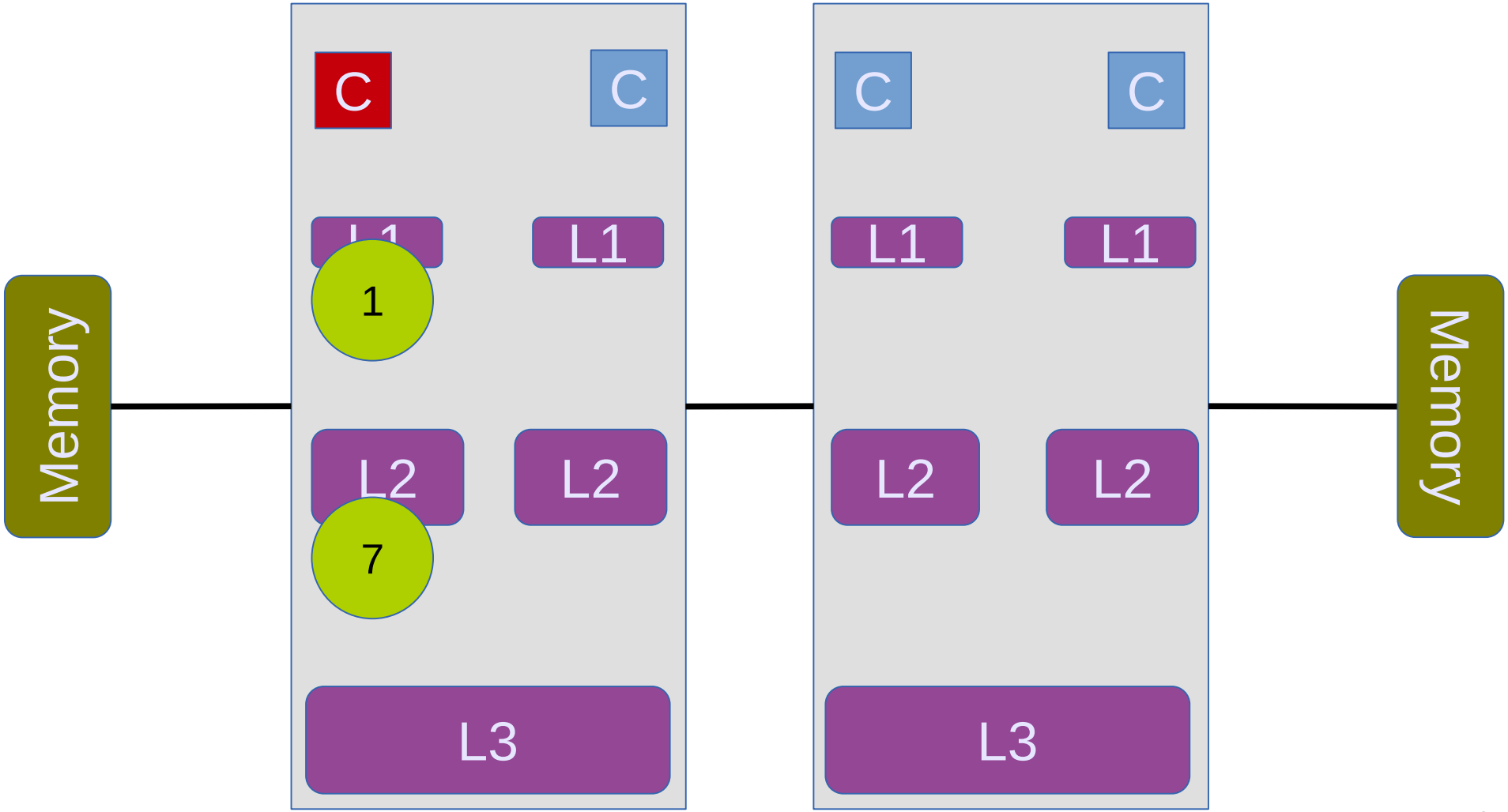

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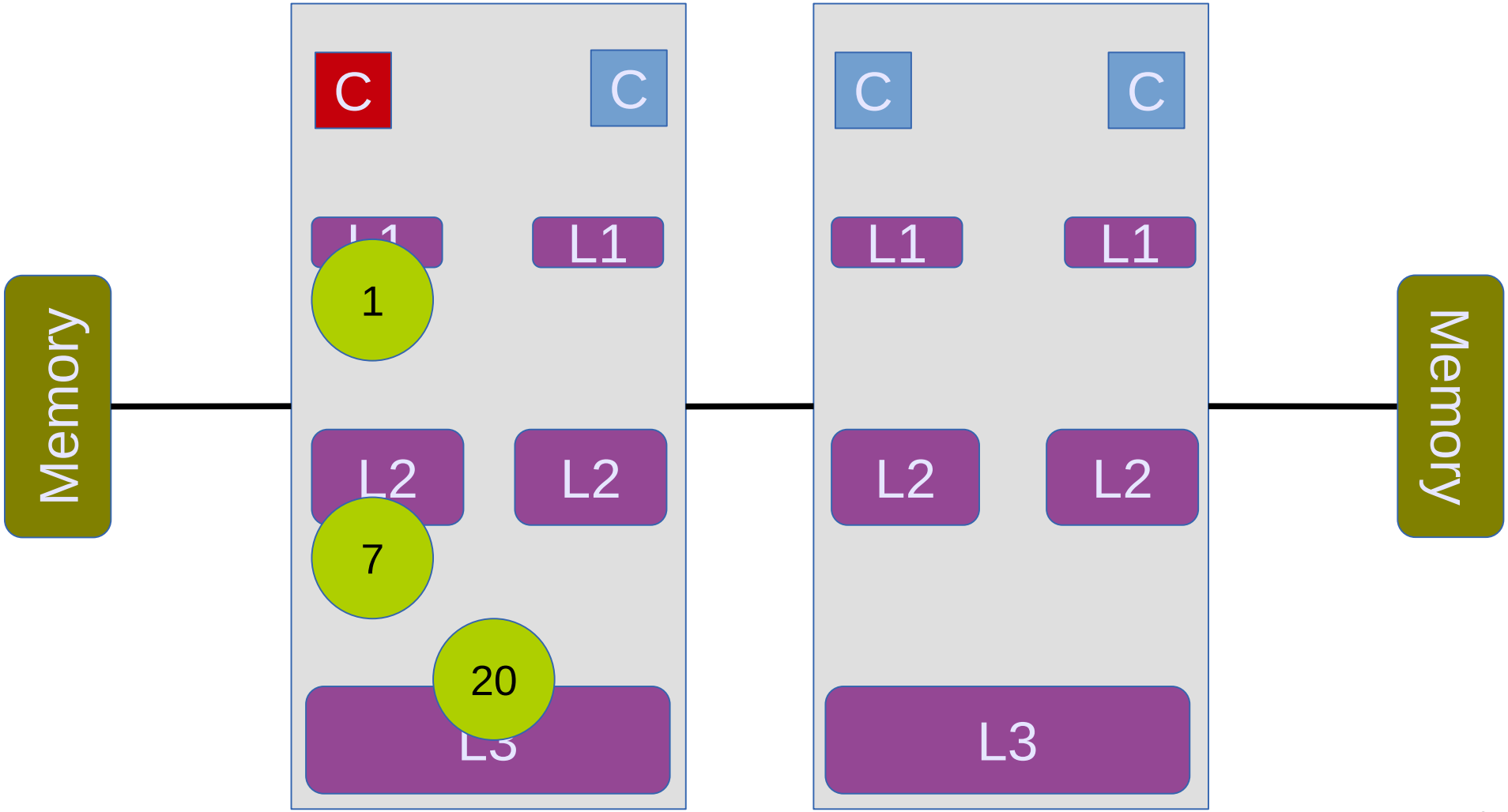

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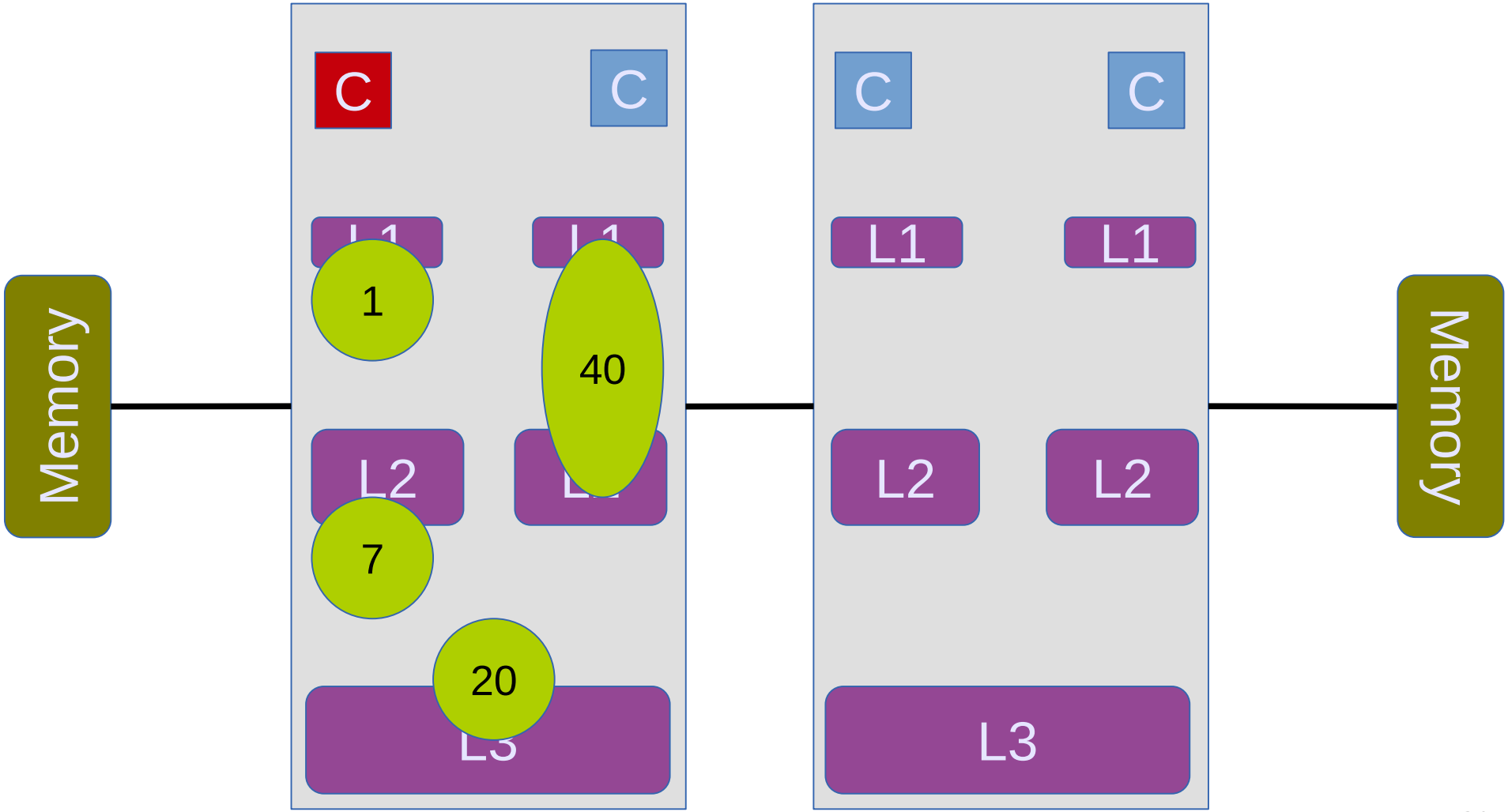

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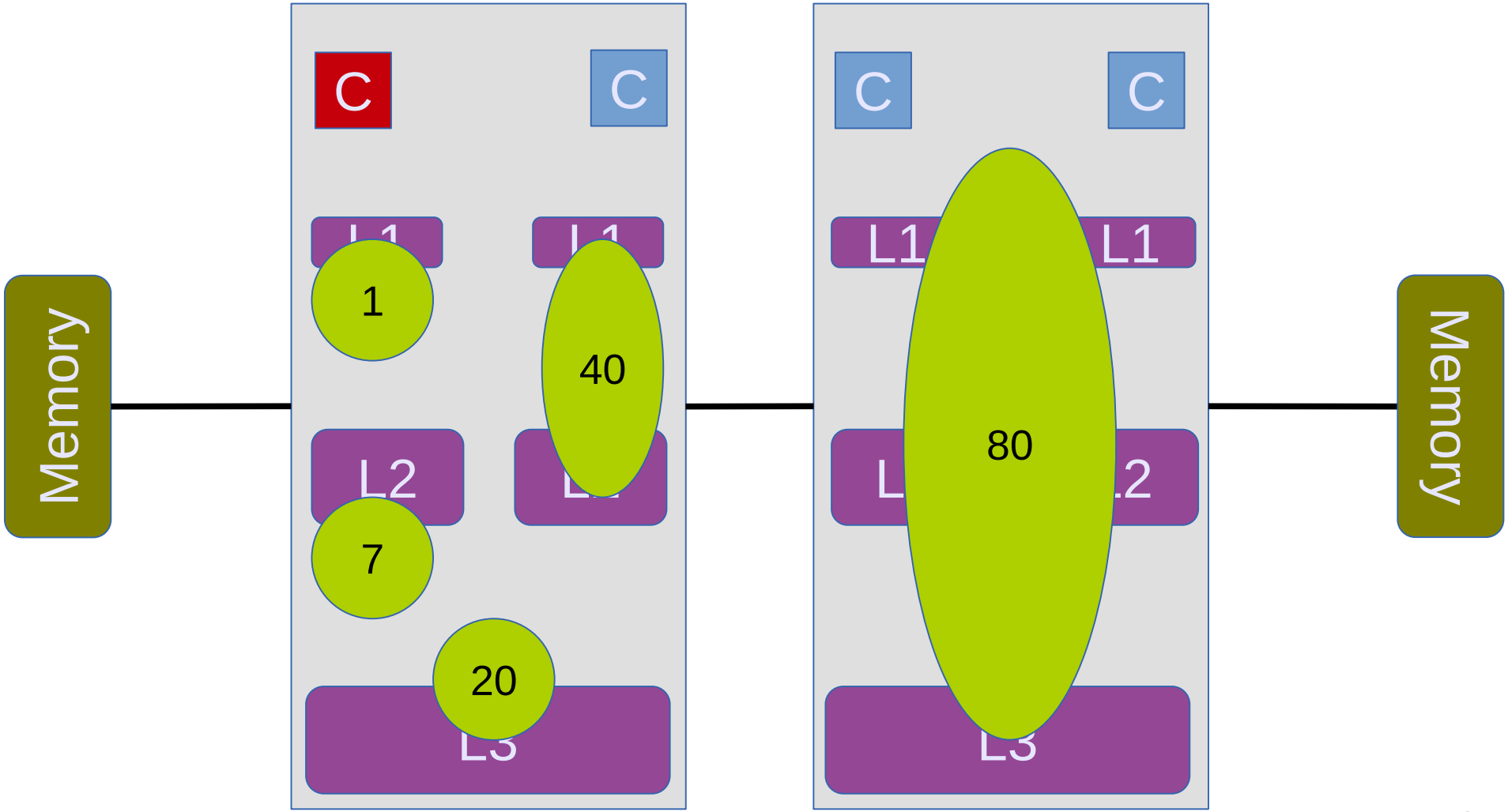

