SCIENCE
PASSION
TECHNOLOGY

Architecture of DB Systems
02 DB System Architectures

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Announcements/Org

- **#1 Video Recording**
  - Link in TeachCenter & TUbe (lectures will be public)
  - Optional attendance (independent of COVID)

TUbe

- **#2 COVID-19 Restrictions** (HS i5)
  - Max 25% room capacity (TC registrations)

max 18/74

- **#3 Programming Projects**
  - Initial test suite, benchmark, and make file
  - Reference implementation Dexter released (you need to implement ./server.h)

```
cd src; make harness_test
./speed_test 1468 0 0 0 0 4000 16000 100
```

seed IX pop TX/IX #IX

```
Creating 100 indices
Populating indices 100
Time to populate: 29ms
Testing the indices
Time to test: 1106ms
Testing complete.
     NUM_DEADLOCK: 0
     NUM_TXN_FAIL: 0
     NUM_TXN_COMP: 1600000
Overall time to run: 1135ms
```

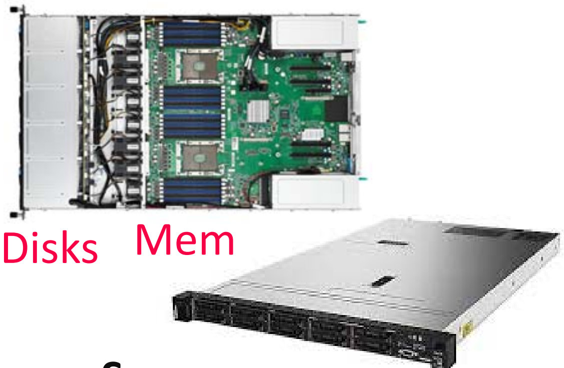
Agenda

- **Basic HW Background**
- **Classification of DB Architectures**

Basic Hardware Background

Anatomy of a Data Center

Commodity CPU:
Xeon E5-2440: 6/12 cores
Xeon Gold 6148: 20/40 cores



Server:
Multiple sockets,
RAM, disks

Rack:
16-64 servers +
top-of-rack switch

Cluster:
Multiple racks + cluster switch

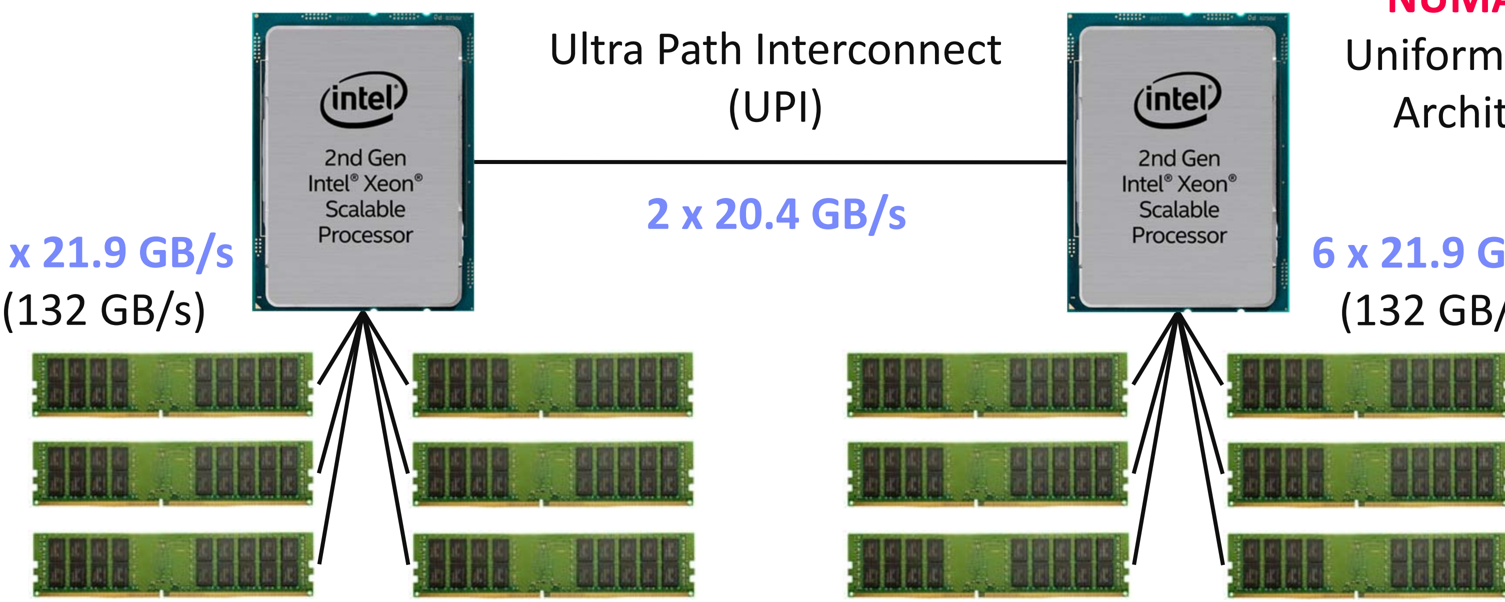
Data Center:
>100,000 servers

[Google Data Center, Eemshaven, Netherlands]

Basic CPU/Memory Architecture

[https://en.wikichip.org/wiki/intel/xeon_gold/6238r]

- **Example DM Cluster** (scale-up)
  - Scale-up Intel Xeon Gold 6238R @ 2.2-4 Ghz (2 x 28 pcores, **2 x 56 vcores**)
  - **768 GB** HPE DDR4 RAM @ 2.933 GHz (12 x 64GB 2Rx4 PC4-2933Y-R)



Basic CPU/Memory Architecture, cont.

- **Example DM Cluster**
  - Scale-up Intel Xeon Gold 6238R @ 2.2-4 GHz (2 x 28 pcores, **2 x 56 vcores**)
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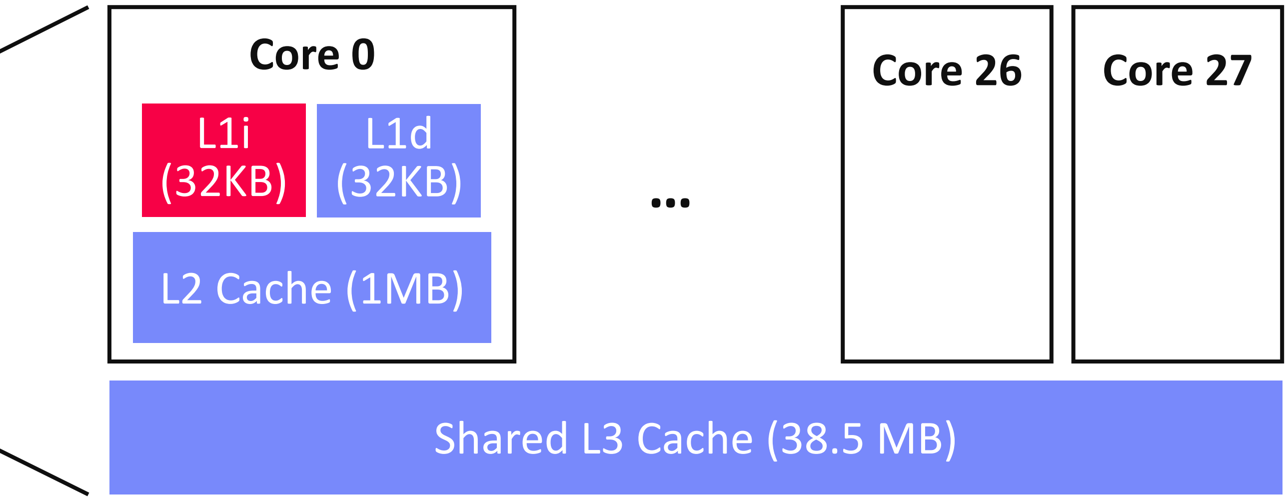


