Data Integration and Large-scale Analysis (DIA)
03 Replication and Message-oriented Middleware

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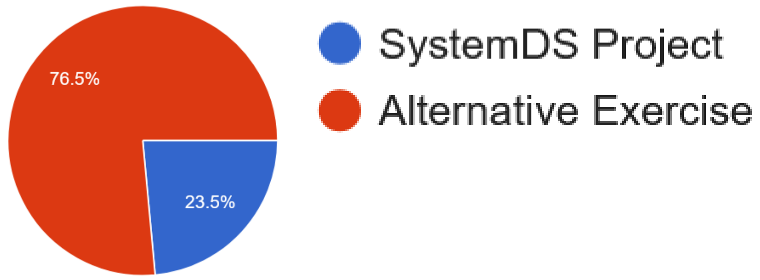
Big Data Engineering (DAMS Lab)

Last update: Oct 24, 2025

Announcements / Administrative Items

- **#1 Video Recording**
  - **Hybrid lectures:** in-person BH-N 243, zoom live streaming, video recording
  - https://tu-berlin.zoom.us/j/9529634787?pwd=R1ZsN1M3SC9BOU1OcFdmem9zT202UT09

- **#2 Project Selection**
  - Binding project/exercise selection by **Oct 31**
  - Via the following form (so far 34):



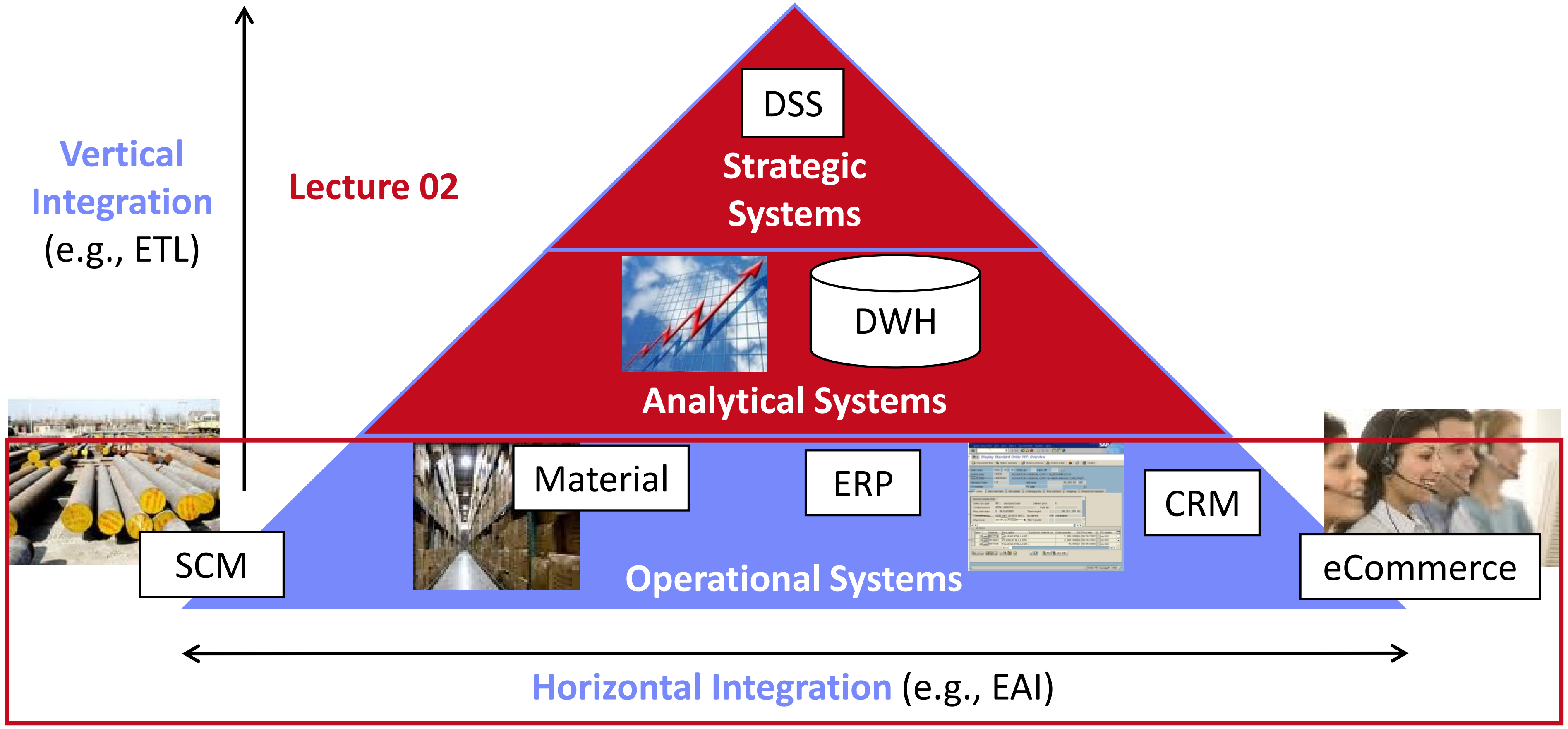
https://tinyurl.com/aytk6bw6

Agenda

- Motivation and Terminology
- Distributed TX & Replication Techniques
- Asynchronous Messaging
- Message-oriented Integration Platforms

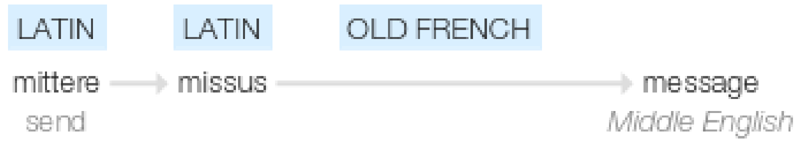
Motivation and Terminology

Recap: Information System Pyramid



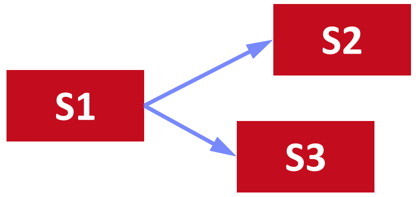
Lecture 03 (today)

Messaging



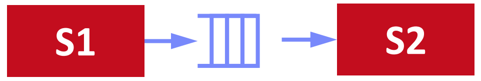
[**Credit:** https://www.gstatic.com/onebox/dictionary/etymology]

- **Def: Message**
  - Piece of information in certain structure
  - Send from source (transmitter) over channel to destination (receiver)
  - **Syntax:** different message formats (binary, text, XML, JSON, Protobuf)
  - **Semantic:** different domain-specific message schemas (aka data models)
- **Synchronous Messaging**
  - **Strict consistency requirements**
  - Overhead for distributed transactions via 2PC
  - Low local autonomy, usually data-driven



$$\begin{tikzcd} & S2 \\ S1 \arrow[ur] \arrow[dr] & \\ & S3 \end{tikzcd}$$

- **Asynchronous Messaging**
  - **Loose coupling**, **eventual consistency** requirements
  - Batching for efficient replication and updates
  - Latency of update propagation



