Data Management
12 Stream Processing

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SCIENCE
PASSION
TECHNOLOGY

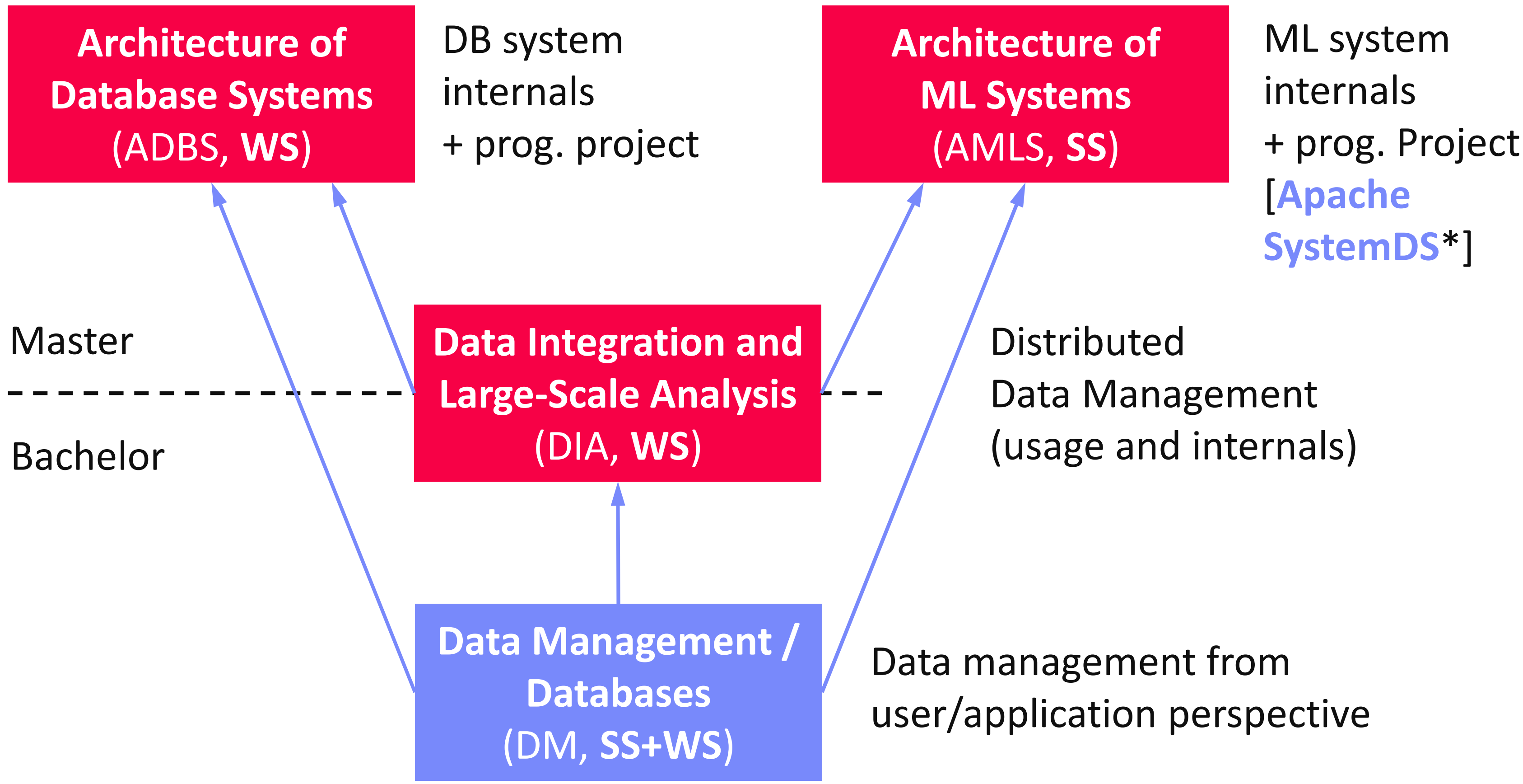
Announcements/Org

- **#1 Video Recording**
  - Link in **TeachCenter** & **TUbe** (lectures will be public)
  - **Live Streaming** Mo 4.10pm until end of semester (June 30)
  - **Office hours:** Mo 1pm-2pm (https://tugraz.webex.com/meet/m.boehm)
- **#2 Exercises**
  - **Exercise 1 graded**, Exercise 2 feedback soon
  - Exercise 4 deadline **June 16 11.59pm**
- **#3 Exam Dates** (VR Teaching Planning until June 27)
  - **June 22: 11am-1pm**, **2pm-4pm**, **5pm-7pm** (concurrently in i7, i11, i12, i13)
  - **Deregistration possible w/o failed attempt** for KU/VUs

DM 11am: **77/77**
DM 2pm: **77/77**
DM 5pm: **53/77**
DB 11am: **15+3/15**
DB 2pm: **15+3/15**
DB 5pm **15+3/15**
DM/DB Oral: **5**

- **#4 Course Evaluation**
  - Please participate; open period: **June 1 – July 15**

