Imperial College London
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Drinking From The Fire Hose: Scalable Stream Processing Systems

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The Data Deluge

1200 Exabytes (billion GBs) created in 2010 alone

– Increased from 150 Exabytes in 2005

Many new sources of data become available

– Sensors, mobile devices
– Web feeds, social networking
– Cameras
– Databases
– Scientific instruments

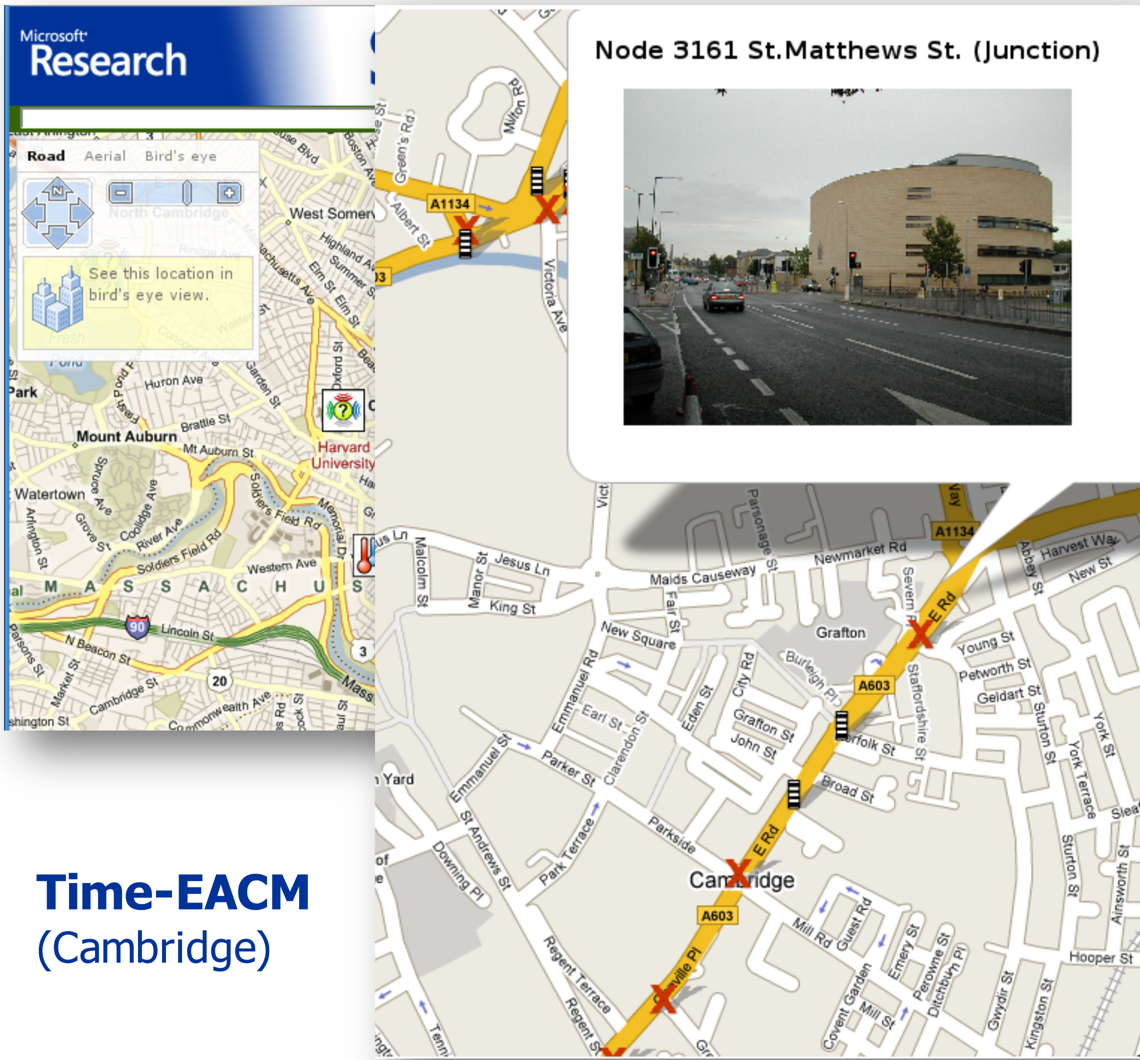


☛ **How can we make sense of all data ?**

– Most data is not interesting
– New data supersedes old data
– Challenge is not only storage but processing

