Concurrent programming: From theory to practice

Concurrent Computing 2025

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From theory to practice

Theoretical (design)

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

Design (pseudo-code)

Practical (design)

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

Design (pseudo-code, prototype)

Practical (implementation)

- **Hardware**
- Which atomic ops
- Memory consistency
- Cache coherence
- Locality
- **Performance**
- **Scalability**

Implementation (code)

Outline

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

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Outline

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

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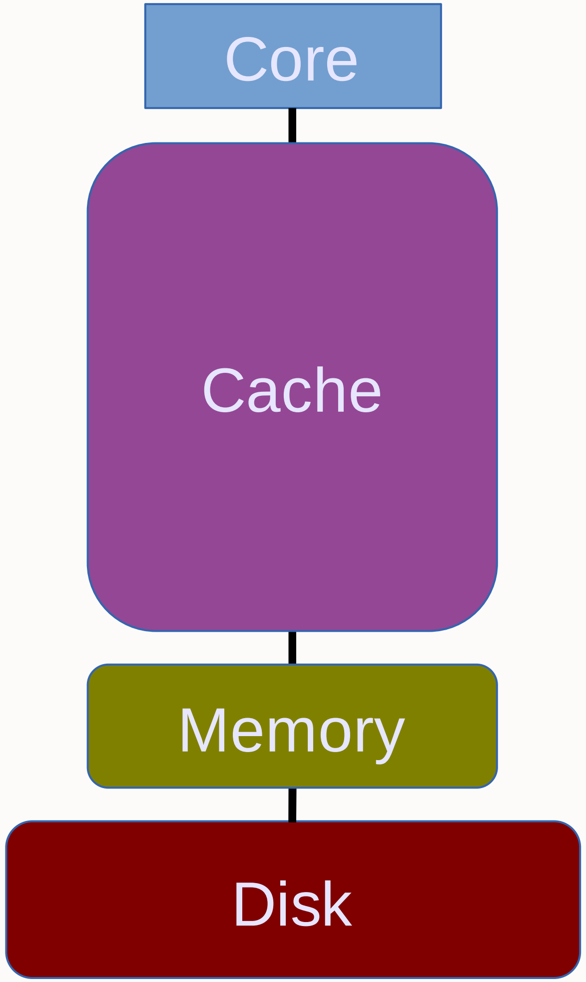
Why do we use caching?



Core freq: 2GHz = 0.5 ns / instr

Core → Disk = ~ms

Core → Memory = ~100ns

Cache

- Large = slow
- Medium = medium
- Small = fast

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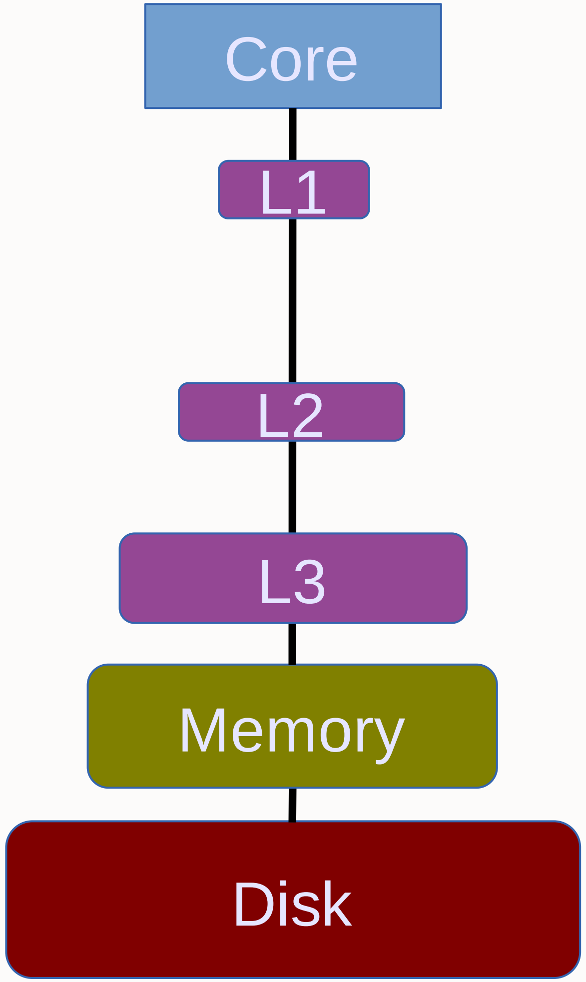
Why do we use caching?



Core freq: 2GHz = 0.5 ns / instr

Core → Disk = ~ms

Core → Memory = ~100ns

Cache

- Core → L3 = ~20ns
- Core → L2 = ~7ns
- Core → L1 = ~1ns

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From typical server configurations a few years back to the ERA of Gen AI

Intel® Xeon®

- 14 cores @ 2.4GHz
- L1: 32KB
- L2: 256KB
- L3: 40MB
- Memory: 512GB

Intel® Xeon® 6 Processors with P(erformance)-Cores
> 70 cores, > 400MB L3

&

Intel® Xeon® 6 Processors with E(nergy)-Cores
> 60 cores, > 90ML L3

https://www.intel.com/content/www/us/en/products/details/processors/xeon.html

AMD Opteron™

- 18 cores @ 2.4GHz
- L1: 64KB
- L2: 512KB
- L3: 20MB
- Memory: 512GB

AMD EPYC™ 9005 Series

Max config:
192 cores, 384MB L3

&

AMD EPYC™ 9004, 8004, 7003, 4004 Series

https://www.amd.com/en/products/processors/server/epyc.html

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Experiment

Throughput of accessing some memory, depending on the memory size

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Outline

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

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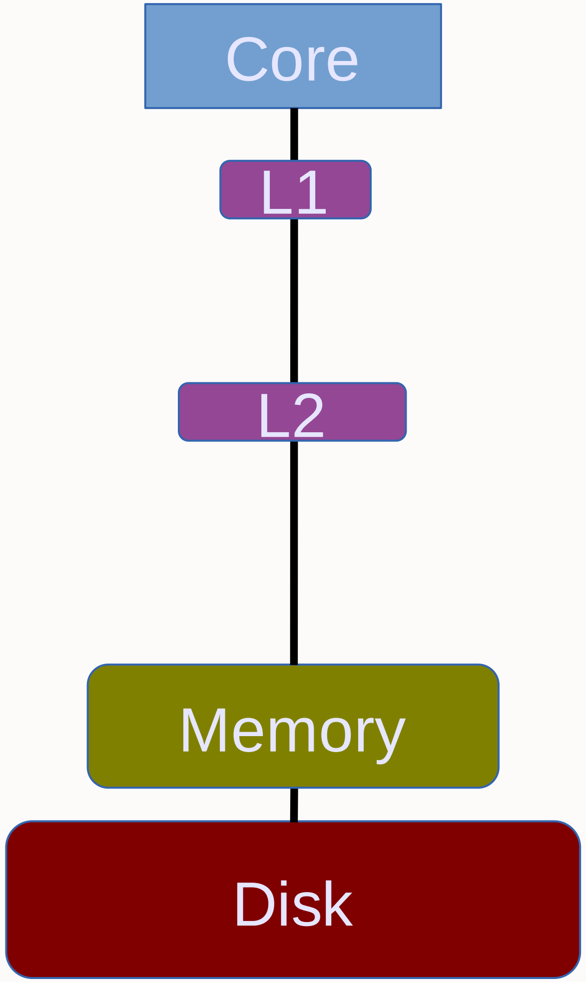
Until ~2004: single-cores