#5 Data Management Courses

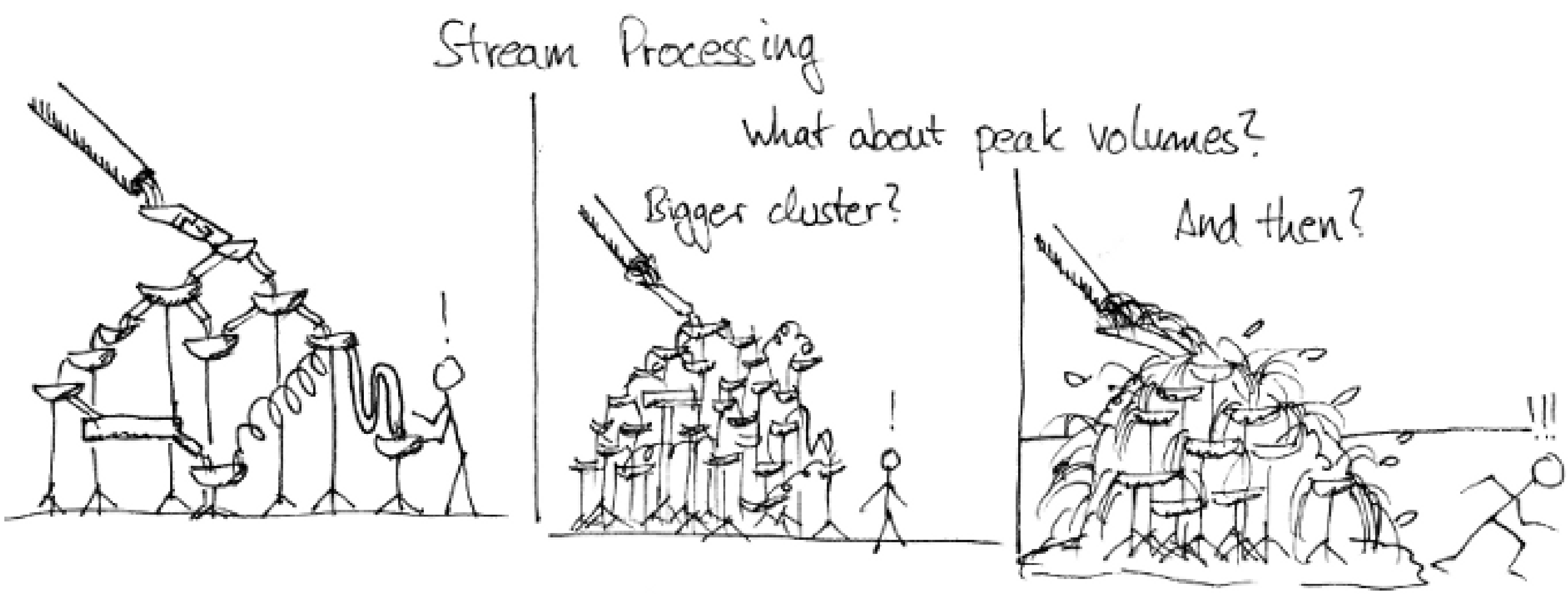


*[https://github.com/apache/systemml]

Agenda

- **Data Stream Processing**
- ~~**Distributed Stream Processing**~~
- **Q&A and Exam Preparation**

Data Integration and Large-Scale Analysis (DIA)
(bachelor/master)

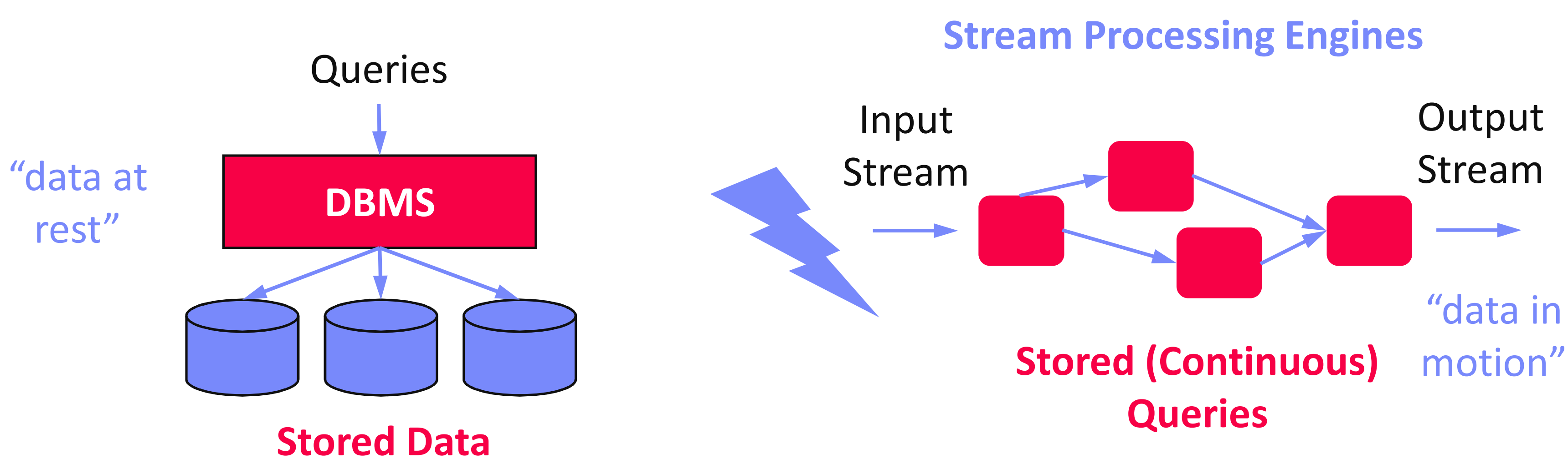


Data Stream Processing

Stream Processing Terminology

- **Ubiquitous Data Streams**
  - **Event and message streams** (e.g., click stream, twitter, etc)
  - Sensor networks, IoT, and monitoring (traffic, env, networks)

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



Stream Processing Terminology, cont.

- **Use Cases**
  - **Monitoring and alerting** (notifications on events / patterns)
  - **Real-time reporting** (aggregate statistics for dashboards)
  - **Real-time ETL** and event-driven data updates
  - Real-time decision making (fraud detection)
  - Data stream mining (summary statistics w/ limited memory)

  Continuously active

- **Data Stream**
  - Unbounded stream of data tuples $S = (s_1, s_2, \ldots)$ with $s_i = (t_i, d_i)$
  - See **10 NoSQL Systems** (time series)

- **Real-time Latency Requirements**
  - **Real-time:** guaranteed task **completion by a given deadline** (30 fps)
  - **Near Real-time:** few milliseconds to seconds
  - In practice, used with much weaker meaning

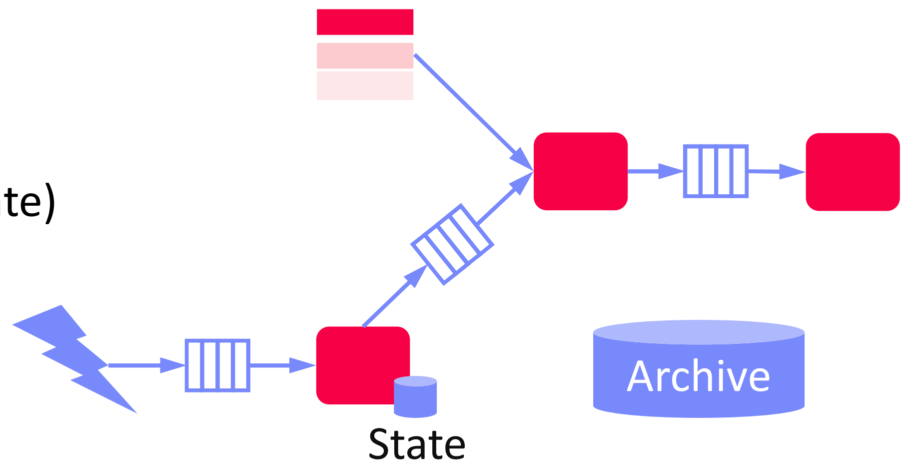
History of Stream Processing Systems

- **2000s**
  - **Data stream management systems** (DSMS, mostly academic prototypes): **STREAM** (Stanford'01), **Aurora** (Brown/MIT/Brandeis'02) → **Borealis** ('05), **NiagaraCQ** (Wisconsin), **TelegraphCQ** (Berkeley'03), and many others