Sensing and IoT

Instrumenting country's transportation infrastructure



Time-EACM
(Cambridge)

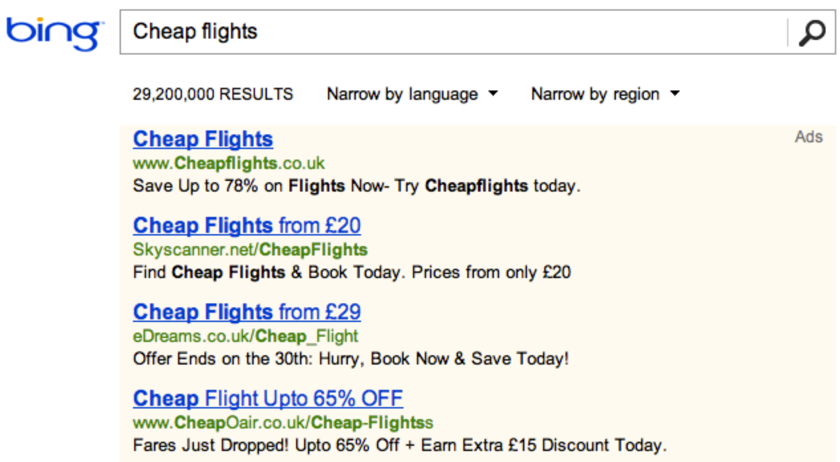
Many parties interested in data

- Road authorities, traffic planners, emergency services, commuters
- But access not everything: Privacy

High-level queries

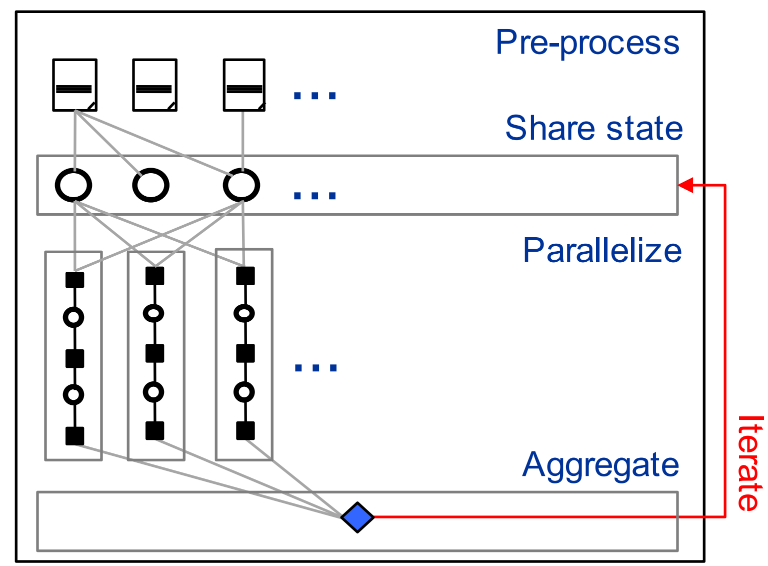
- "What is the best time/route for my commute through central London between 7-8am?"

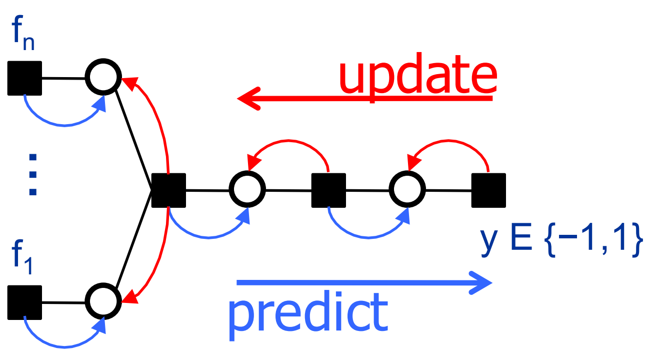
Click Stream Analysis



Problem:

Want to provide up-to-date predictions regarding which ads to serve

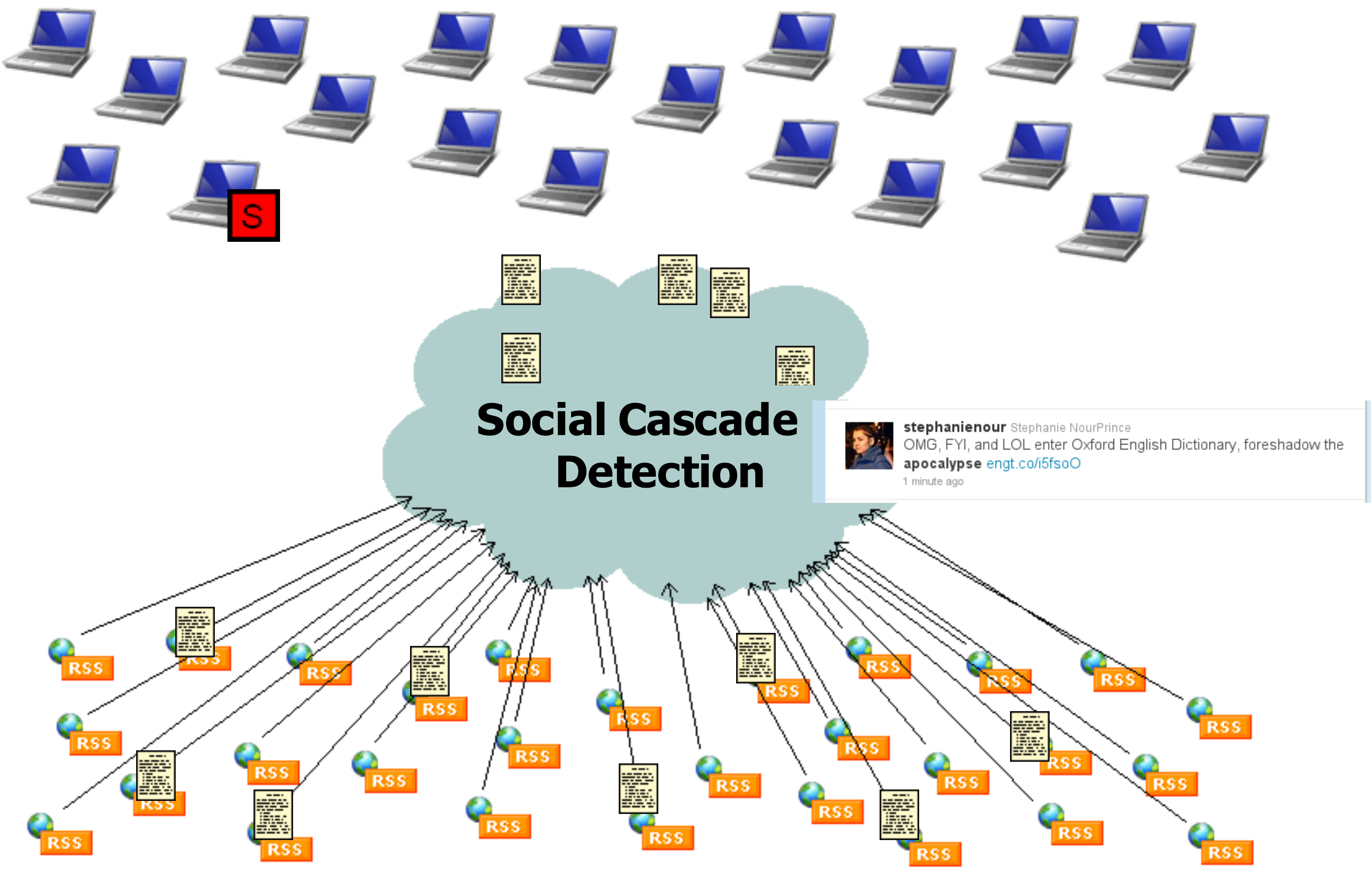




Solution:

Bayesian online learning algorithm ranks adverts according to probability of "click"

Social Data Mining



Detection and reaction to social cascades

Fraud Detection

How to detect identity fraud as it happens?

Illegal use of mobile phone, credit card, etc.