Micro Architecture:
Cascade Lake '19

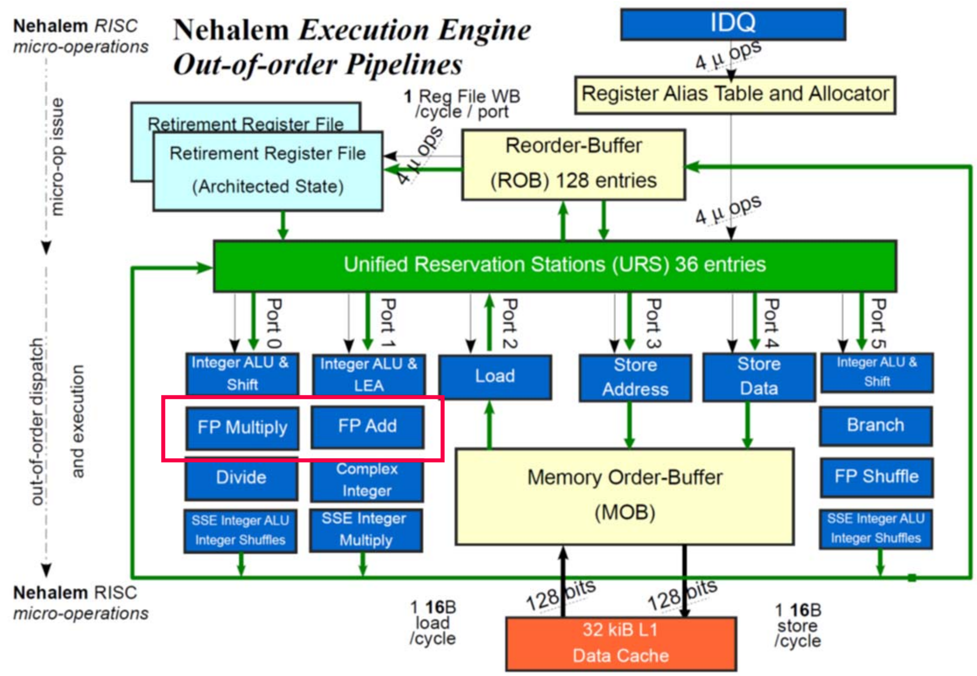
Why do we need a cache hierarchy?

- **Cache Coherence Protocols** (e.g., dictionary, snooping)

CPU (Core) Microarchitecture

- **Example Nehalem**
  - **Frontend:** Instruction Fetch, Pre-Decode, and Decode
  - **Backend:** Rename/Allocate, Scheduler, Execute
  - Out-of-Order Execution Engine (128b FP Mult/Add)

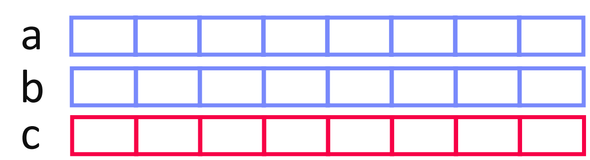
[M. E. Thomadakis: The Architecture of the Nehalem Processor and Nehalem EP SMP Platforms, Report, 2010]



- **SIMD Processing**
  - Single-instruction, multiple data
  - Process the same operation on multiple elements at a time
  - Data/instruction parallelism
  - Example: `VFMADD132PD`

2009 Nehalem: **128b** (2xFP64)
2012 Sandy Bridge: **256b** (4xFP64)
2017 Skylake: **512b** (8xFP64)

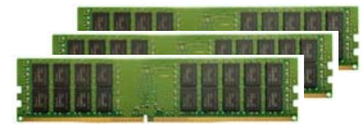
```
c = _mm512_fmadd_pd(a, b);
```



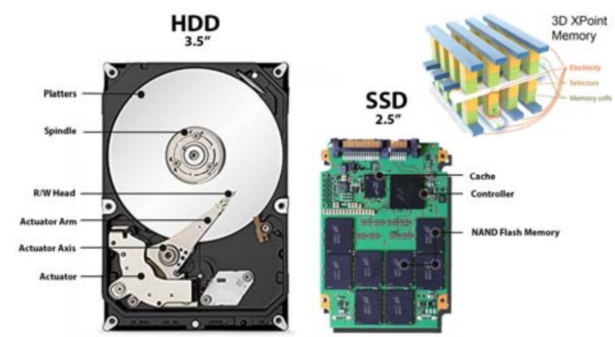
Basic Storage Architecture

Perf ←→ Cost per GB

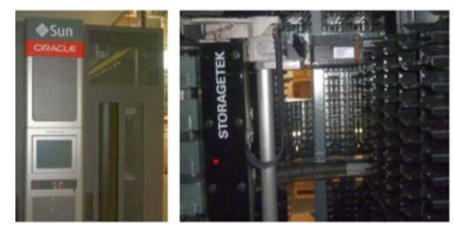
- **Primary Storage**
  - Main Memory (volatile, often charge-based)
  - Capacitors leak charge → periodic refresh (**~64ms**)



- **Secondary Storage** (non-volatile storage)
  - **HDD:** hard disk drive (magnetic, rotating platters)
  - **SSD:** solid-state drives (flash memory)
  - **NVM:** non-volatile memory (flash/resistive)



- **Tertiary Storage** (archival mass storage)
  - Optical disks (special materials), Magneto-optical disks
  - Tape drives: magnetic tape w/ high capacity cartridges



50PB tape library

Why do we need a storage hierarchy?

[Thomas Hahmann, Hans Weber, Erhard Diedrich, Gunter Schreier: SENTINEL-1 AND SENTINEL-3-OLCI PAC AT **DLR**, ESA-SP 722, **2013**]

Basic Network Architecture

- **Example DM Cluster**
  - 2 Racks Inffeldgasse 31
  - Switch: **HPE FlexFabric 5710 48XGT** (48x **10 GbE**, or 6x 40 GbE, 2 x 100 GbE)

[https://www.bechtle.com/at/shop/hpe-flexfabric-5710-48xgt-switch--4288448--p]