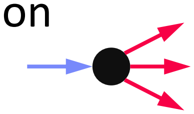
    ➔ but mostly unsuccessful in industry/practice
  - **Message-oriented middleware** and **Enterprise Application Integration** (EAI): IBM **Message Broker**, SAP **eXchange Infra.**, MS **Biztalk Server**, **TransConnect**
- **2010s**
  - **Distributed stream processing engines**, and "unified" batch/stream processing
  - **Proprietary systems:** Google Cloud Dataflow, MS StreamInsight / Azure Stream Analytics, IBM InfoSphere Streams / Streaming Analytics, AWS Kinesis
  - **Open-source systems:** **Apache Spark Streaming** (Databricks), **Apache Flink** (Data Artisans/Alibaba), **Apache Beam**, **Apache Kafka**, **Apache Storm**

System Architecture – Native Streaming

- **Basic System Architecture**
  - Data flow graphs (potentially w/ multiple consumers)
  - **Nodes:** asynchronous ops (w/ state) (e.g., separate threads)
  - **Edges:** data dependencies (tuple/message streams)
  - **Push model:** data production controlled by source



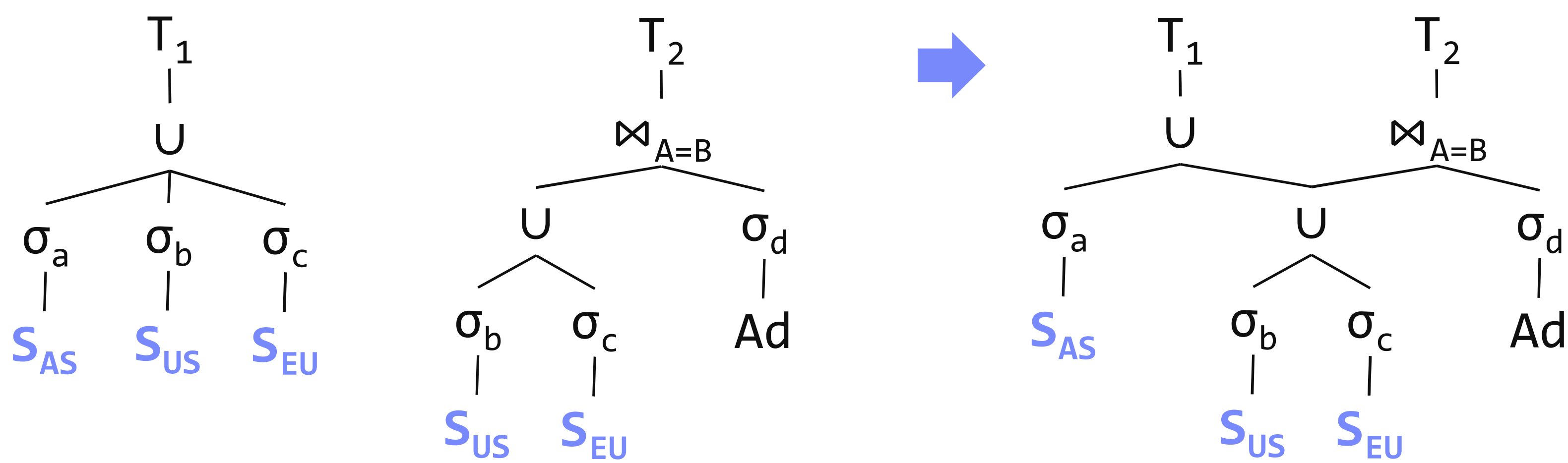
- **Operator Model**
  - Read from input queue
  - Write to potentially many output queues
  - Example Selection $\sigma_{A=7}$



```
while( !stopped ) {
   r = in.dequeue(); // blocking
   if( pred(r.A) )   // A==7
      for( Queue o : out )
         o.enqueue(r); // blocking
}
```

System Architecture – Sharing

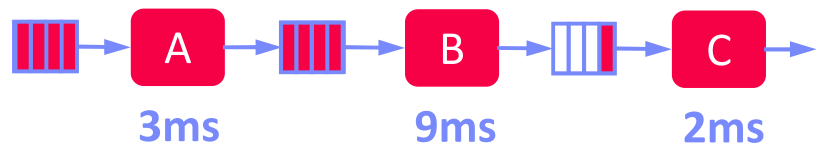
- **Multi-Query Optimization**
  - Given **set of continuous queries** (deployed), compile DAG w/o redundancy (see **08 Physical Design MV**) → **common subexpression elimination**



- **Operator and Queue Sharing**
  - **Operator sharing:** complex ops w/ multiple predicates for adaptive reordering
  - **Queue sharing:** avoid duplicates in output queues via masks

System Architecture – Handling Overload

- **#1 Back Pressure**
  - Graceful handling of overload w/o data loss
  - **Slow down sources**
  - E.g., blocking queues



Self-adjusting operator scheduling
Pipeline runs at rate of slowest op

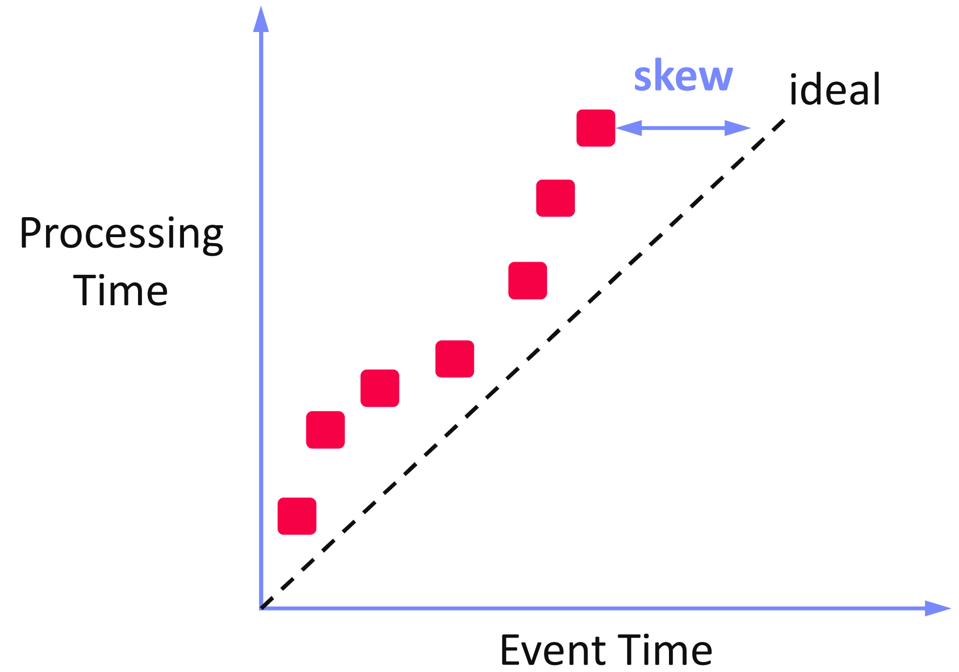
- **#2 Load Shedding**
  - #1 **Random-sampling**-based load shedding
  - #2 **Relevance-based** load shedding
  - #3 **Summary-based** load shedding (synopses)
  - Given SLA, select queries and shedding placement that minimize error and satisfy constraints

