Vector Database Systems

Shan-Hung Wu and DataLab
CS, NTHU

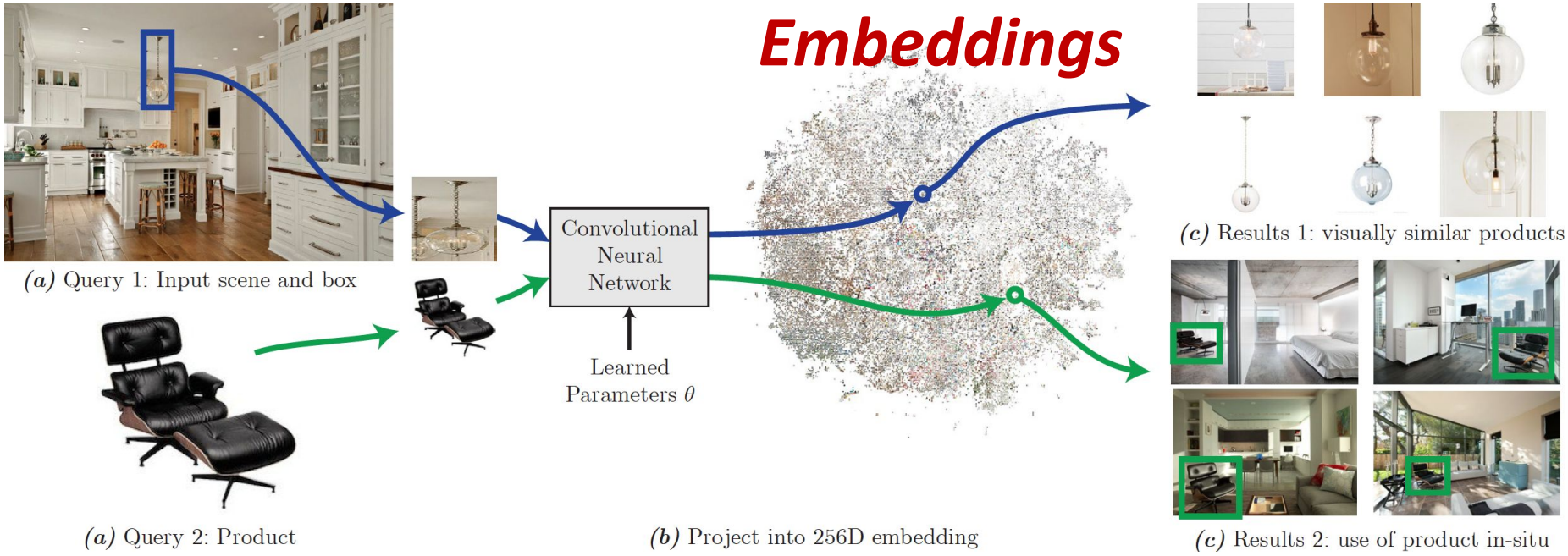
Outline

- Why Vector DBMS?
- AKNN Search Algorithms
- Challenges at System-level
- Case study: PASE (System R-like)
  - Data model & Query Format
  - Index Building & Update
  - Planning & Cost Estimation
- Case study: Milvus (purpose-built)
  - Storage & Consistency Model
  - Computing & Threads
  - Query Algorithms