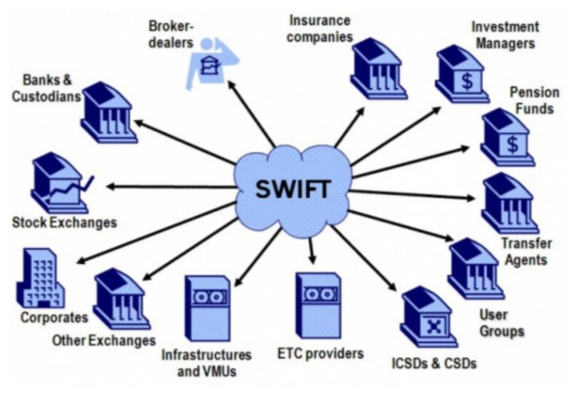
Types of Data Formats

- **General-Purpose Formats**
  - CLI/API access to DBs, KV-stores, doc-stores, time series DBs, etc
  - CSV (comma separated values)
  - JSON (javascript object notation), XML, Protobuf
- **Sparse Matrix Formats**
  - Matrix market: text IJV (row, col, value)
  - Libsvm: text compressed sparse rows
  - Scientific formats: NetCDF, HDF5
- **Large-Scale Data Formats**
  - ORC, Parquet (column-oriented file formats)
  - Arrow (cross-platform columnar in-memory data)
- **Domain-specific Formats: often binary, structured text, XML**

```
%%MatrixMarket matrix coordinate real general
% -------------------------------------------
% 0 or more comment lines
% -------------------------------------------
5  5  8
1 1 1.000e+00
2 2 1.050e+01
3 3 1.500e-02
1 4 6.000e+00
4 2 2.505e+02
4 4 -2.800e+02
4 5 3.332e+01
5 5 1.200e+01
```

Example Domain-specific Message Formats

- **Finance: SWIFT**
  - Society for Worldwide Interbank Financial Telecommunication
  - >10,000 orgs (banks, stock exchanges, brokers and traders)
  - Network and message formats for financial messaging
  - MT and MX (XML, ISO 20022) messages



[https://ihodl.com]

- **Health Care: HL/7, DICOM**
  - Health Level 7 (HL7) messages for clinical/admin data exchange (v2.x structured text msgs, v3 XML-based msgs)
  - Digital Imaging and Communications in Medicine (DICOM)
- **Automotive: ATF, MDF**
  - Association for Standardisation of Automation and Measuring Systems (ASAM)
  - E.g., Open Transport Data Format (ATF), Measurement Data Format (MDF), calibrations (CDF), auto-lead XML (ADF), open platform communications (OPC)

➔ **Sometimes Large-scale analytics over histories of messages** (e.g., health care analytics, fraud detection, money laundering)

Types of Message-Oriented Middleware

- **#1 Distributed TXs & Replication**

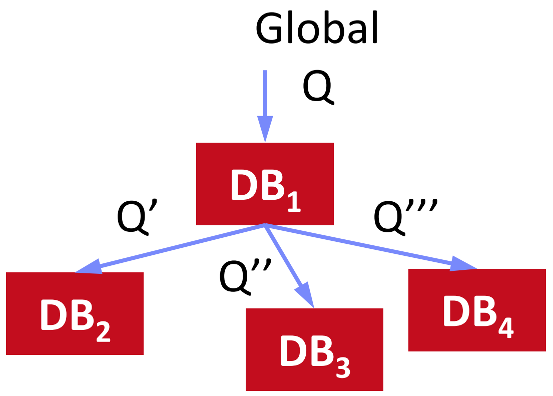
- **#2 Message Queueing**
  - Persistent message queues with well-defined delivery semantics
  - Loose coupling of connected systems or services (e.g., availability)

- **#3 Publish Subscribe**
  - Large number of subscribers to messages of certain topics/predicates
  - Published messages forwarded to qualifying subscriptions

- **#4 Integration Platforms**
  - Inbound/outbound adapters for external systems
  - Sync and async messaging, message transformations, enrichment

Distributed TX & Replication Techniques

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

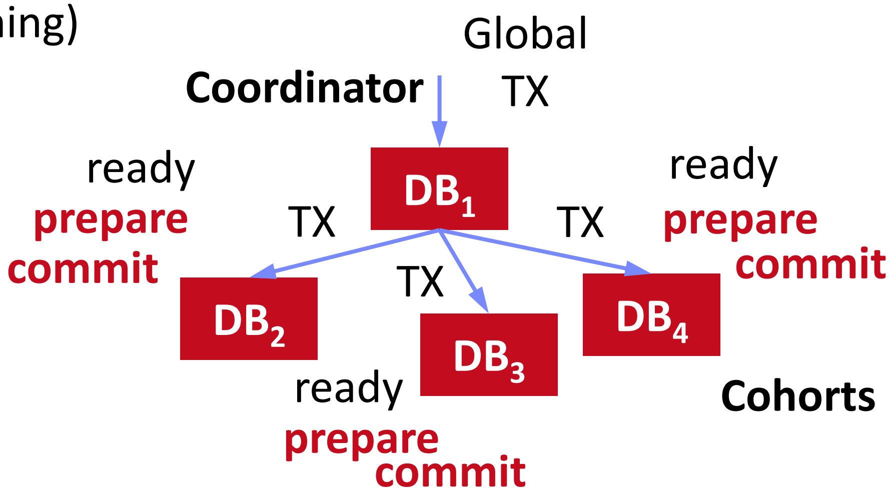
Two-Phase Commit (2PC)

- **Recap: Database Transaction**
  - A transaction (TX) is a **series of steps** that brings a database from a **consistent state** into another (not necessarily different) **consistent state**
  - **ACID properties** (atomicity, consistency, isolation, durability)

- **Problems in Distributed DBS**
  - Node failures, and communication failures (e.g., network partitioning)

  ➔ **Distributed TX processing to ensure consistent view** (atomicity/durability)

- **Two-Phase Commit** (via 4*(n-1) msgs)
  - **Phase 1 PREPARE:** check for successful completion, logging
  - **Phase 2 COMMIT:** commit/abort, release locks, and other cleanups
  - What happens if nodes unavailable, or report errors on prepare



Two-Phase Commit (2PC), cont.

- **Excursus: Wedding Analogy**
  - Coordinator: marriage registrar
  - Phase 1: Ask for willingness
  - Phase 2: If all willing, declare marriage
- **#1 Problem: Many Messages**
  - 4(n-1) messages in successful case, otherwise additional msgs
- **#2 Problem: Blocking Protocol**
  - Local node PREPARE → FAILED ➔ TX is guaranteed to be aborted
  - Local node PREPARE → READY ➔ waiting for global response
  - Failure of coordinator+cohort, or participating coordinator → **outcome unknown**
- **Other Problems**
  - Atomicity in heterogeneous systems w/o XA
  - Deadlock detection, optimistic concurrency control, etc

Note: APIs for automatic vs programmatic 2PC

Extended Distributed Commit Protocols

- **2PC Improvements**
  - **Hierarchical Commit:** establish message tree from coordinator to local nodes
    ➔ parallelization of message handling over inner nodes
  - **Presumed Abort:** assume abort if there are no commit log entries
    ➔ asynchronous logging of aborts, no ACK on abort

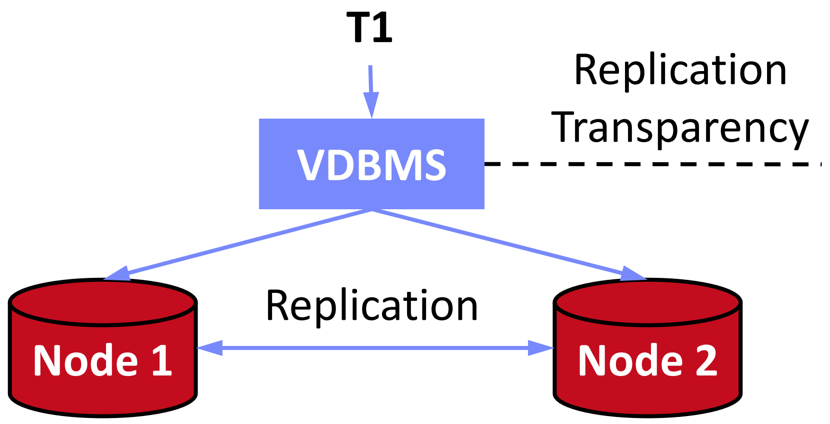
- **1PC (fewer messages)**
  - Combine TX operations w/ PREPARE to reduce 2(n-1) messages
  - Local nodes enter waiting state earlier

- **3PC (non-blocking)**
  - a) CAN COMMIT? Yes/no
  - b) PREPARE COMMIT? Ack
  - c) COMMIT? Ack
  - Cohorts can collectively decide on commit if at least one in PREPARE-COMMIT