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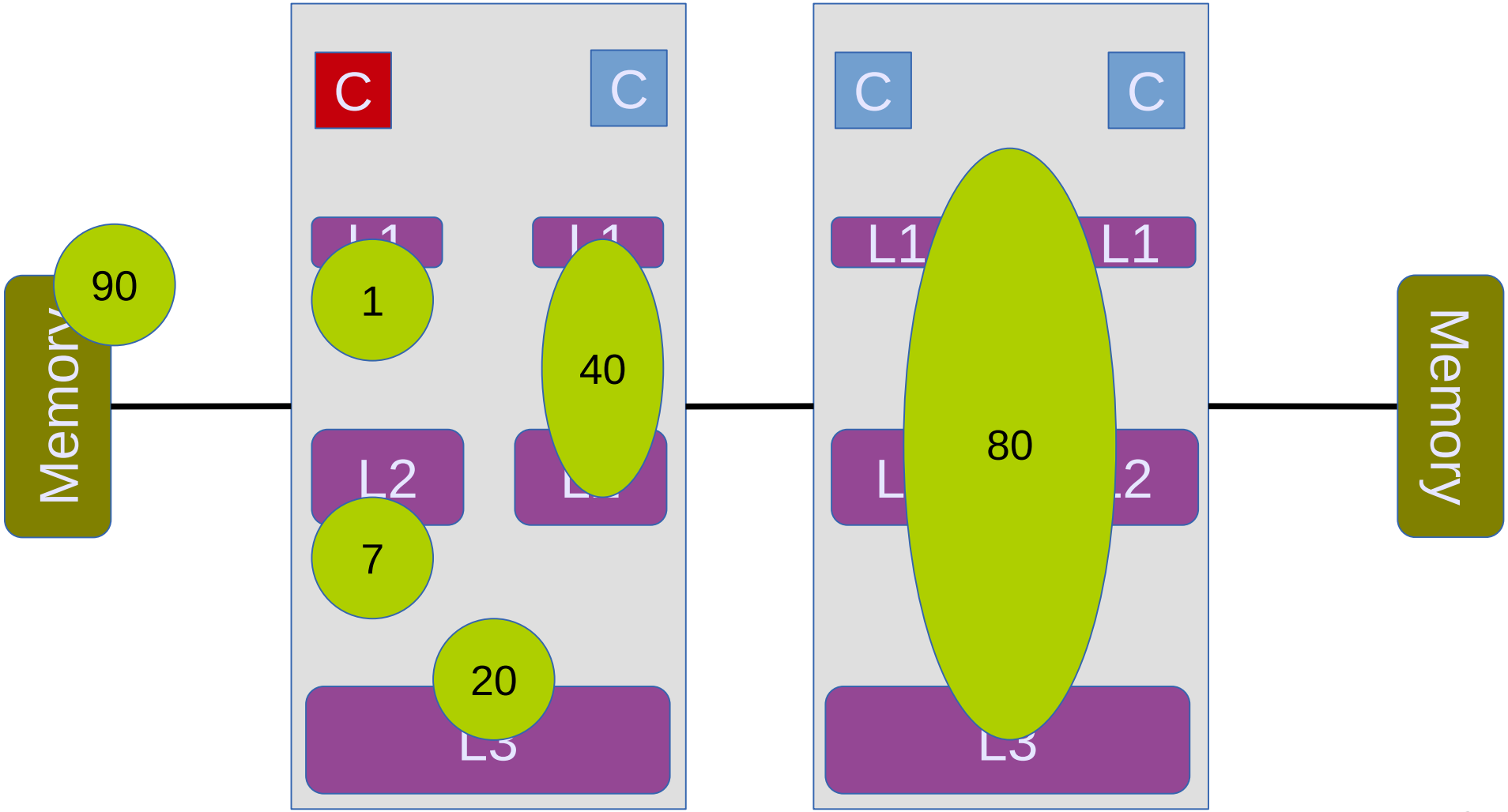

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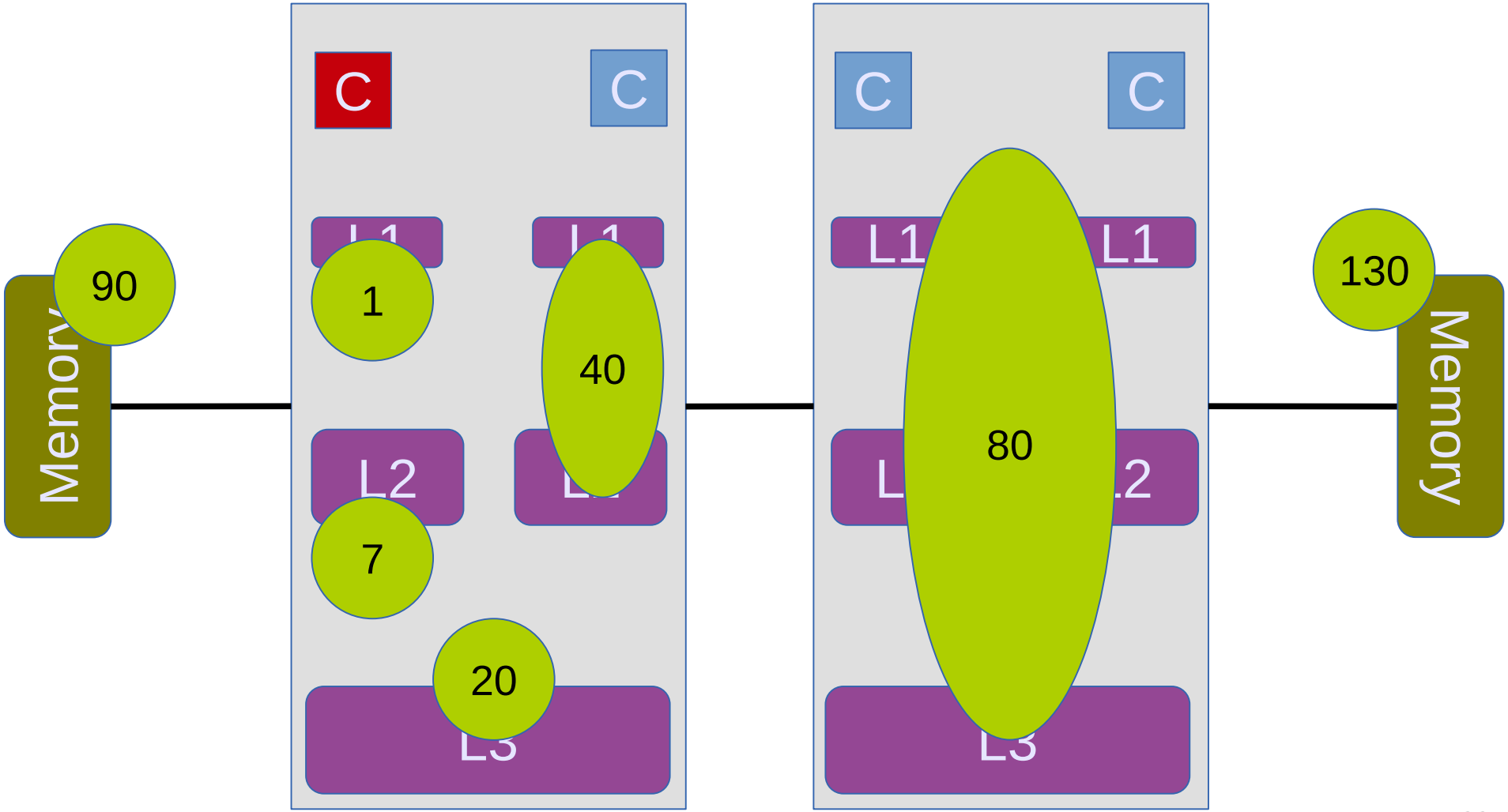

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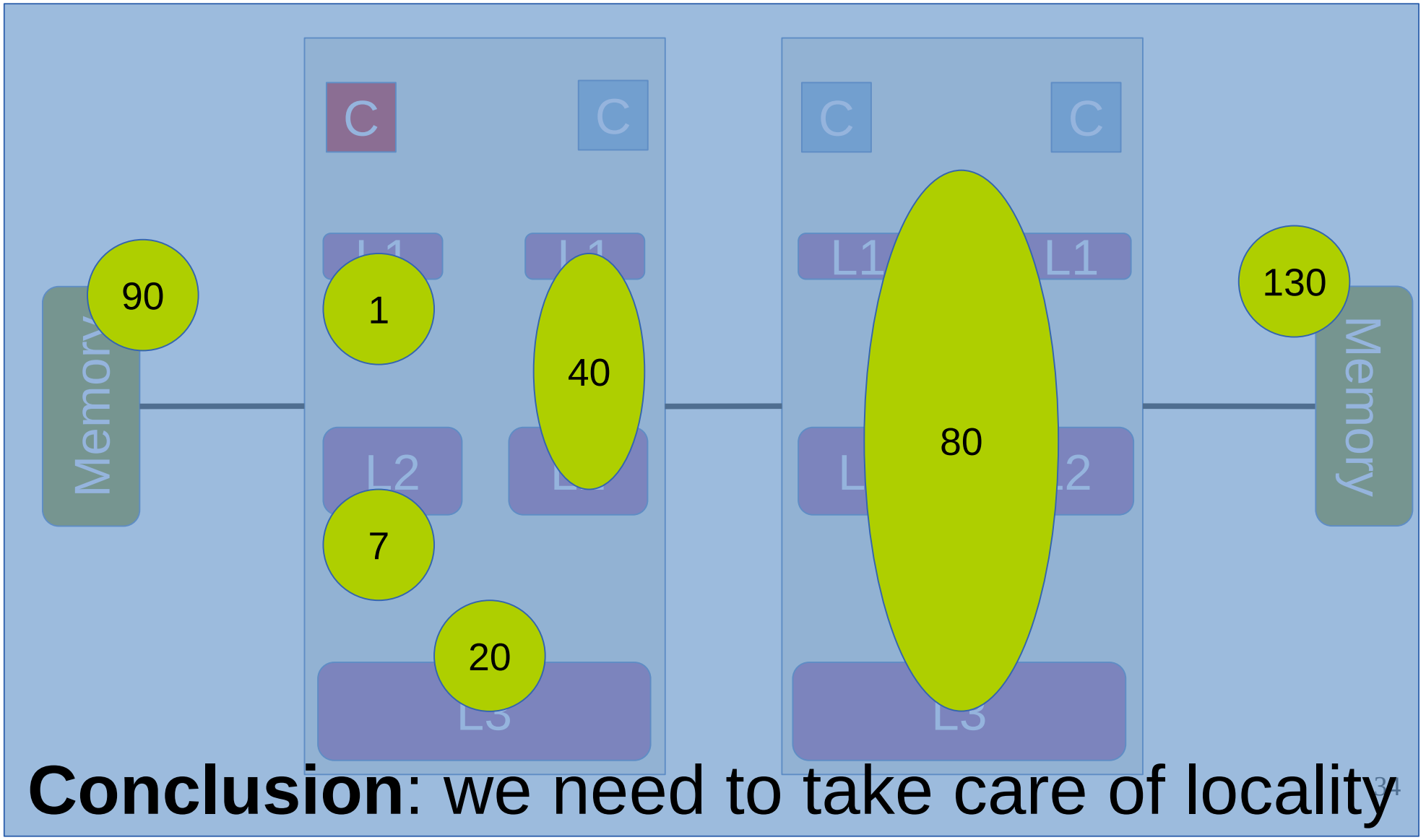

Conclusion: we need to take care of locality

Experiment

The effects of locality

Experiment

The effects of locality

```
vtrigona $ ./test_locality -x0 -y1
Size:             8 counters = 1 cache lines
Thread 0 on core : 0
Thread 1 on core : 2
Number of threads: 2
Throughput       : 104.27 Mop/s
```

Same memory node

```
vtrigona $ ./test_locality -x0 -y10
Size:             8 counters = 1 cache lines
Thread 0 on core : 0
Thread 1 on core : 10
Number of threads: 2
Throughput       : 43.16 Mop/s
```

Different memory nodes

Outline

- CPU caches
- Cache coherence
- Placement of data
- **Graph processing: Concurrent data structures**

Graph processing

Relational view

People Table

Name	Likes
Vasilis	Breaking bad
Rachid	Dexter
Vasilis	Dexter

Series Table

Name	Similar
Breaking bad	Dexter
Dexter	Breaking bad

Graph processing

Relational view

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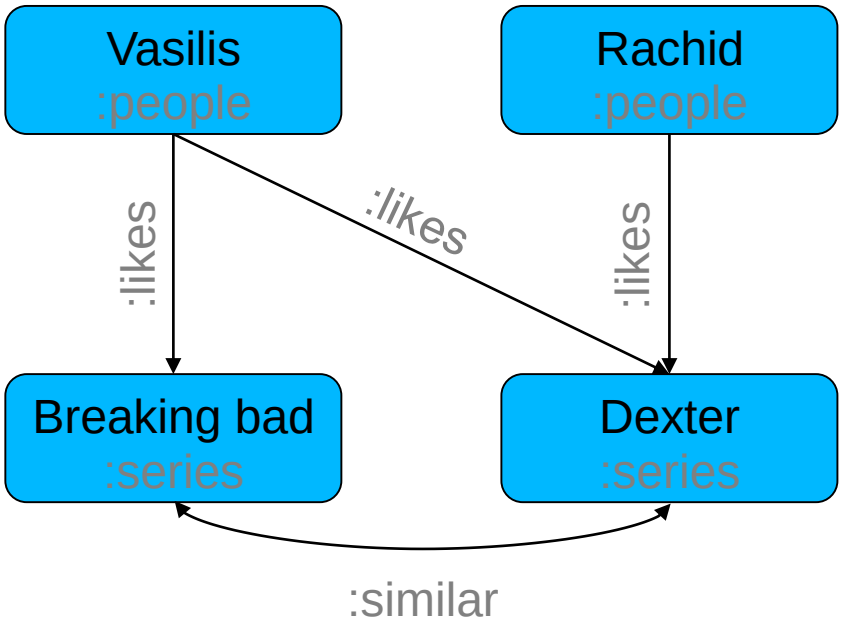
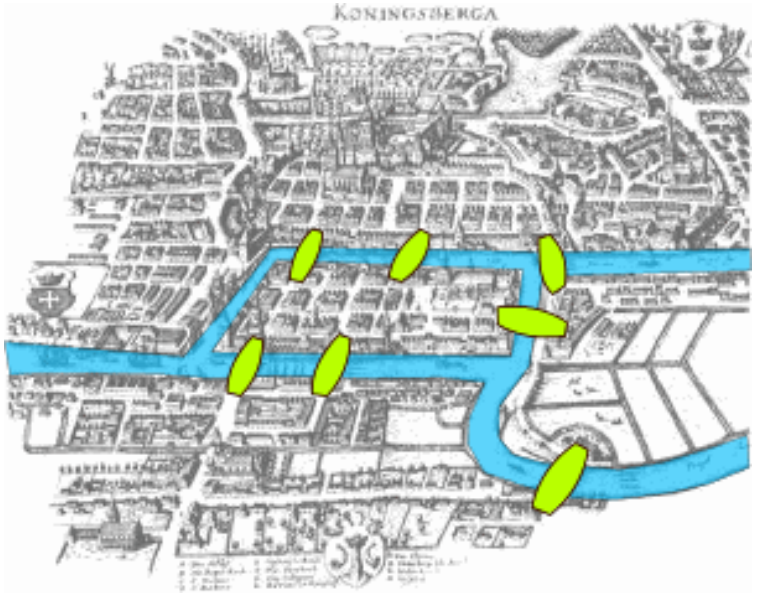
Graph view