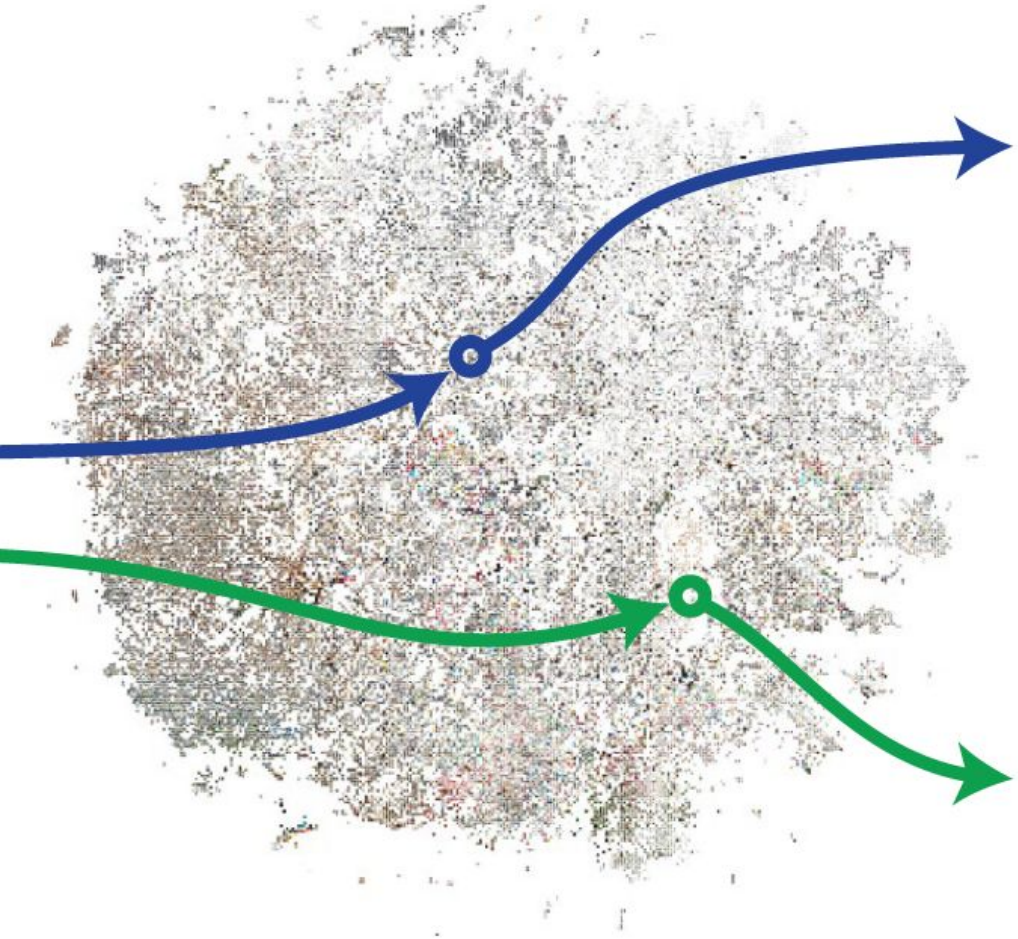
Outline

- Why Vector DBMS?
- AKNN Search Algorithms
- Challenges at System-level
- Case study: PASE (System R-like)
  - Data model & Query Format
  - Index Building & Update
  - Planning & Cost Estimation
- Case study: Milvus (purpose-built)
  - Storage & Consistency Model
  - Computing & Threads
  - Query Algorithms

The Emerge of AI & Embeddings



- Used by search engines, recommender systems, personalized ads, etc.



How to store & search billions of embeddings?

Outline

- Why Vector DBMS?
- AKNN Search Algorithms
- Challenges at System-level
- Case study: PASE (System R-like)
  - Data model & Query Format
  - Index Building & Update
  - Planning & Cost Estimation
- Case study: Milvus (purpose-built)
  - Storage & Consistency Model
  - Computing & Threads
  - Query Algorithms

Approximate K Nearest Neighbor (AKNN) Search

- Given a query vector q, find k vectors $V=\{v_1, v_2, \ldots, v_k\}$ in storage that are approximately nearest to q
- Distance measure?
  - Euclidian distance, cosine similarity, etc.
- The higher ***recall*** the better
  - Let ground truth: V^*
  - Recall = $| V \cap V^* | / | V^* |$