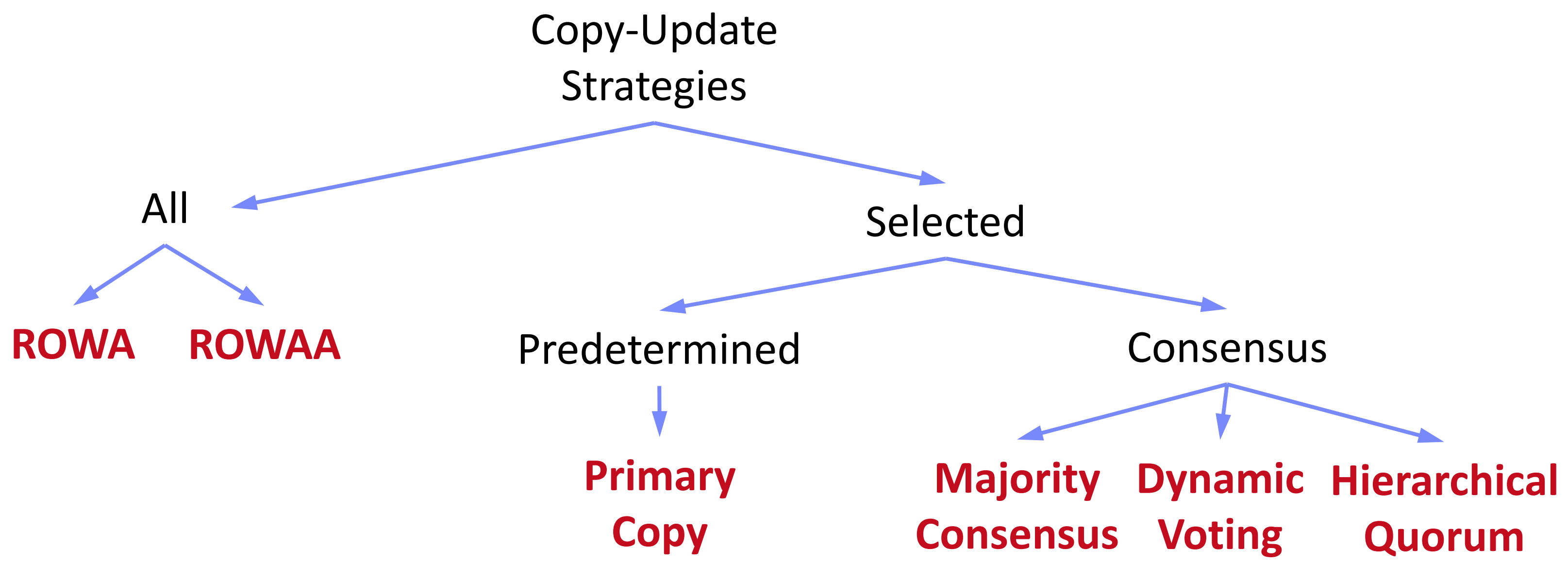
Protocol	# Msgs
1PC	2(n-1)
2PC	4(n-1)
3PC	6(n-1)

Replication Overview

- **Replication**
  - Redundancy of stored fragments
  - Availability/efficiency (read) vs update overhead / storage

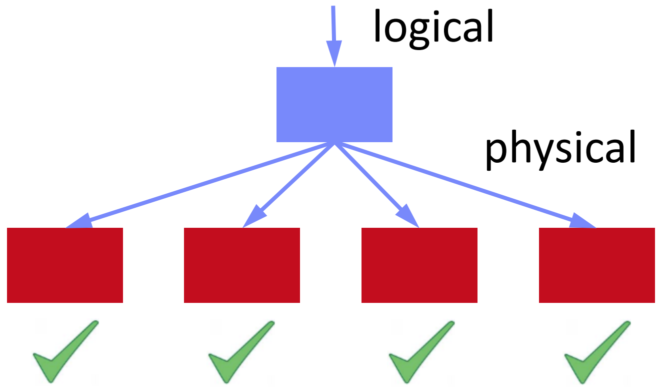


- **Replication Techniques**

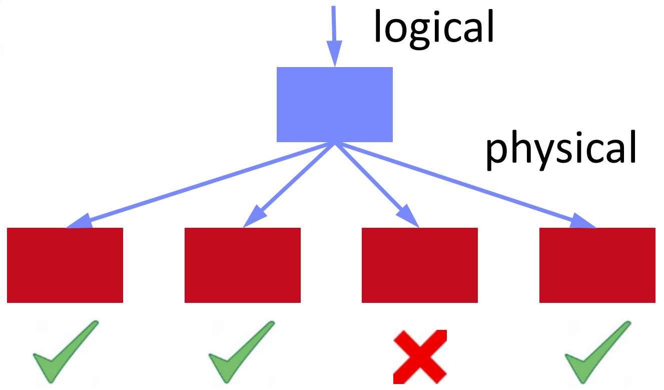


Replication Techniques

- **ROWA**
  - Read-One/Write-All
  - **Read:** good performance/availability
  - **Write:** high overhead and only successful if all available



- **ROWAA**
  - Read-One/Write-All-Available
  - **Relaxed availability requirement** for write operations

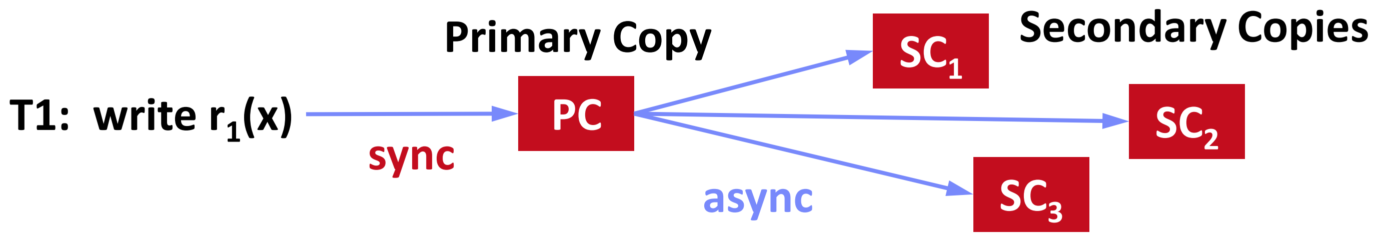


„Update anywhere-anytime-anyway transactional replication has unstable behavior as the workload scales up: **a ten-fold increase in nodes and traffic gives a thousand fold increase in deadlocks or reconciliations**. Master copy replication (**primary copy**) schemes reduce this problem."

[**Jim Gray**, Pat Helland, Patrick E. O'Neil, Dennis Shasha: The Dangers of Replication and a Solution, **SIGMOD 1996**]

Replication Techniques, cont.

- **Primary Copy**
  - Update single primary copy **synchronously**
  - **Asynchronous propagation** of updates to other replicates, read from all



  - **Pro:** Higher update performance, good locality, and availability
  - **Con:** Potentially stale read on secondary copies (w/ and w/o locks)
  - **Load balancing:** place PC of different objects on different nodes

Replication Techniques, cont.