Single core

Core freq: 3+GHz

Core → Disk

Core → Memory

Cache

- Core → L2
- Core → L1

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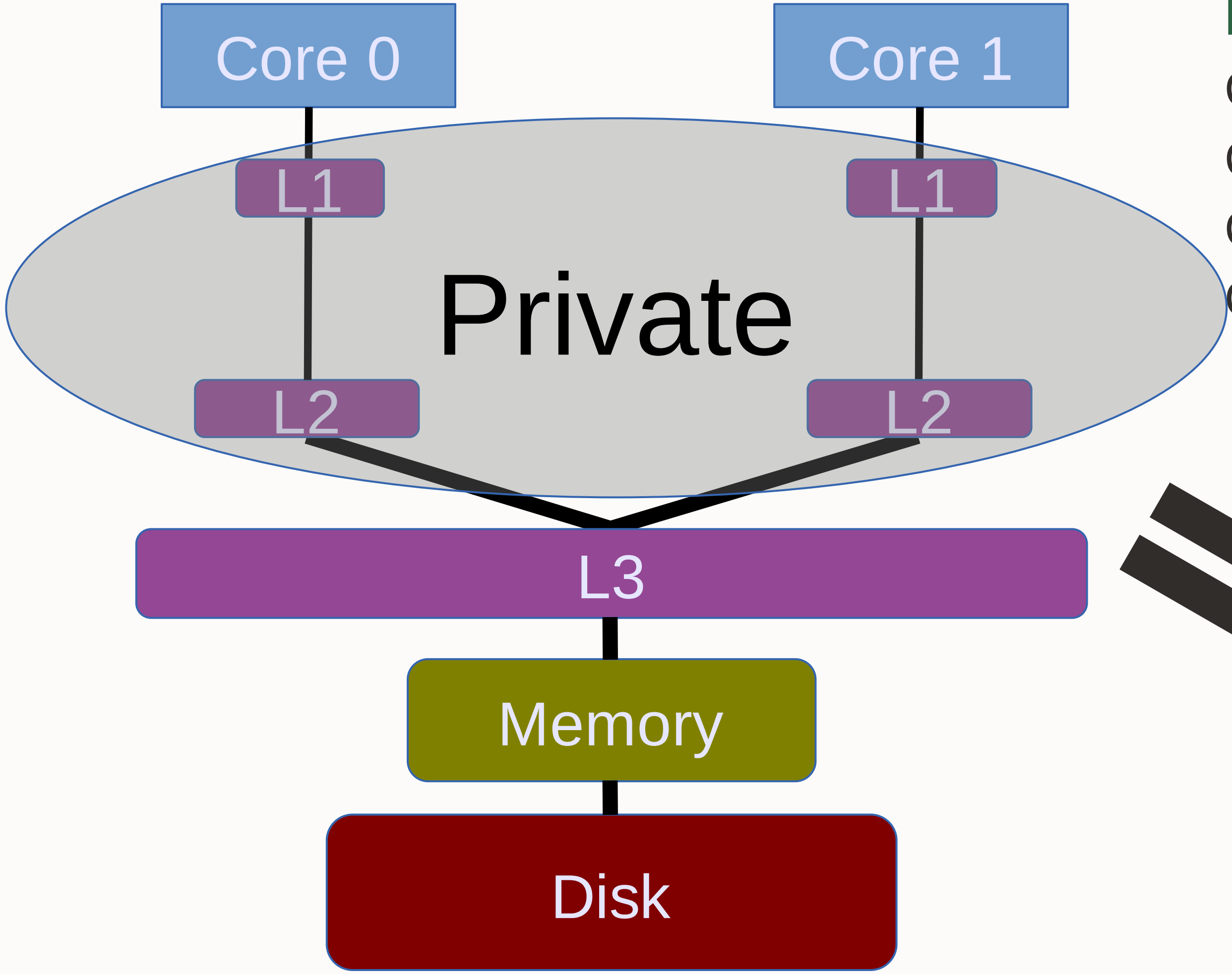
After ~2004: multi-cores



Multiple cores

Core freq: ~2GHz

Core → Disk

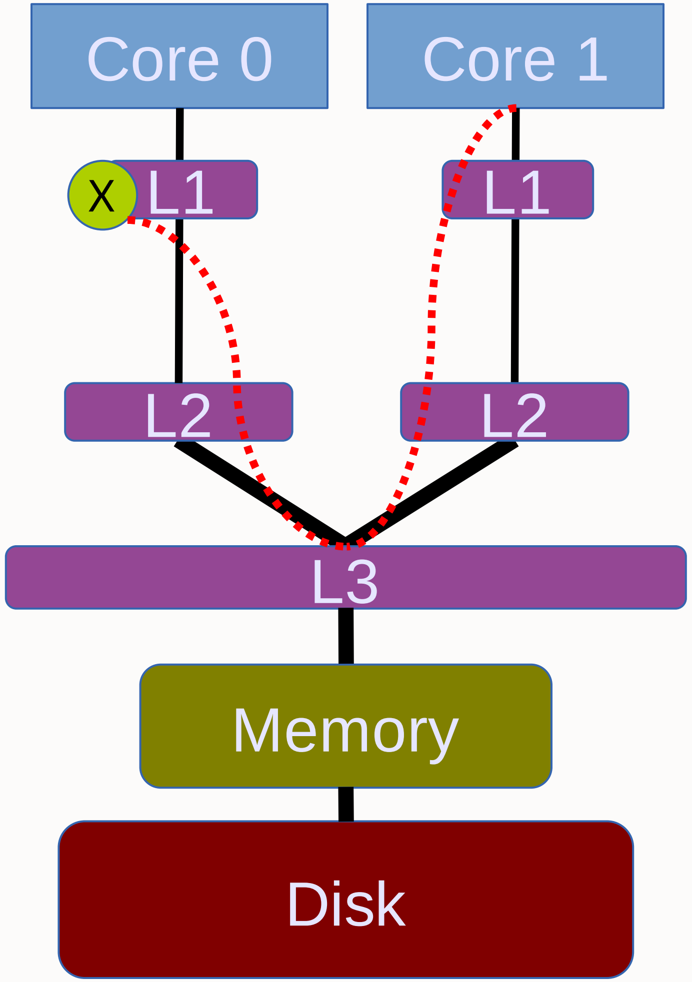
Core → Memory

Cache

- Core → shared L3
- Core → L2
- Core → L1

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?

To perform a **write**

- invalidate all readers, or
- previous writer

To perform a **read**

- find the latest copy

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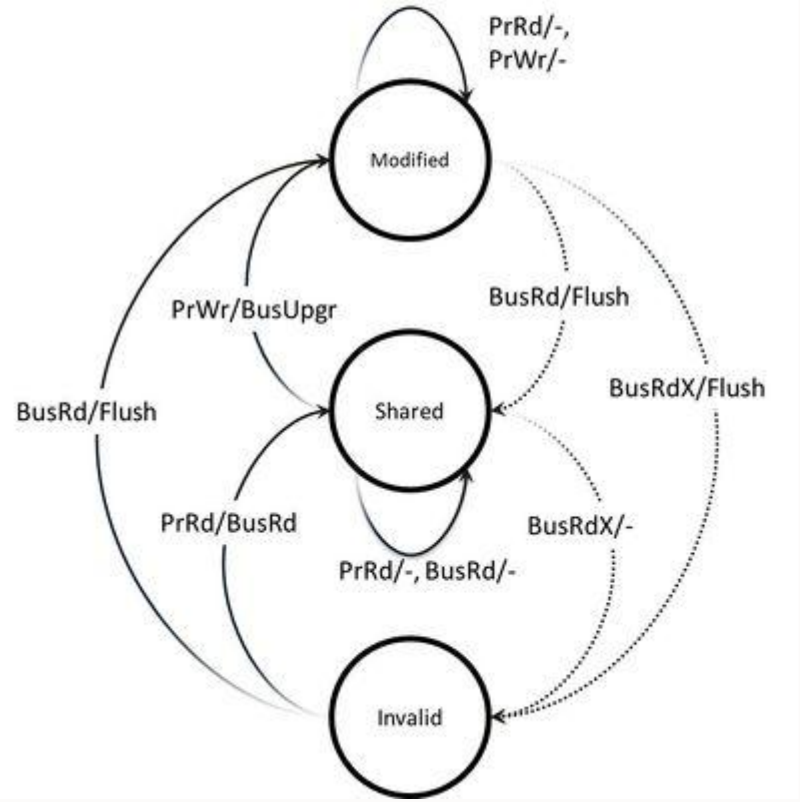
Cache coherence with MESI

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



Which state is our "favorite?"