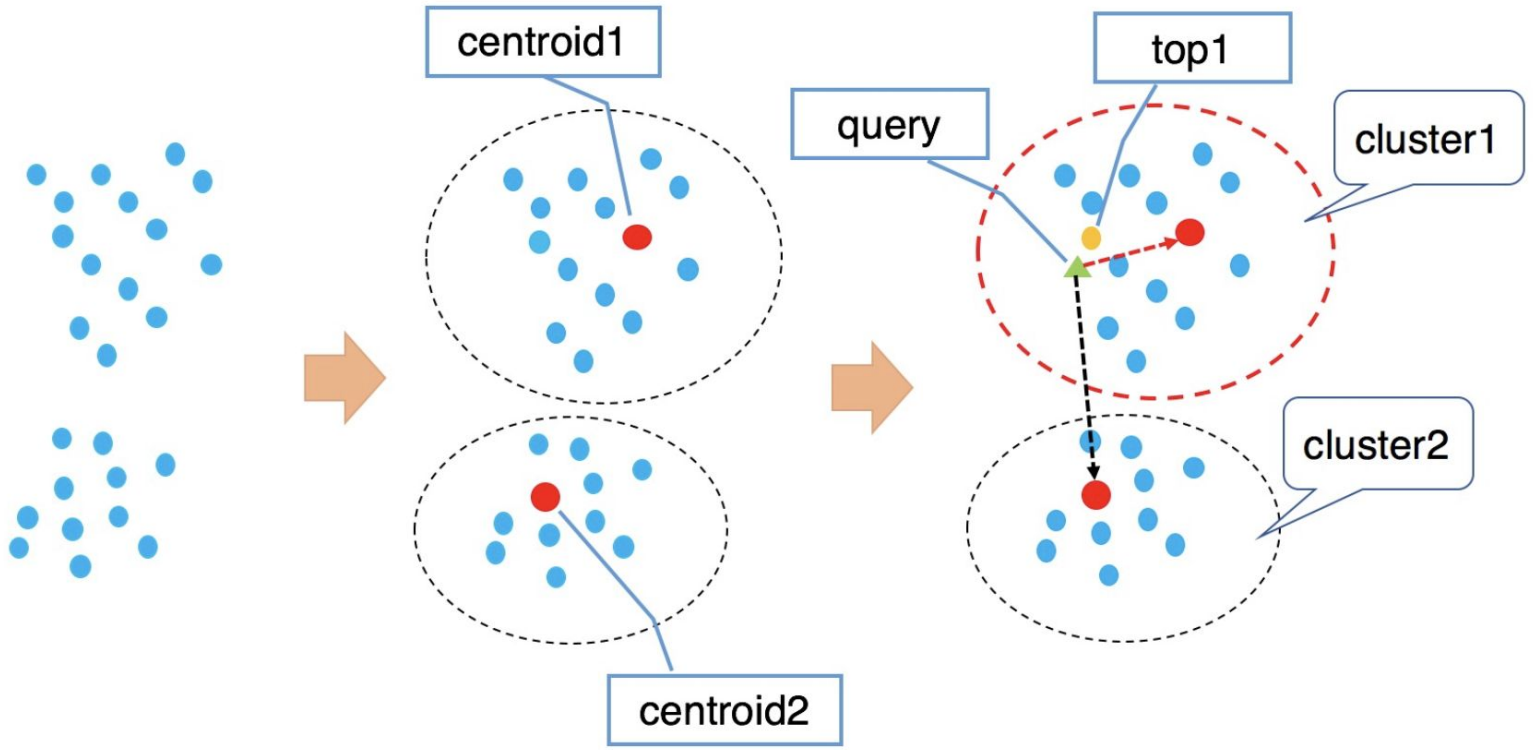
AKNN Algorithms

- Tree-based: KD-tree, R-tree
- Quantization-based: IVF_FLAT/SQ8/PQ
- Graph-based: HNSW, NSG, SSG
- Locality sensitive hashing (LSH)

AKNN Algorithms

- Tree-based: KD-tree, R-tree
  - Runs slowly on high-dimensional data
- ***Quantization-based***: IVF_FLAT/SQ8/PQ
  - ***High recall, codebooks are update-insensitive***
- Graph-based: HNSW, NSG, SSG
  - High recall, graph take time/space to maintain
- Locality sensitive hashing (LSH)
  - Low recall