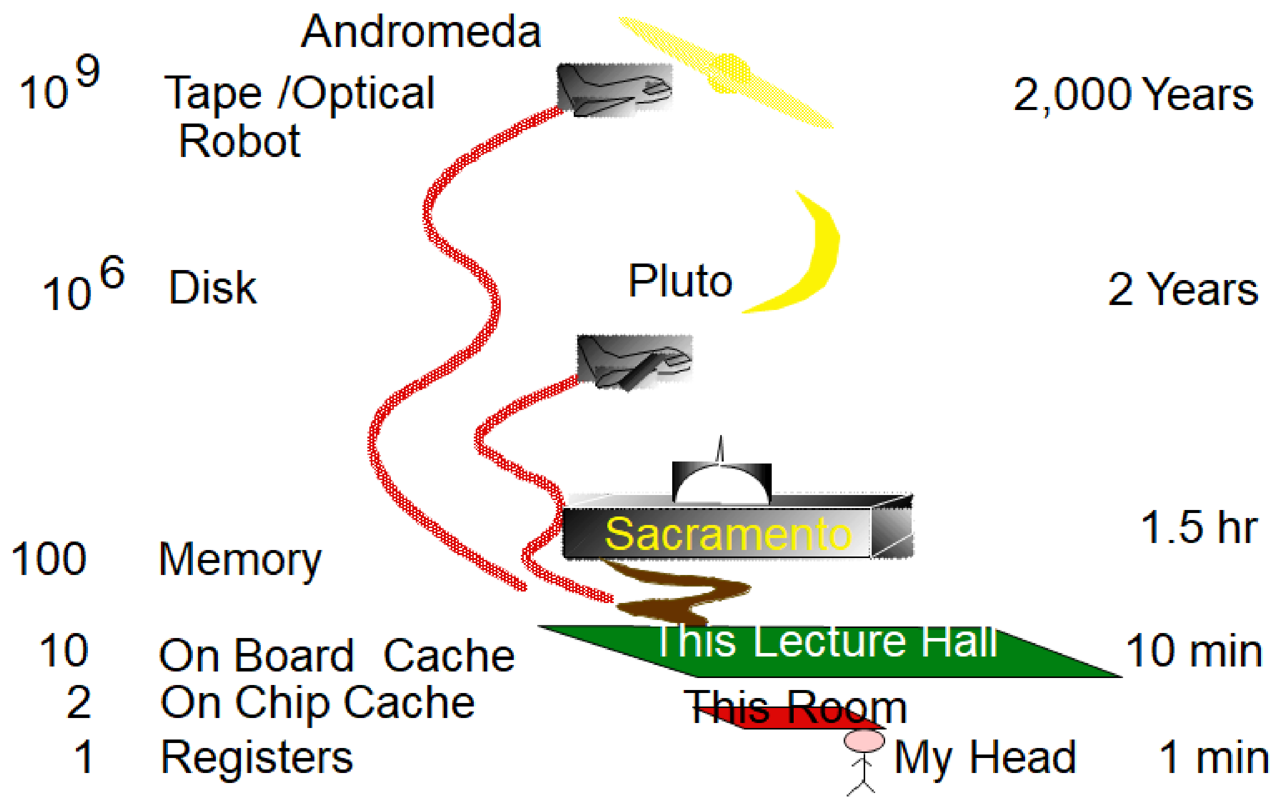
  - 1 Node (scale-up, 2 SSD system, 12 SSD data, T4 GPU)
  - 14 Nodes (scale-out)
    - AMD EPYC 7302 CPU at 3.0-3.3 GHz (16 pcores / **32 vcores**)
    - **128GB** HPE DDR4 RAM @ 2.933 GHz (8x 16GB 1Rx4 PC4-2933Y-R)
    - 2x 480GB SATA SDDs (system), 12x 2TB SATA HDDs (data)
    - **2x 10Gb** Ethernet (2 port adapter)

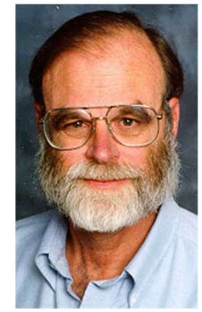
Latency Numbers Every Programmer Should Know

Operation	Time [ns]	Time [us]	Time [ms]
Inst execute / L1 cache reference	0.5		
Branch mispredict	5		
L2 cache reference	7		
Mutex lock/unlock	25		
Main memory reference	100		
Send 1K bytes over 1 Gb Ethn	10,000	10	
Read 4K randomly from SSD	150,000	150	
Read 1 MB sequentially from RAM	250,000	250	
Round trip within same datacenter	500,000	500	
Read 1 MB sequentially from SSD	1,000,000	1,000	1
Disk seek	10,000,000	10,000	10
Read 1 MB sequentially from disk	20,000,000	20,000	20
Send packet US←→Europe	150,000,000	150,000	150

[https://gist.github.com/jboner/2841832, **2012**]

Jim Gray's Storage Latency Analogy





Turing Award '98

[Joseph M. Hellerstein: CS 186: Introduction to Database Systems – Storing Data: Disks and Files, **Fall 2002,** https://dsf.berkeley.edu/jmh/cs186/f02/lecs/lec15_6up.pdf]

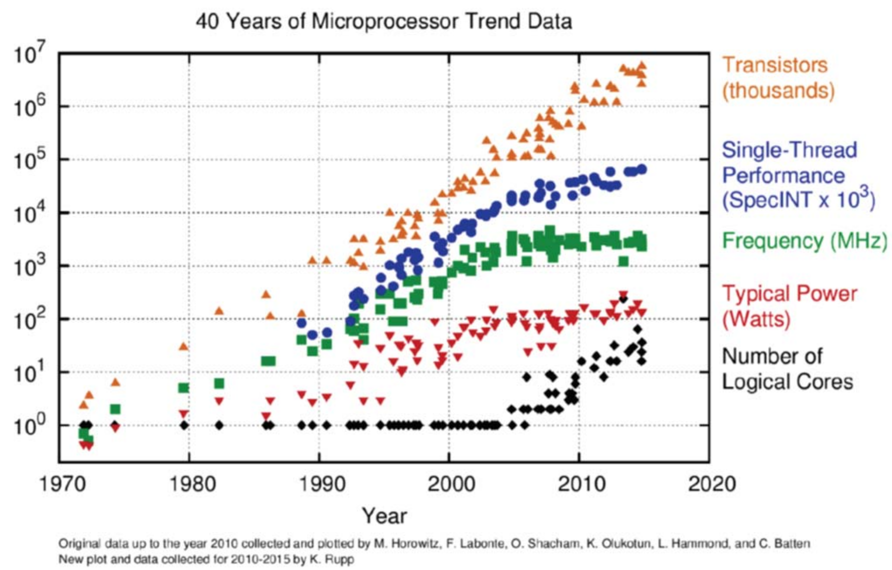
HW Challenges

[S. Markidis, E. Laure, N. Jansson, S. Rivas-Gomez and S. W. D. Chien: Moore's Law and Dennard Scaling]

- **#1 End of Dennard Scaling** (~2005)
  - Law: power stays proportional to the area of the transistor
  - Ignored leakage current / threshold voltage
    → **increasing power density S^2** (power wall, heat) → stagnating frequency

$P = \alpha CFV^2$ (**power density 1**)
(P .. Power, C .. Capacity, F .. Frequency, V .. Voltage)

- **#2 End of Moore's Law** (~2010-20)
  - Law: #transistors/performance/ CPU frequency doubles every 18/24 months
  - Original: # transistors per chip doubles every two years **at constant costs**
  - Now increasing costs