Graphs keep the connections among entities materialized

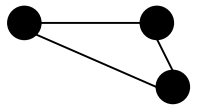
Graph analytics

- Graphs have been studied in Math for centuries
  - Since Euler's "Seven Bridges of Königsberg", 1736
- **Repeatedly traverse your graph and calculate math properties**
- Classic graph problems
  - Graph isomorphism
  - Travelling salesman's problem
  - Max flow, min cut
  - …
- More recent developments
  - Pagerank
  - Infomap



Graph queries

- Graph pattern matching
  - Query graphs to find sub-graphs that match a pattern
    e.g., triangle counting



- Essentially: SQL for graphs

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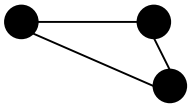
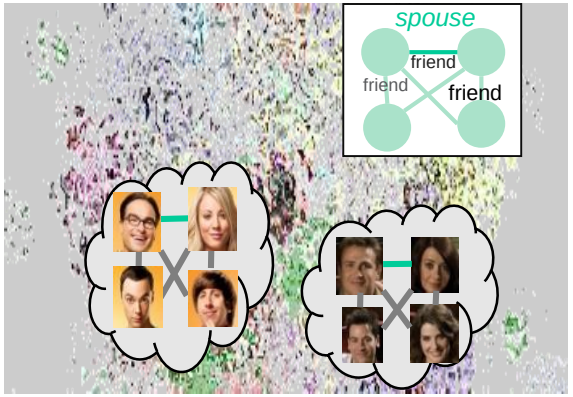


- Essentially: SQL for graphs
- Example: Friends of my friends

```
SELECT p1, p3, COUNT(p2)
MATCH (p1)-[:friend]->(p2)->[:friend]->(p3),
          ! (p1)-[:friend]->(p3)
WHERE p1.country = p2.country
GROUP BY p1, p3
ORDER BY COUNT(p2) DESC
```



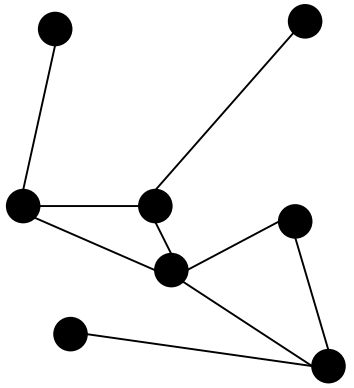
Graph processing frequently involves both analytics and queries

Dissecting a graph processing system

with a focus on (concurrent) data structures

Architecture of a graph processing system

Graph



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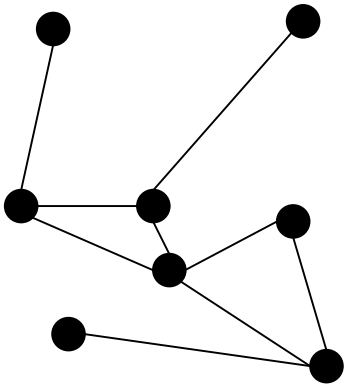


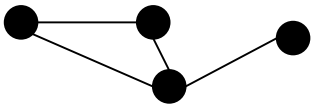
Tons of other data and metadata to store

Graph

tmp graph structure

“Vasilis”, “Breaking bad”, :likes
“Rachid”, “Dexter”, :likes
“Vasilis”, “Dexter”, :likes
“Dexter”, “Breaking bad”, :similar
“Breaking bad”, “Dexter”, :similar

graph structure



user-ids - internal ids

Vasilis → 0
Rachid → 1
Breaking bad → 2
Dexter → 3

0 → Vasilis
1 → Rachid
2 → Breaking bad
3 → Dexter

labels

:likes, :people, :similar, …

properties

“Vasilis”, {people, male}, 33, Zurich
“Rachid”, {people, male}, ??, Lausanne

lifetime management

number_of_references: X

Graph

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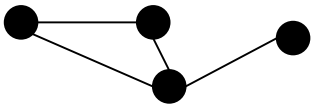

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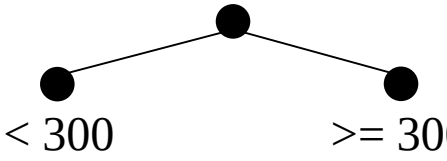
indices / metadata

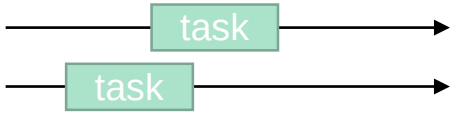


buffer management

1MB 1MB 1MB 1MB

task / job scheduling

Producers Consumers



labels

:likes, :people, :similar, :male …

1 2 3 4

{people, male} → {2,4}

renaming (ids)

used		used	used

Graph

tmp graph structure

“Vasilis”, “Breaking bad”, :likes
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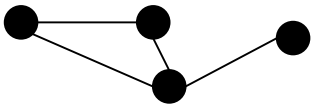
graph structure



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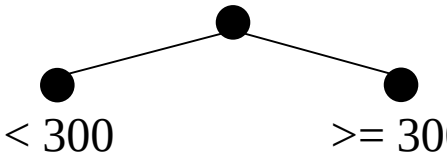

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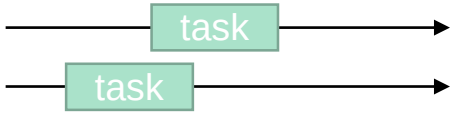


labels

:likes, :people, :similar, :male …

1 2 3 4

{people, male} → {2,4}

renaming (ids)

used		used	used

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

→

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

→

Vasilis
Rachid

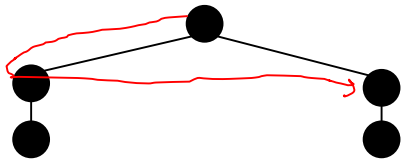
limit (top k)

11 12 0 9 8 13
8 9 11 23 32 9
1 2 3 5 7 3 2 0

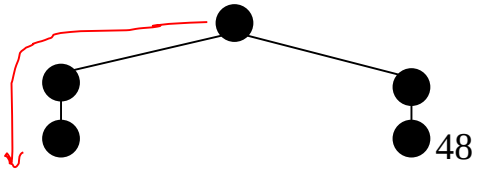
→

32
23
13

BFS



DFS

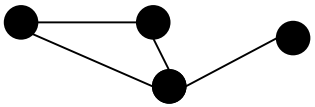


Graph

tmp graph structure

“Vasilis”, “Breaking bad”, :likes
“Rachid”, “Dexter”, :likes
“Vasilis”, “Dexter”, :likes
“Dexter”, “Breaking bad”, :similar
“Breaking bad”, “Dexter”, :similar

graph structure



user-ids - internal ids

Vasilis → 0
Rachid → 1
Breaking bad → 2
Dexter → 3

0 → Vasilis
1 → Rachid
2 → Breaking bad
3 → Dexter

labels

:likes, :people, :similar, …

properties

“Vasilis”, {people, male}, 33, Zurich
“Rachid”, {people, male}, ??, Lausanne

lifetime management

number_of_references: X

- tmp graph structure
  - append only
  - dynamic schema

Graph

tmp graph structure

“Vasilis”, “Breaking bad”, :likes
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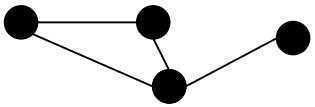
“Dexter”, “Breaking bad”, :similar
“Breaking bad”, “Dexter”, :similar

graph structure



user-ids - internal ids

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Rachid → 1	1 → Rachid
Breaking bad → 2	2 → Breaking bad
Dexter → 3	3 → Dexter

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:likes, :people, :similar, …

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number_of_references: X

- tmp graph structure
  - append only
  - dynamic schema
  - → **segmented table**

Graph

tmp graph structure

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“Vasilis”, “Dexter”, :likes
“Dexter”, “Breaking bad”, :similar
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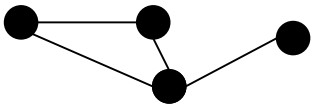
graph structure



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number_of_references: X

- tmp graph structure
  - append only
  - dynamic schema
  - → **segmented table**
- Classic graph structures

Graph

tmp graph structure

“Vasilis”, “Breaking bad”, :likes
“Rachid”, “Dexter”, :likes
“Vasilis”, “Dexter”, :likes
“Dexter”, “Breaking bad”, :similar
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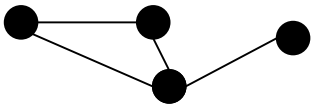
graph structure



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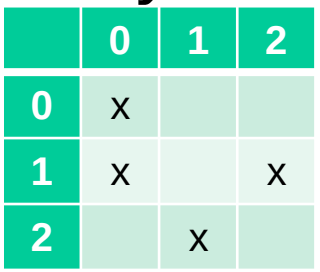
lifetime management

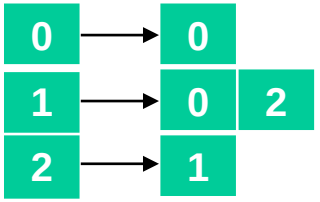
number_of_references: X

- tmp graph structure
  - append only
  - dynamic schema
  - → **segmented table**

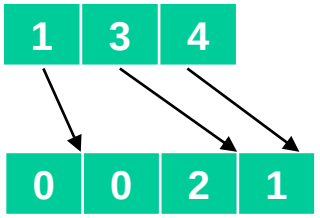
- Classic graph structures
  1. connectivity matrix



  2. adjacency list



  3. compressed source row (CSR)



Graph

tmp graph structure

"Vasilis", "Breaking bad", :likes
"Rachid", "Dexter", :likes
"Vasilis", "Dexter", :likes
"Dexter", "Breaking bad", :similar
"Breaking bad", "Dexter", :similar

segmented buffer

graph structure

user-ids - internal ids

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Rachid → 1
Breaking bad → 2
Dexter → 3

0 → Vasilis
1 → Rachid
2 → Breaking bad
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labels

:likes, :people, :similar, …

properties

"Vasilis", {people, male}, 33, Zurich
"Rachid", {people, male}, ??, Lausanne

lifetime management

number_of_references: X

- Mapping user ids to internal ids
  - create once
  - read-only after

Graph

tmp graph structure

"Vasilis", "Breaking bad", :likes
"Rachid", "Dexter", :likes
"Vasilis", "Dexter", :likes
"Dexter", "Breaking bad", :similar
"Breaking bad", "Dexter", :similar

segmented buffer

graph structure

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  - create once
  - read-only after

→ **hash map, lock-free reads**

Graph

tmp graph structure

"Vasilis", "Breaking bad", :likes
"Rachid", "Dexter", :likes
"Vasilis", "Dexter", :likes
"Dexter", "Breaking bad", :similar
"Breaking bad", "Dexter", :similar

segmented buffer

graph structure

user-ids - internal ids

Vasilis → 0
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labels

:likes, :people, :similar, …

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lifetime management

number_of_references: X

- Mapping user ids to internal ids
  - create once
  - read-only after
  - → **hash map, lock-free reads**
- Mapping internal ids to user ids
  - create once
  - read-only after
  - fixed key range: [0, N}

Graph

tmp graph structure

"Vasilis", "Breaking bad", :likes
"Rachid", "Dexter", :likes
"Vasilis", "Rachid", :knows
"Dexter", "Breaking bad", :similar
"Breaking bad", "Dexter", :similar

segmented buffer

graph structure

user-ids - internal ids

Vasilis → 0
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Breaking bad → 2
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labels