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The ultimate goal for scalability

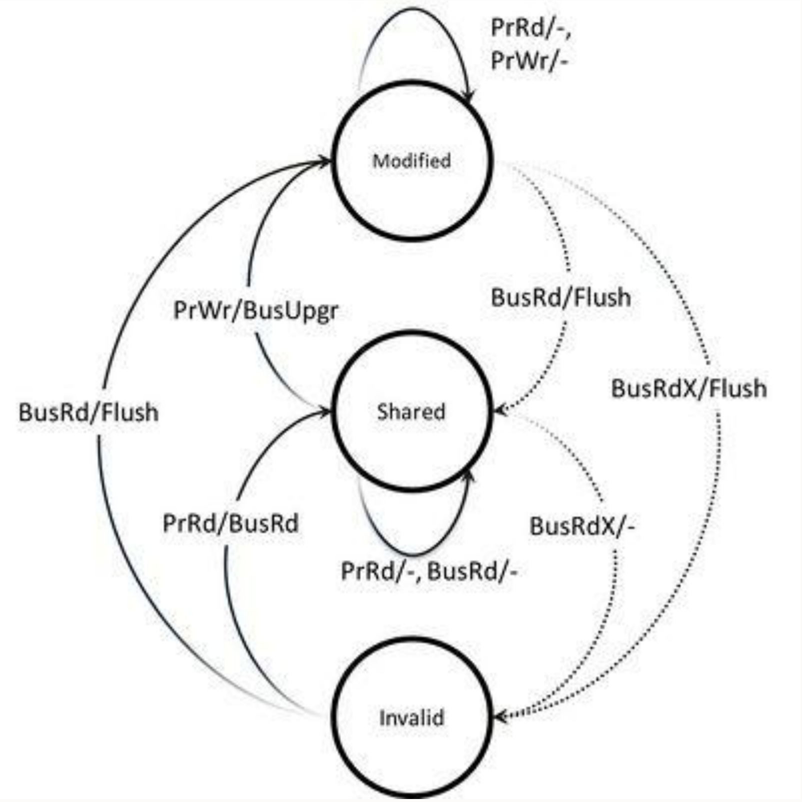
A **state diagram**

State (per cache line)

- **M**odified: the only dirty copy
- **E**xclusive: the only clean copy
- **Shared**: a clean copy
- **I**nvalid: useless data

= threads can keep the data close (L1 cache)

= faster



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Experiment

The effects of false sharing

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Outline

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

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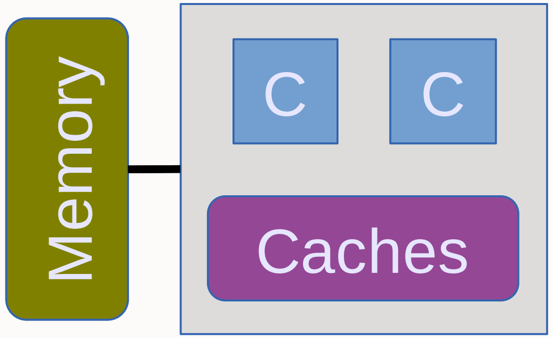
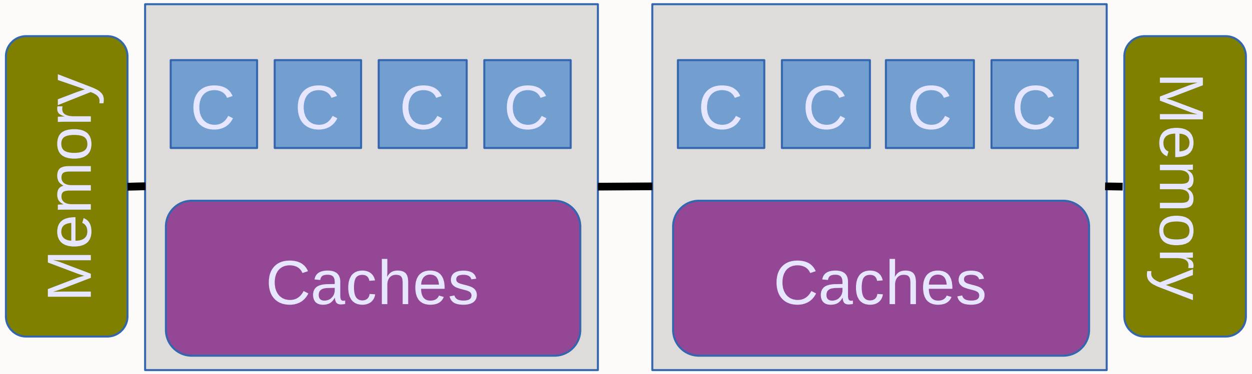
Uniformity vs. non-uniformity

Typical desktop machine



= Uniform

Typical server machine



= non-Uniform
(aka. NUMA)