IVF_FLAT/SQ8/PQ



- Search in each cluster: brut force (FLAT) vs. compressed (SQ8) vs. quantization of subvectors (PQ)

Outline

- Why Vector DBMS?
- AKNN Search Algorithms
- Challenges at System-level
- Case study: PASE (System R-like)
  - Data model & Query Format
  - Index Building & Update
  - Planning & Cost Estimation
- Case study: Milvus (purpose-built)
  - Storage & Consistency Model
  - Computing & Threads
  - Query Algorithms

AKNN Libraries from AI Community

- Facebook **Faiss**, Microsoft **SPTAG**, Spotify **Annoy**, etc.
  - Implement various AKNN algorithms

- Pros: computation optimized
  - Support SIMD instructions (SSE, AVX, AVX2)
  - Faiss even supports GPU acceleration

AKNN Libraries from AI Community

- Facebook **Faiss**, Microsoft **SPTAG**, Spotify **Annoy**, etc.
  - Implement various AKNN algorithms

- ***Cons***:
  - Assume memory storage only
  - No support for dynamic data (updates/deletes)
  - No attribute filtering (e.g., “100 < price < 200”)

Outline

- Why Vector DBMS?
- AKNN Search Algorithms
- Challenges at System-level
- Case study: PASE (System R-like)
  - Data model & Query Format
  - Index Building & Update
  - Planning & Cost Estimation
- Case study: Milvus (purpose-built)
  - Storage & Consistency Model
  - Computing & Threads
  - Query Algorithms

PHASE

- “PostgreSQL Ultra-High-Dimensional Approximate Nearest Neighbor Search Extension,” in SIGMOD’20
  - A PostgreSQL extension
  - Can be implemented in any System R-like DBMS
- Pros:
  - Supports disk storage
  - Supports dynamic data
  - Supports attribute filtering

Data Model

- Treats vectors as a ***field*** in a table
  - Type: `float_vector(d)`
- Index creation:

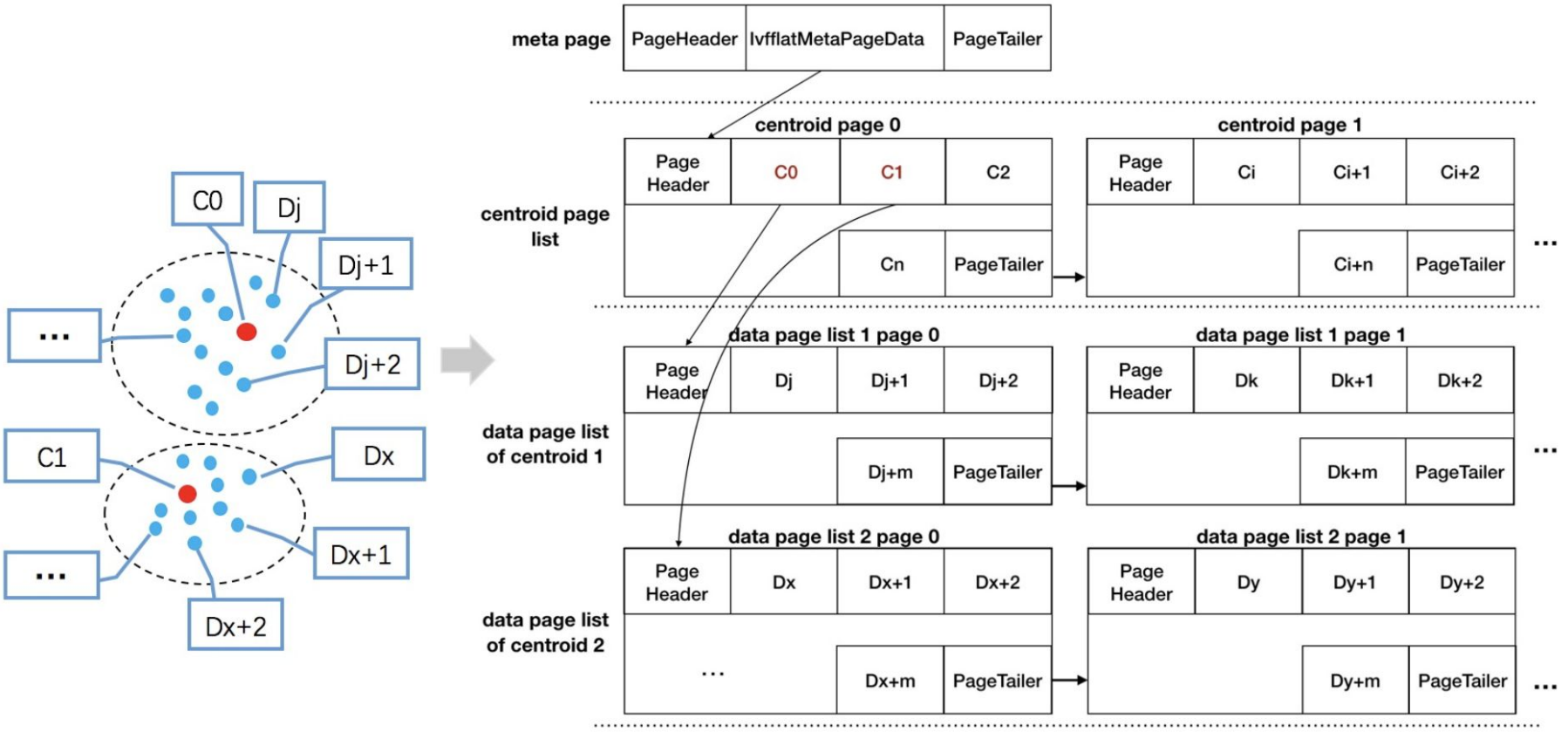
```
CREATE INDEX idx_text ON posts(text_vector)
USING ivf_flat;
```

Query Format

- AKNN query:

```
SELECT p.id,
       p.text_vector <-> '...' AS dist
FROM posts AS p
ORDER BY dist ASC LIMIT 10;
```

Index Building (IVF_FLAT)



- Each page is the unit of buffering and searching

Index Update (IVF_FLAT)

- Do nothing if the data distribution does not change
- Otherwise, continue clustering for few iterations

Planning

```
SELECT p.id,
       p.text_vector <-> '...' AS dist
FROM posts AS p
ORDER BY dist ASC LIMIT 10;
```

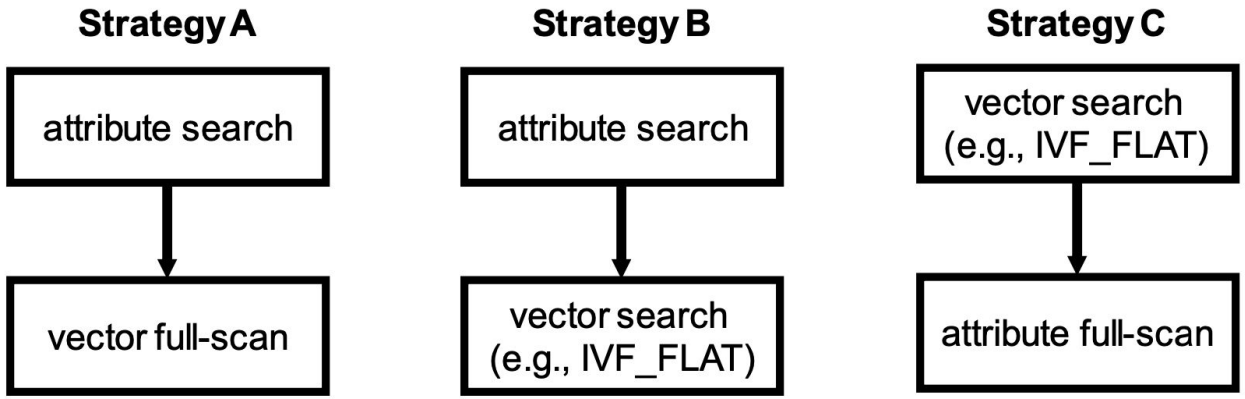
- New `SortPlan` in algebra tree
  - Needs to estimate its own cost