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properties

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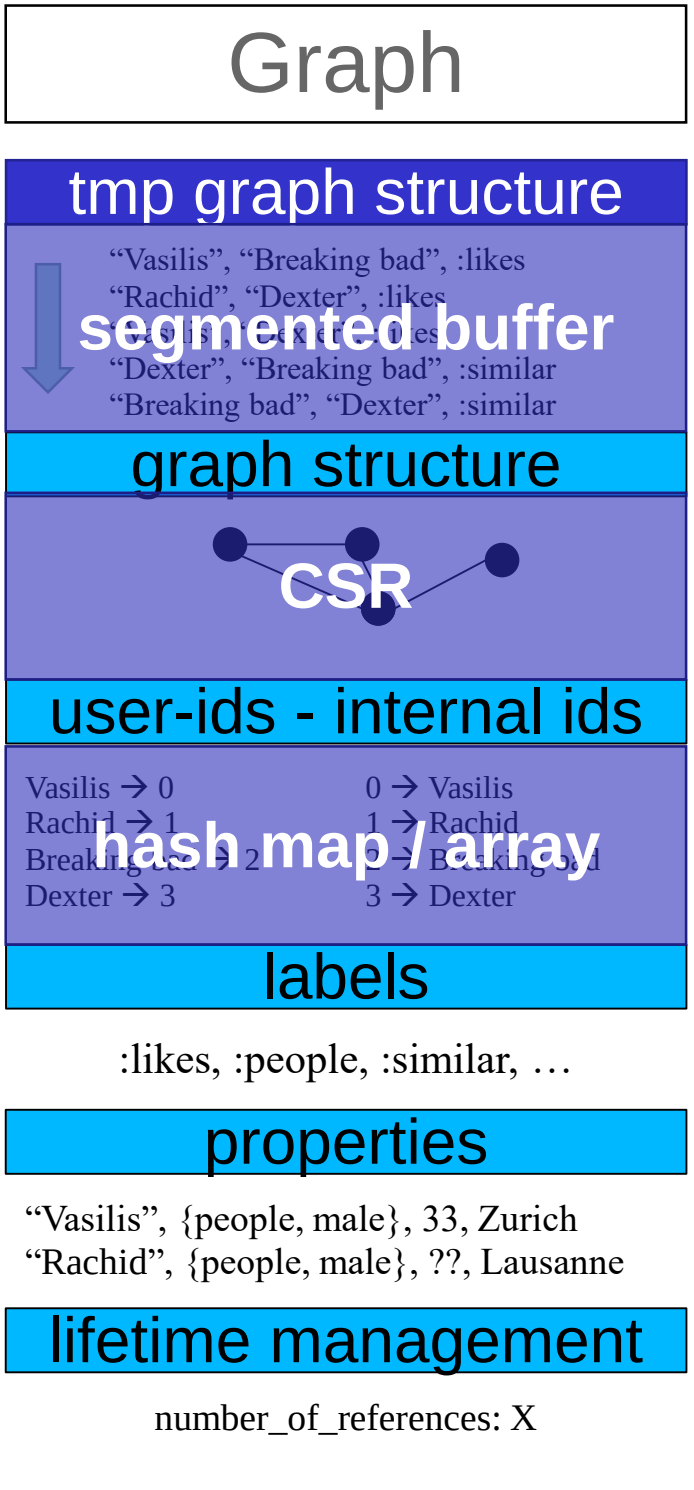
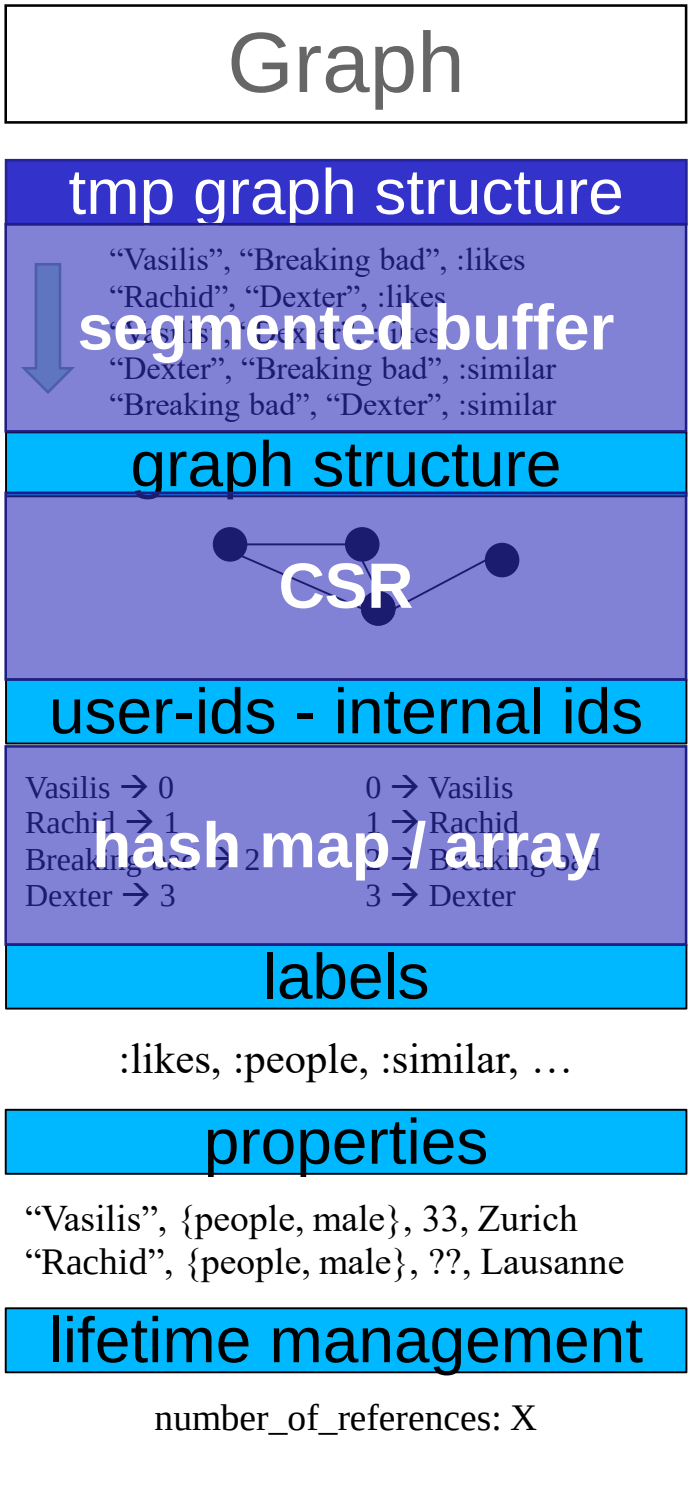
lifetime management

number_of_references: X

- Mapping user ids to internal ids
  - create once
  - read-only after
  - → **hash map, lock-free reads**
- Mapping internal ids to user ids
  - create once
  - read-only after
  - fixed key range: [0, N}
  - → **(sequential) array**

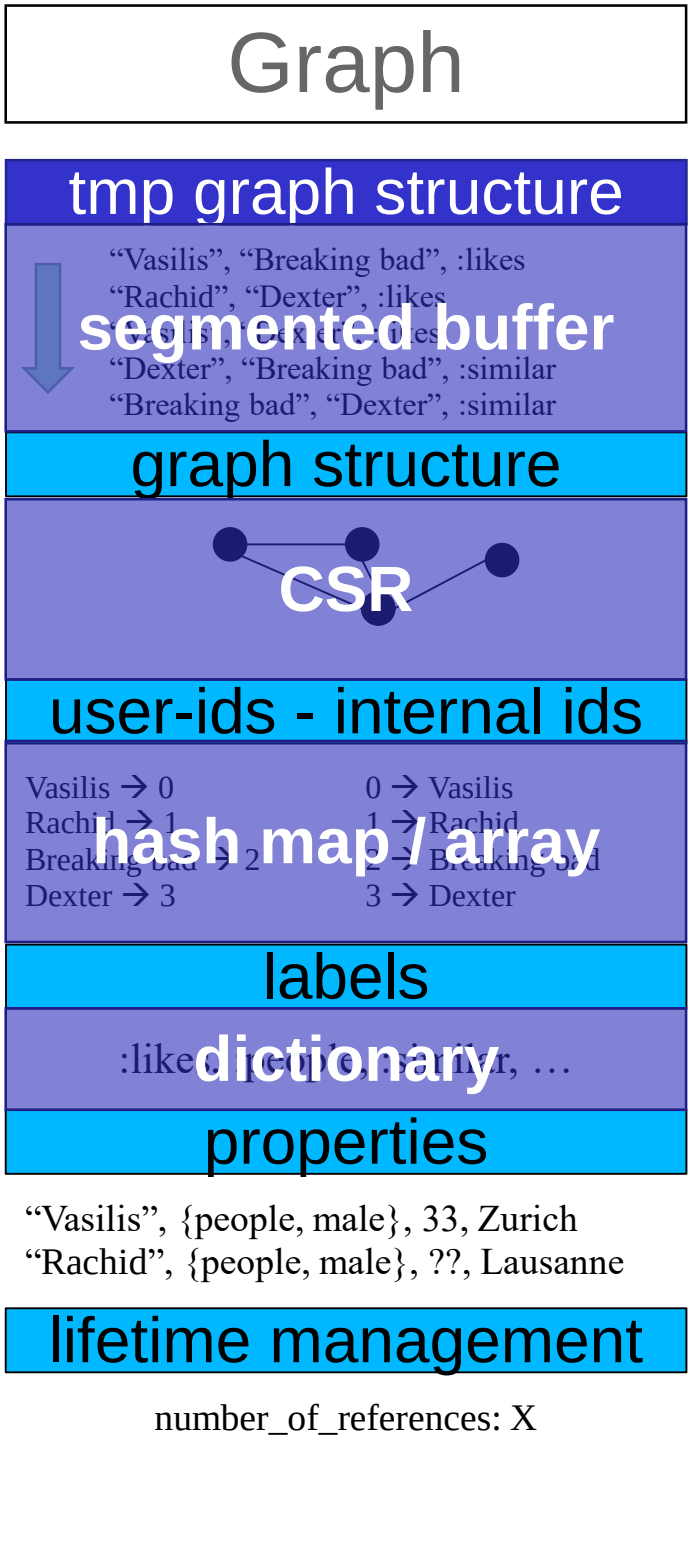


- Storing labels
  - usually a small enumeration
    e.g., person, female, male
  - storing strings is expensive
    "person" → ~ 7 bytes
  - comparing strings is expensive

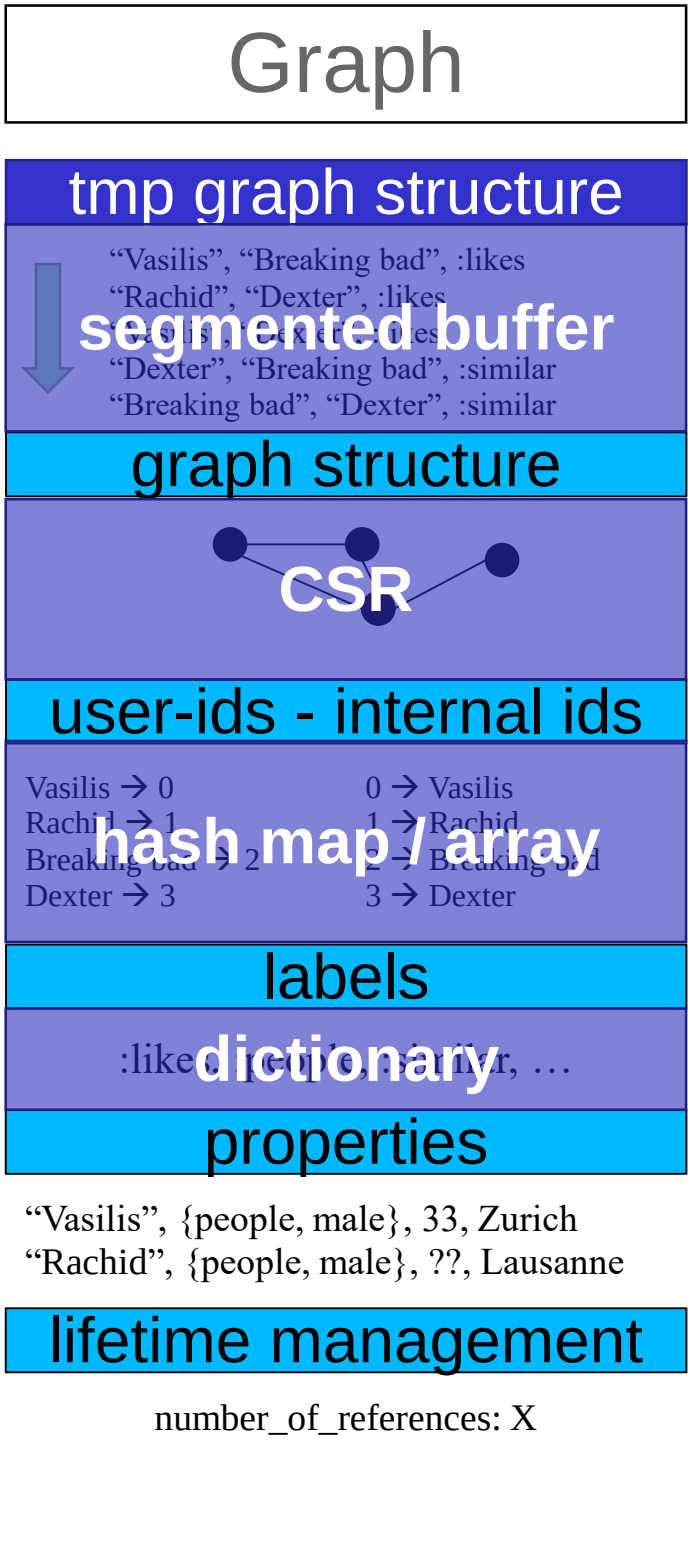


- Storing labels
  - usually a small enumeration e.g., person, female, male
  - storing strings is expensive "person" → ~ 7 bytes
  - comparing strings is expensive

  → **dictionary encoding**, e.g.,
    - person → 0
    - female → 1
    - male → 2
- Ofc, **hash map** to
  - store those
  - translate during runtime



- Property
  - one type per property, e.g., int
  - 1:1 mapping with vertices/edges



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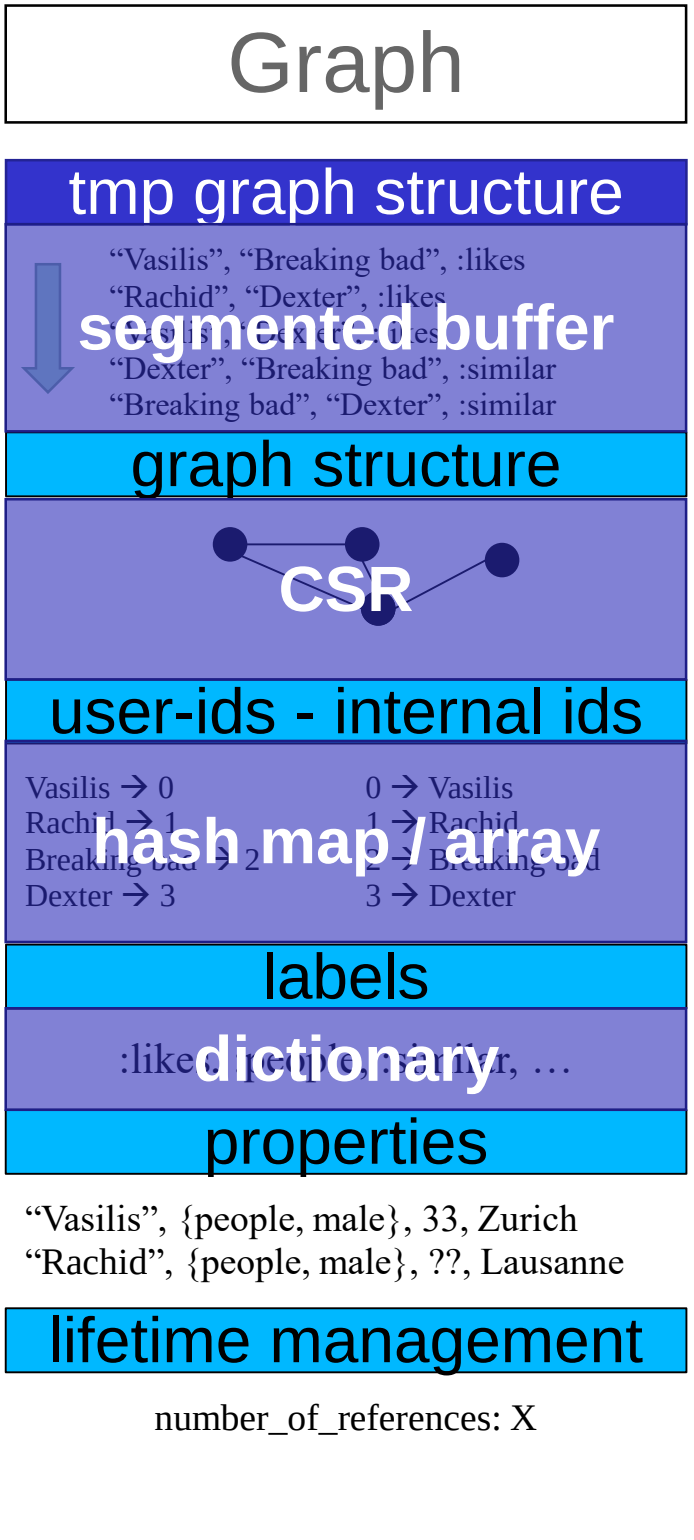
→ **(sequential) arrays**