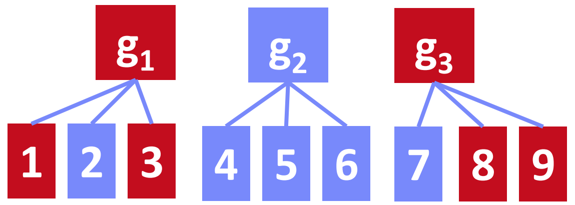
- **Consensus Protocols**
  - **Basic idea:** voting if read/write access is permissible (w.r.t. serializability)
  - Each replicate has vote → all votes Q
  - Read quorum Q_R and write quorum Q_W

Overlap Rules:

$Q_R + Q_W > Q$

$Q_W > Q/2$

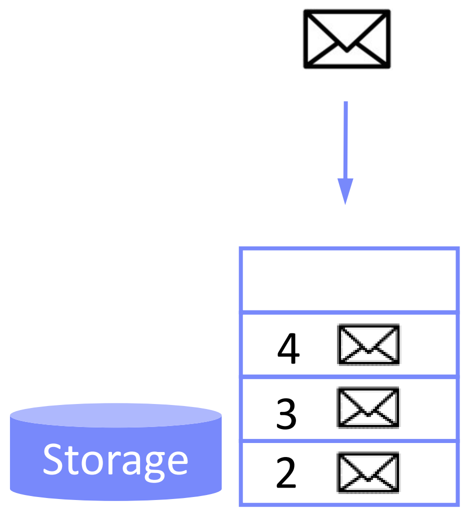
- **#1 Majority Consensus**
  - Read requires $Q_R > Q/2$, lock all and read newest replica
  - Write requires $Q_W > Q/2$, lock and update all
- **#2 Dynamic Quorums**
  - Problem: network partitioning → retain vote for updated replica
- **#3 Hierarchical Quorums**
  - Obtain majority of nodes (here **two**) in multiple levels of the tree



Asynchronous Messaging

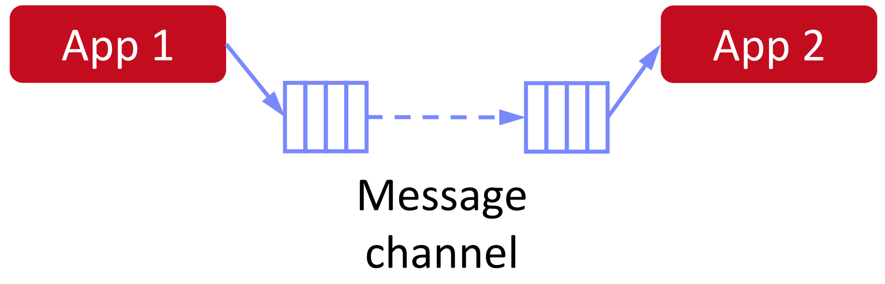
Message Queueing

- **Message**
  - Atomic packet of data + meta data, wrapped as a message



- **Message Queue**
  - FIFO or priority queue of messages
  - In-memory, sometimes with persistent storage backend and transactional semantics
  - Internal IDs, receive time

- **Remote Message Queues**
  - Loose coupling of applications (no direct API calls, etc)
  - Independent of HW and OS



Recap: Message Delivery 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

BREAK and Test Yourself!

- Assume a message-oriented middleware with a single FIFO message queue. Indicate, in the table below, true (✓) properties of the following three message delivery guarantees. [5 points]

	At Most Once	At Least Once	Exactly Once
Requires Message Persistence		✓	✓
Requires Delivery TX Mechanism			✓
Prevents Message Outrun	✓	✓	✓
Prevents Message Loss		✓	✓
Prevents Message Double Delivery	✓		✓

Example Systems

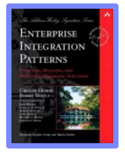
- **IBM MQSeries**
  - Message-oriented middleware for async queue communication
  - Connections/objects: **MQCONN**, MQDISC, MQOPEN, MQCLOSE
  - Queue ops: MQCRTMH, **MQPUT**, **MQGET**, MQSET, MQINQ, MQSTAT
  - Transactions: MQBEGIN, MQBACK, MQCMIT

- **JMS (Java Message Service)**
  - J2EE API of messaging services in Java (messages, queues, sessions, etc)
  - JMS providers: e.g., **IBM Websphere MQ**, **Apache ActiveMQ, RabbitMQ**

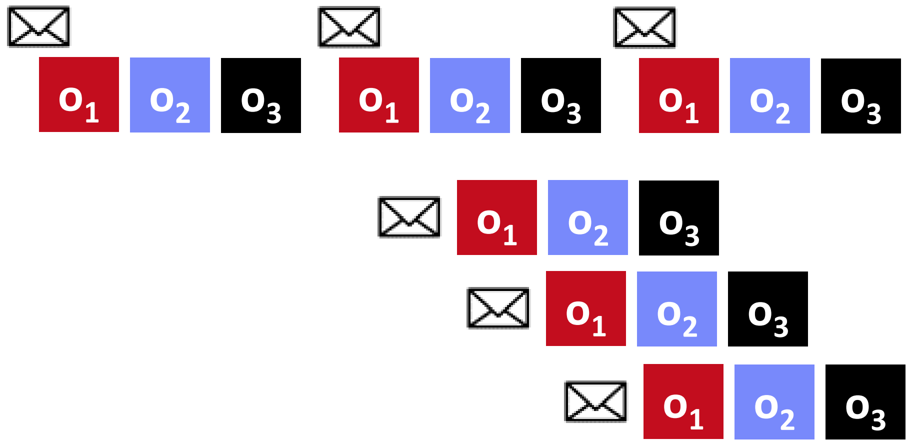
- **AWS Simple Queueing Service (SQS)**
  - Message queueing service for loose coupling of micro services
  - Default queue: best effort order, **at-least-once**, high throughput
  - FIFO: guarantees FIFO order, and **exactly-once**

Parallel Message Processing

[Gregor Hohpe, Bobby Woolf: Enterprise Integration Patterns, Addison-Wesley, 2004]

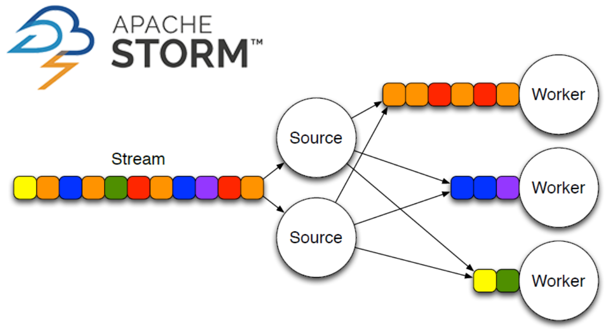


- **#1 Pipeline Parallelism**
  - **"Pipes and filters"**: leverage pipeline parallelism of chains of operators
  - More complex w/ routing / control flow (possible via punctuations)



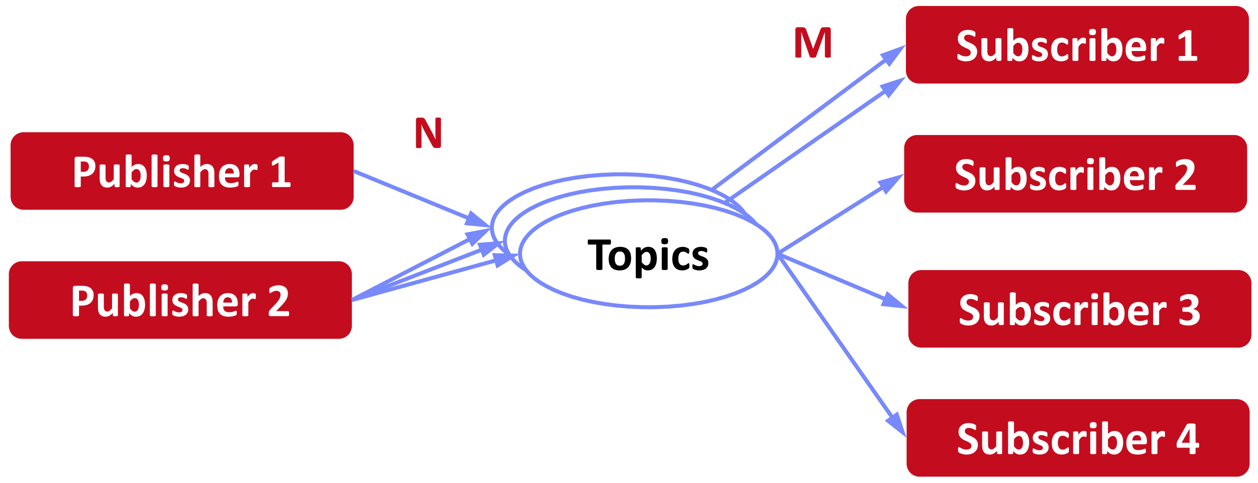
- **#2 Operator Parallelism**
  - Multi-threaded execution of multiple messages within one operator (pattern **"competing consumers"**)
  - Requires robustness against partial out-of-order, or resequencing