→ **Consequences: Dark Silicon and Specialization**

Classification of DB Architectures

Background and Design Dimensions

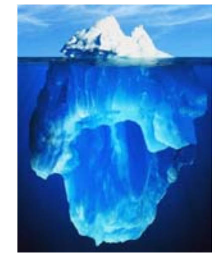
Recap Data Models, Consistency Models

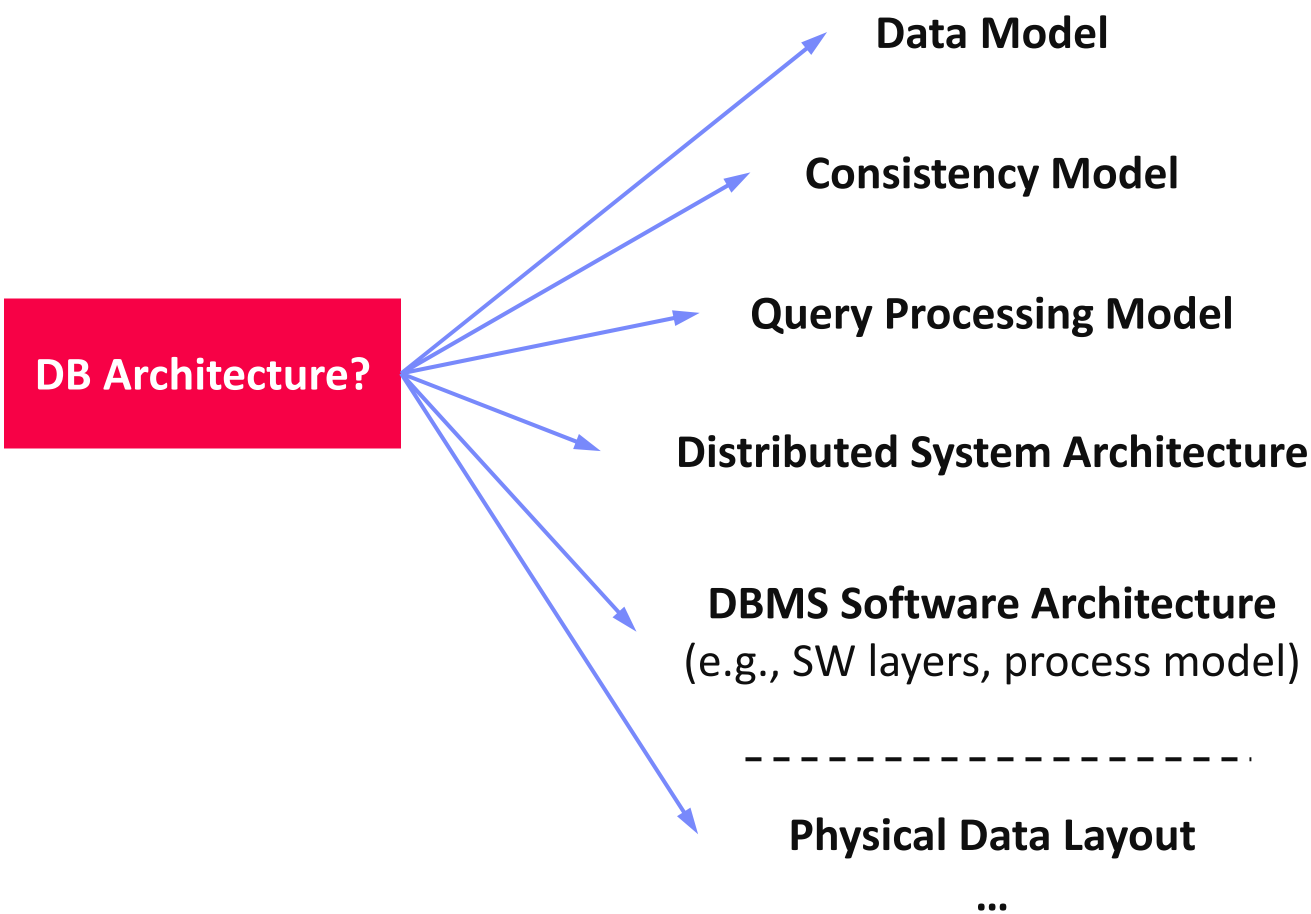
Recap Query Processing Models

Distributed Systems & DBMS Architecture

Row & Column Storage

Classification Dimensions





Recap: Data Models

- **Conceptual Data Models**
  - Entity-Relationship Model (ERM), focus on data, ~1975
  - Unified Modeling Language (UML), focus on data and behavior, ~1990

- **Logical Data Models**
  - Relational (Object/Relational)
  - Key-Value
  - Document (XML, JSON)
  - Graph
  - Time Series
  - Matrix/Tensor
  - Object-oriented
  - Network
  - Hierarchical

  } Mostly obsolete (Object-oriented, Network, Hierarchical)

- **Physical Data Models**
  - Row / column (page layouts)
  - LSM
  - Nested text/binary, flattened
  - Vertex-centric
  - TSM
  - Row-/column-major, tiled, etc

Recap: Relational Data Model

- **Domain D (value domain): e.g., Set S, INT, Char[20]**
- **Relation R**
  - **Relation schema** RS: Set of k attributes $\{A_1,\ldots,A_k\}$
  - **Attribute** A_j: value domain $D_j = dom(A_j)$
  - **Relation:** subset of the Cartesian product over all value domains D_j
    $R \subseteq D_1 \times D_2 \times \ldots \times D_k, k \geq 1$

Attribute

A1 INT	A2 INT	A3 BOOL
3	7	T
1	2	T
3	4	F
1	7	T

Tuple

cardinality: 4
rank: 3

- **Additional Terminology**
  - **Tuple**: row of k elements of a relation
  - **Cardinality** of a relation: number of tuples in the relation
  - **Rank** of a relation: number of attributes
  - **Semantics:** Set := no duplicate tuples (in practice: Bag := duplicates allowed)
  - **Order of tuples and attributes is irrelevant**

Recap: Key-Value Stores

- **Motivation**
  - Basic key-value mapping via simple API (more complex data models can be mapped to key-value representations)
  - Reliability at massive scale on commodity HW (cloud computing)

- **System Architecture**
  - Key-value maps, where values can be of a variety of data types
  - APIs for CRUD operations (create, read, update, delete)
  - Scalability via sharding (horizontal partitioning)

users:1:a	"Inffeldgasse 13, Graz"
users:1:b	"[12, 34, 45, 67, 89]"
users:2:a	"Mandellstraße 12, Graz"
users:2:b	"[12, 212, 3212, 43212]"

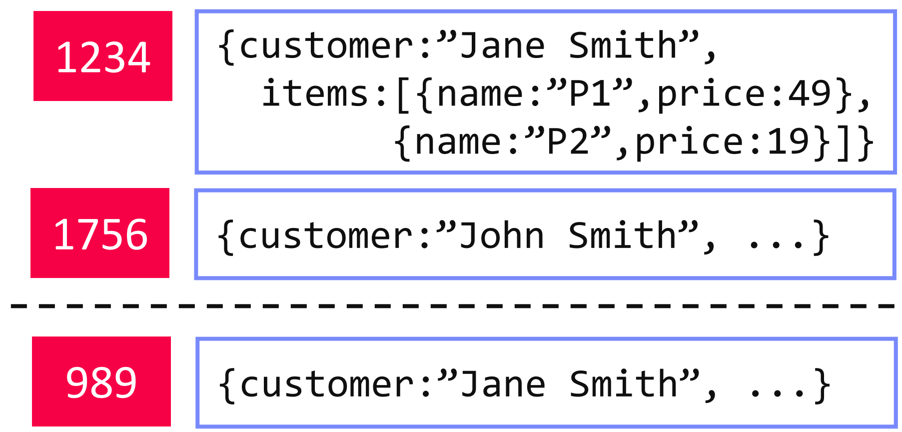
- **Example Systems**
  - Dynamo (2007, AP) → Amazon DynamoDB (2012)
  - Redis (2009, CP/AP)

[Giuseppe DeCandia et al: Dynamo: amazon's highly available key-value store. **SOSP 2007**]

Recap: Document Stores

- **Motivation**
  - Application-oriented management of **structured, semi-structured, and unstructured information** (pay-as-you-go, schema evolution)
  - Scalability via parallelization on commodity HW (cloud computing)

- **System Architecture**
  - Collections of (**key**, **document**)
  - Scalability via sharding (horizontal partitioning)
  - Custom SQL-like or functional query languages

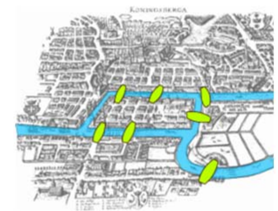


- **Example Systems**
  - **MongoDB** (C++, 2007, **CP**) → **RethinkDB**, **Espresso**, **Amazon DocumentDB** (Jan 2019)
  - **CouchDB** (Erlang, 2005, **AP**) → **CouchBase**