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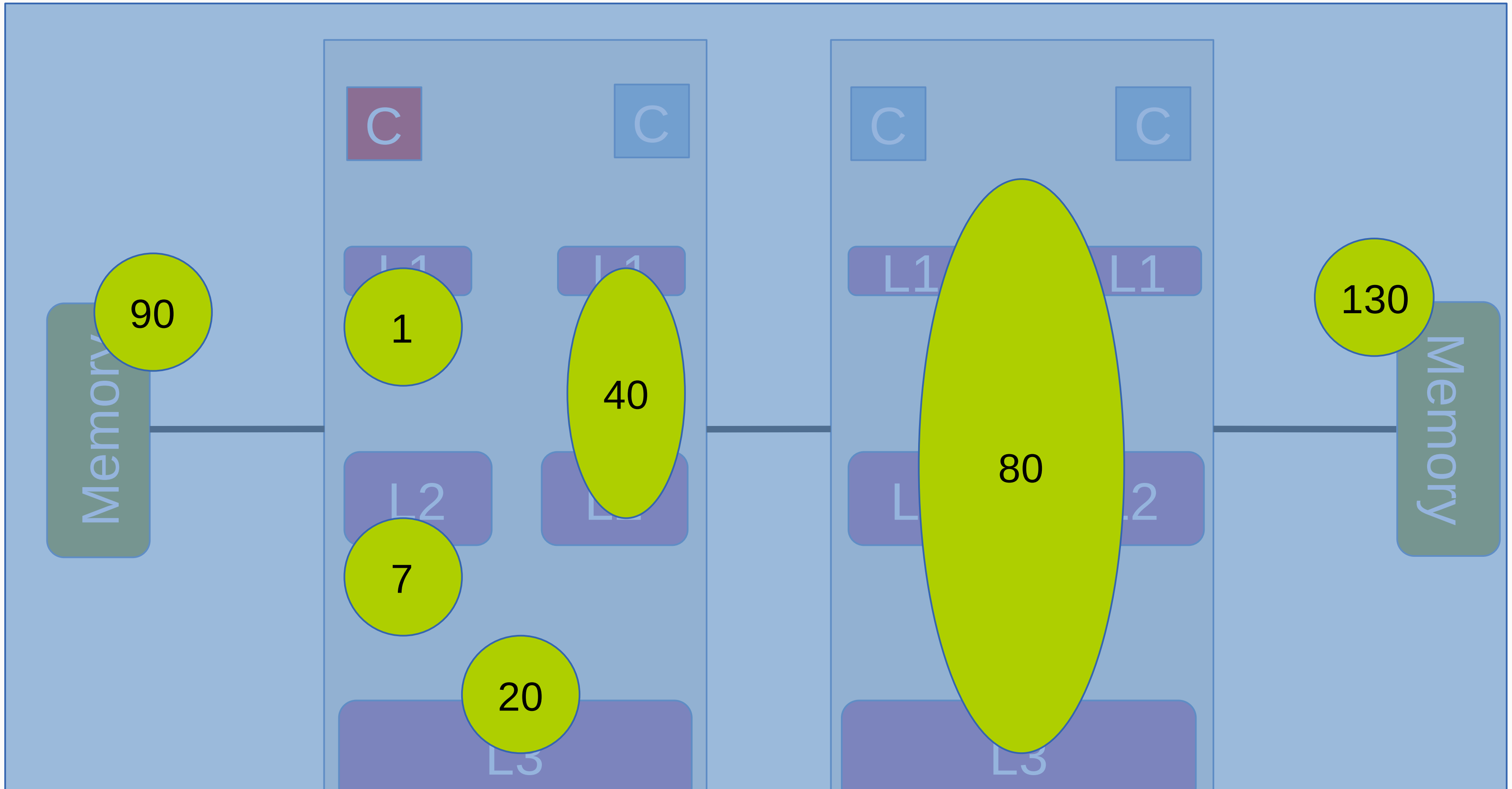
Latency (ns) to access data in a NUMA multi-core server



Conclusion: we need to take care of locality

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Experiment

The effects of locality

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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

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Outline

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

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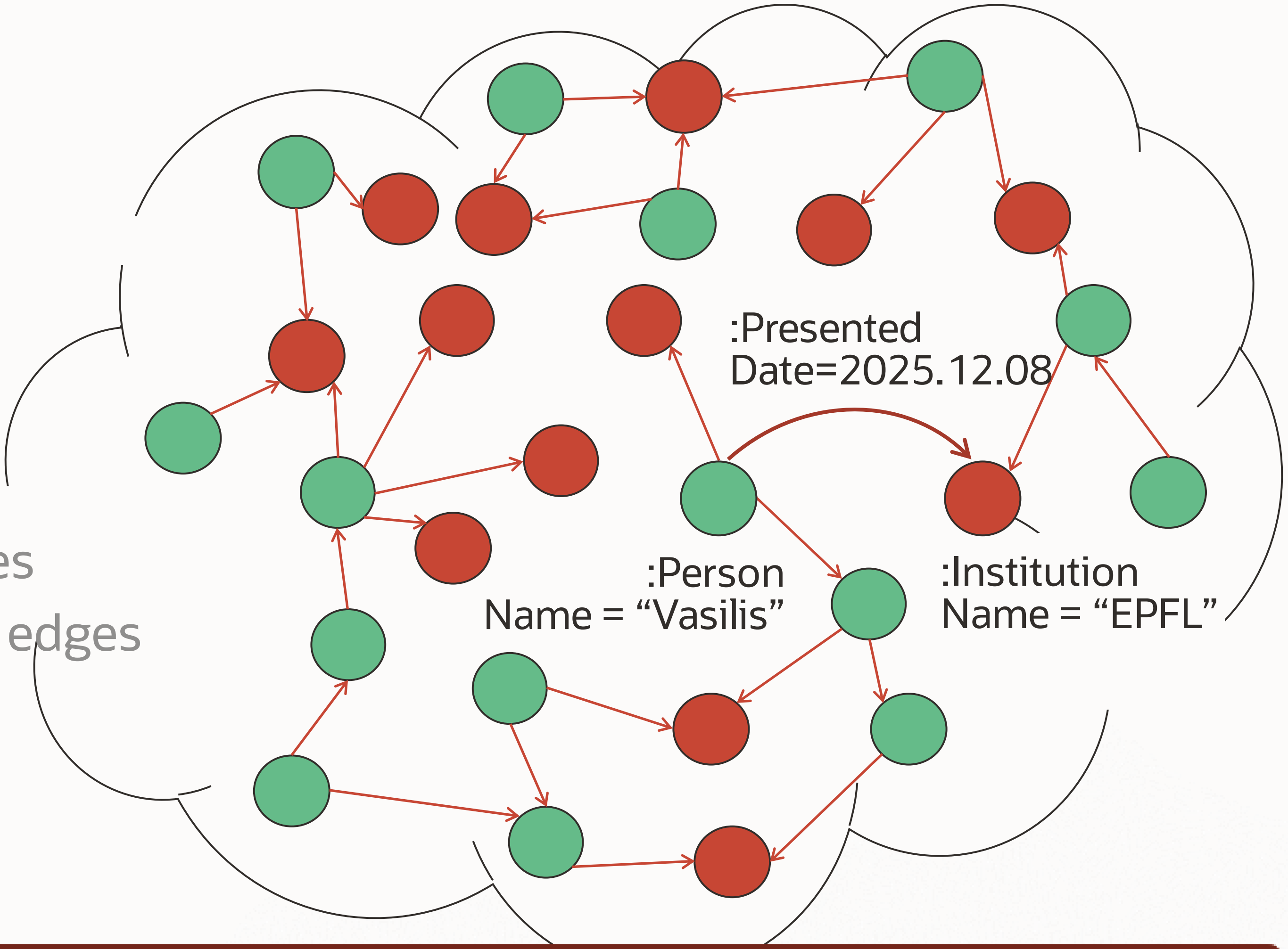
Your Data is a Graph!

- Represent it as a property graph
  - Entities are vertices
  - Relationships are edges
- Annotate your graph
  - Labels identify vertices and edges
  - Properties describe vertices and edges
- For the purpose of
  - Data modeling
  - Data analysis



Navigate multi-hop relationships quickly (instead of joins)