- **#3 Key Range Partitioning**
  - Explicit routing to independent pipelines (patterns **"message router"**, **"content-based router"**)
  - Ordering requirements only within each pipeline



Publish/Subscribe Architecture

- **Overview Publish-Subscribe (Pub/Sub)**



- **Key Characteristics**
  - Often imbalance between few publishers and many subscribers
  - Topics: explicit or implicit (e.g., predicates) groups of messages to publish into or subscribe from
  - Addition and deletion of subscribers rare compared to message load
  - ECA (event condition action) evaluation model
  - Often **at-least-once** guarantee

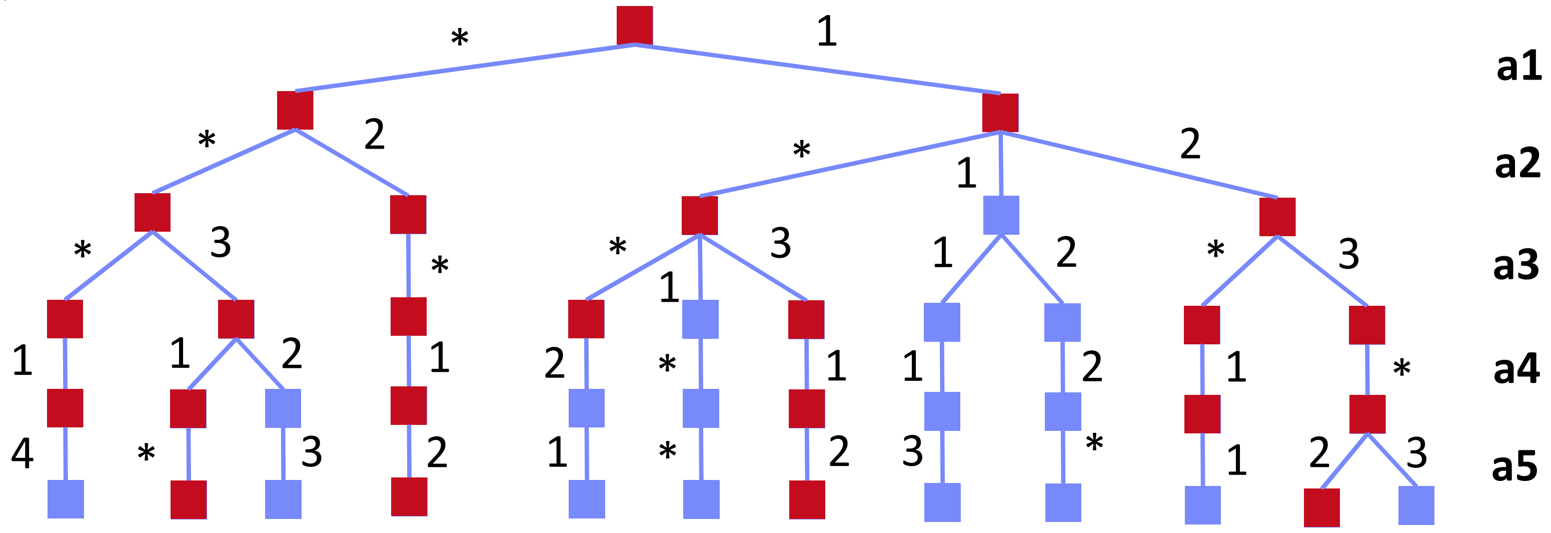
Alternative Exercise:
Streaming Full Text Search
[https://mboehm7.github.io/teaching/ws2425_dia/DIA_2024_Exercise.pdf]

Publish/Subscribe Architecture, cont.

- **Subscriber Filtering**
  - Complex predicates of range filters, equi-predicates, and negation
  - **Goal:** Avoid naïve scan over all subscriber predicates / topics
- **Matching Algorithm**
  - Matching event against a set of subscriptions
  - **Approach:** sorting and parallel search tree

[Guruduth Banavar et al: An Efficient Multicast Protocol for Content-Based Publish-Subscribe Systems. **ICDCS 1999**]

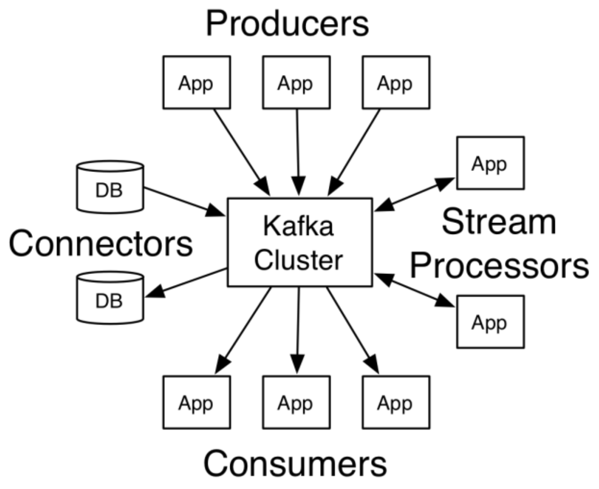
Example Publish
$\{a_1=1, a_2=2, a_3=3, a_4=1, a_5=2\}$



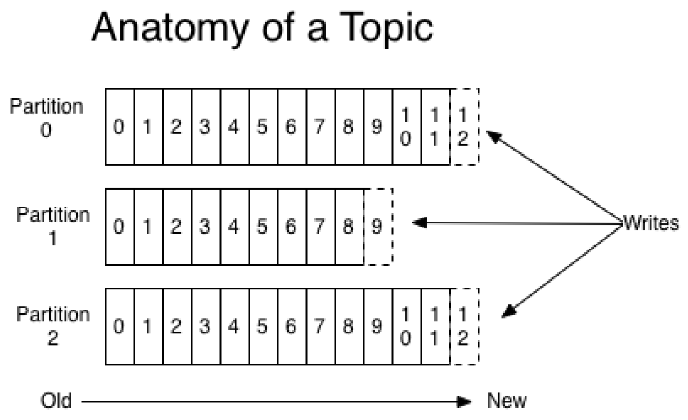
Apache Kafka

[https://kafka.apache.org/documentation]

- **Overview System Architecture**
  - **Publish & Subscribe** system w/ partitioned topics
  - **Storage of data streams** in distributed, fault-tolerant cluster (replicated)
  - Configurable **retention periods** (e.g., days)
  - **APIs:** producer API, consumer API, streams API, Connector API



- **Topics**
  - Explicit categories w/ user-defined (semantic) partitioning
  - Partitions are ordered, immutable sequences of records (log) w/ **offsets**
  - Current **offset** per consumer stored