Recap: Graph Processing

[Grzegorz Malewicz et al: Pregel: a system for large-scale graph processing. **SIGMOD 2010,** (SIGMOD 2020 TTA)]

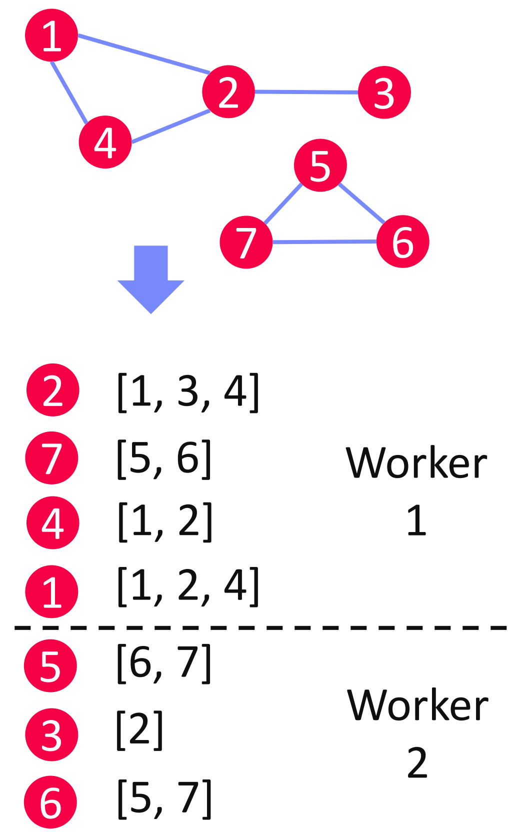
- **Google Pregel**
  - Name: Seven Bridges of Koenigsberg (Euler 1736)
  - **"Think-like-a-vertex"** computation model
  - Iterative processing in super steps, comm.: message passing



- **Programming Model**
  - Represent graph as collection of vertices w/ edge (adjacency) lists
  - Implement algorithms via Vertex API
  - Terminate if all vertices halted / no more msgs

```
public abstract class Vertex {
  public String getID();
  public long superstep();
  public VertexValue getValue();

  public compute(Iterator<Message> msgs);
  public sendMsgTo(String v, Message msg);
  public void voteToHalt();
}
```



Recap: ACID Properties

- **Atomicity**
  - A transaction is executed atomically (**completely or not at all**)
  - If the transaction fails/aborts no changes are made to the database (**UNDO**)
- **Consistency**
  - A successful transaction ensures that all **consistency constraints are met** (referential integrity, semantic/domain constraints)
- **Isolation**
  - Concurrent transactions are executed in isolation of each other
  - **Appearance of serial transaction execution**
- **Durability**
  - **Guaranteed persistence** of all changes made by a successful transaction
  - In case of system failures, the database is recoverable (**REDO**)

Recap: CAP Theorem

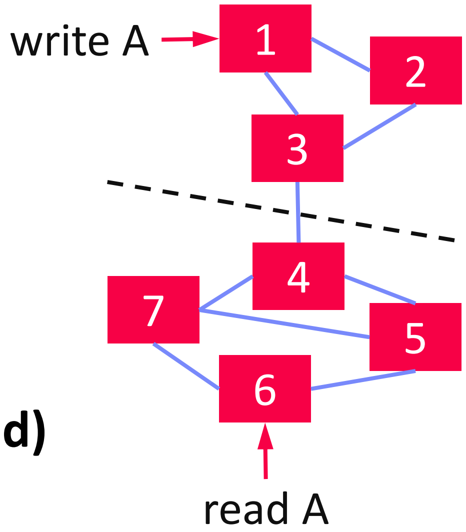
- **Consistency**
  - Visibility of updates to distributed data (atomic or linearizable consistency)
  - Different from ACIDs consistency in terms of integrity constraints
- **Availability**
  - Responsiveness of a services (clients reach available service, **read/write**)
- **Partition Tolerance**
  - Tolerance of temporarily unreachable network partitions
  - System characteristics (e.g., latency) maintained
- **CAP Theorem**
- **Proof**

"You can have AT MOST TWO of these properties for a networked shared-data systems."

[Eric A. Brewer: Towards robust distributed systems (abstract). **PODC 2000**]

[Seth Gilbert, Nancy A. Lynch: Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services. **SIGACT News 2002**]

Recap: CAP Theorem, cont.



- **CA: Consistency & Availability (ACID single node)**
  - Network partitions cannot be tolerated
  - Visibility of updates (**consistency**) in conflict with **availability** ➔ **no distributed systems**

- **CP: Consistency & Partition Tolerance (ACID distributed)**
  - Availability cannot be guaranteed
  - **On connection failure, unavailable** (wait for overall system to become consistent)

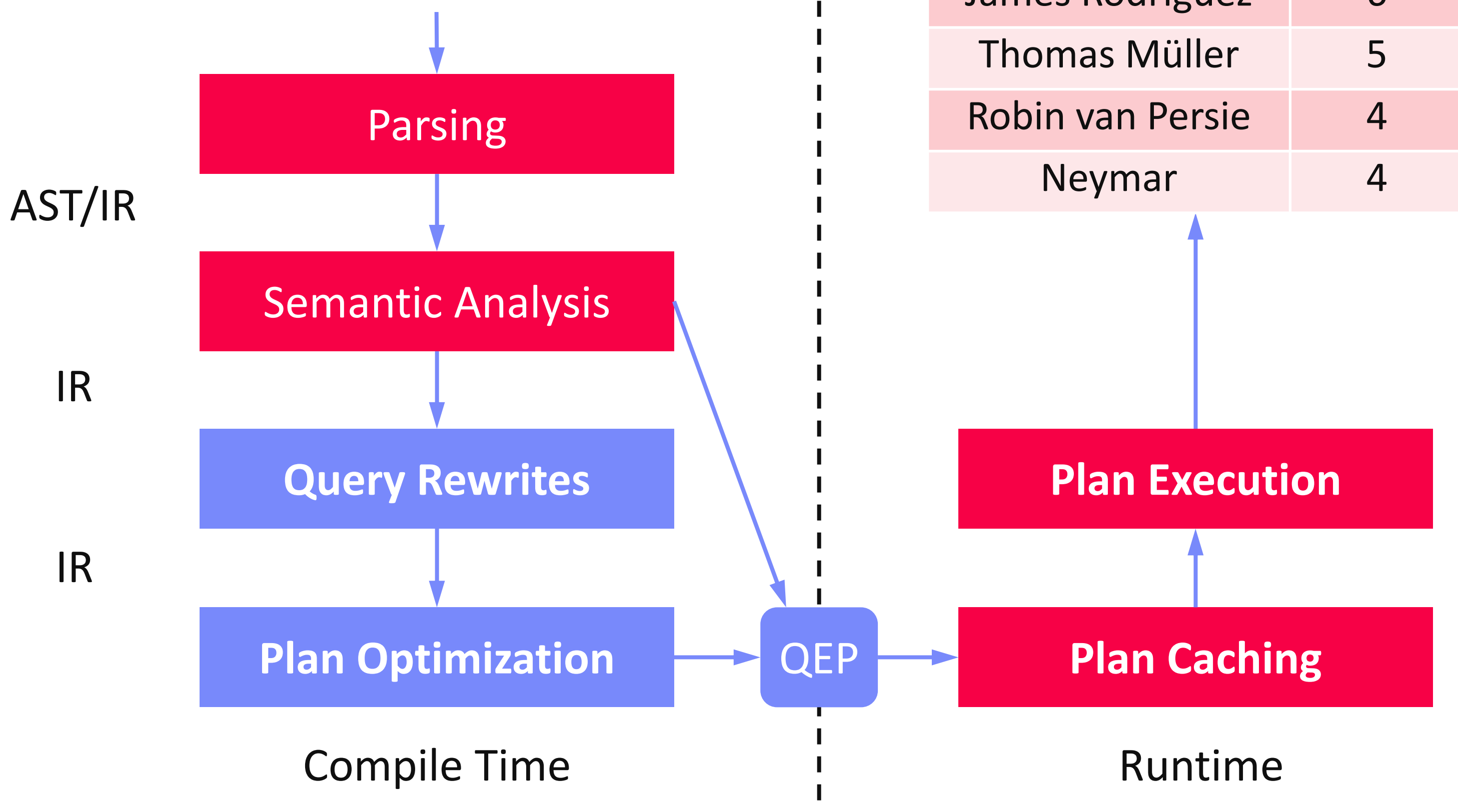
- **AP: Availability & Partition Tolerance (BASE)**
  - Consistency cannot be guaranteed, use of optimistic strategies
  - Simple to implement, main concern: availability to ensure revenue ($$$)