Relational (Database) Model → Property Graph Model

user_id (PK)	name
0	Vasilis
1	Rachid
…	…

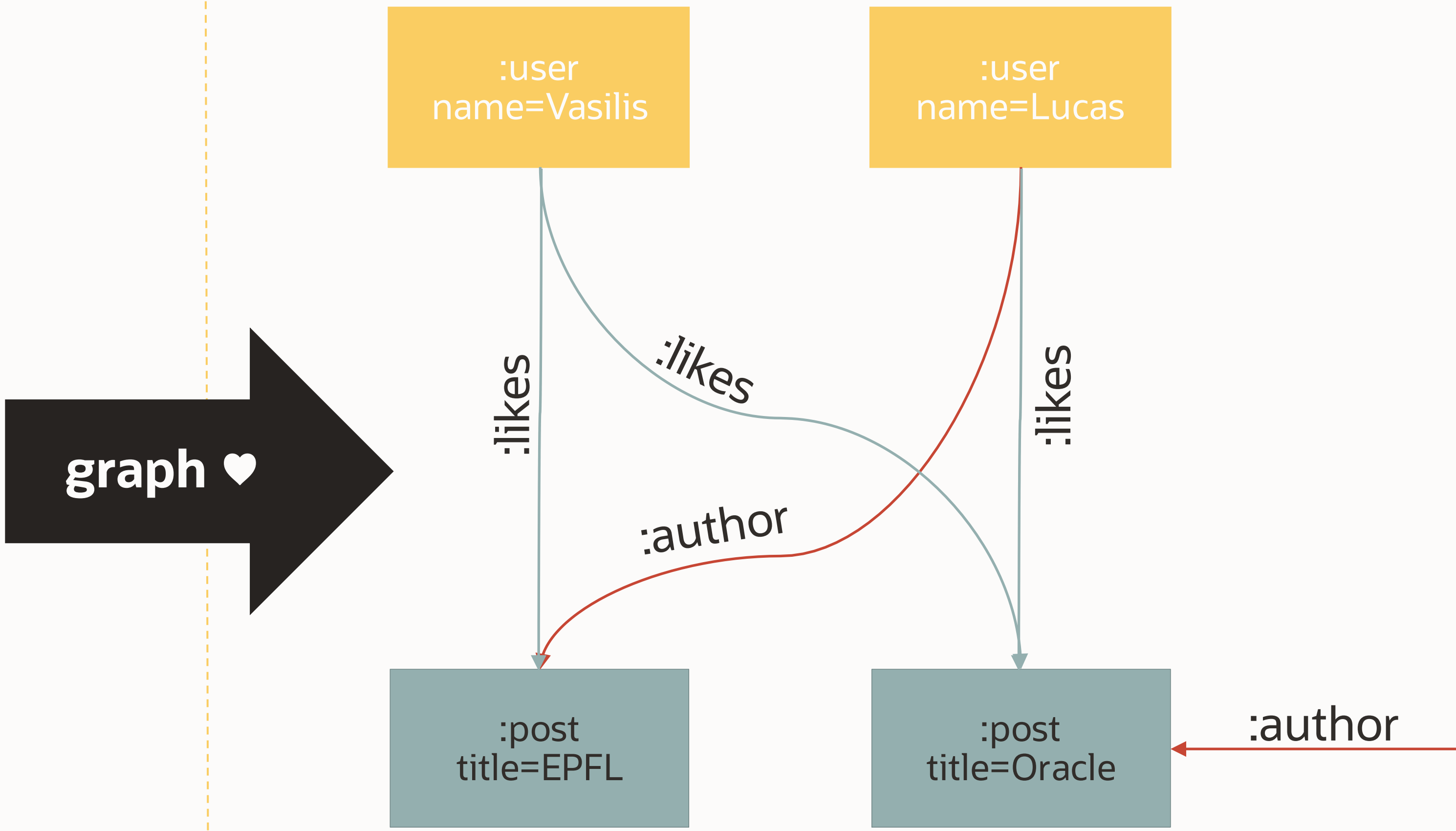
users

user_id	post_id
0	0
0	1
1	1

user_likes

author_id	post_id (PK)	title
1	0	EPFL
123	1	Oracle
…	…	…

posts



Essentially having "materialized joins"

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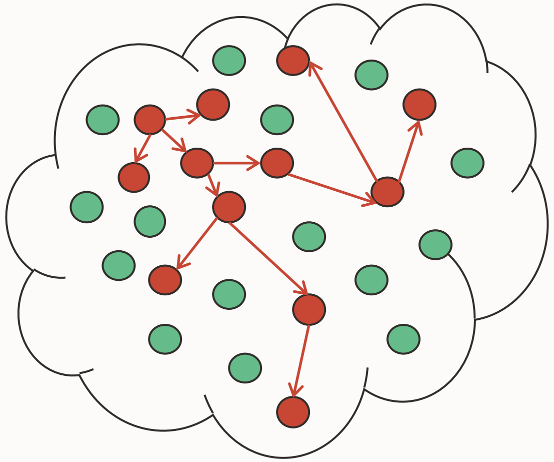
Main Approaches of Graph Processing

1. Computational graph analytics [ASPLOS'12, VLDB'16]
   - Iterate the graph multiple times and compute mathematical properties using Greenmarl / PGX Algorithm (e.g., Pagerank)
   - e.g, `graph.getVertices().forEach(n -> …)`
2. Graph querying and pattern matching [GRADES'16/23, VLDB'16, Middleware Ind. 23]
   - Query the graph using PGQL or SQL/PGQ to find sub-graphs that match to the given relationship pattern
   - e.g., `SELECT … MATCH (a) -[edge]-> (b) …`
3. Graph ML
   - Use the structural information latent in graphs
   - e.g., graph similarity



$$PR(p_i) = \frac{1-d}{N} + d \sum_{p_j \in M(p_i)} \frac{PR(p_j)}{L(p_j)}$$

4. Vector similarity graph indices
   - Hierarchical navigable small world (HNSW)
5. Graph RAG
   - Retrieval-Augmented Generation (RAG)
   - Enhancing RAG with knowledge graphs

Dissecting a graph processing system

with a focus on (concurrent) data structures

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Dissecting a graph processing system and preparing for a job interview

with a focus on (concurrent) data structures

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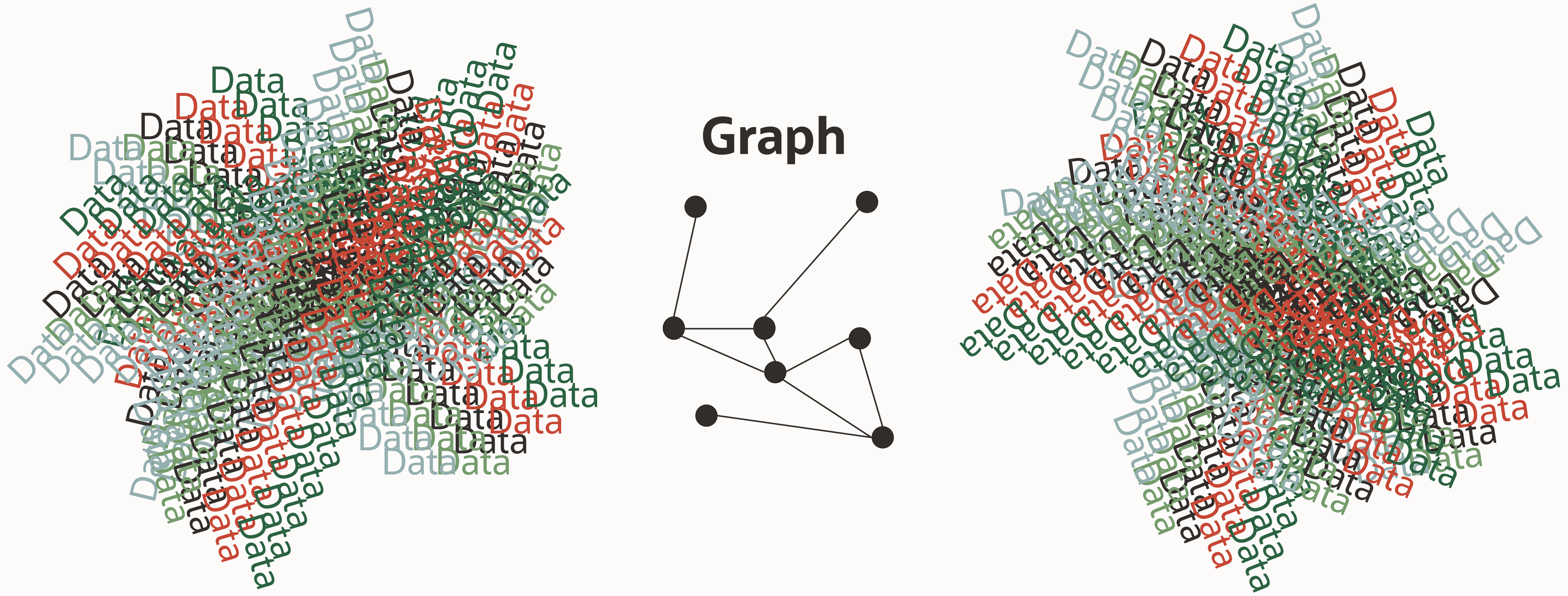
Architecture of a graph processing system