- Offline: avoid aggravating customer
- Online: detect and intervene

Huge volume of call records

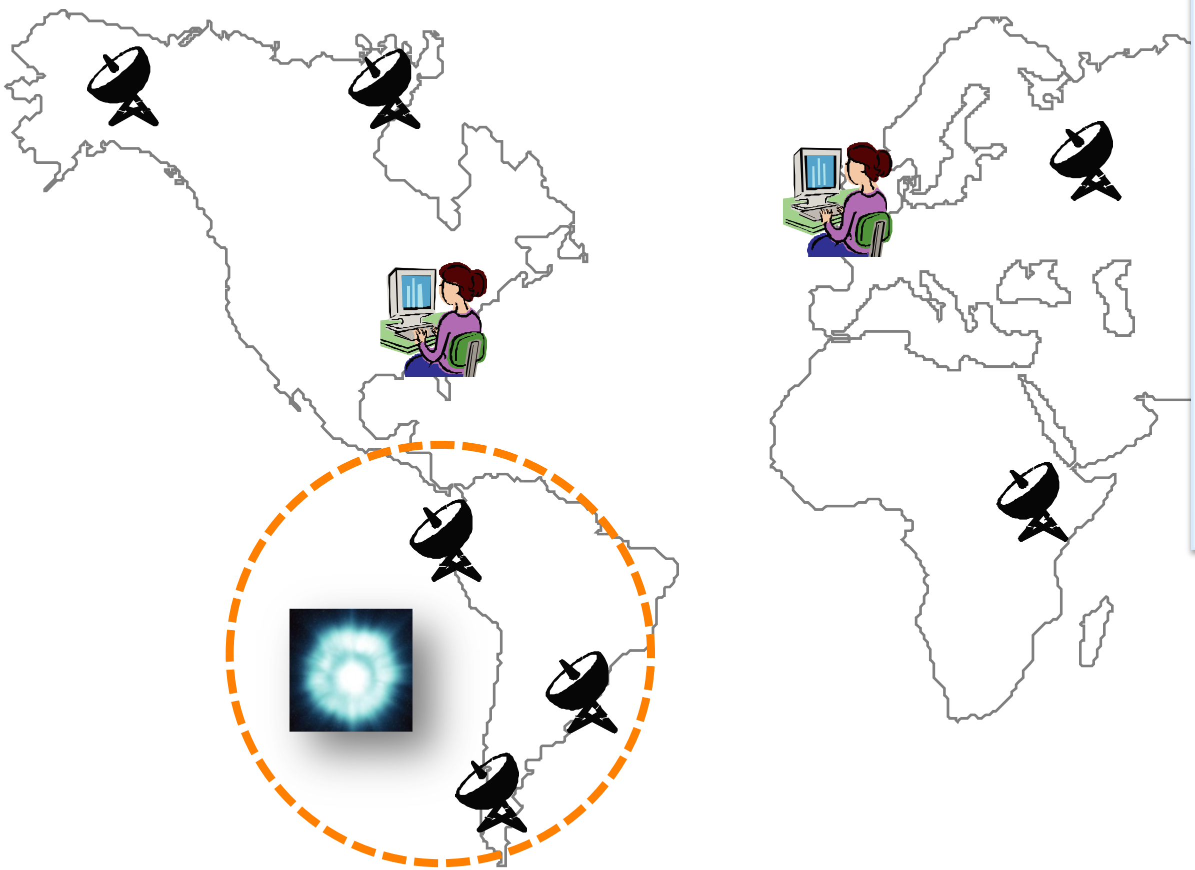
More sophisticated forms of fraud

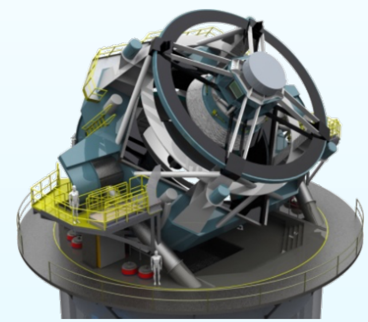
- e.g. insider trading

Supervision of laws and regulations

- e.g. Sabanes-Oxley, real-time risk analysis

Astronomic Data Processing





Large Synoptic Survey Telescope (LSST)

- Generates 1.28 Petabytes per year

Analysing transient cosmic events: γ-ray bursts

Stream Processing to the Rescue!