  ➔ **BASE consistency model** (basically available, soft state, eventual consistency)

Recap: Traditional Query Processing (OLTP/OLAP)

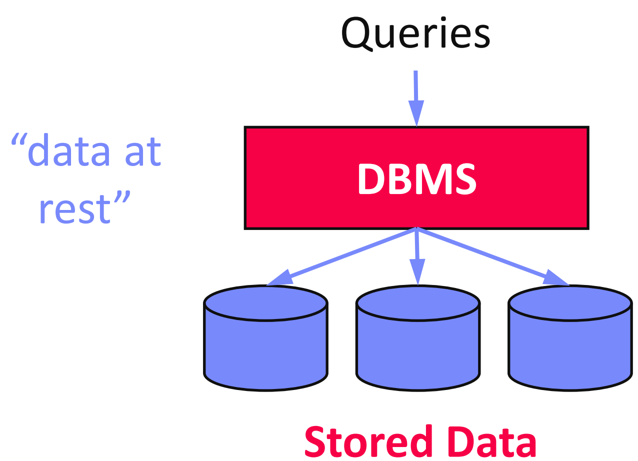
```
SELECT * FROM TopScorer
  WHERE Count>=4
```

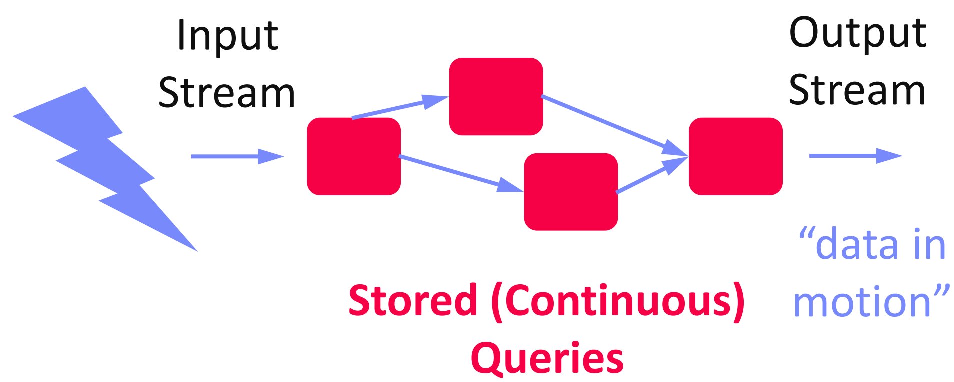
Name	Count
James Rodríguez	6
Thomas Müller	5
Robin van Persie	4
Neymar	4



Continuous Query Processing / Streaming

- **Stream Processing Architecture**
  - **Infinite input streams**, often with window semantics
  - Continuous (aka standing) queries



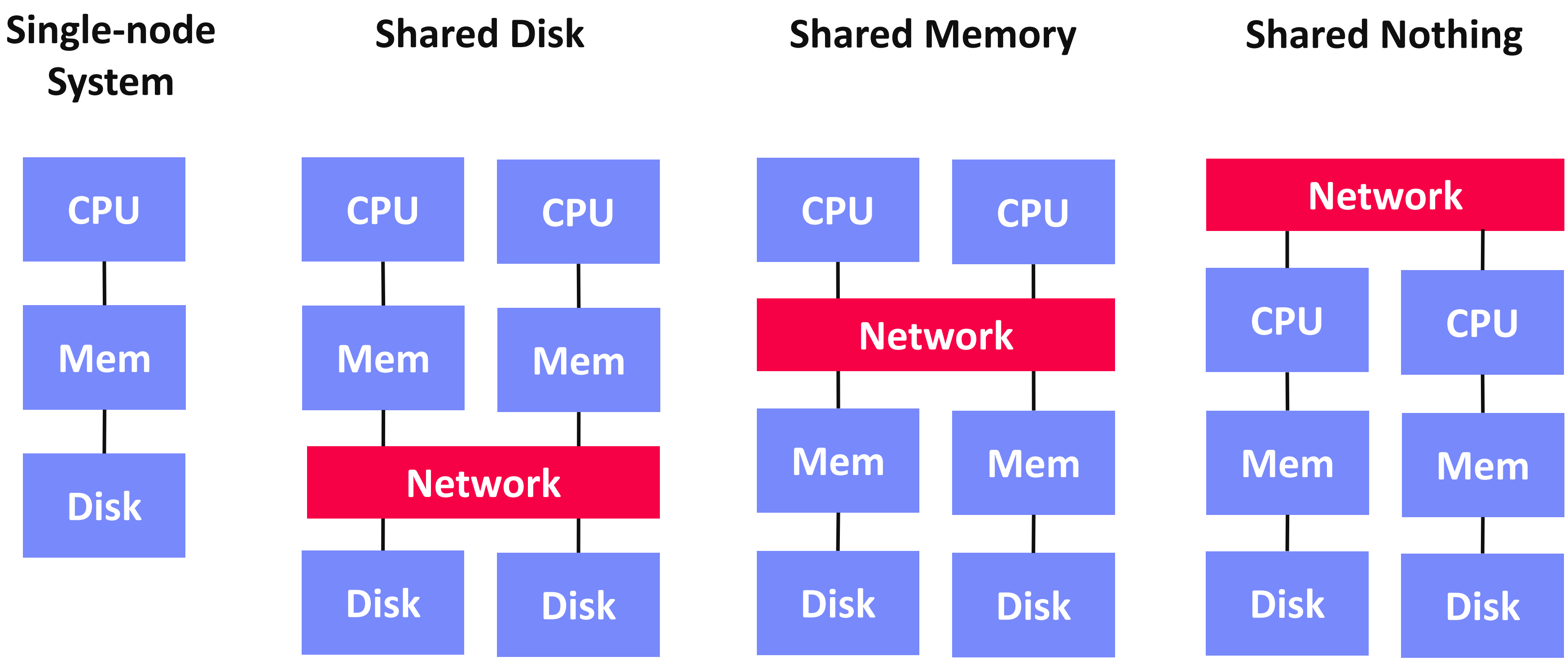


- **Optimizing Continuous Queries**
  - Multi-query optimization (multiple deployed queries)
  - Adaptive query optimization (based on changing workload)