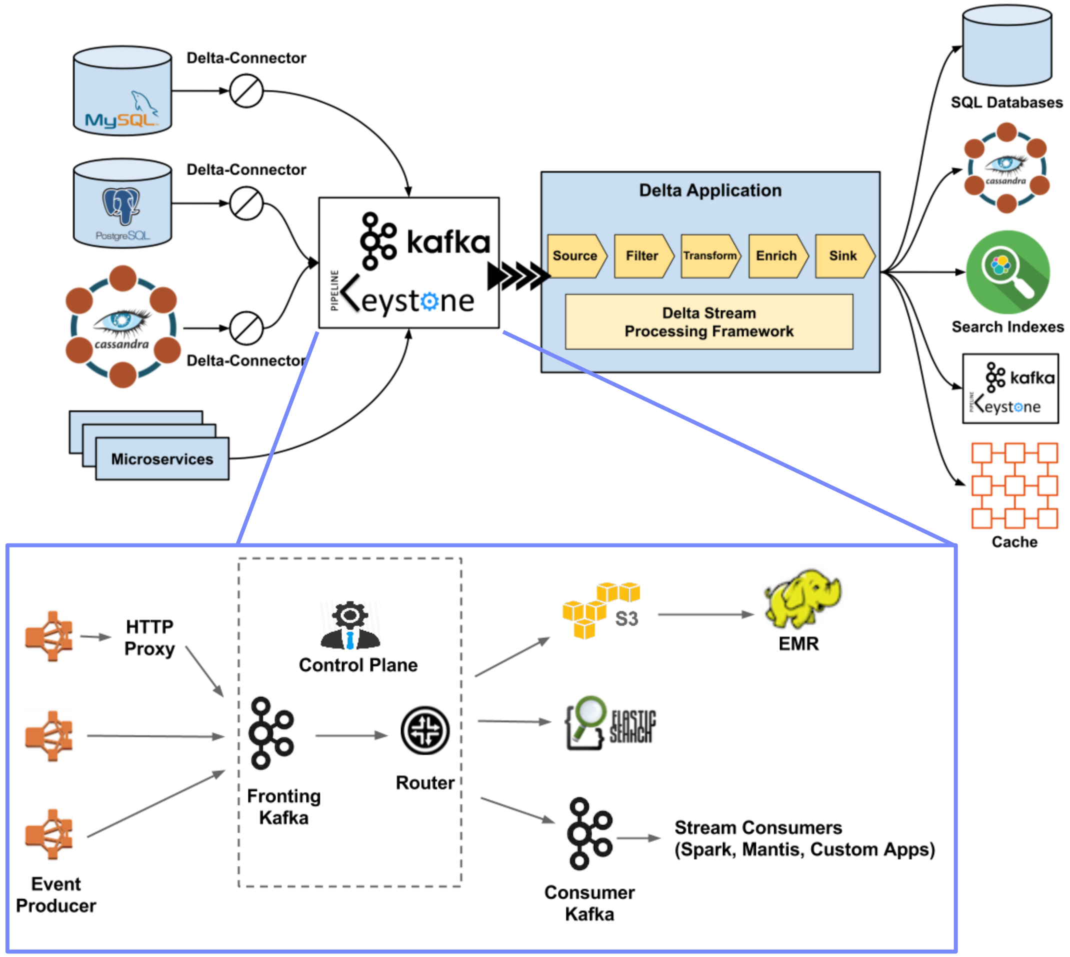
Apache Kafka, cont.

[https://medium.com/netflix-techblog/delta-a-data-synchronization-and-enrichment-platform-e82c36a79aee, Oct 15 2019]

- **Netflix Delta**
  - **A Data Synchronization and Enrichment Platform**
  - DSL and UDF APIs for custom filters and transformations

- **Netflix Keystone** (Kafka frontend)
  - **~500G events/day** (5M events/s peak)
  - **~1.3PB/day**

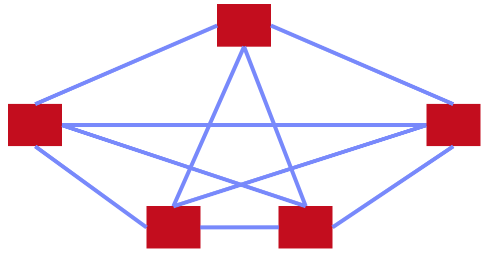
[https://medium.com/netflix-techblog/evolution-of-the-netflix-data-pipeline-da246ca36905]

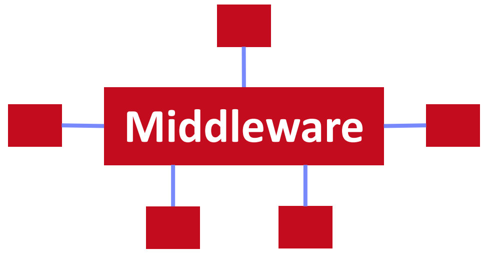


Message-oriented Integration Platforms

Overview Message-oriented Integration Platforms

- **Motivation**
  - Integration of many applications and systems via common IR
  - **Beware:** syntactic vs semantic data models

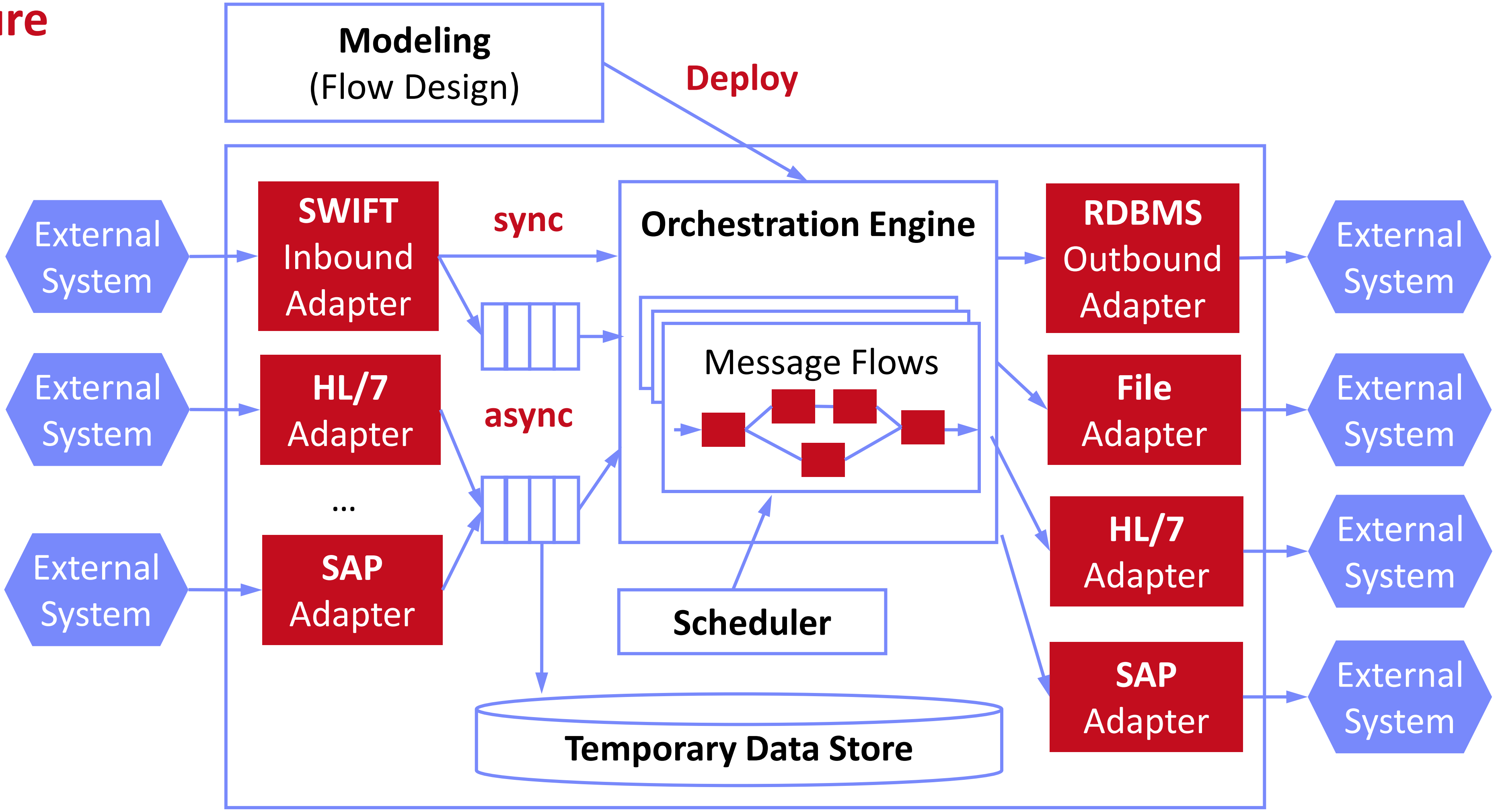




- **Evolving Names**
  - **Enterprise Application Integration** (EAI)
  - **Enterprise Service Bus** (ESB)
  - **Message Broker**

- **Example Systems**
  - IBM App Connect Enterprise (aka Integration Bus, aka Message Broker)
  - MS Azure Integration Services + Service Bus (aka Biztalk Server)
  - SAP Process Integration (aka Exchange Infrastructure)
  - SQL AG TransConnect

Common System Architecture



Common System Architecture, cont.