☛ Process data streams on-the-fly without storage

Stream data rates can be high

- High resource requirements for processing (clusters, data centres)

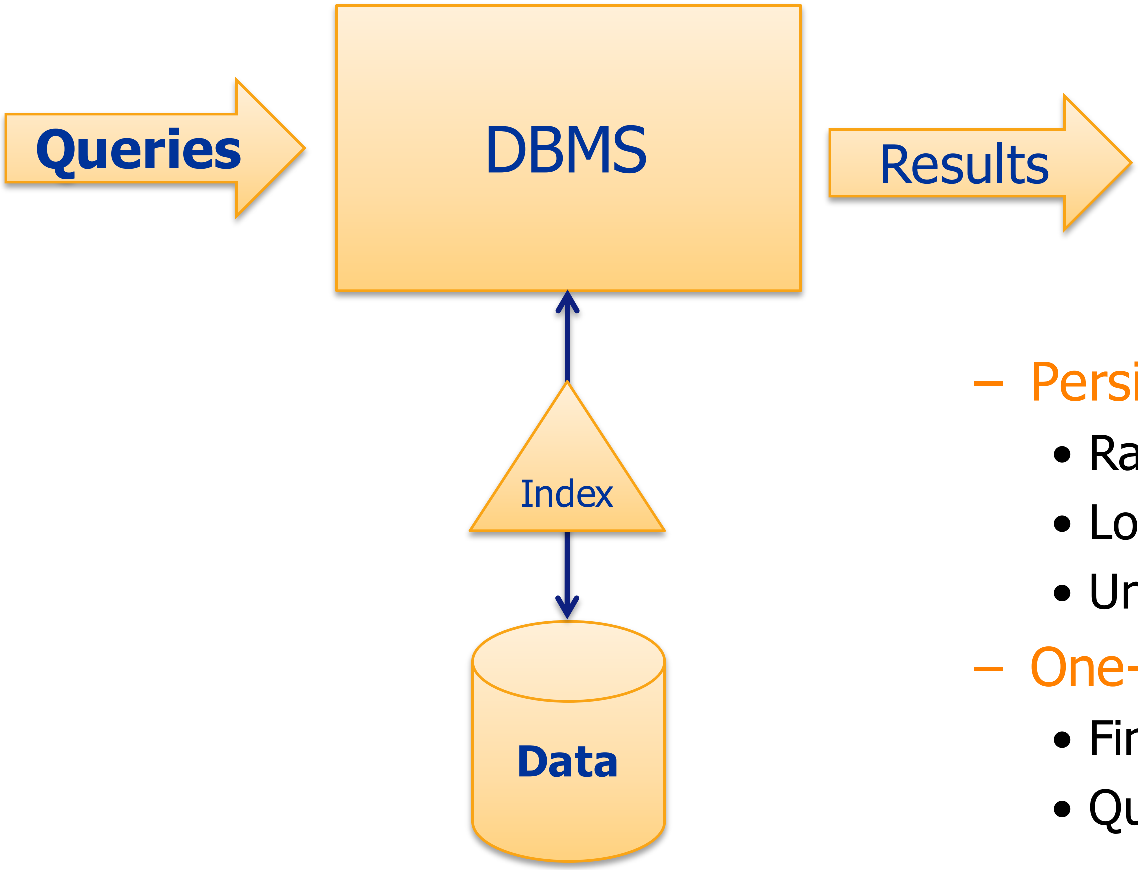
Processing stream data has real-time aspect

- Latency of data processing matters
- Must be able to react to events as they occur

Traditional Databases (Boring)

Database Management System (DBMS):

