Data Management
12 Stream Processing

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Last update: Jun 08, 2020
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

#4 Course Evaluation
- Please participate; open period: June 1 – July 15
#5 Data Management Courses

- **Architecture of Database Systems (ADBS, WS)**
- **DB system internals + prog. project**
- **Architecture of ML Systems (AMLS, SS)**
  - ML system internals + prog. Project
  - [Apache SystemDS*]

- **Data Integration and Large-Scale Analysis (DIA, WS)**
- **Distributed Data Management (usage and internals)**

- **Data Management / Databases (DM, SS+WS)**
- **Data management from user/application perspective**

*See [GitHub](https://github.com/apache/systemml) for more information.*
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)

- **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 with multiple consumers)
  - **Nodes**: asynchronous ops (with 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
    \[ \sigma_{A=7} \]

```java
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

![Diagram of query optimization](image)

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

\[ T_1 \mid U \mid \sigma_a \mid \sigma_b \mid \sigma_c \mid S_{AS} \mid S_{US} \mid S_{EU} \]

\[ T_2 \mid \sigma_d \mid Ad \]

\[ T_1 \mid U \mid \sigma_a \mid \sigma_b \mid \sigma_c \mid Ad \]

\[ T_2 \mid \sigma_d \mid Ad \]
System Architecture – Handling Overload

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

- **#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

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

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

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

// 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();

// 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));
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)

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

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

[Image: Diagram of stream processing, with a handshake-join concept.]

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

- **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)

```
Stream R  Stream S

H_{R,RID}  1, 1, 2, 7  H_{S,SID}  1, 7, 7

RID=SID

1 ab  7 zy
2 cd  1 xw
1 ef  7 vu
7 gh
```

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

- **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

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

- **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 \((\text{min}, \text{max})\) 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 3\(^{rd}\) 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 \(\rightarrow\) Country

- **Solution**
  - **Phones**\((\text{Number:char}(16), \text{HID}^{FK}:\text{int}, \text{PID}^{FK}:\text{int})\)
  - **Cities**\((\text{City:varchar}(64), \text{Country:varchar}(64))\)
  - **Hospitals**\((\text{HID:}\text{int}, \text{City}^{FK}:\text{varchar}(64))\)

  - **1\(^{st}\) Normal Form**: no multi-valued attributes
  - **2\(^{nd}\) Normal Form**: 1NF + all non-key attributes fully functional dependent on PK
  - **3\(^{rd}\) Normal Form**: 2NF + no dependencies among non-key attributes
#2 Structured Query Language

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

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

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

**Q3:**
```
SELECT Customer, sum(O.Quantity * P.Price)
FROM Orders O, Products P
WHERE O.PID = P.PID
GROUP BY Customer
```
#2 Structured Query Language, cont.

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

<table>
<thead>
<tr>
<th>Orders</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>OID</td>
<td>PID</td>
</tr>
<tr>
<td>Customer</td>
<td>Name</td>
</tr>
<tr>
<td>Date</td>
<td>Price</td>
</tr>
<tr>
<td>Quantity</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td></td>
</tr>
</tbody>
</table>

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

```sql
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?

```sql
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 than 90 generate (return (product name, revenue))? 

```sql
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)

$$Q7: \text{SELECT } R.a, S.d \text{ FROM } R, S \text{ WHERE } R.b = S.c \text{ AND } S.e < 3 \text{ UNION ALL SELECT } R.a, S.d \text{ FROM } R, S \text{ WHERE } R.b = S.c \text{ AND } S.e = 7$$

- **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**
  - \( S.e \rightarrow \text{index scan} \)
    - (lookup \( e=7 \), lookup \( e=3 \) and scan DESC)
  - \( R.b \) (or \( S.c \) → index nested loop join
    - (for every \( S \) tuple \( s \), lookup \( s.c \) in IX)

\[
\begin{align*}
\pi_{a,d} & \quad | \quad \bowtie_{b=c} \\
R & \quad | \quad \sigma_{e<3 \lor e=7} \\
S
\end{align*}
\]
#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 leaves
  - **Open:** operator initialization
  - **Next:** compute next tuple (selection: call next of input until next qualifying tuple found)
  - **Close:** cleanup resources
  - **Space complexity:** $O(1)$

```c
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)