[Nesime Tatbul et al: Load Shedding in a Data Stream Manager. **VLDB 2003**]

- **#3 Distributed Stream Processing** (see course DIA)
  - Data flow partitioning (distribute the query)
  - Key range partitioning (distribute the data stream)

Time (Event, System, Processing)

- **Event Time**
  - Real time when the event/ data item was created
- **Ingestion Time**
  - System time when the data item was received
- **Processing Time**
  - System time when the data item is processed



- **In Practice**
  - Delayed and unordered data items
  - Use of heuristics (e.g., **water marks = delay threshold**)
  - Use of more complex triggers (**speculative and late results**)

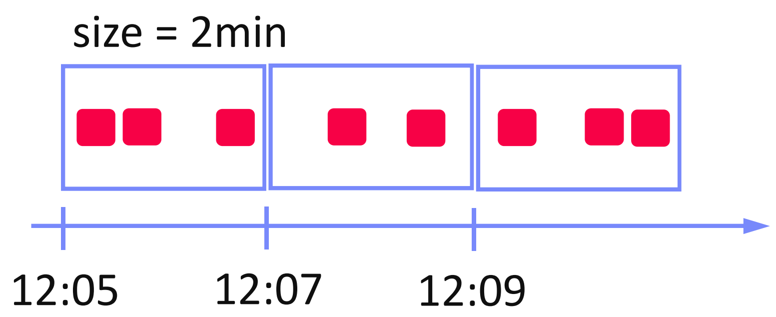
Durability and Consistency Guarantees

- **#1 At Most Once**
  - **"Send and forget"**, ensure data is never counted twice
  - Might cause data loss on failures
- **#2 At Least Once**
  - **"Store and forward"** or acknowledgements from receiver, replay stream from a checkpoint on failures
  - Might create incorrect state (processed multiple times)
- **#3 Exactly Once**
  - **"Store and forward" w/ guarantees** regarding state updates and sent msgs
  - Often via dedicated transaction mechanisms

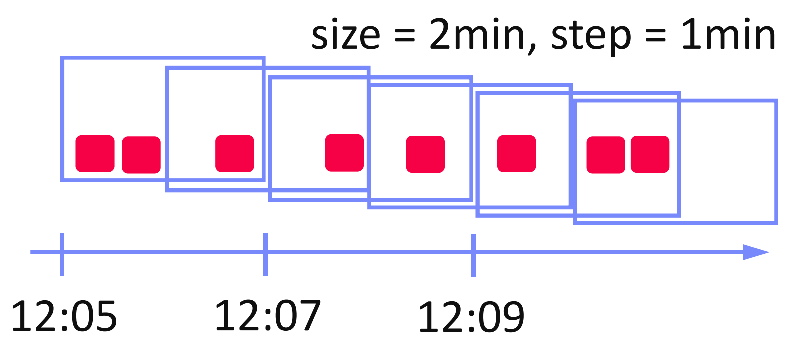
Window Semantics

- **Windowing Approach**
  - Many operations like joins/aggregation **undefined over unbounded streams**
  - Compute operations over **windows of time or elements**

- **#1 Tumbling Window**
  - Every data item is only part of a single window
  - Aka Jumping window



- **#2 Sliding Window**
  - Time- or tuple-based sliding windows
  - Insert new and expire old data items



Spark Streaming Example

[https://spark.apache.org/docs/latest/streaming-programming-guide.html]

```
// create spark context w/ batch interval 1s
sc = new JavaStreamingContext(conf, Durations.seconds(1));

// create DStream listening on socket (ip, port)
lines = sc.socketTextStream("localhost", 9999);

// traditional word count example on Dstream batches
JavaPairDStream<String, Integer> wordCounts = lines
   .flatMap(x -> Arrays.asList(x.split(" ")).iterator())
   .mapToPair(s -> new Tuple2<>(s, 1))
   .reduceByKey((i1, i2) -> i1 + i2);
wordCounts.print();
```

Tumbling
1s Window

```
// extended word count example on Dstream windows
JavaPairDStream<String, Integer> wordCounts2 = lines
   .flatMap(x -> Arrays.asList(x.split(" ")).iterator())
   .mapToPair(s -> new Tuple2<>(s, 1))
   .reduceByKeyAndWindow((i1, i2) -> i1 + i2,
      Durations.seconds(30), Durations.seconds(10));
```

Sliding
30s Window

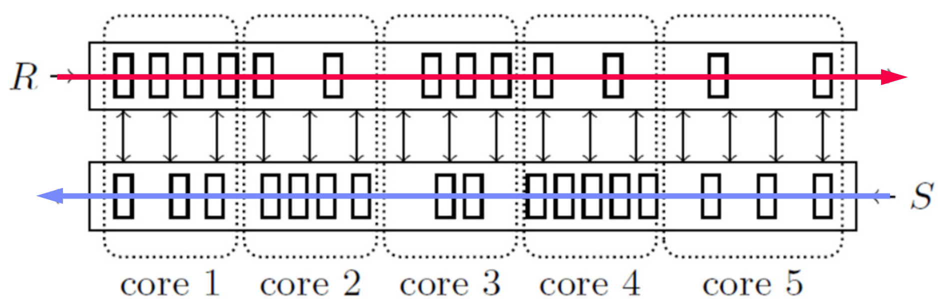
Window Length (Durations.seconds(30)) — **Sliding Interval** (Durations.seconds(10))

Stream Joins

- **Basic Stream Join**
  - **Tumbling window:** use classic join methods
  - **Sliding window** (symmetric for both R and S)
    - Applies to arbitrary join pred
    - See **08 Query Processing (NLJ)**

```
For each new r in R:
   1. Scan window of stream S
      to find match tuples
   2. Insert new r into window
      of stream R
   3. Invalidate expired tuples
      in window of stream R
```

- **Excursus: How Soccer Players Would do Stream Joins**
  - **Handshake-join** w/ 2-phase forwarding