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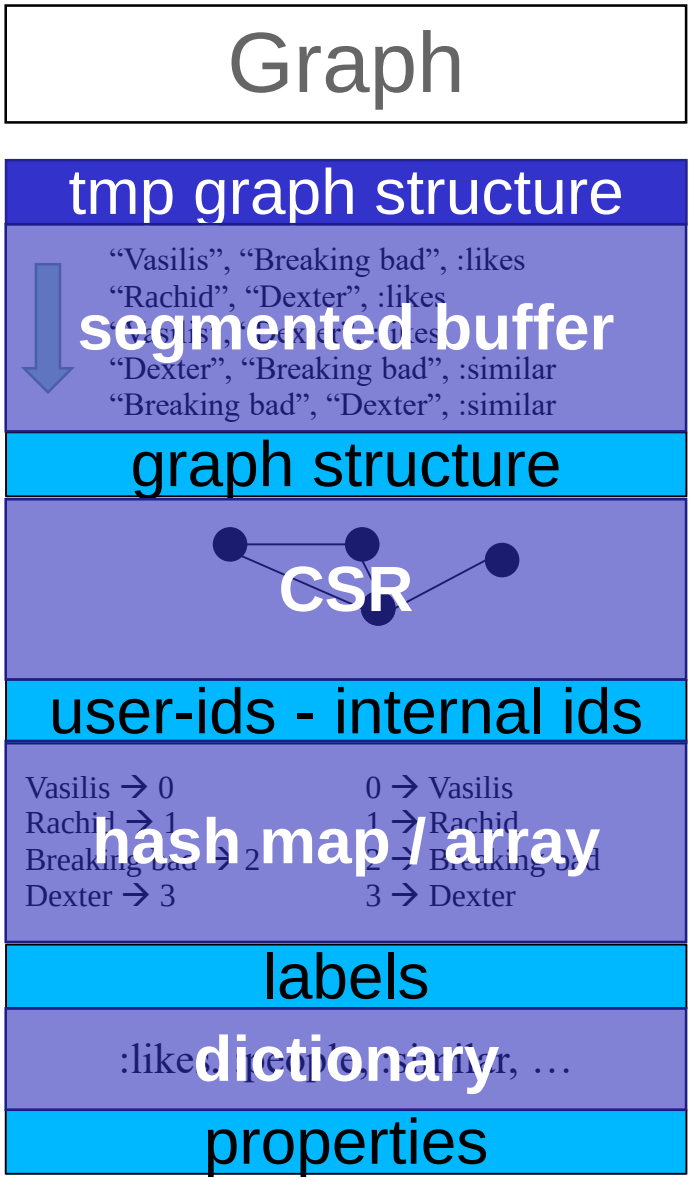
- Lifetime management (and other counters)
  - cache coherence: atomic counters can be expensive



- Property
  - one type per property, e.g., int
  - 1:1 mapping with vertices/edges
  - → **(sequential) arrays**

- Lifetime management (and other counters)
  - cache coherence: atomic counters can be expensive
  - Two potential solutions
    1. **approximate counters**
    2. **stripped counters**

Thread local:	counter[0]	counter[1]	counter[2]

```
increment(int by) { counter[my_thread_id] += by; }
int value() {
   int sum = 0;
   for (int i = 0; i < num_threads; i++) { sum += counter[i]; }
   return sum;
}
```

Graph

tmp graph structure

"Vasilis", "Breaking bad", :likes
"Rachid", "Dexter", :likes
"Vasilis", "Dexter", :likes
"Dexter", "Breaking bad", :similar
"Breaking bad", "Dexter", :similar

segmented buffer

graph structure

CSR

user-ids - internal ids

Vasilis → 0
Rachid → 1
Breaking bad → 2
Dexter → 3

0 → Vasilis
1 → Rachid
2 → Breaking bad
3 → Dexter

hash map / array

labels

dictionary (= map)

properties

"Vasilis", {people, male}, 33, Zurich
"Rachid", {people, male}, ??, Lausanne

array

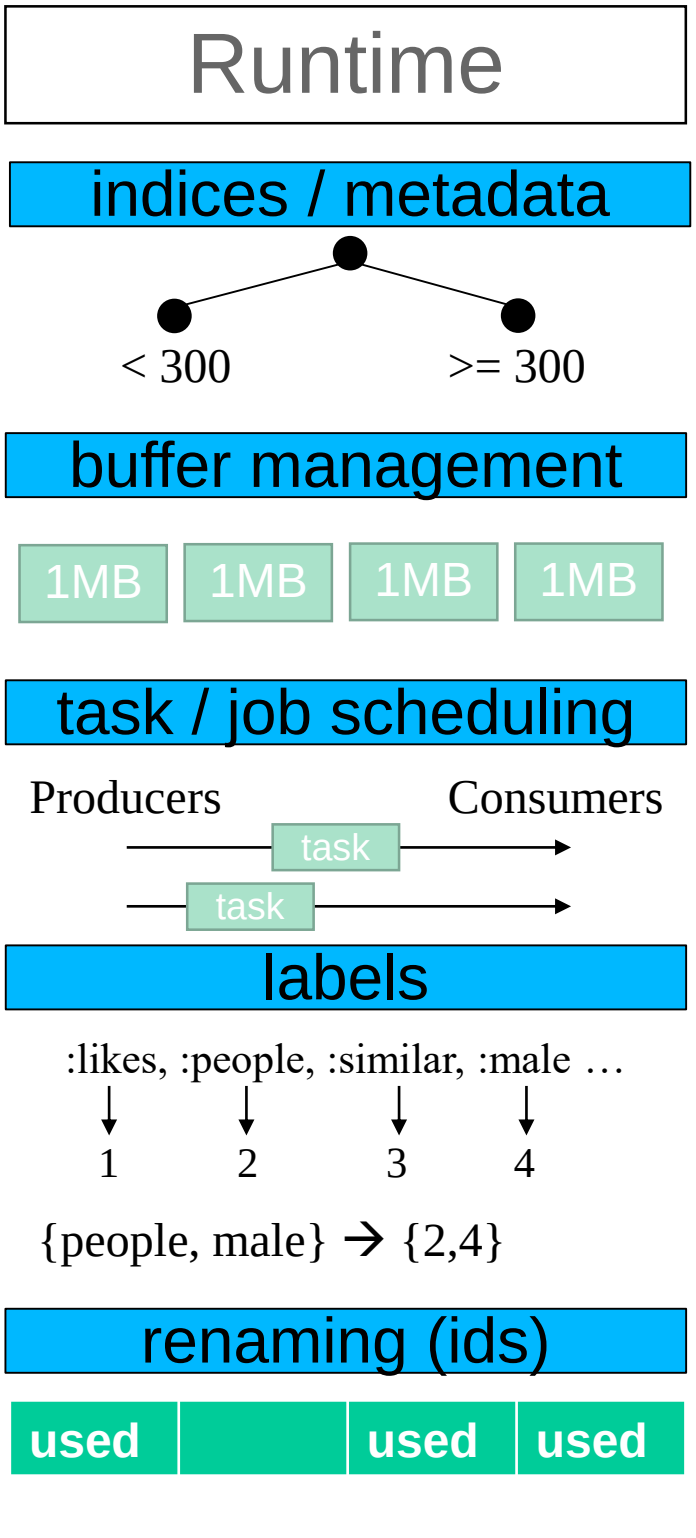
lifetime management

number_of_references: X

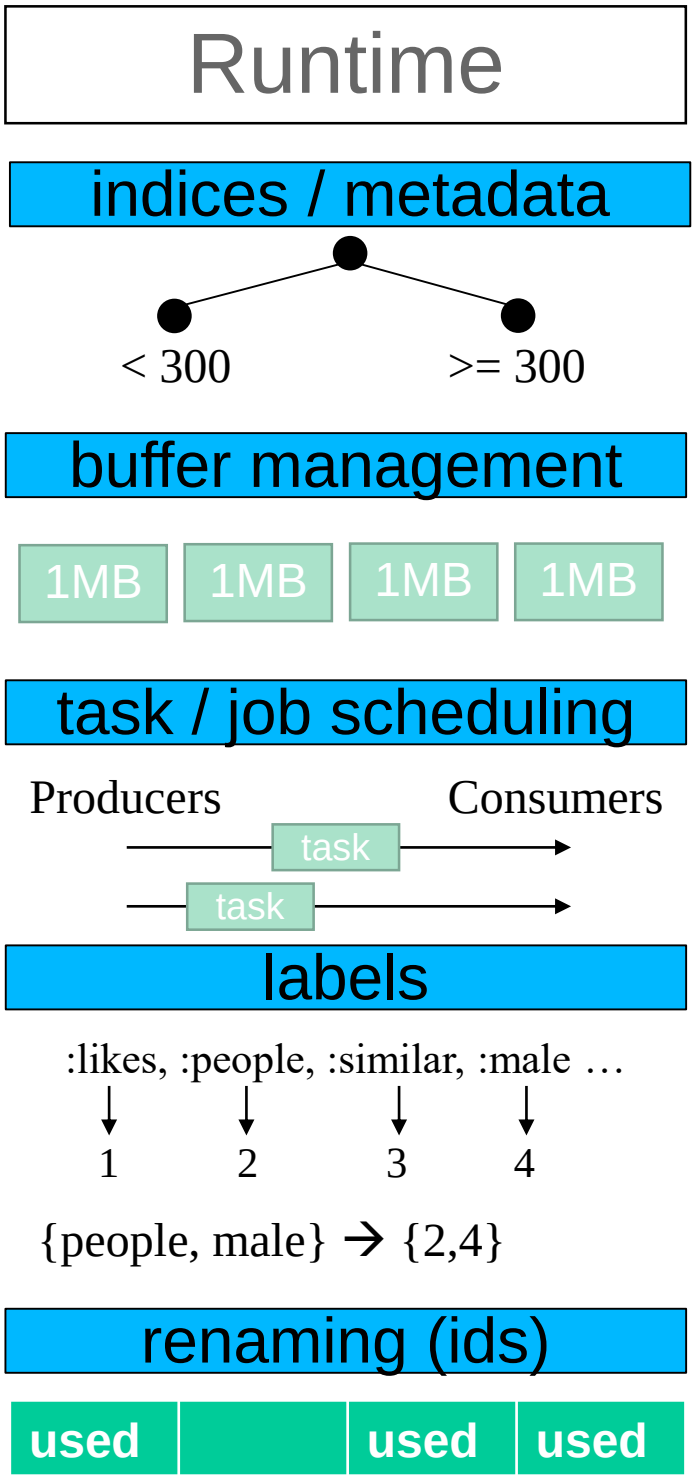
stripped counter

Score

Structure	# Usages
array / buffer	5
map	2



- Indices
  - Used for speeding up “queries”
    - Which vertices have label :person?
    - Which edges have value > 1000?



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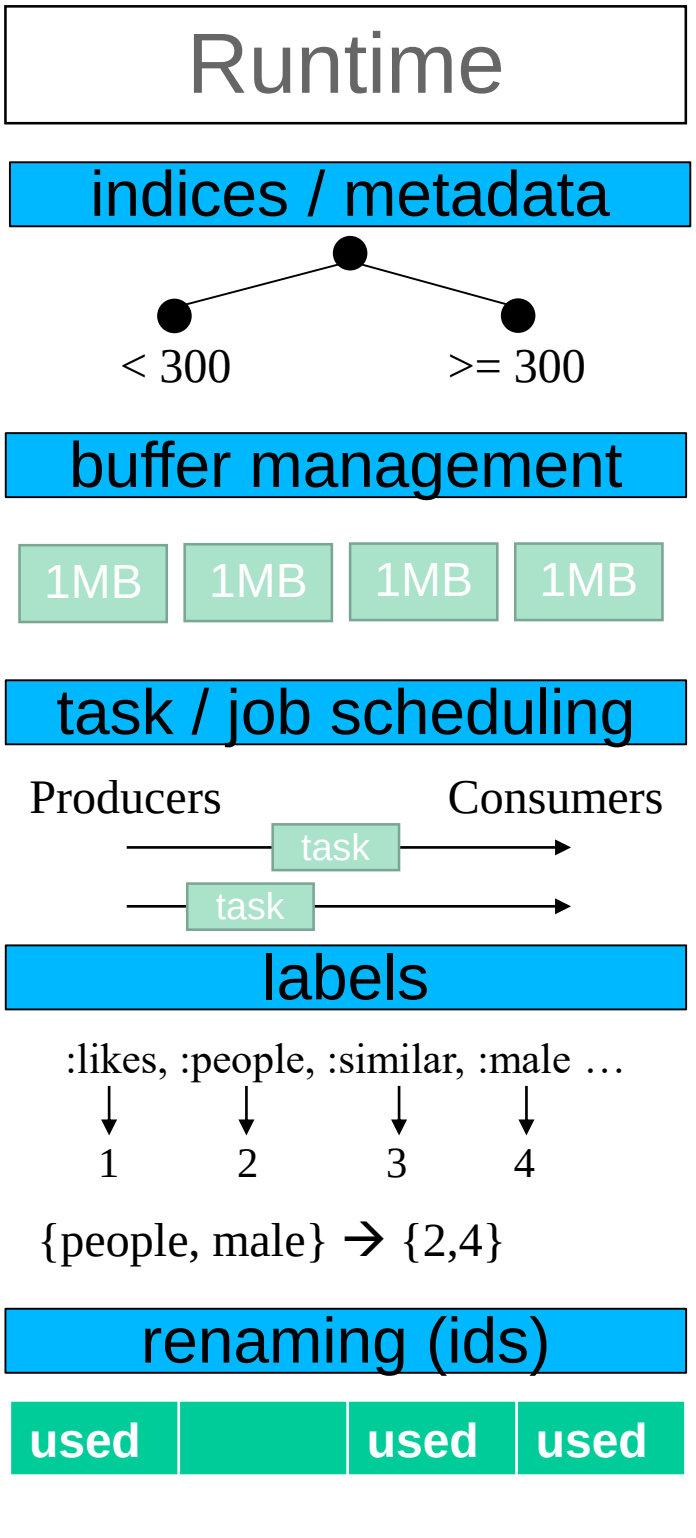
  →maps, trees