Cost Estimation (IVF_FLAT)

- To select top clusters: B(centroid file)
- Scan for each cluster: B(data file of a centroid)

Attribute Filtering

```
SELECT p.id,
       p.text_vector <-> '...' AS dist
FROM posts AS p
WHERE p.date < '...'
ORDER BY dist ASC LIMIT 10;
```



- Best strategy determined by estimated costs

Outline

- Why Vector DBMS?
- AKNN Search Algorithms
- Challenges at System-level
- Case study: PASE (System R-like)
  - Data model & Query Format
  - Index Building & Update
  - Planning & Cost Estimation
- Case study: Milvus (purpose-built)
  - Storage & Consistency Model
  - Computing & Threads
  - Query Algorithms

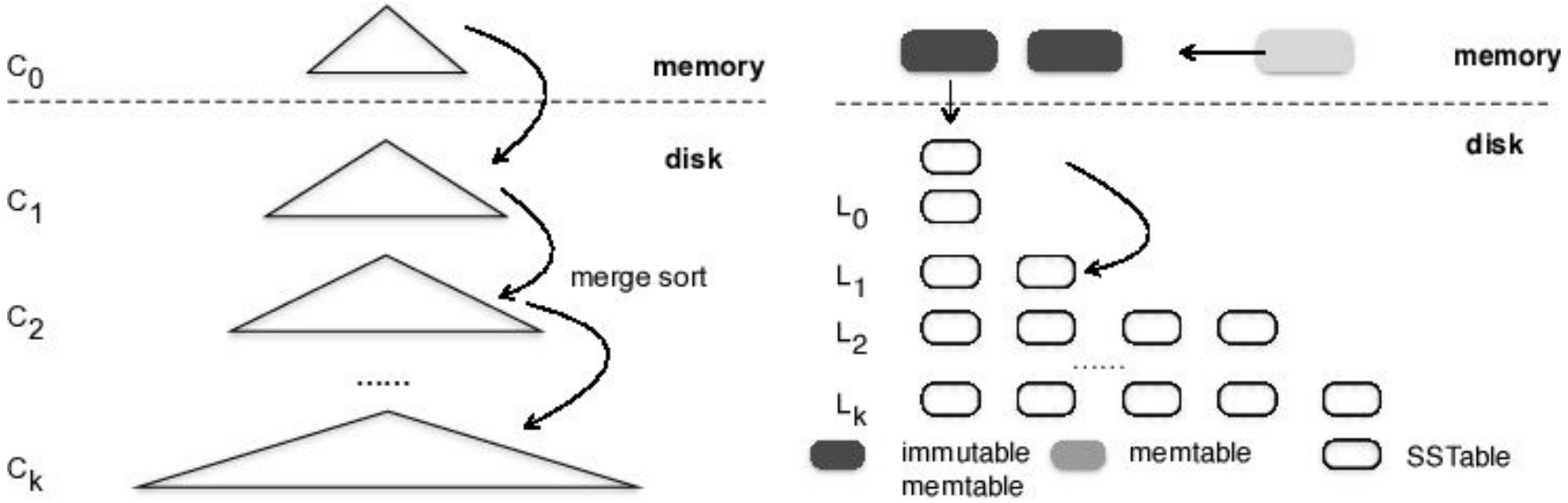
Milvus

- “Milvus: A Purpose-Built Vector Data Management System,” in SIGMOD’21
  - A dedicated system

- Pros:
  - Supports disk storage, dynamic data, attribute filtering
  - Much higher performance than PASE