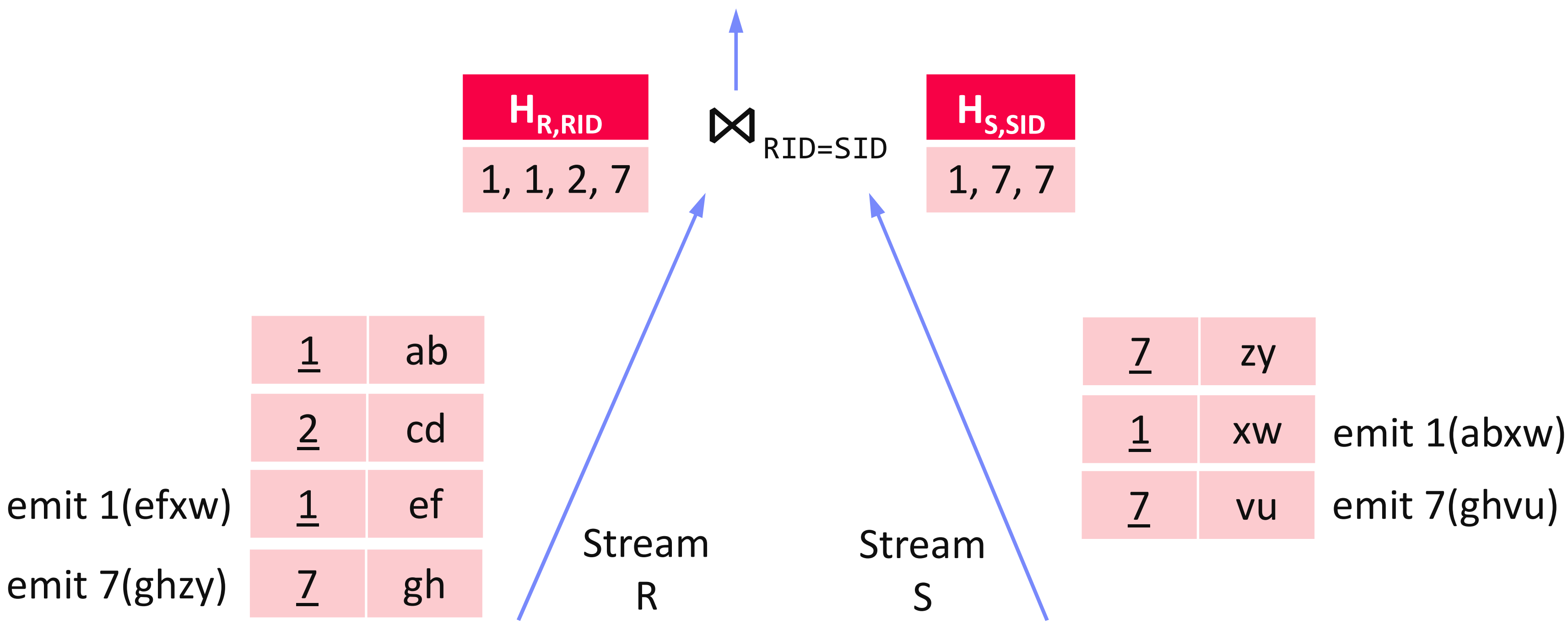


[Jens Teubner, René Müller: How soccer players would do stream joins. **SIGMOD 2011**]

Stream Joins, cont.

[Zachary G. Ives, Daniela Florescu, Marc Friedman, Alon Y. Levy, Daniel S. Weld: An Adaptive Query Execution System for Data Integration. **SIGMOD 1999**]

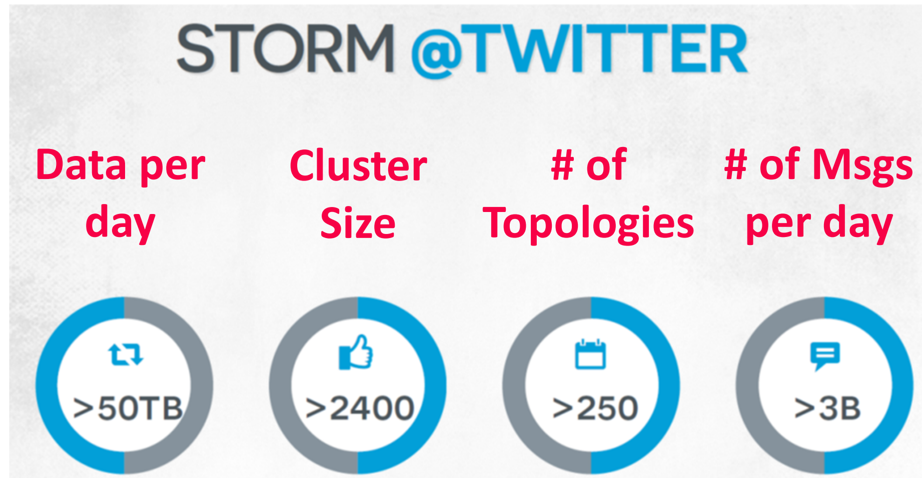
- **Double-Pipelined Hash Join**
  - Join of bounded streams (or unbounded w/ invalidation)
  - **Equi join predicate**, **symmetric and non-blocking**
  - For every incoming tuple (e.g. left): probe (right)+emit, and build (left)



Excursus: Example Twitter Heron

[**Credit:** Karthik Ramasamy]

- **Motivation**
  - Heavy use of Apache Storm at Twitter
  - Issues: **debugging**, **performance**, shared **cluster resources**, back pressure mechanism



- **Twitter Heron**
  - API-compatible distributed streaming engine
  - De-facto streaming engine at Twitter since 2014

[Sanjeev Kulkarni et al: Twitter Heron: Stream Processing at Scale. **SIGMOD 2015**]

- **Dhalion (Heron Extension)**
  - Automatically reconfigure Heron topologies to meet throughput SLO

[Avrilia Floratou et al: Dhalion: Self-Regulating Stream Processing in Heron. **PVLDB 2017**]

- **Now back pressure implemented in Apache Storm 2.0 (May 2019)**

Q&A and Exam Preparation

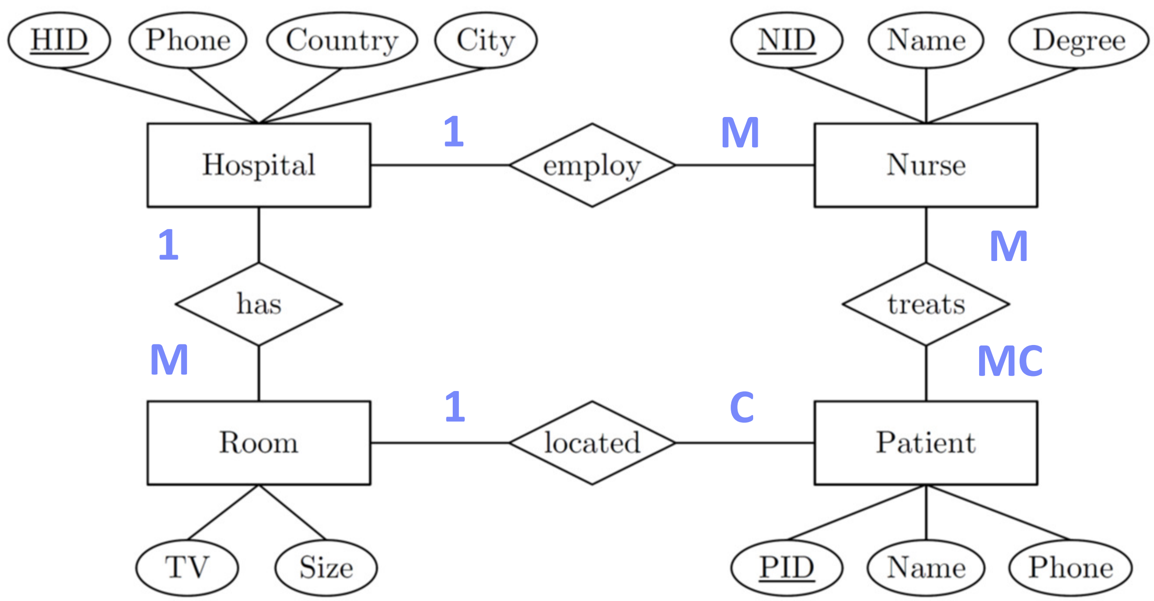
Basic focus: fundamental concepts and ability to apply learned techniques to given problems