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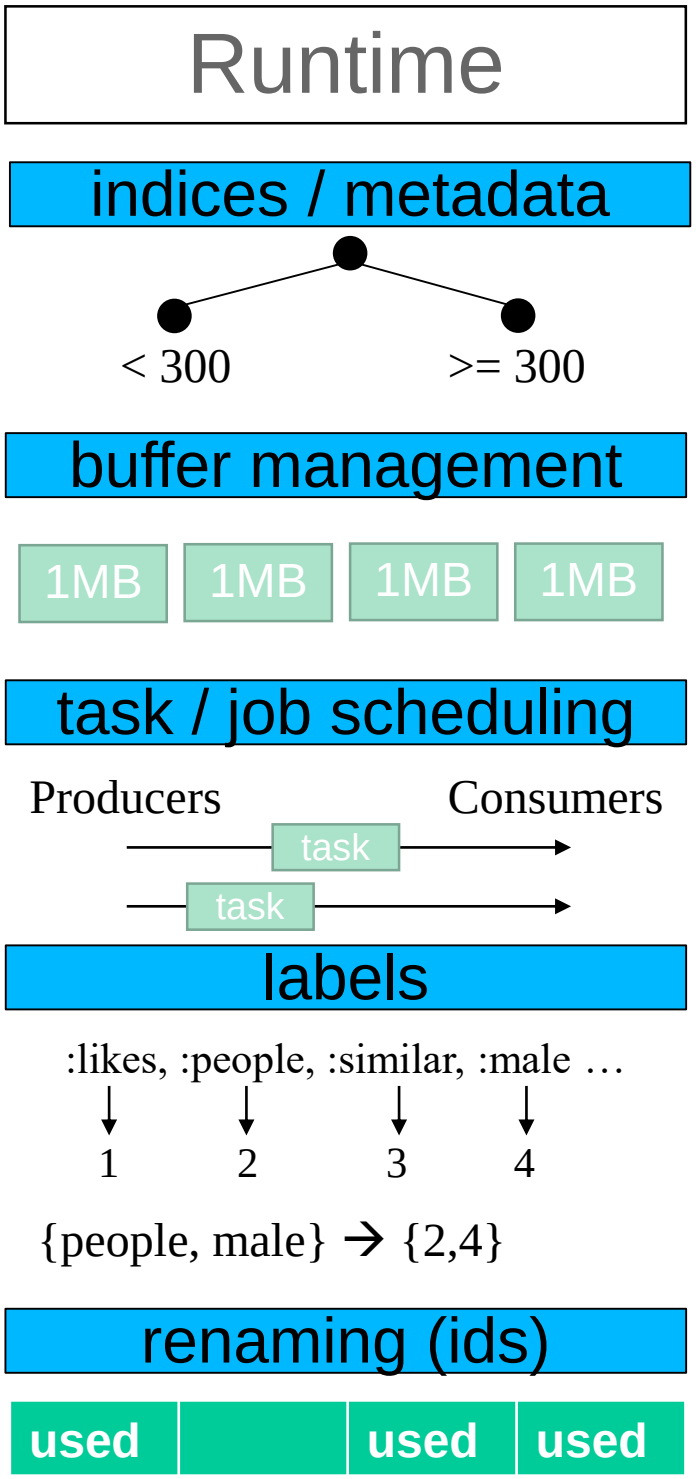
- Buffer management
  - In “real” systems, resource management is very important
  - buffer pools
    - no order
    - insertions and deletions
    - no keys



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  → **maps, trees**

- Buffer management
  - In “real” systems, resource management is very important
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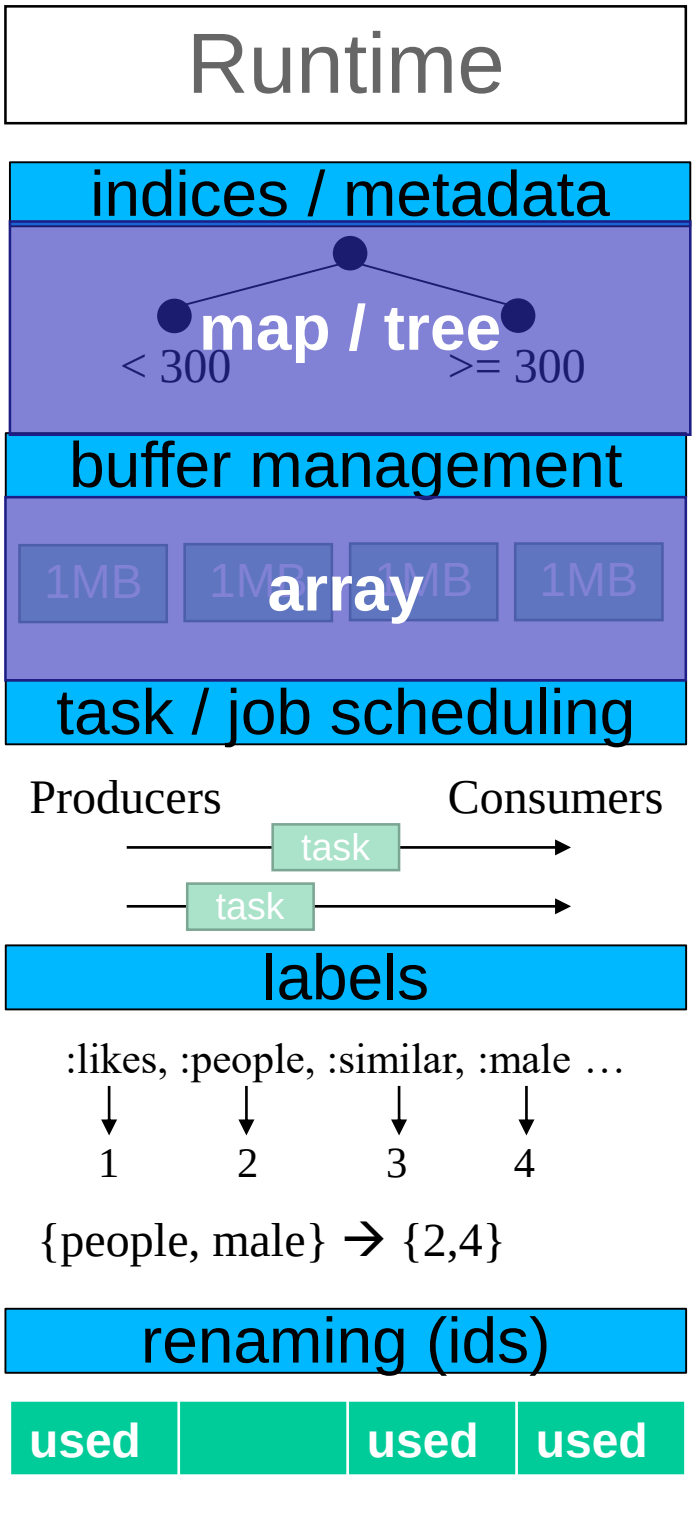
    - no order
    - insertions and deletions
    - no keys

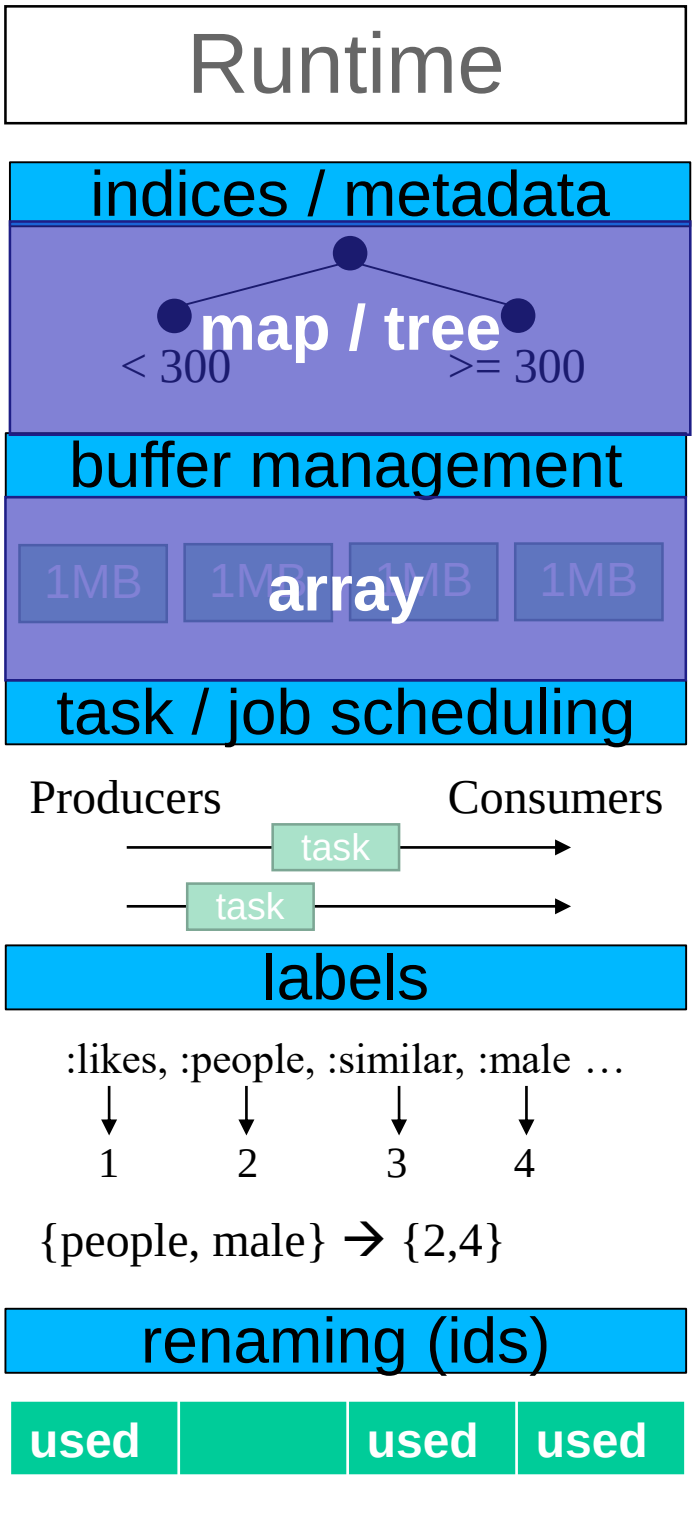
  → Fixed num object pool: **array**

  → Otherwise: **list**

  → Variable-sized elements: **heap**



- Task and job scheduling
  - producers create and share tasks
  - consumers get and handle tasks
  - insertions and deletions
  - usually FIFO requirements



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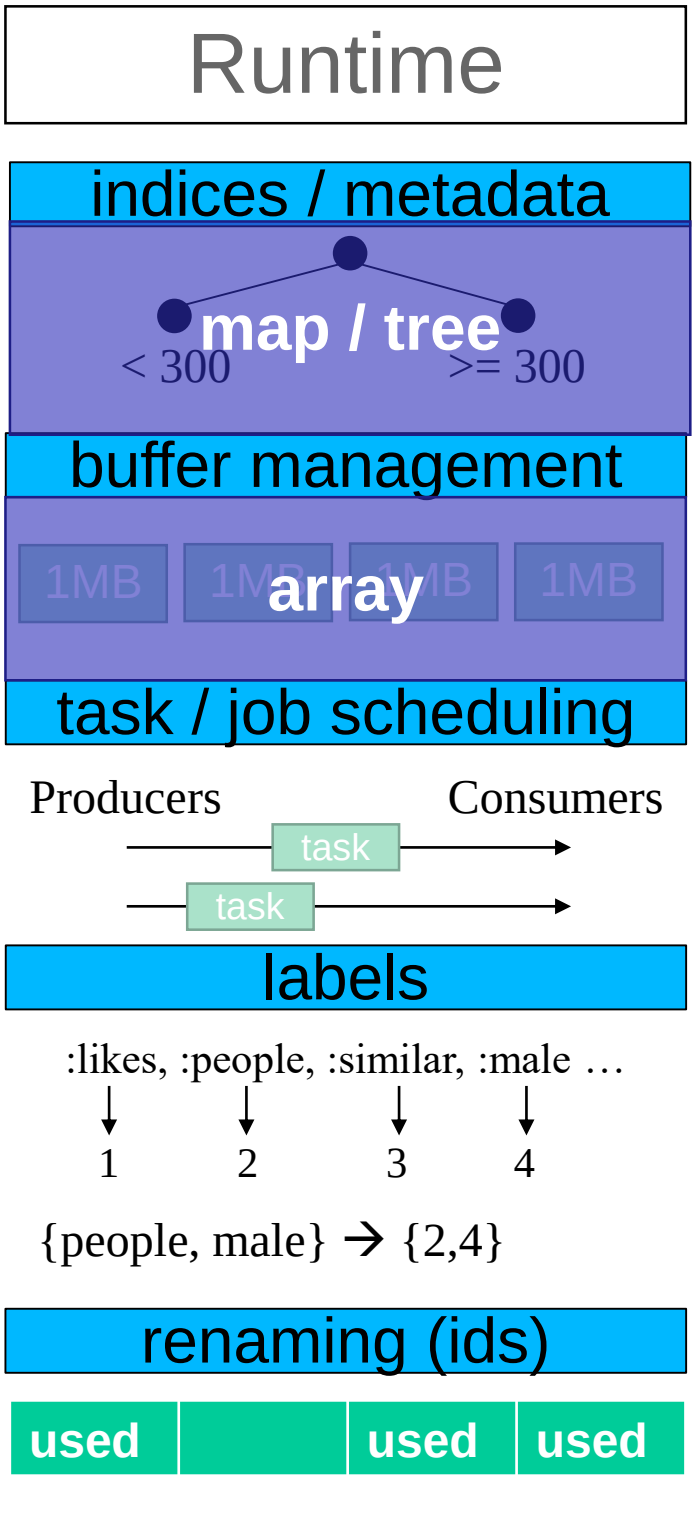
  → **queues**