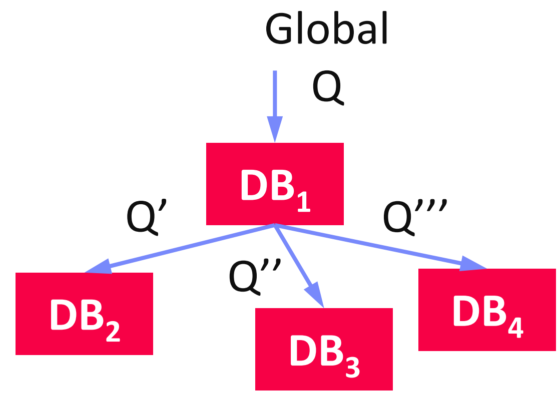
Network System Architectures

[David J. DeWitt, Jim Gray: Parallel Database Systems: The Future of High Performance Database Systems. Commun. ACM 35(6), **1992**]

- **Parallel DBS**
  - Goal: parallel query processing



Distributed Database Systems



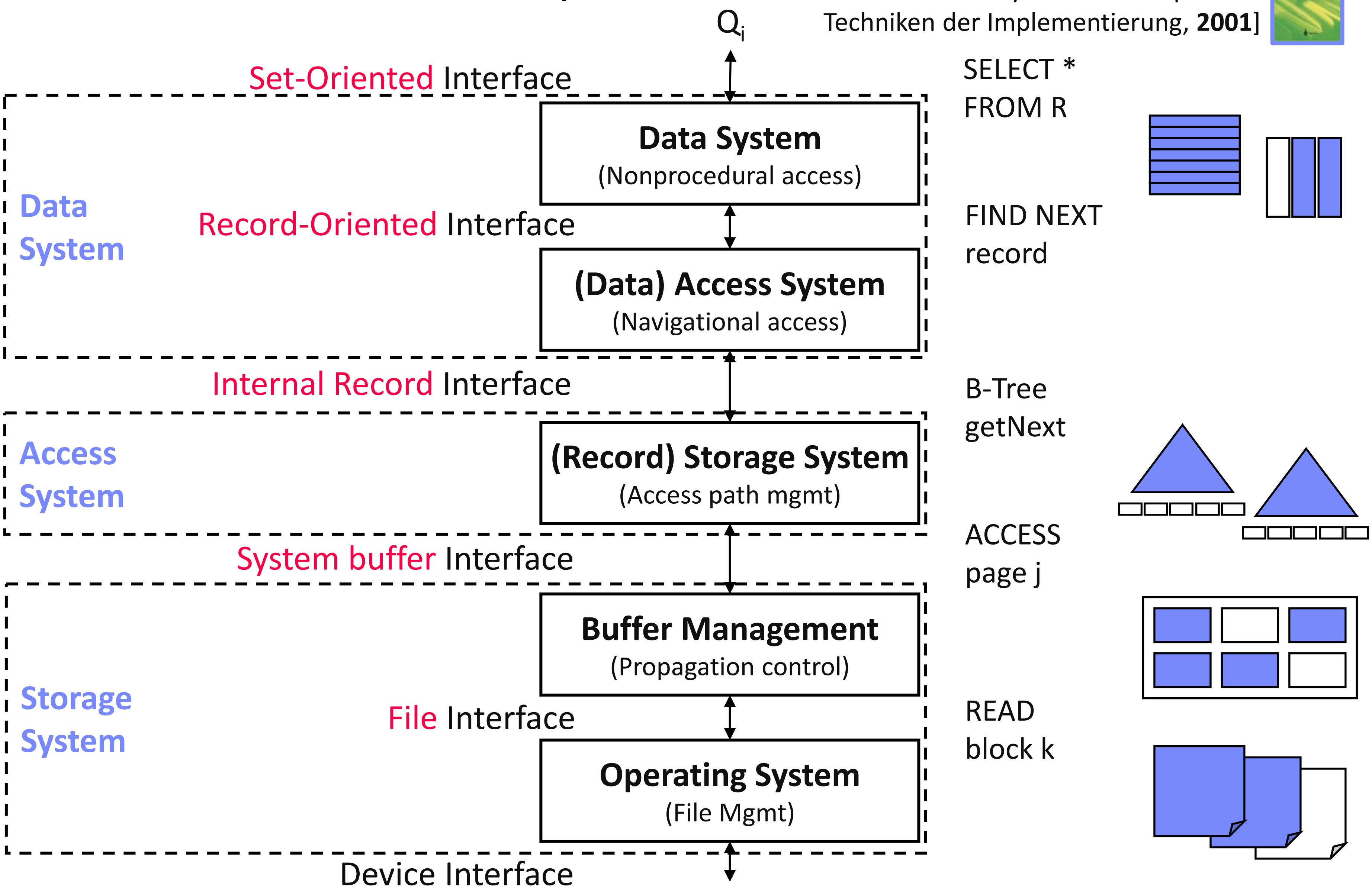
- **Distributed DBS**
  - Distributed database: Virtual (logical) database that appears like a local database but consists of multiple physical databases
  - Multiple local DBMS, components for global query processing
  - **Terminology:** **virtual DBS** (homogeneous), **federated DBS** (heterogeneous)

- **Challenges**
  - **Tradeoffs:** Transparency – autonomy, **consistency – efficiency/fault tolerance**
  - **#1** Global view and query language → schema architecture
  - **#2** Distribution transparency → global catalog
  - **#3** Distribution of data → data partitioning
  - **#4** Global queries → distributed join operators, etc
  - **#5** Concurrent transactions → **2PC**
  - **#6** Consistency of copies → **replication**

Beware: Meaning of "Transparency" (invisibility) here

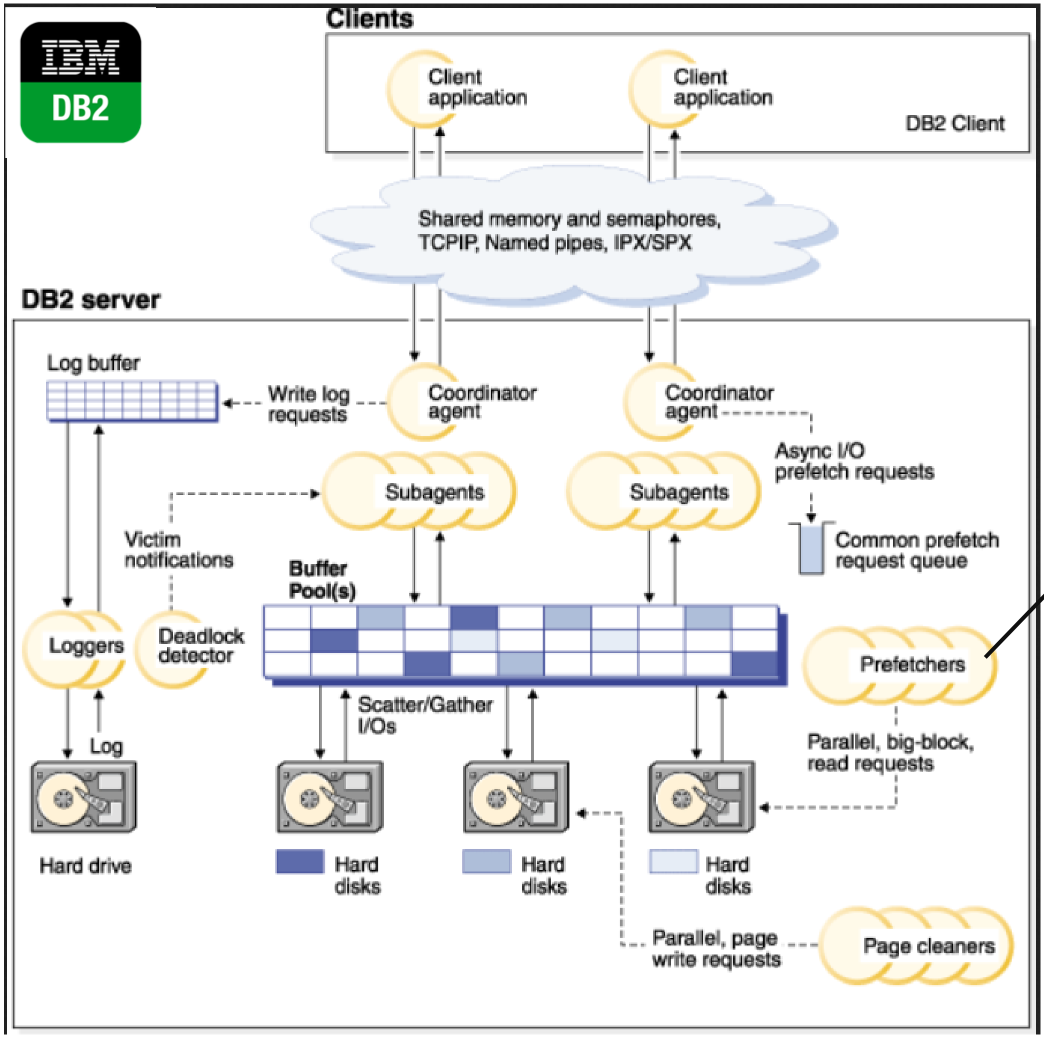
DBMS Architecture, cont.