Storage

- Column storage based on Log StructuredMerge (LSM) tree

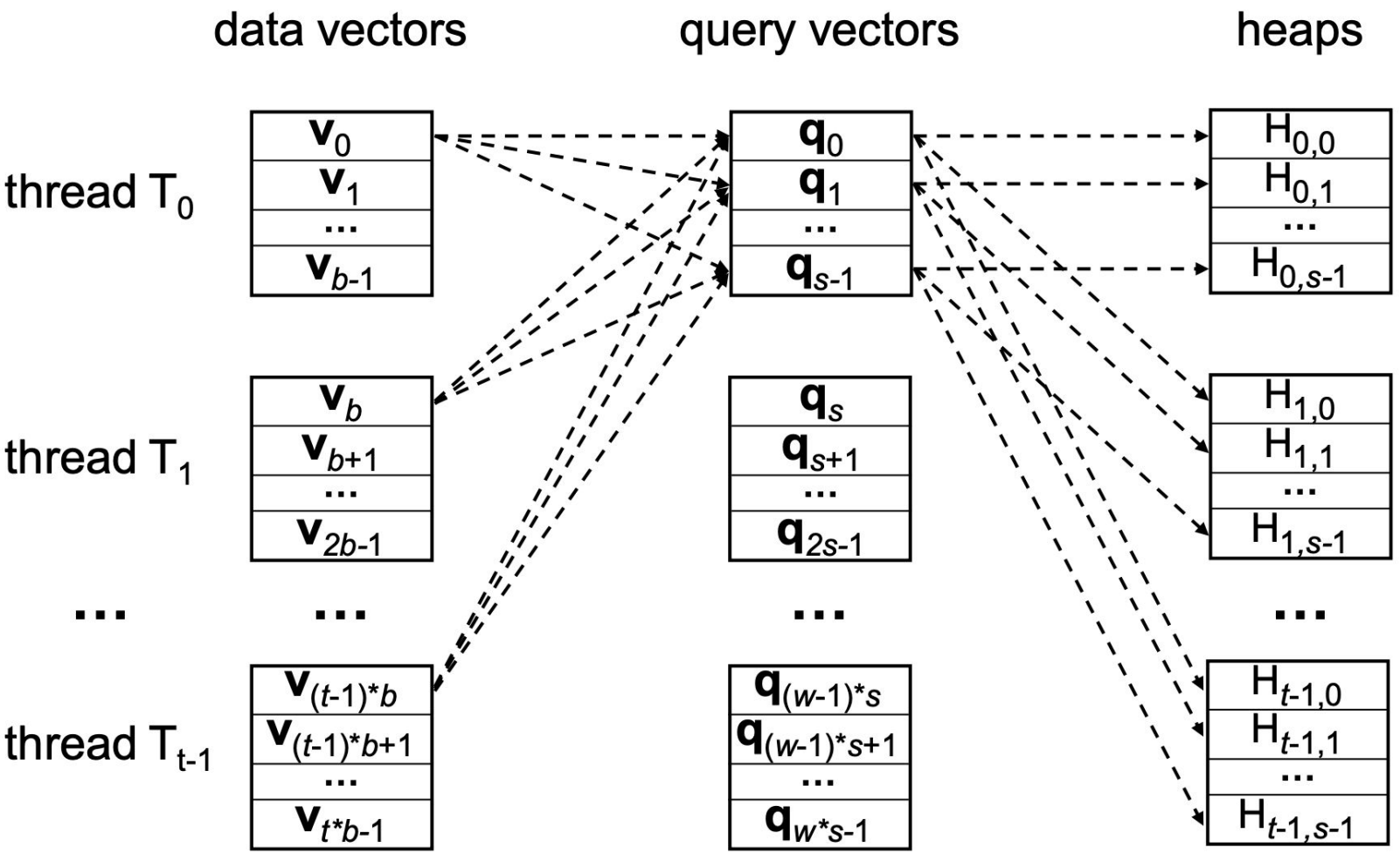


- Out-of-place updates
- SSTables (segments) are the unit of buffering/searching

Consistency Model

- Snapshot isolation

Thread Model



Query Planning