Tons of other data and metadata to store

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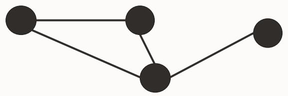
Graph

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

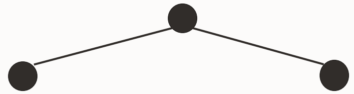
"Vasilis", {people, male}, 20, Zurich
"Rachid", {people, male}, ??, Lausanne

lifetime management

number_of_references: X

Runtime

indices / metadata



< 300 >= 300

buffer management

1MB 1MB 1MB 1MB

task / job scheduling

Producers Consumers

task
task

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

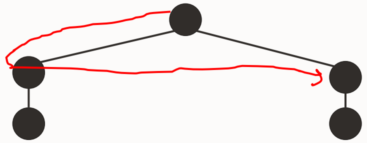
limit (top k)

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

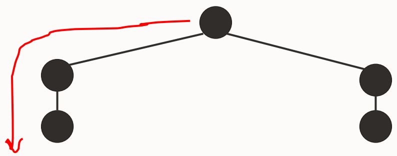
→

32
23
13

BFS



DFS



Graph

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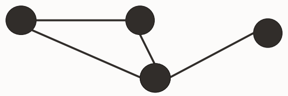
“Breaking bad”, “Dexter”, :similar

graph structure



user-ids - internal ids

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

labels

:likes, :people, :similar, …

properties

“Vasilis”, {people, male}, 20, Zurich
“Rachid”, {people, male}, ??, Lausanne

lifetime management

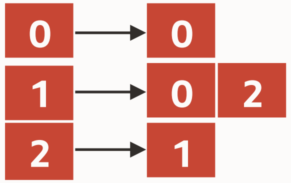
number_of_references: X

- tmp graph structure
  - append only
  - dynamic schema
  - → **dataframe** = segmented buffer

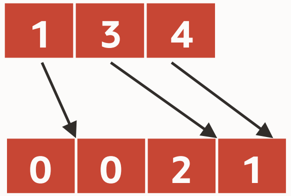
- Classic graph structures
  1. adjacency matrix

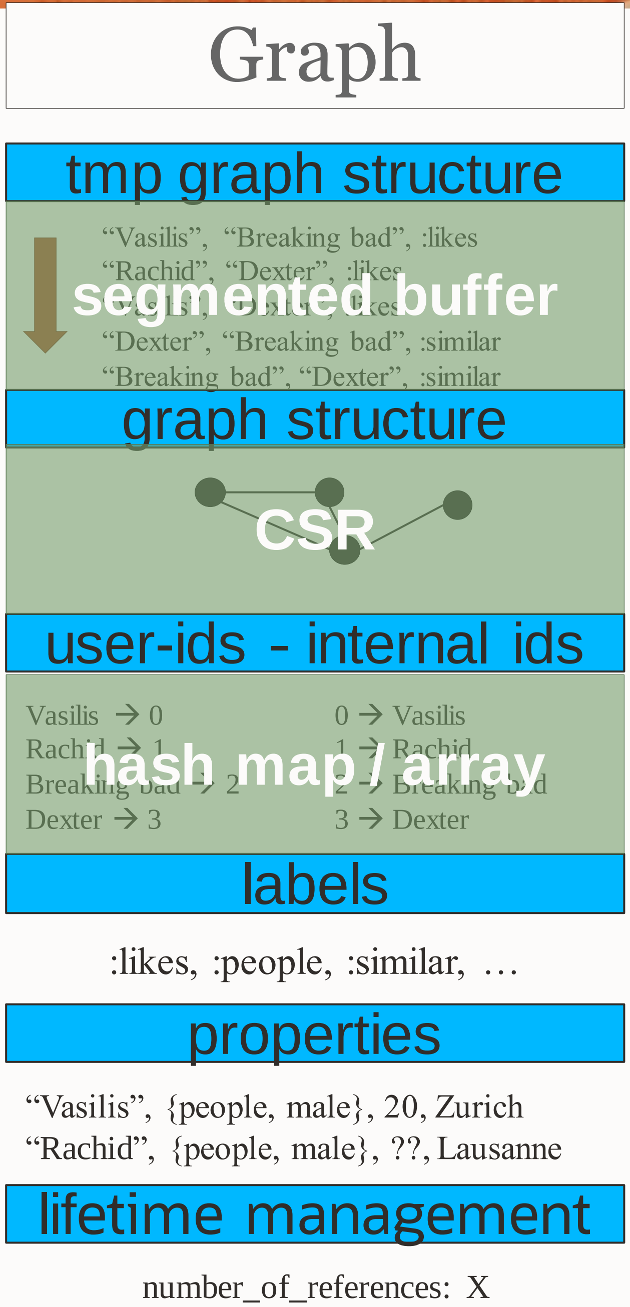
	0	1	2
0	x		
1	x		x
2		x	

  2. adjacency list



  3. compressed source row (CSR)

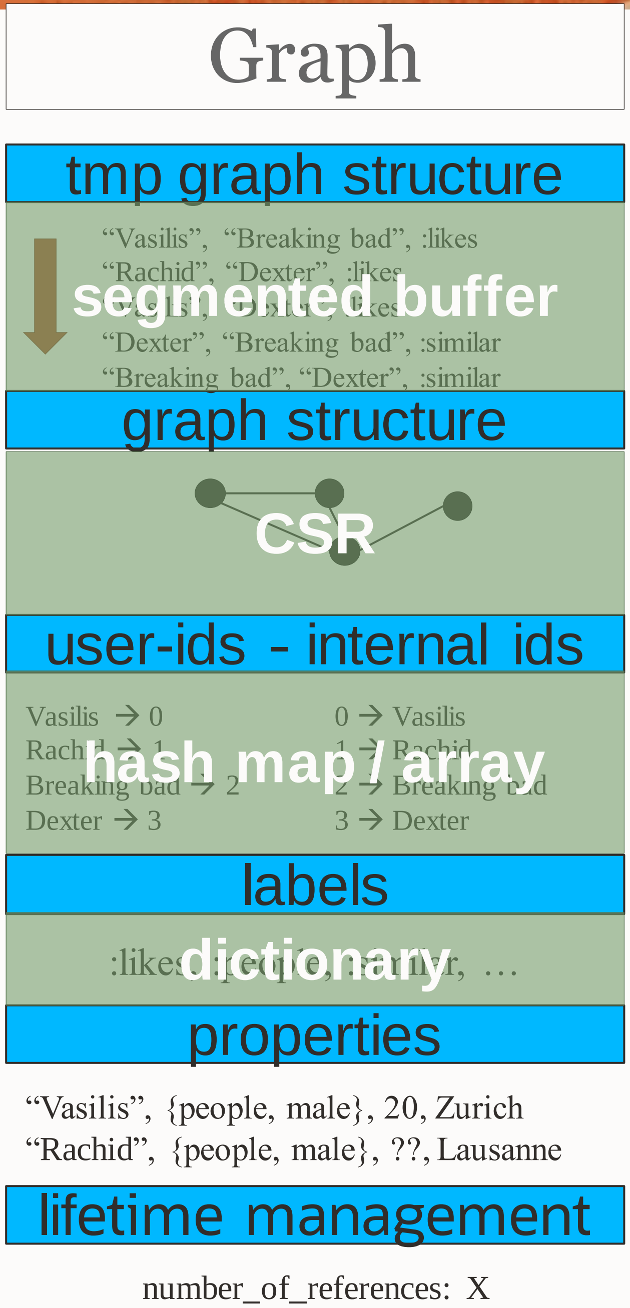




- Storing labels
  - usually a small enumeration e.g., person, female, male
  - storing strings is expensive “person” → ~ 7 bytes
  - comparing strings is expensive