- Data relatively static but queries dynamic

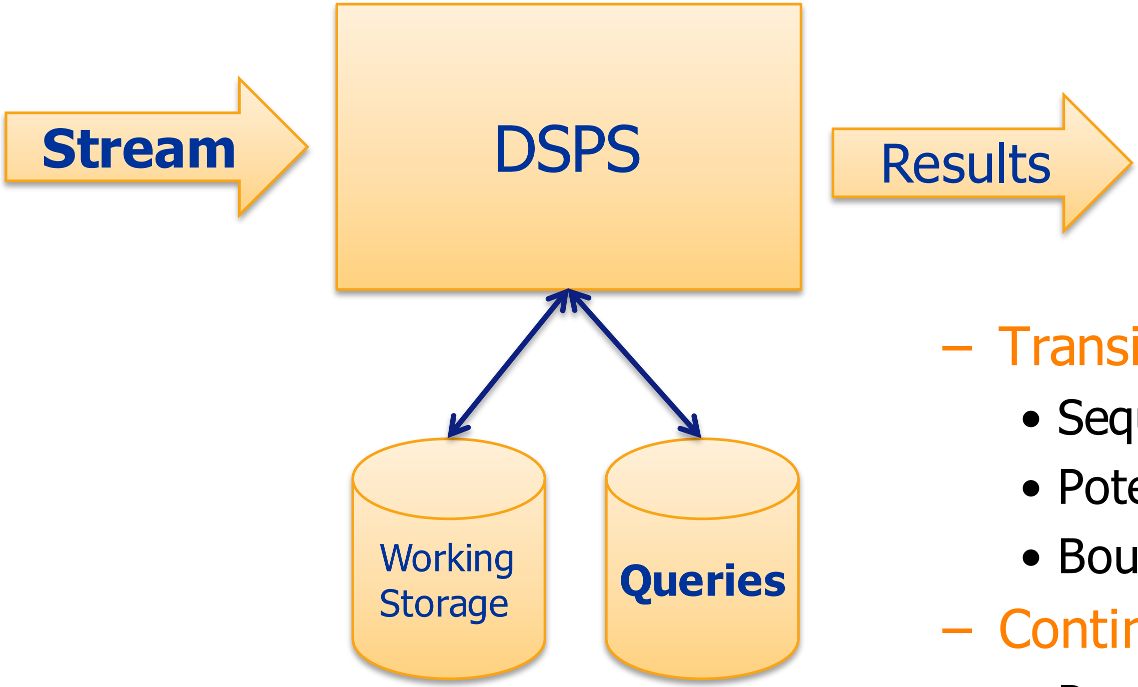


- Persistent relations
  - Random access
  - Low update rate
  - Unbounded disk storage
- One-time queries
  - Finite query result
  - Queries exploit (static) indices

Data Stream Processing System

DSPS: Queries static but data dynamic

- Data represented as time-dependant **data stream**



- Transient streams
  - Sequential access
  - Potentially high rate
  - Bounded main memory
- Continuous queries
  - Produce time-dependant result stream
  - Indexing?

Overview

Why Stream Processing?

Stream Processing Models

- Streams, windows, operators

Scalable Stream Processing Systems

- Distributed stream processing
- Stream processing with distributed dataflows

Scalable Stateful Stream Processing

- Managing state in stream processing
- Elasticity and fault tolerance mechanisms

Stream Processing

Need to define

1. Data model for streams

2. Processing (query) model for streams

Data Stream

"A **data stream** is a real-time, continuous, ordered (implicitly by arrival time or explicitly by timestamp) **sequence of items**. It is impossible to control the order in which items arrive, nor is it feasible to locally store a stream in its entirety."
[Golab & Ozsu (SIGMOD 2003)]

Relational model for stream structure?

- Can't represent audio/video data
- Can't represent analogue measurements

Relational Data Stream Model

Streams consist of infinite sequence of tuples

- Tuples often have associated time stamp
  - e.g. arrival time, time of reading, ...