Exam Logistics

- **Timing/Logistics**
  - [COVID-19]: Procedure and behavioral guide for on-campus exams (students) https://www.youtube.com/watch?v=dE4xoCjONRM&feature=youtu.be
  - Exam starts 10min after official start
  - 90min working time (plenty of time to think about answers)
  - **Write into the worksheet if possible**, additional paper allowed
  - Grading for June 22 will happen ~ June 27/28 → later exams as replacement
- **Covered Content**
  - **Must-have:** Data modeling/normalization, SQL query processing
  - Relational algebra, physical design, query and transaction processing
  - **DM only:** NoSQL, distributed storage and computation, streaming
- **Past Exams**
  - https://mboehm7.github.io/teaching/ws1920_dbs/index.htm (3+3)
  - https://mboehm7.github.io/teaching/ss19_dbs/index.htm (3+3)

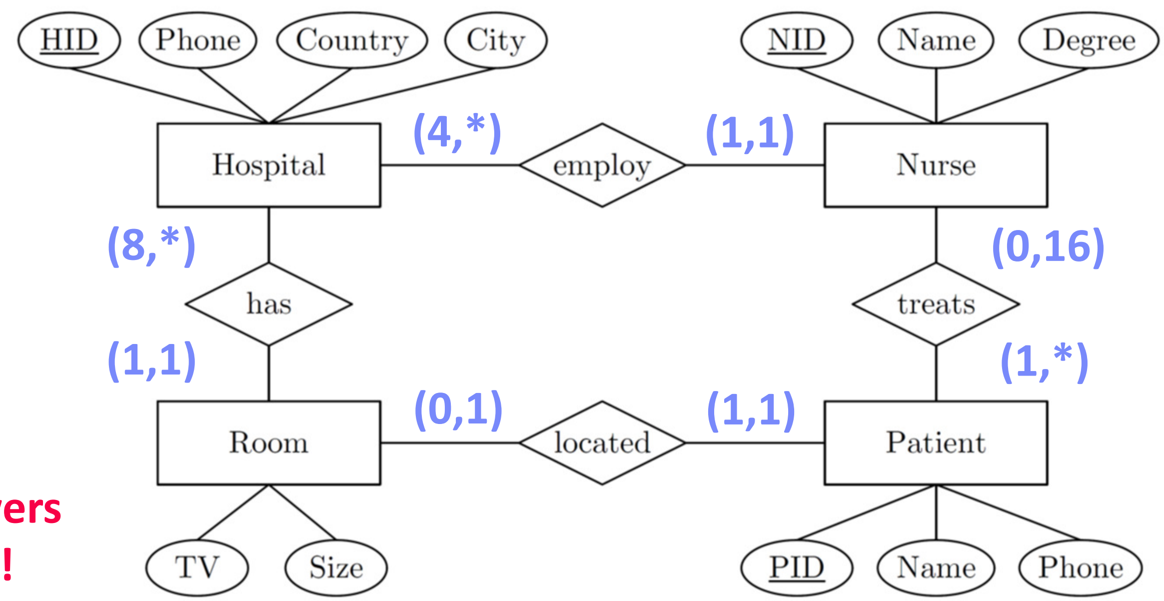
#1 Data Modeling

- **Task 1a: Specify the cardinalities in Modified Chen notation** (8 Points)
  - A hospital employs at least 4 nurses and has at least 8 patient rooms.
  - A nurse works in exactly one hospital and treats up to 16 patients.
  - A patient is treated by at least one but potentially many nurses.
  - Every patient has a room, a rooms belongs to exactly one hospital, and rooms are never shared by multiple patients.



#1 Data Modeling, cont.

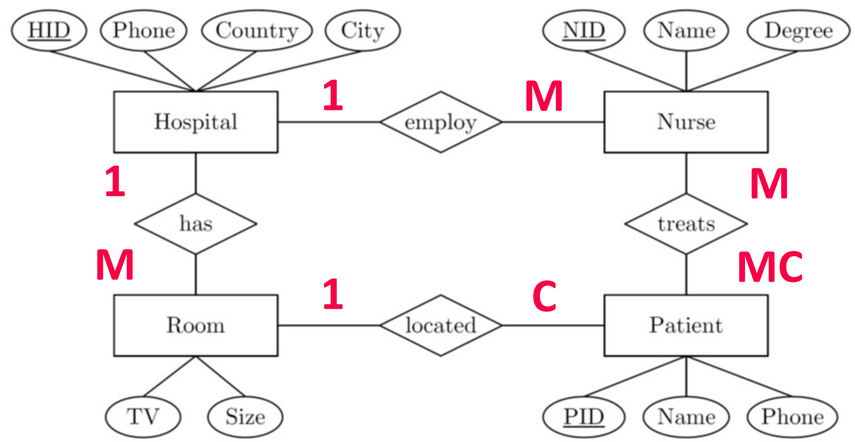
- **Task 1b: Specify the cardinalities in (min, max) notation (4 Points)**
  - A hospital employs at least 4 nurses and has at least 8 patient rooms.
  - A nurse works in exactly one hospital and treats up to 16 patients.
  - A patient is treated by at least one but potentially many nurses.
  - Every patient has a room, a rooms belongs to exactly one hospital, and rooms are never shared by multiple patients.



Only provide answers you're asked for!

#1 Data Modeling, cont.

- **Task 1c: Map the given ER diagram into a relational schema (10 points)**
  - Including data types, primary keys, and foreign keys



- **Solution**
  - Hospitals(
    HID:int, phone:char(16), Country:varchar(64), City:varchar(64))
  - Nurses(
    NID:int, Name:varchar(64), Degree:varchar(32), HID^{FK}:int)
  - Patient(
    PID:int, Name:varchar(64), Phone:char(16), RID^{FK}:int)
  - Room(
    RID:int, TV:boolean, Size:int, HID^{FK}:int)
  - Treated(
    NID^{FK}:int, PID^{FK}:int)

#1 Data Modeling, cont.