  → **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
  - → **(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;
}
```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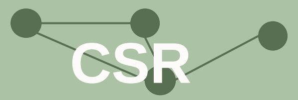
Graph

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 (= map)

properties

“Vasilis”, {people, male}, 20, Zurich
“Rachid”, {people, male}, ??, Lausanne

array

lifetime management

number_of_references: X

stripped counter

Score

Structure	# Usages
array / buffer	5
map	2

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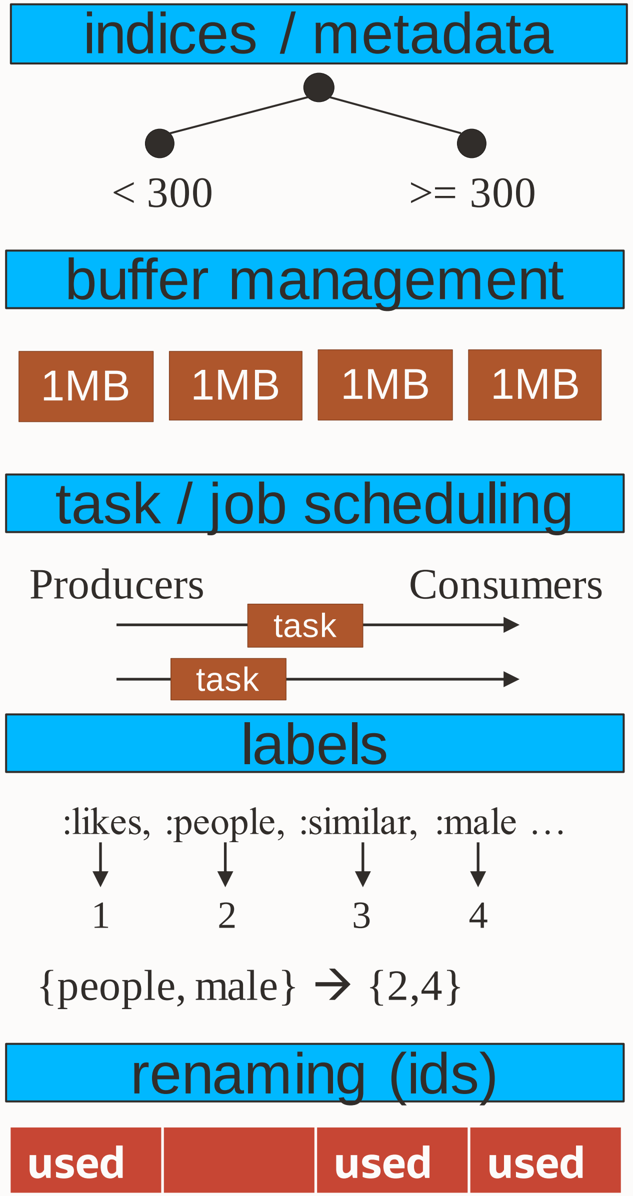
Runtime



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

  → **maps, trees**

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

  → Fixed num object pool: **array**

  → Otherwise: **list**

  → Variable-sized elements: **heap**

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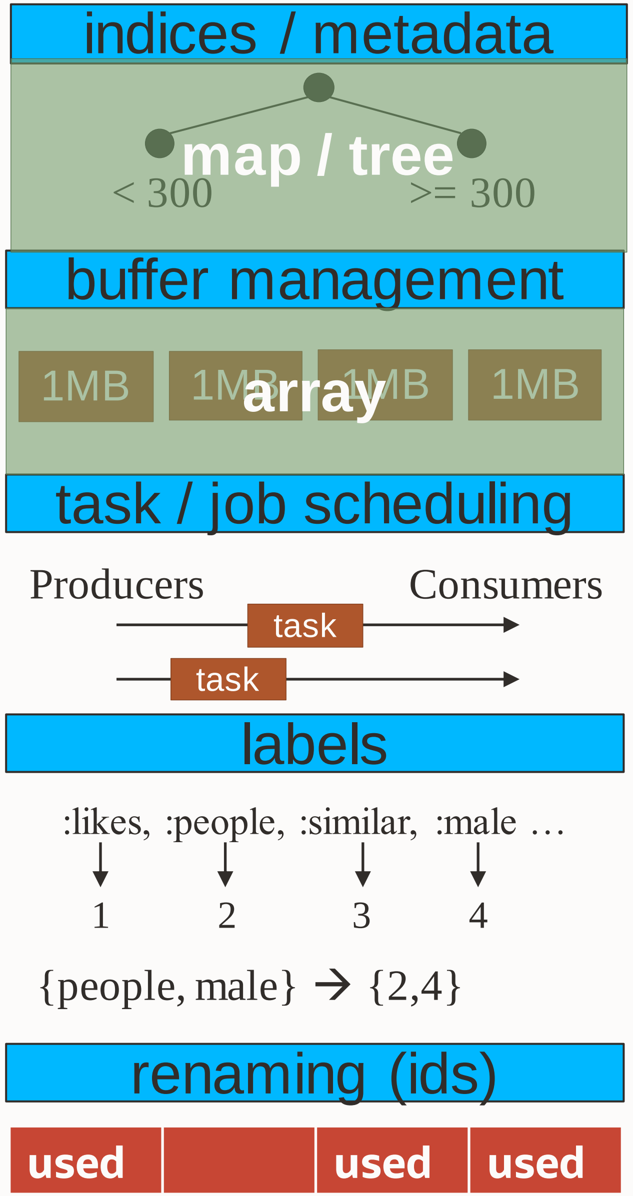
Runtime



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

  → **queues**

- Storing / querying sets of labels
  - set equality expensive
  - usually common groups
    e.g., {person, female}, {person, male}

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

- Giving unique ids (renaming)

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

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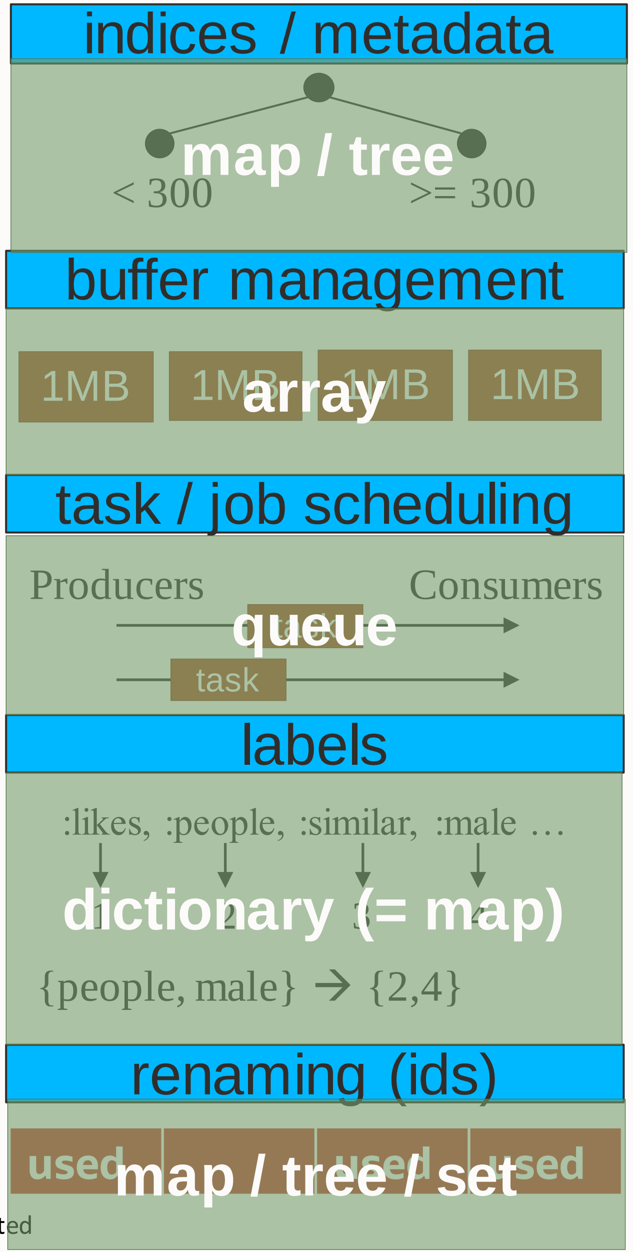
Runtime



Score

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

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Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter
→
Vasilis, 2
Rachid, 1

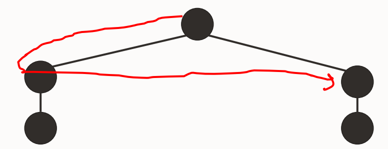
distinct

Vasilis
Rachid
Vasilis
→
Vasilis
Rachid

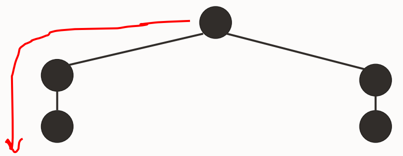
limit (top k)

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



- 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

  → **hash map, lock-free probing**

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)

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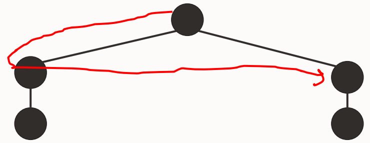
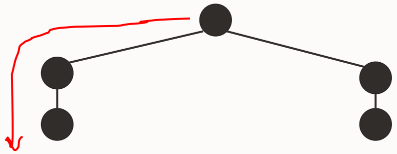


DFS



- Distinct
  - can be solved with sorting, or

Operations

group by / join

map / atomics

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
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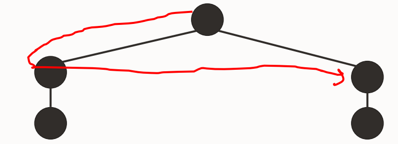
BFS



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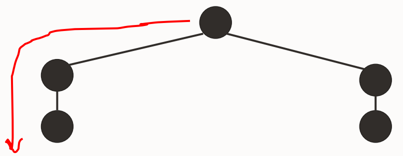

- Distinct
  - can be solved with sorting, or