[Theo Härder, Erhard Rahm: Datenbanksysteme: Konzepte und Techniken der Implementierung, **2001**]



IBM DB2 11.5 Architecture

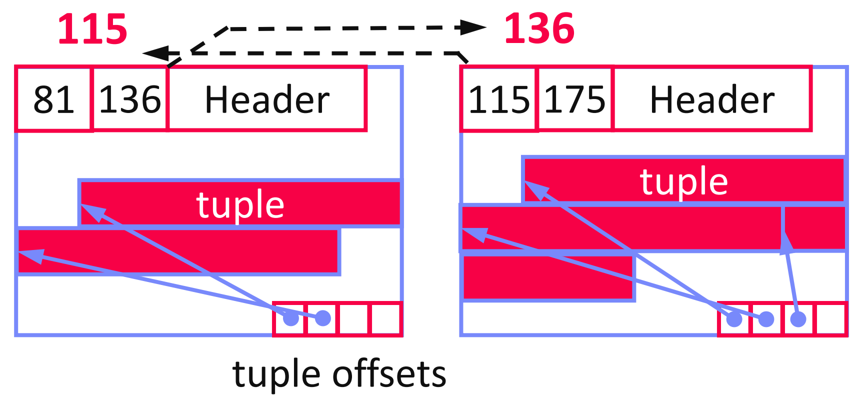
[https://www.ibm.com/support/knowledgecenter/SSEPGG_11.5.0/com.ibm.db2.luw.admin.perf.doc/doc/c0005418.html]



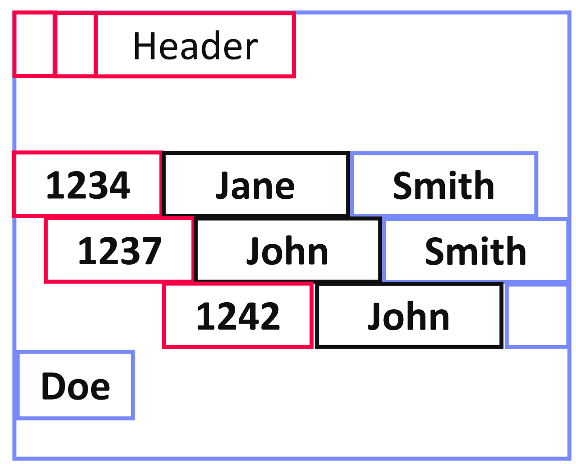
Engine Dispatchable Units (EDUs, e.g., db2 agents), implemented as OS threads

Row and Column Stores

- **Background: Storage System**
  - Buffer and storage management (incl. I/O) at granularity of **pages**
  - PostgreSQL default: **8KB**
  - Different table/page layouts

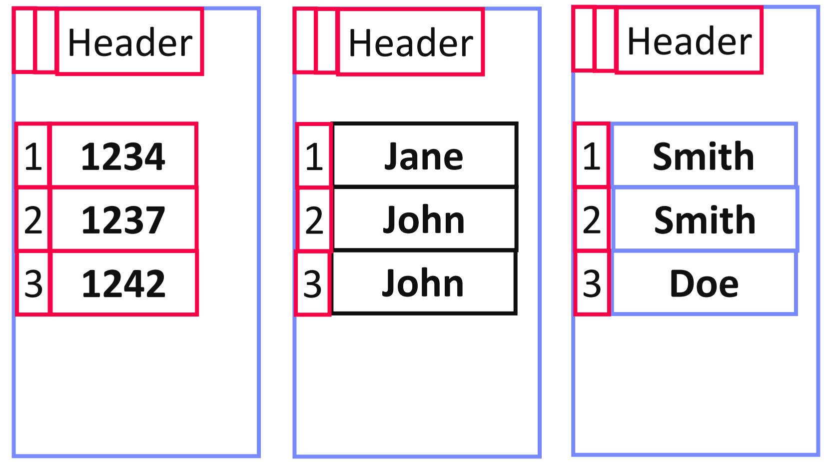


- **Row Storage**
  - **NSM** (nary storage model)
  - Store tuple attributes in contiguous form
  - Fast get/insert/delete
  - Slow column aggregates



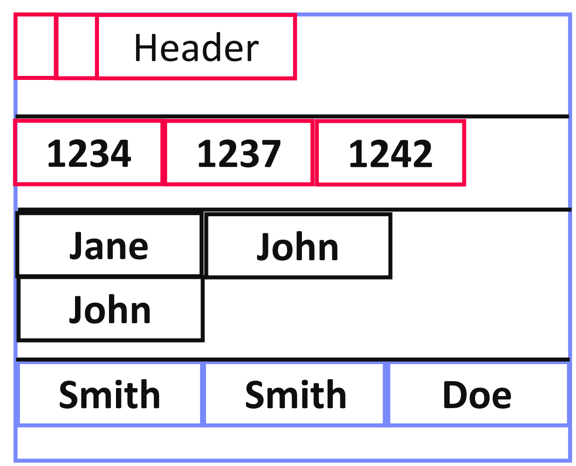
Row and Column Stores, cont.

- **Column Storage**
  - **DSM** (decomposed storage model) [**SIGMOD'85**, **ICDE'87**]
  - Store attribute values contiguously
  - Good compression, fast aggregates
  - Fast get/insert/delete (reconstruction needed)



- **Hybrid**
  - **PAX** (partition attributes across)
  - Combine advantages of NSM+DSM
  - **Cache-friendly page processing**
  - Variants in many modern systems

[Anastassia Ailamaki, David J. DeWitt, Mark D. Hill, Marios Skounakis: Weaving Relations for Cache Performance. **VLDB 2001**]



Summary and Q&A

- **Basic HW Background**
- **Classification of DB Architectures**
  - Data Model, Consistency Model, Query Processing Model,
  - Distributed System Architecture, DBMS Software Architecture,
  - Physical Data Layout

- **Programming Projects**
  - Initial test suite, benchmark, make file, and reference implementation
  - Try compiling it, and start **your own implementation** in next weeks

- **Next Lectures**
  - 03 **Data Layouts and Bufferpool Management** [Oct 21]
  - 04 **Index Structures and Partitioning** [Oct 28]
  - 05 **Compression Techniques** [Nov 04]