- Storing / querying sets of labels
  - set equality expensive
  - usually common groups

    e.g., {person, female}, {person, male}



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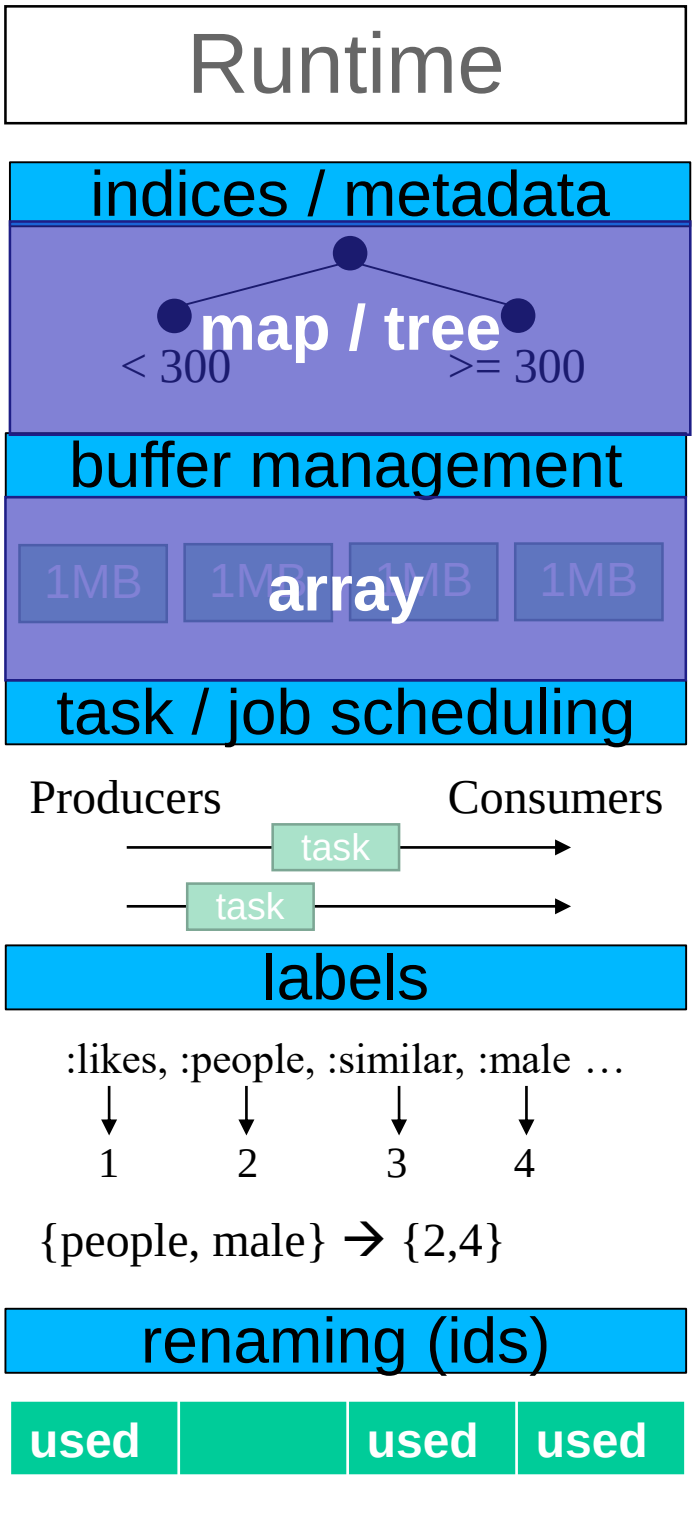
  → 2-level **dictionary** encoding
    - {person, female} → 0
    - {person, male} → 1



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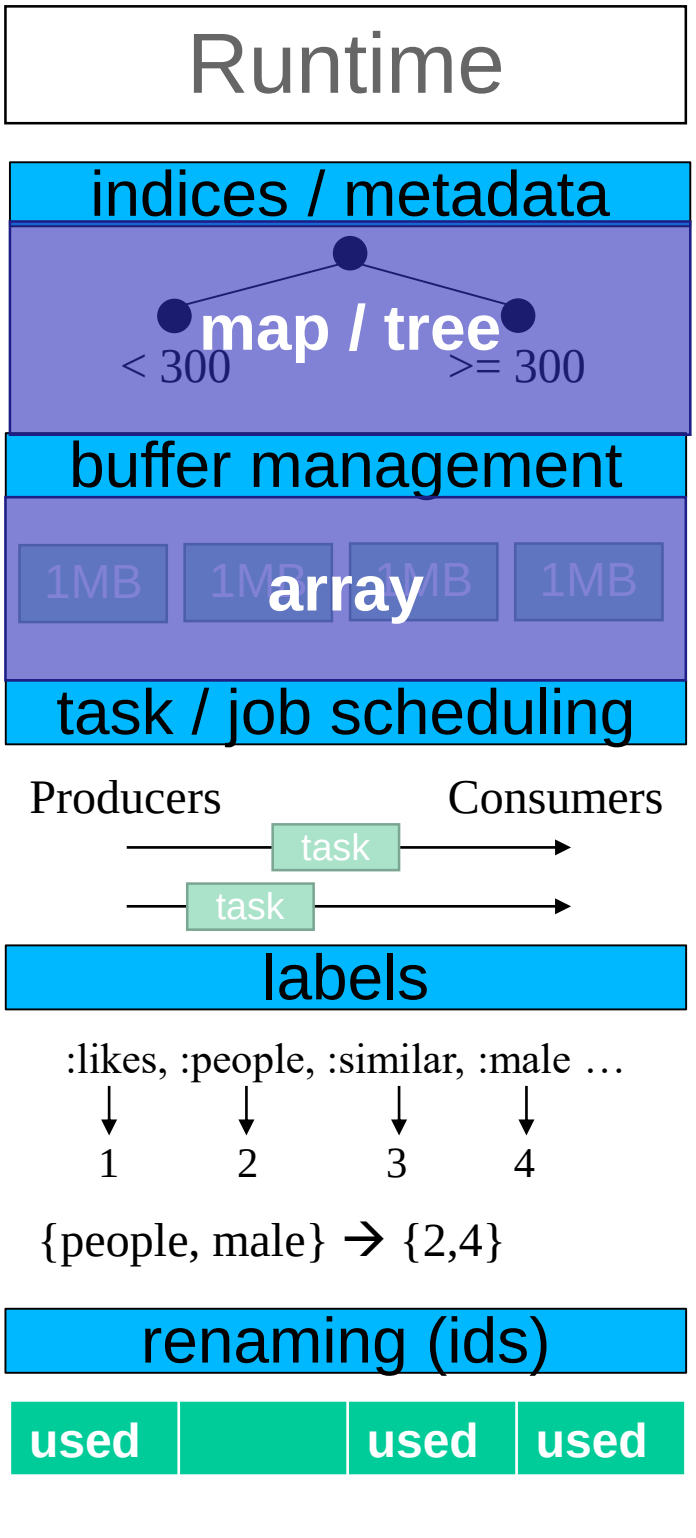
- Giving unique ids (renaming)



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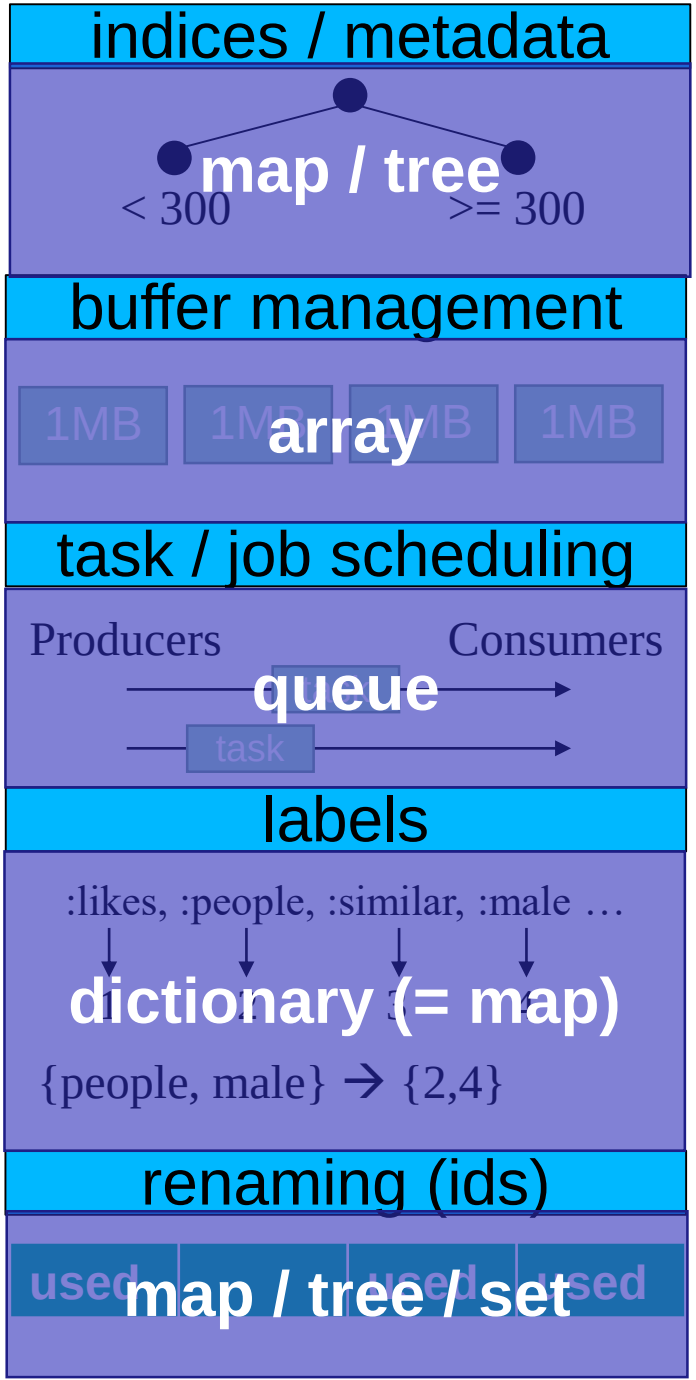
- Giving unique ids (renaming)

  → **tree, map, set**, **counter**, other?

Runtime



Score

Structure	# Usages
array / buffer	6
map	5
tree / heap	2
set	1
queue	1

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

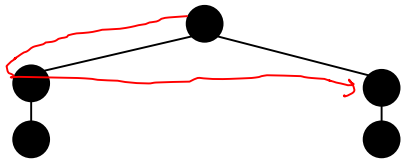
Vasilis
Rachid

limit (top k)

11 12 0 9 8 13
8 9 11 23 32 9
1 2 3 5 7 3 2 0

32
23
13

BFS



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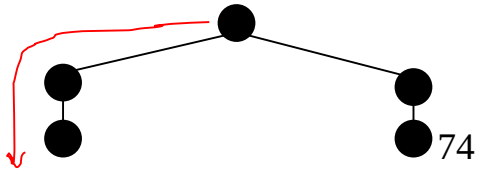

- Group by
  1. Mapping from keys to values
  2. Atomic value aggregations
     e.g., COUNT, SUM, MAX
     - insertion only

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

→

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

→

Vasilis
Rachid

limit (top k)

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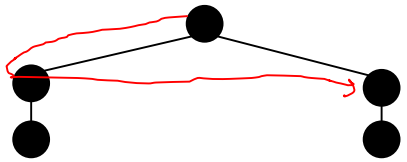

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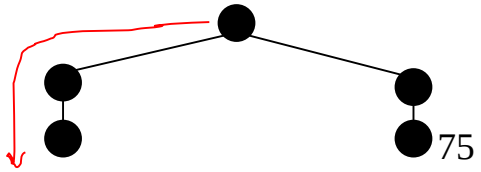

- Group by
  1. Mapping from keys to values
  2. Atomic value aggregations
     e.g., COUNT, SUM, MAX
     - insertion only

→ **hash map**

→ **atomic inc / sum / max**, etc.

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

→

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

→

Vasilis
Rachid

limit (top k)

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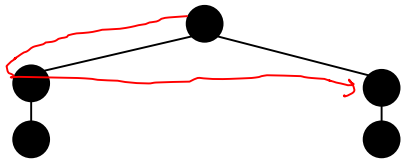
→

32
23
13

BFS



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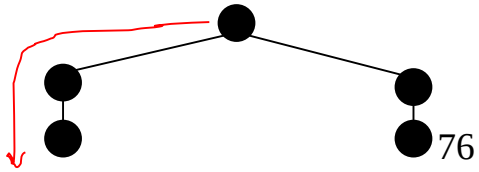


- Group by
  1. Mapping from keys to values
  2. Atomic value aggregations
     e.g., COUNT, SUM, MAX
     - insertion only

  → **hash map**

  → **atomic inc / sum / max**, etc.

- Join
  - create a map of the small table
  - insertion phase, followed by
  - probing phase

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

→

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

→

Vasilis
Rachid

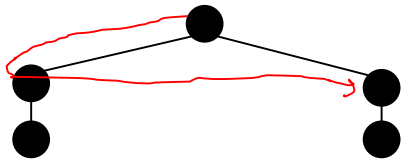
limit (top k)

11 12 0 9 8 13
8 9 11 23 32 9
1 2 3 5 7 3 2 0

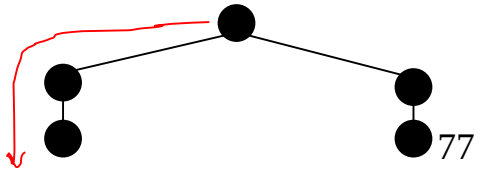
→

32
23
13

BFS



DFS



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  2. Atomic value aggregations
     e.g., COUNT, SUM, MAX
     - insertion only

  → **hash map**

  → **atomic inc / sum / max**, etc.

- Join
  - create a map of the small table
  - insertion phase, followed by
  - probing phase

  → **hash map, lock-free probing**

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

map / atomics

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

Vasilis
Rachid

limit (top k)

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13

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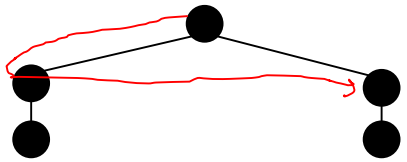
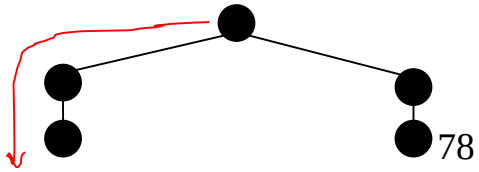


DFS



- Distinct
  - can be solved with sorting, or

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

map / atomics

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

Vasilis
Rachid

limit (top k)

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8 9 11 23 32 9
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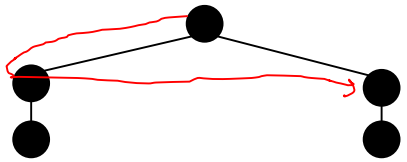
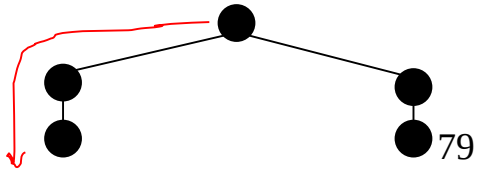
23
13

BFS



DFS



- Distinct
  - can be solved with sorting, or

  → **hash set**

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

Vasilis, 2
Rachid, 1

map / atomics

distinct

Vasilis
Rachid
Vasilis

Vasilis
Rachid

limit (top k)

11 12 0 9 8 13
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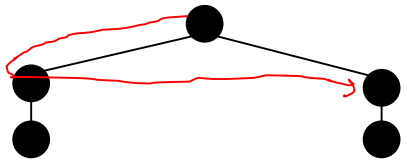
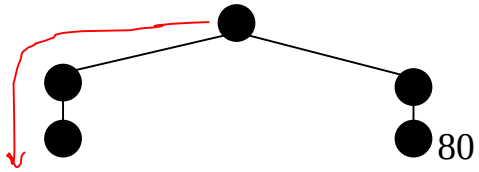
32
23
13