- **Task 1d: Bring your schema in 3rd normal form and explain why it is in 3NF (12 points)**
  - Let Hospital.Phone and Patient.Phone be multi-valued attributes
  - Assume the functional dependency City → Country

- **Solution**
  - `Phones(Number:char(16), HID^FK:int, PID^FK:int)` (primary key: Number)
  - `Cities(City:varchar(64), Country:varchar(64))` (primary key: City)
  - `Hospitals(HID:int, City^FK:varchar(64))` (primary key: HID)

  - **1st Normal Form:** no multi-valued attributes
  - **2nd Normal Form:** 1NF + all non-key attributes fully functional dependent on PK
  - **3rd Normal Form:** 2NF + no dependencies among non-key attributes

#2 Structured Query Language

- **Task 2a: Compute the results for the following queries (15 points)**

Orders

OID	Customer	Date	Quantity	PID
1	A	'2019-06-25'	3	2
2	B	'2019-06-25'	1	3
3	A	'2019-06-25'	1	4
4	C	'2019-06-26'	2	2
5	D	'2019-06-26'	1	4
6	C	'2019-06-26'	1	1

Products

PID	Name	Price
1	X	100
2	Y	15
4	Z	75
3	W	120

```
Q1: SELECT DISTINCT Customer, Date
      FROM Orders O, Products P
      WHERE O.PID = P.PID AND Name IN('Y','Z')
```

Customer	Date
A	'2019-06-25'
C	'2019-06-26'
D	'2019-06-26'

```
Q2: SELECT Customer, count(*) FROM Orders
      GROUP BY Customer
      ORDER BY count(*) DESC, Customer ASC
```

Customer	Count
A	2
C	2
B	1
D	1

```
Q3: SELECT Customer, sum(O.Quantity * P.Price)
      FROM Orders O, Products P
      WHERE O.PID = P.PID
      GROUP BY Customer
```

Customer	Sum
A	120
B	120
C	130
D	75

#2 Structured Query Language, cont.

- **Task 2b: Write SQL queries to answer the following Qs** (15 points)

Orders

OID	Customer	Date	Quantity	PID
1	A	‘2019-06-25’	3	2
2	B	‘2019-06-25’	1	3
3	A	‘2019-06-25’	1	4
4	C	‘2019-06-26’	2	2
5	D	‘2019-06-26’	1	4
6	C	‘2019-06-26’	1	1

Products

PID	Name	Price
1	X	100
2	Y	15
4	Z	75
3	W	120

Q4: Which products where bought on 2019-06-25 (return the distinct product names)?

```
SELECT DISTINCT P.Name
  FROM Orders O, Products P
  WHERE O.PID = P.PID
    AND Date = ‘2019-06-25’
```

Q5: Which customers placed only one order?

```
SELECT Customer FROM Orders
  GROUP BY Customer HAVING count(*) = 1
```

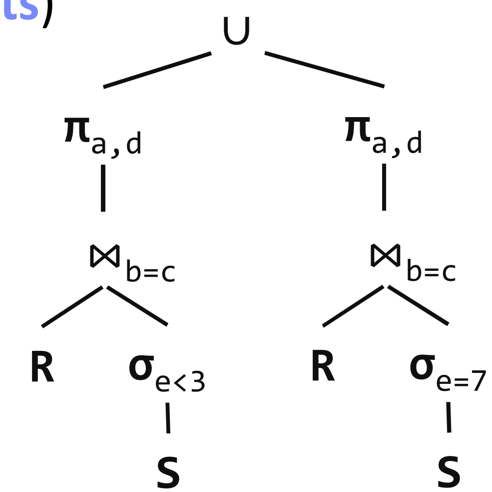
Q6: How much revenue (sum(O.Quantity * P.Price)) did products with a price less then 90 generate (return (product name, revenue))?

```
SELECT P.Name, sum(O.Quantity * P.Price)
  FROM Orders O, Products P
  WHERE O.PID = P.PID AND Price < 90
  GROUP BY P.Name
```

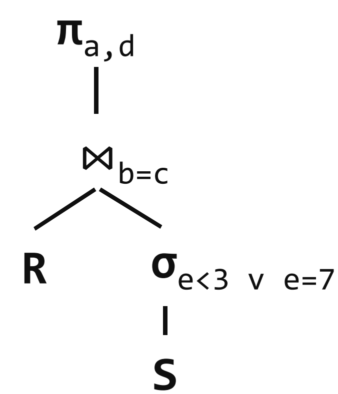
#3 Query Processing

- **Task 3a: Assume tables R(a,b), and S(c,d,e), draw a logical query tree in relational algebra for the following query: (5 points)**

```
Q7: SELECT R.a, S.d FROM R, S
      WHERE R.b = S.c AND S.e < 3
    UNION ALL
    SELECT R.a, S.d FROM R, S
      WHERE R.b = S.c AND S.e = 7
```

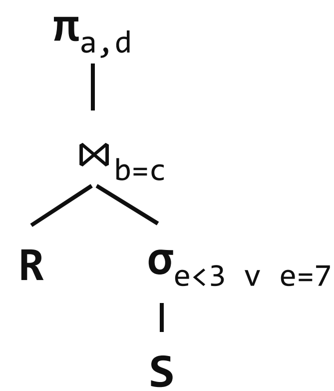


- **Task 3b: Draw an optimized logical query tree for the above query in relational algebra by eliminating the union operation (3 points)**

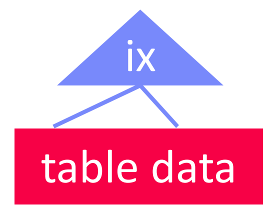


#3 Query Processing, cont.

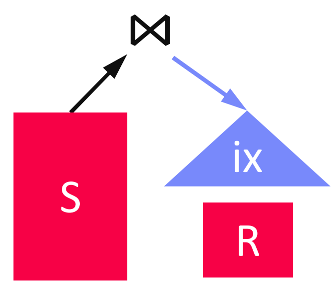
- **Task 3c: Given the schema and query above, which attribute or attributes are good candidates for secondary indexes and how could they be exploited during query processing? (4 points)**



- **Solution**
  - S.e → index scan
    (lookup e=7,
    lookup e=3 and scan DESC)



  - R.b (or S.c) → index nested loop join
    (for every S tuple s, loopup s.c in IX)



#3 Query Processing, cont.