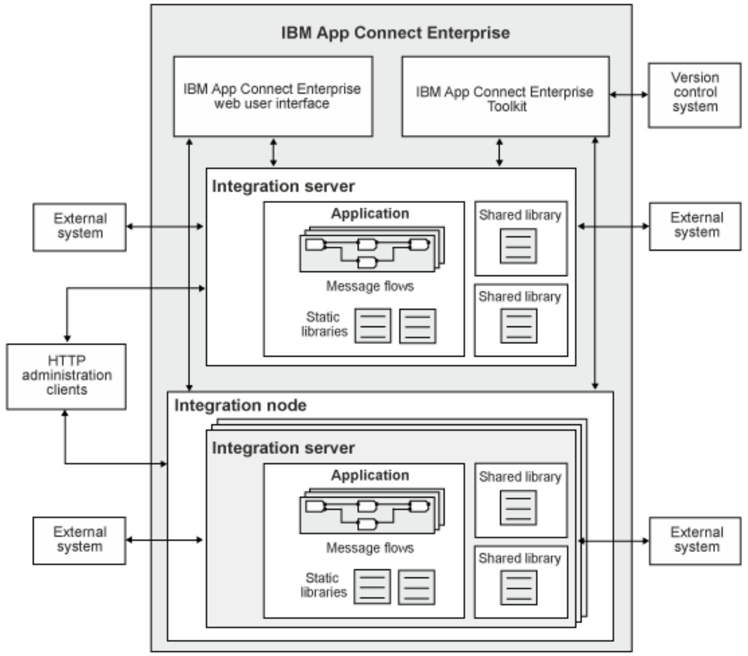
- **#1 Synchronous Message Processing**
  - **Event: client input message**
  - Client system blocks until message flow executed to output messages delivered to target systems

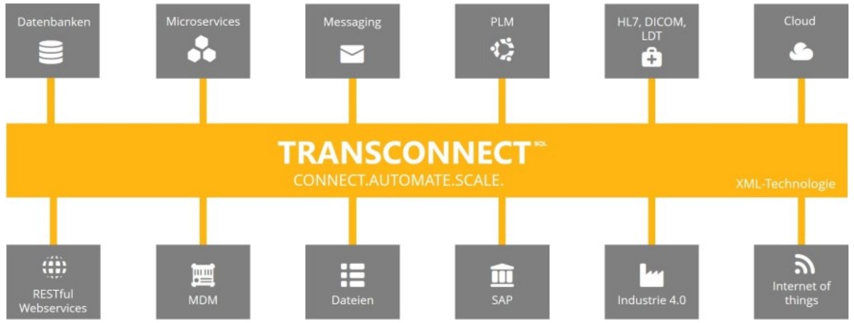
- **#2 Asynchronous Message Processing**
  - **Event: client input message from queue**
  - Client system blocks until input message stored in queue
  - Asynchronous message flow processing and output message delivery (**streaming**)
  - Optional acknowledgement, when input message successfully processed

- **#3 Scheduled Processing**
  - **Event: time-based scheduled** message flows (CronJobs)
  - Periodic data replication and loading (e.g., **ETL use cases**)

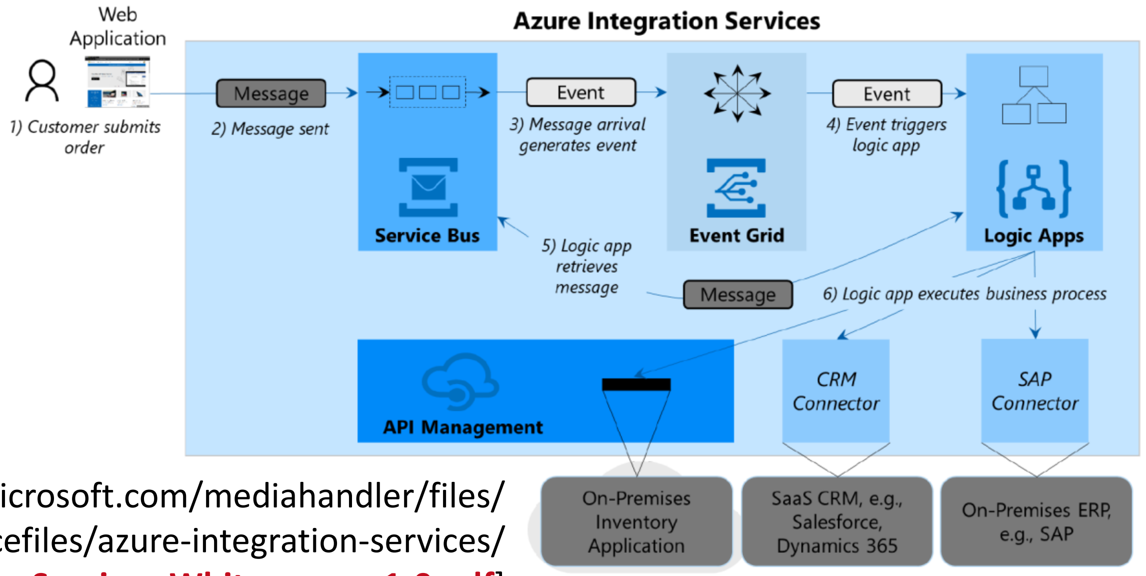
Commercial Systems

[**IBM App Connect Enterprise:** https://www.ibm.com/support/knowledgecenter/en/SSTTDS_11.0.0/com.ibm.etools.mft.doc/ab20551_.htm]


IBM App Connect Enterprise
IBM App Connect Enterprise web user interface
IBM App Connect Enterprise Toolkit
Version control system
Integration server
Application
Message flows
Static libraries
Shared library
External system
HTTP administration clients
Integration node



[**SQL AG:** https://www.transconnect-online.de/]

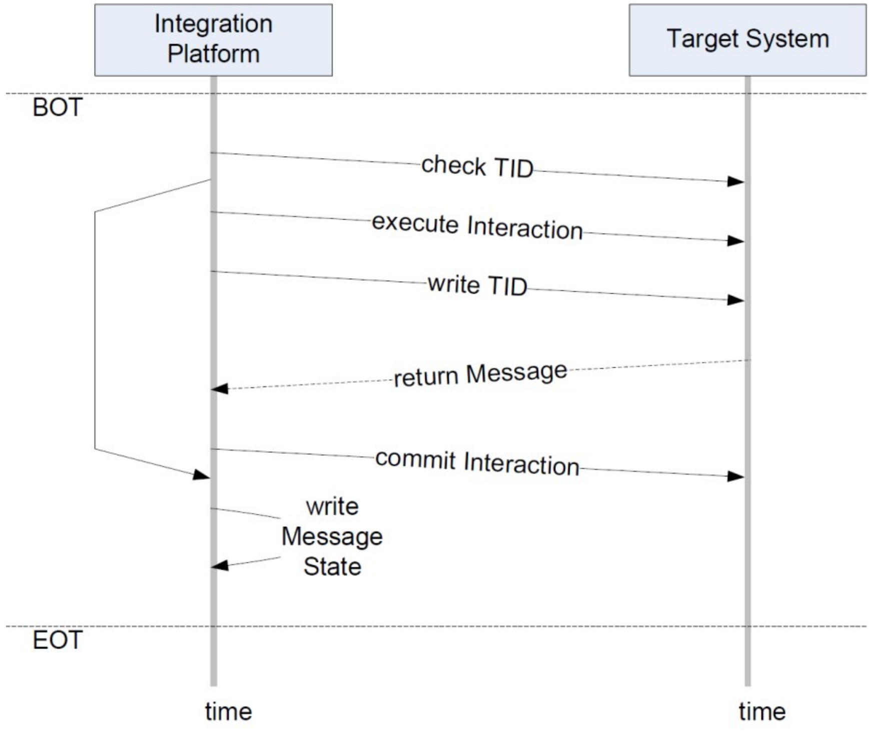

Web Application
Azure Integration Services
1) Customer submits order
Message
2) Message sent
Service Bus
Event
3) Message arrival generates event
Event Grid
Event
4) Event triggers logic app
Logic Apps
5) Logic app retrieves message
Message
6) Logic app executes business process
API Management
CRM Connector
SAP Connector
On-Premises Inventory Application
SaaS CRM, e.g., Salesforce, Dynamics 365
On-Premises ERP, e.g., SAP