BFS

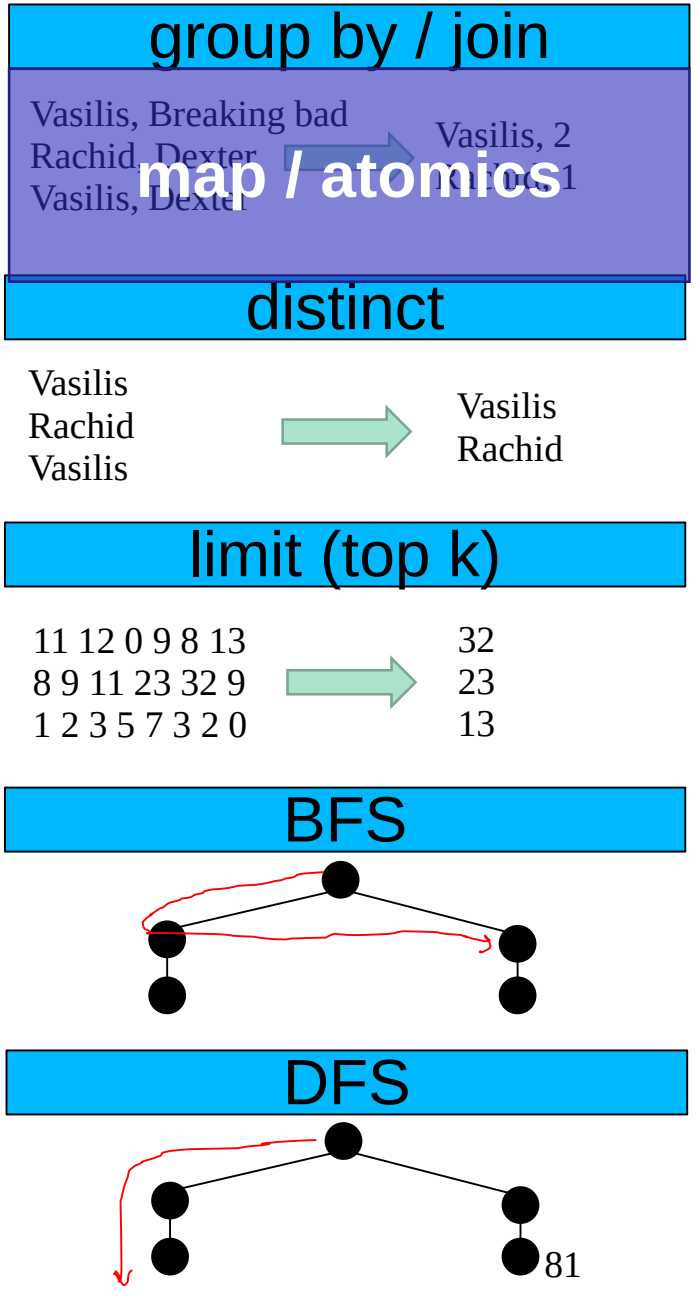


DFS



- Distinct
  - can be solved with sorting, or
  - → **hash set**
- Limit (top k)
  - can be solved with sorting, or
  - different specialized structures

Operations



- Distinct
  - can be solved with sorting, or

  → **hash set**

- Limit (top k)
  - can be solved with sorting, or
  - different specialized structures

  → **tree**

  → **heap**

  → ~ **list**

  → **array** (e.g., 2 elements only)

  → **register** (1 element only)

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

map / atomics

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

hash set

Vasilis
Rachid

limit (top k)

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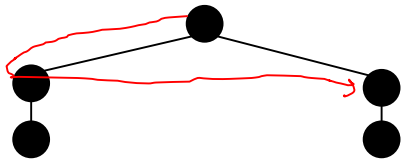
8 9 11 12 32 9
1 2 3 5 7 3 2 0

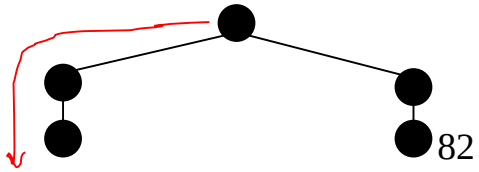
tree / heap / list

32
23
13

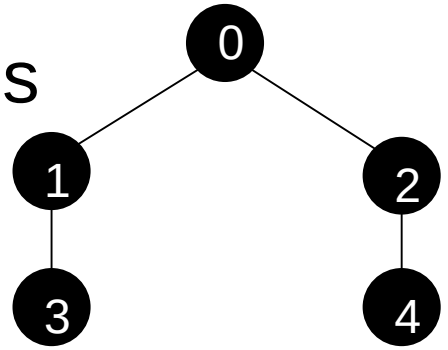
BFS



DFS



- Breadth-first search (BFS)
  - FIFO order
  - track visited vertices



Operations

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Vasilis

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tree / heap / list

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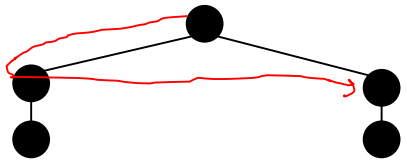
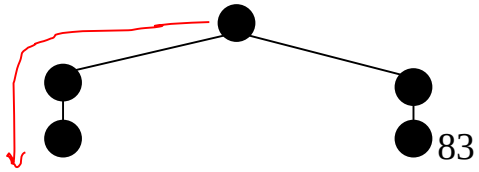
23
13

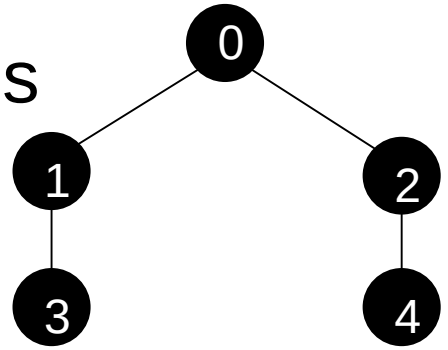
BFS



DFS



- Breadth-first search (BFS)
  - FIFO order
  - track visited vertices
  - → **queue**
  - → **set**



Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
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Vasilis
Rachid
Vasilis

hash set

Vasilis
Rachid

limit (top k)

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tree / heap / list

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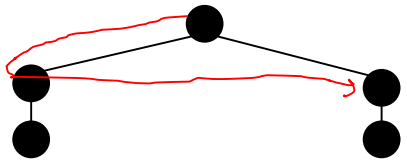
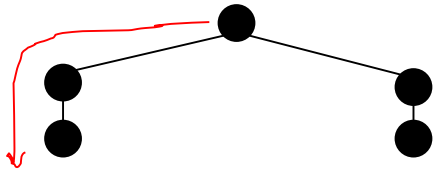
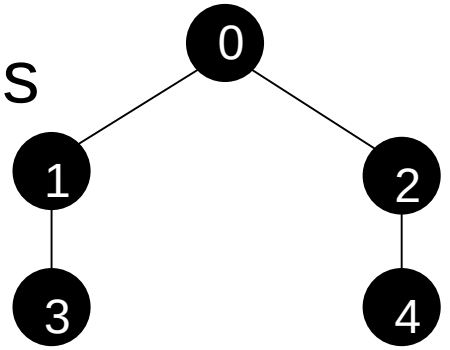
BFS



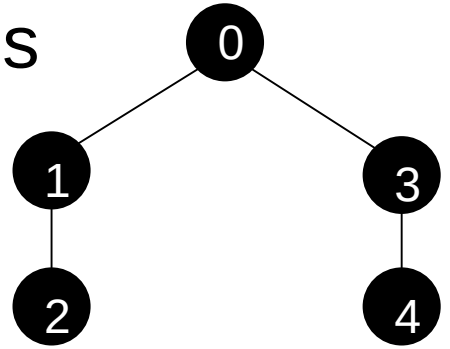
DFS



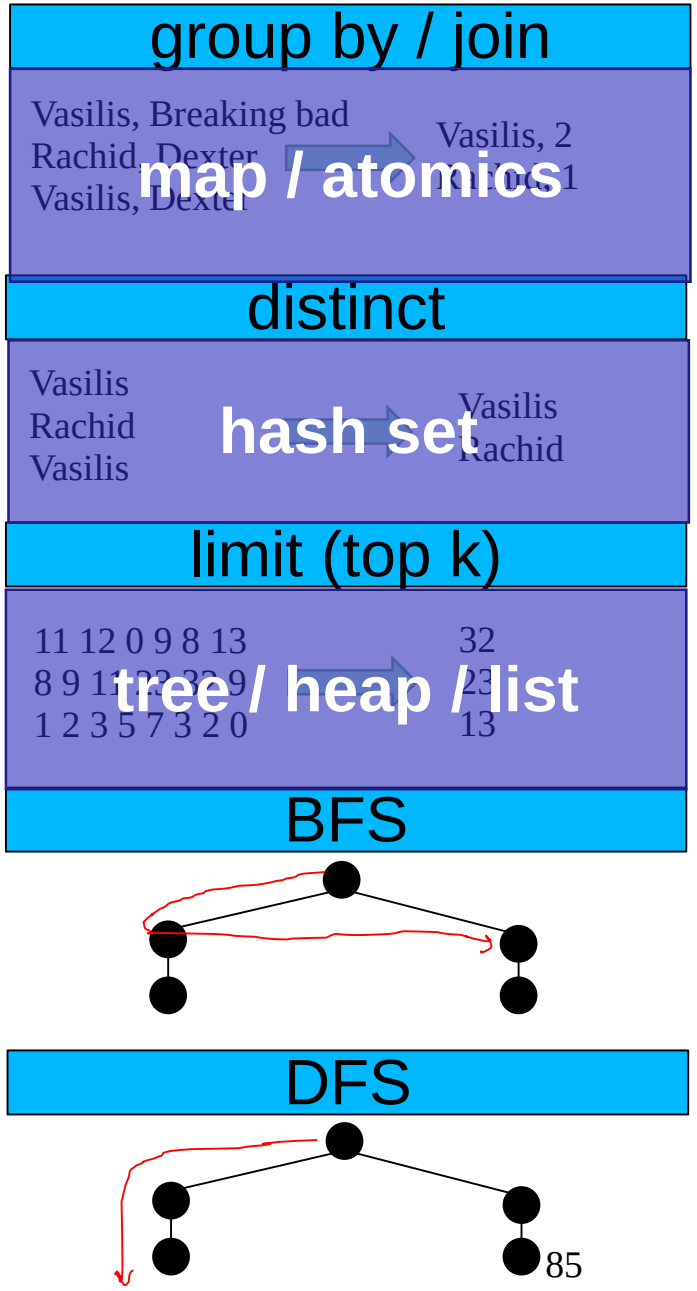
- Breadth-first search (BFS)
  - FIFO order
  - track visited vertices
  - → **queue**
  - → **set**



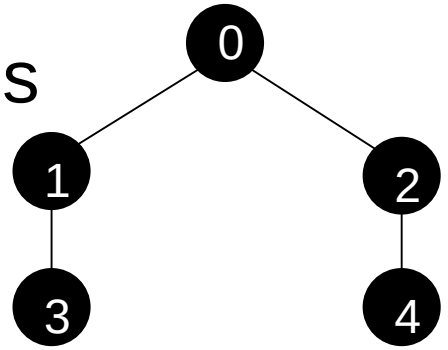
- Depth-first search (DFS)
  - LIFO order
  - track visited vertices



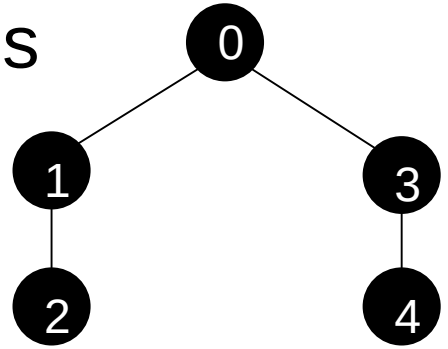
Operations



- Breadth-first search (BFS)
  - FIFO order
  - track visited vertices
  - → **queue**
  - → **set**



- Depth-first search (DFS)
  - LIFO order
  - track visited vertices
  - → **stack**
  - → **set**



Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

map / atomics

Vasilis, 2
Rachid, 1

distinct

Vasilis
Rachid
Vasilis

hash set

Vasilis
Rachid

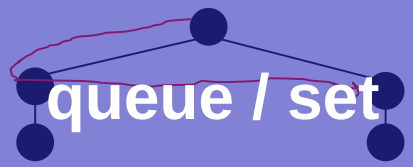
limit (top k)

11 12 0 9 8 13
8 9 11 12 32 9
1 2 3 5 7 3 2 0

tree / heap / list

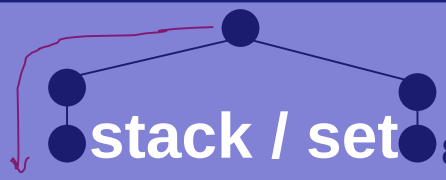
32
23
13

BFS



queue / set

DFS



stack / set

86

Score

Structure	# Usages
array / buffer	7
map	6
set	4
tree / heap	3
queue	2
stack	1
list	1

Graph

tmp graph structure

"Vasilis", "Breaking bad", :likes
"Rachid", "Dexter", :likes
"Vasilis", "Dexter", :likes
"Dexter", "Breaking bad", :similar
"Breaking bad", "Dexter", :similar

segmented buffer

graph structure

CSR

user-ids - internal ids

Vasilis → 0
Rachid → 1
Breaking bad → 2
Dexter → 3

0 → Vasilis
1 → Rachid
2 → Breaking bad
3 → Dexter

hash map / array

labels

:likes, :people, :similar, …

dictionary

properties

"Vasilis", {people, male}, 33, Zurich
"Rachid", {people, male}, ??, Lausanne

array

lifetime management

number_of_references: X

stripped counter

Runtime

indices / metadata

map / tree

< 300 >= 300

buffer management

1MB 1MB 1MB 1MB

array

task / job scheduling

Producers Consumers

queue

task

labels

:likes, :people, :similar, :male …

1 2 3 4

dictionary

{people, male} → {2,4}

renaming (ids)

used used used

map / tree / set

Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

map / atomics

distinct

Vasilis
Rachid
Vasilis

hash set

limit (top k)

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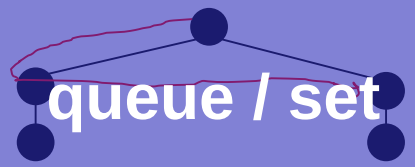
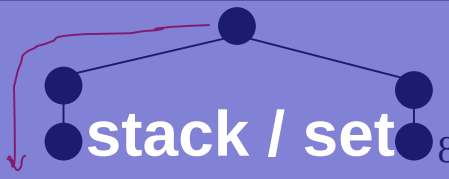
tree / heap / list

BFS



queue / set

DFS



stack / set

Conclusions

- Both theory and practice are necessary for
  - Designing, and
  - Implementing fast / scalable data structures
- Hardware plays a huge role on implementations
  - How and which memory access patterns to use
- **(Concurrent) Data structures**
  - **The backbone of every system**
  - **An “open” and challenging area or research**

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