  - → **hash set**

- 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)

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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

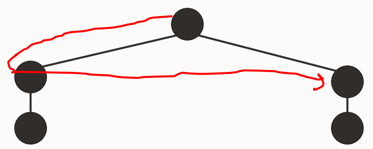
limit (top k)

11 12 0 9 8 13
8 9 11 23 29
1 2 3 5 7 3 2 0

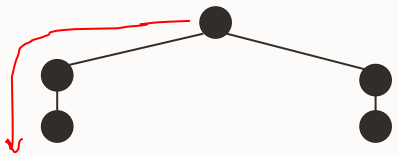
tree / heap / list

32
23
13

BFS

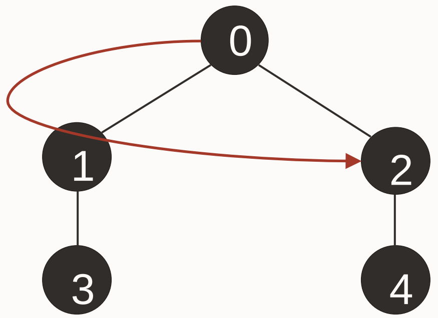


DFS



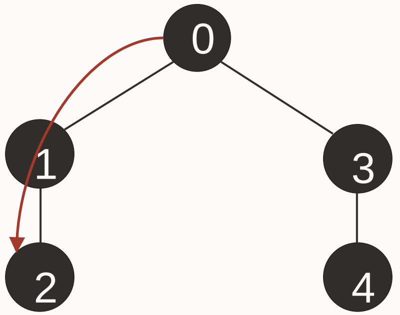
- Breadth-first search (BFS)
  - FIFO order
  - track visited vertices

→ **queue**
→ **set**



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

→ **stack**
→ **set**



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Operations

group by / join

Vasilis, Breaking bad
Rachid, Dexter
Vasilis, Dexter

Vasilis, 2
Rachid, 1

map / atomics

distinct

Vasilis
Rachid
Vasilis

Vasilis
Rachid

hash set

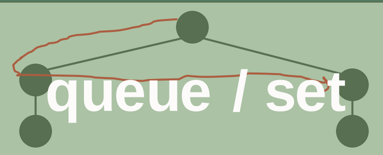
limit (top k)

11 12 0 9 8 13
8 9 11 [illegible] 9
1 2 3 5 7 3 2 0

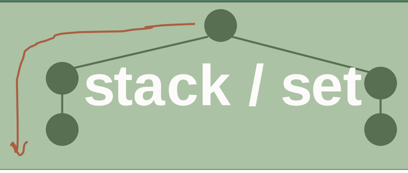
32
23
13

tree / heap / list

BFS



DFS



Score

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

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Your new cheatsheet for interviews!

Graph	Runtime	Operations
tmp graph structure: segmented buffer ("Vasilis", "Breaking bad", :likes; "Rachid", "Dexter", :likes; "Dexter", "Breaking bad", :similar; "Breaking bad", "Dexter", :similar)	**indices / metadata**: map / tree (< 300, >= 300)	**group by / join**: map / atomics (Vasilis, Breaking bad; Rachid, Dexter; Vasilis, Dexter)
graph structure: CSR	**buffer management**: array (1MB, 1MB, 1MB, 1MB)	**distinct**: hash set (Vasilis, Rachid, Vasilis)
user-ids - internal ids: hash map / array (Vasilis → 0, Rachid → 1, Breaking bad → 2, Dexter → 3; 0 → Vasilis, 1 → Rachid, 2 → Breaking bad, 3 → Dexter)	**task / job scheduling**: queue (Producers, Consumers, task)	**limit (top k)**: tree / heap / list (11 12 0 9 8 13; 8 9 11 ... 9; 1 2 3 5 7 3 2 0)
labels: dictionary (:likes, :people, :similar, …)	**labels**: dictionary (:likes, :people, :similar, :male … → 1, 2, 3, 4; {people, male} → {2,4})	**BFS**: queue / set
properties: array ("Vasilis", {people, male}, 20, Zurich; "Rachid", {people, male}, ??, Lausanne)		**DFS**: stack / set
lifetime management: stripped counter (number_of_references: X)	**renaming (ids)**: map / tree / set (used, used, used)	

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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