[https://azure.microsoft.com/mediahandler/files/resourcefiles/azure-integration-services/**Azure-Integration-Services-Whitepaper-v1-0.pdf**]

Message Delivery Guarantees, cont.

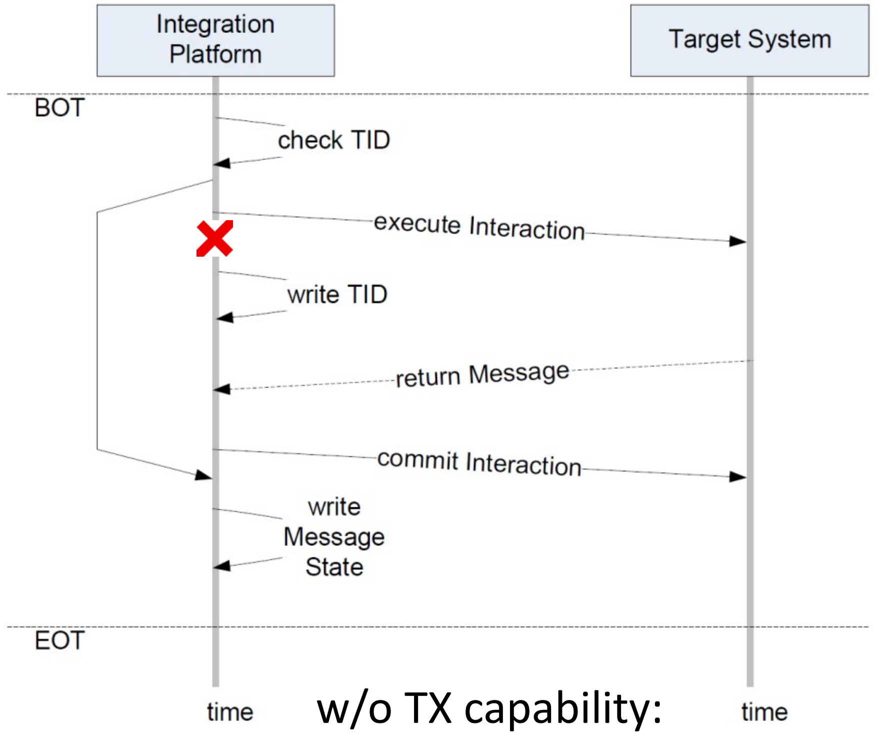
- **Example**
  Exactly-Once

Remote ID Maintenance w/ TX capability



[**Credit:** SQL AG - **https://www.transconnect-online.de/**]

Local ID Maintenance w/ TX capability



w/o TX capability:
at-least-once

Recap: XML (Extensible Markup Language)

- **XML Data Model**
  - Meta language to define specific **exchange formats**
  - Document format for **semi-structured data**
  - Well formedness
  - XML schema / DTD
- **XPath** (XML Path Language)
  - Query language for **accessing collections of nodes** of an XML document
  - Axis specifies for ancestors, descendants, siblings, etc
- **XSLT** (XML Stylesheet Language Transformations)
  - Schema mapping (transformation) language for XML documents
- **XQuery**
  - Query language to extract, transform, and analyze XML documents

```
<?xml version="1.0" encoding="UTF-8"?>
<data>
  <student id="1">
    <course id="INF.01014UF" name="Databases"/>
    <course id="706.550" name="AMLS"/>
  </student>
  <student id="5">
    <course id="706.004" name="Databases 1"/>
  </student>
</data>
```

```
/data/student[@id='1']/course/@name
```

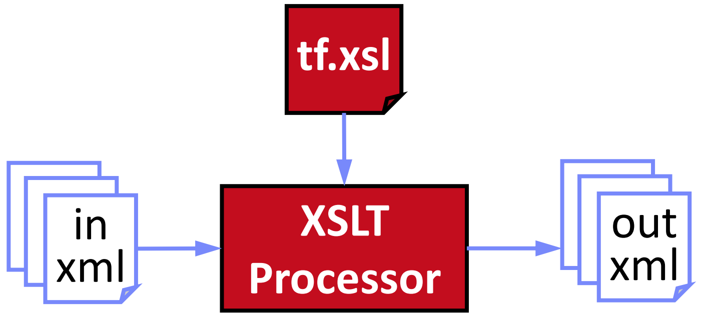
↓

"Databases"
"AMLS"

XSLT in Integration Platforms

- **Problem**
  - XML often used as **external and internal data representation**
  - Different schemas (message types) ➔ **requires mapping**

- **XSLT Overview**
  - XSLT processor transforms input XML document according to XML stylesheet to output XML documents
  - Subtree specifications via XPath, loops, branches, built-in functions for text processing, etc
  - **Streaming:** STX or XSLT 3.0 streaming
  - **CSV** and **JSON** input/output possible



- **Note: Similar tools/libraries for JSON**

XSLT Example

```
<?xml version="1.0" encoding="UTF-8"?>
<xsl:stylesheet version="2.0“ xmlns:xsl="http://www.w3.org/1999/XSL/Transform">
<xsl:template match="/">
  <xsl:element name=“suppliers">
    <xsl:for-each select="/resultsets/resultset[@Tablename='Supplier']/row">
      <xsl:element name=“supplier">
        <xsl:attribute name=“ID"><xsl:value-of select="Suppkey"/></xsl:attribute>
        <xsl:element name="Name"><xsl:value-of select="SuppName"/></xsl:element>
        <xsl:element name="Address"><xsl:value-of select="SuppAddress"/></xsl:element>
      </xsl:element>
    </xsl:for-each>
  </xsl:element>
</xsl:template>
</xsl:stylesheet>
```

```
<resultssets>
  <resultset Tablename=“Supplier”>
    <row>
      <Suppkey>7</Suppkey>
      <SuppName>MB</Suppname>
      <SuppAddress>1035 Coleman Rd</SuppAddress>
    </row>
    <row> … </row>
  </resultset>
</resultsets>
```

```
<suppliers>
  <supplier ID=“7”>
    <Name>MB</Name>
    <Address>1035 Coleman Rd</Address>
  </supplier>
  <supplier> … </supplier>
<suppliers>
```

Summary and Q&A

- **Distributed TX & Replication Techniques**
  - Distributed commit protocols
  - Different replication techniques
- **Message-oriented Middleware**
  - Asynchronous Messaging
    (message queueing, publish/subscribe)
  - Message-oriented Integration Platforms
    (system architecture, systems, transformations)
- **Next Lectures (Data Integration Architectures)**
  - **04 Schema Matching and Mapping** [Nov 06]
  - **05 Entity Linking and Deduplication** [Nov 13]
  - **06 Data Cleaning and Data Fusion** [Nov 20]
  - **07 Data Provenance and Catalogs** [Nov 27]

Macroscopic View

Microscopic View