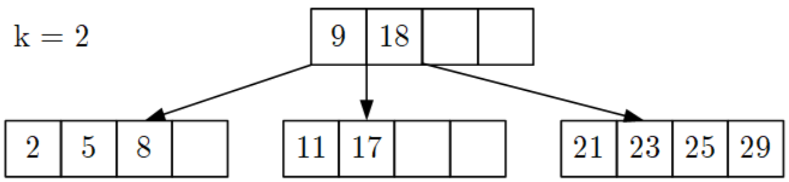
- **Task 3d: Describe the volcano (open-next-close) iterator model by example of a selection operator and discuss the space complexity of this selection operator.** (6 points)

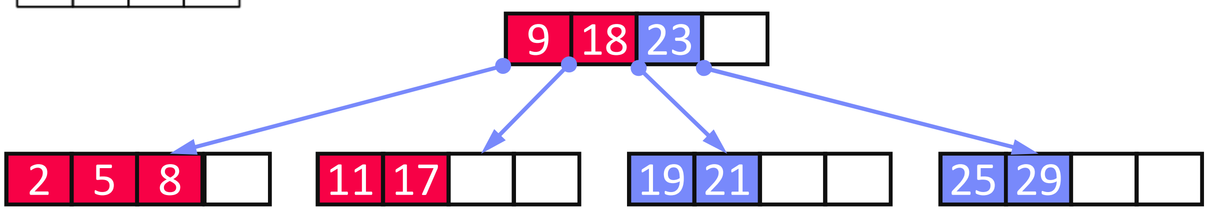
- **Solution**
  - Open, next, close calls propagate from root to leafs
  - **Open:** operator initialization
  - **Next:** compute next tuple (selection: call next of input until next qualifying tuple found)
  - **Close:** cleanup resources
  - **Space complexity:** O(1)

```
void open() { R.open(); }

void close() { R.close(); }

Record next() {
  while( (r = R.next()) != EOF )
    if( p(r) ) //A==7
      return r;
  return EOF;
}
```

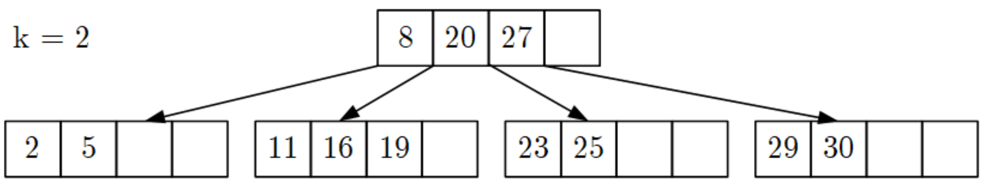
#4 Physical Design – B-Trees

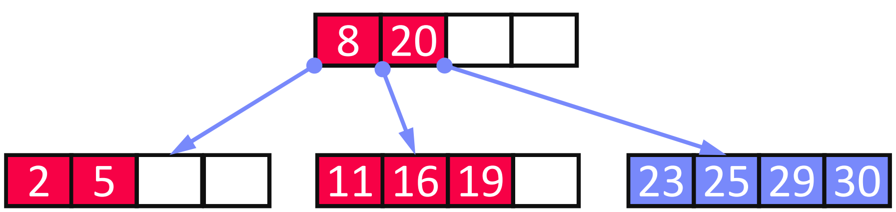
- **Task 4a: Given B-tree, insert key 19 and draw resulting B-tree (7 points)**





- **Task 4b: Given B-tree, delete key 27, and draw resulting B-tree (8 points)**

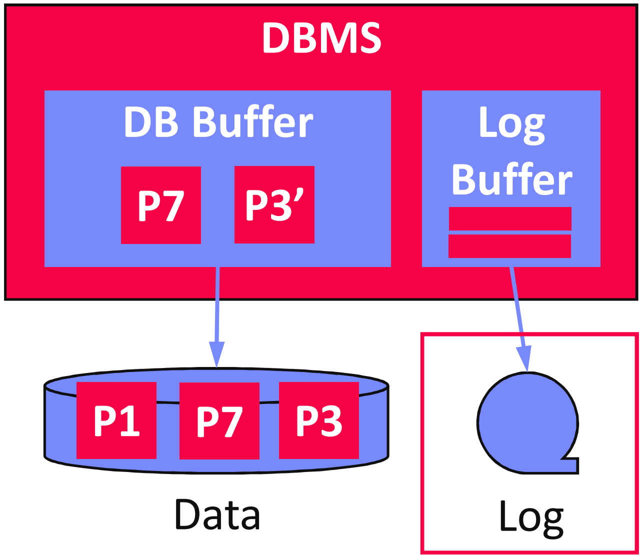




#5 Transaction Processing

- **Task 5a: Describe the concept of a database transaction log, and explain how it relates to the ACID properties Atomicity and Durability** (7 points)

- **Solution**
  - Log: append-only TX changes, often on separate devices
  - Write-ahead logging (log written before DB, forced-log on commit)
  - Recovery: forward (REDO) and backward (UNDO) processing

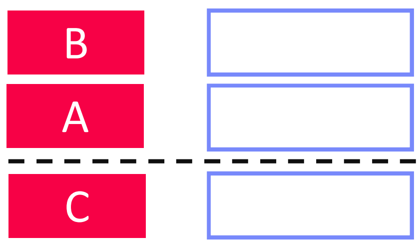


  - **#1 Atomicity:** A TX is executed atomically (completely or not at all); on failure/aborts no changes in DB (**UNDO**)
  - **#2 Durability: Guaranteed persistence** of changes of successful TXs; in case of system failures, the database is recoverable (**REDO**)

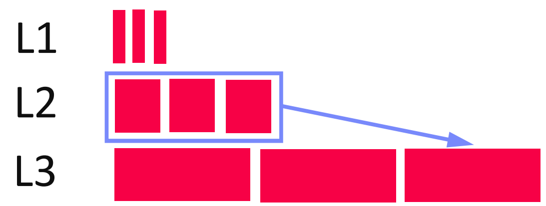
#6 NoSQL

- **Task 6a:** Describe the concept and system architecture of a **key-value store**, including techniques for achieving **high write throughput**, and **scale-out** in distributed environments. Please focus specifically on aspects of physical design such as **index structures**, and **distributed data storage**. (10 points)

- **Solution**
  - KV store: simple map of key-value pairs, w/ get/put interface, often distributed



  - Index structure for high write throughput: Log-structured merge trees (LSM)



  - Distributed data storage for scale-out:
    horizontal partitioning (sharding) via hash or range partitioning,
    partitioning via selection, reconstruction via union
    eventual consistency for high availability and partition tolerance

Conclusions and Q&A

- **12 Stream Processing Systems**
- **Q&A and Exam Preparation**

- **Misc**
  - Last Office Hour: **June 15, 1pm**
  - Exercise 4 Reminder: **June 16, 11.59pm** + [7+3 late days]

- **Exams**
  - **June 22: 11am-1pm**, **2pm-4pm**, **5pm-7pm** (i7, i11, i12, and i13)
  - **Oral exams** for international students (so far 5, to be scheduled)
  - 2nd Exam: July 1, 2pm (i7, i11, i12, and i13)
  - 3rd Exam: July 29, 2pm (i7, i11, i12, and i13)