Tuples have fixed relational schema

- Set of attributes

id = 27182 temp = 24 C rain = 20mm

sensor output

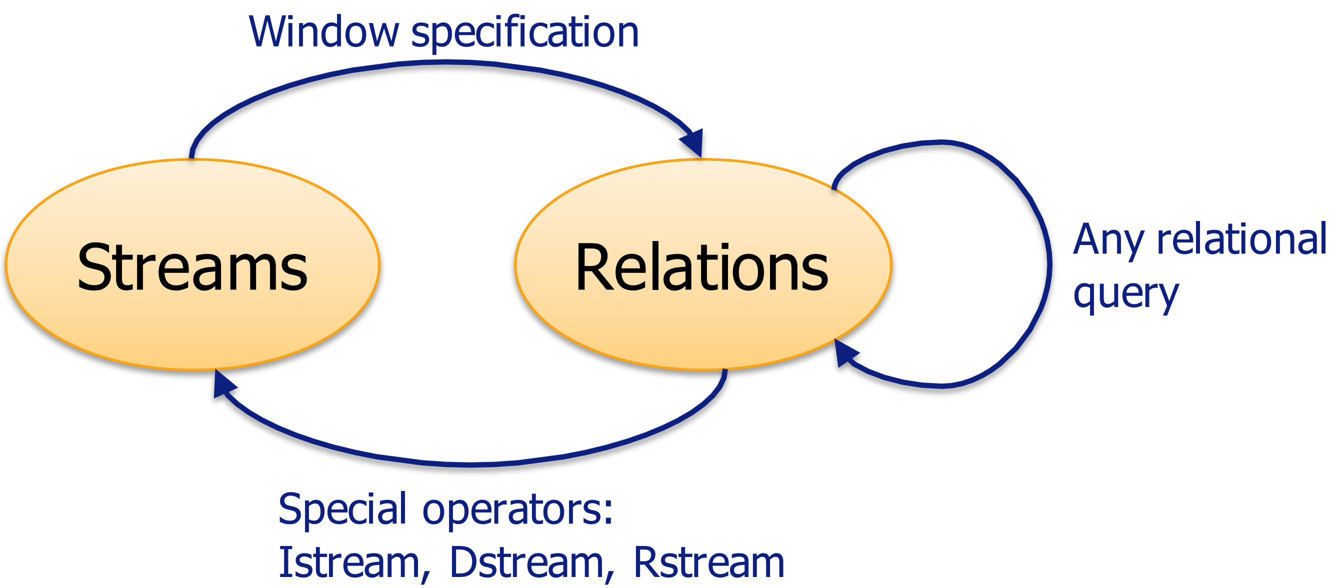
`Sensors(id, temp, rain)`

t_1	t_2	t_3	t_4	...					
id temp rain	id temp rain	id temp rain	id temp rain	id temp rain	id temp rain	id temp rain	id temp rain	id temp rain	id temp rain

Sensors data stream

time

Stream Relational Model



Window converts stream to dynamic relation

- Similar to maintaining view
- Use regular relational algebra operators on tuples
- Can combine streams and relations in single query

Sliding Window I

How many tuples should we process each time?

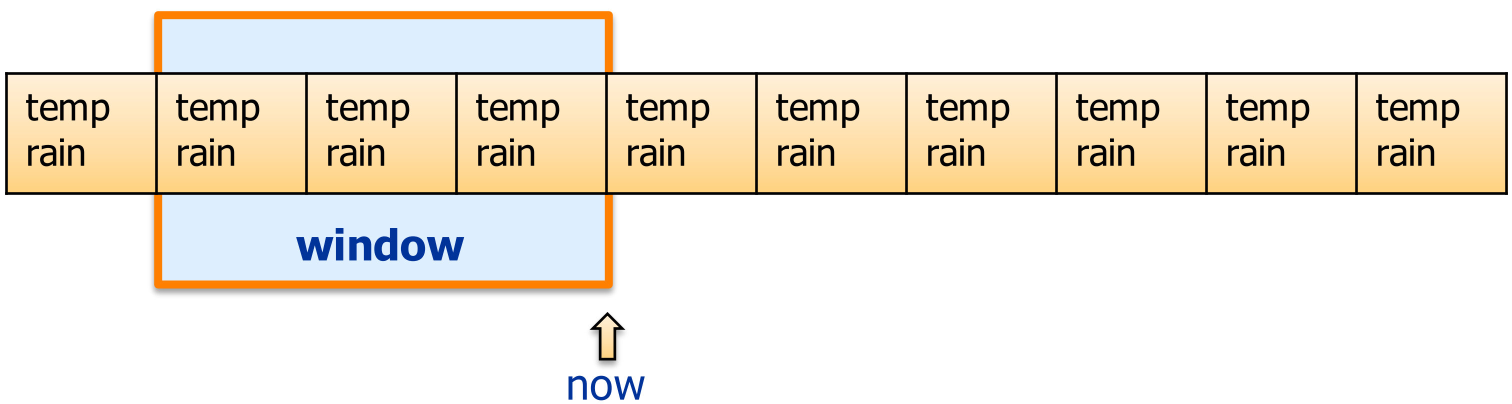
Process tuples in window-sized batches

Time-based window with size τ at current time t

- **[t - τ : t]** `Sensors [Range τ seconds]`
- **[t : t]** `Sensors [Now]`

Count-based window with size n:

- **last n tuples** `Sensors [Rows n]`



Sliding Window II

How often should we evaluate the window?

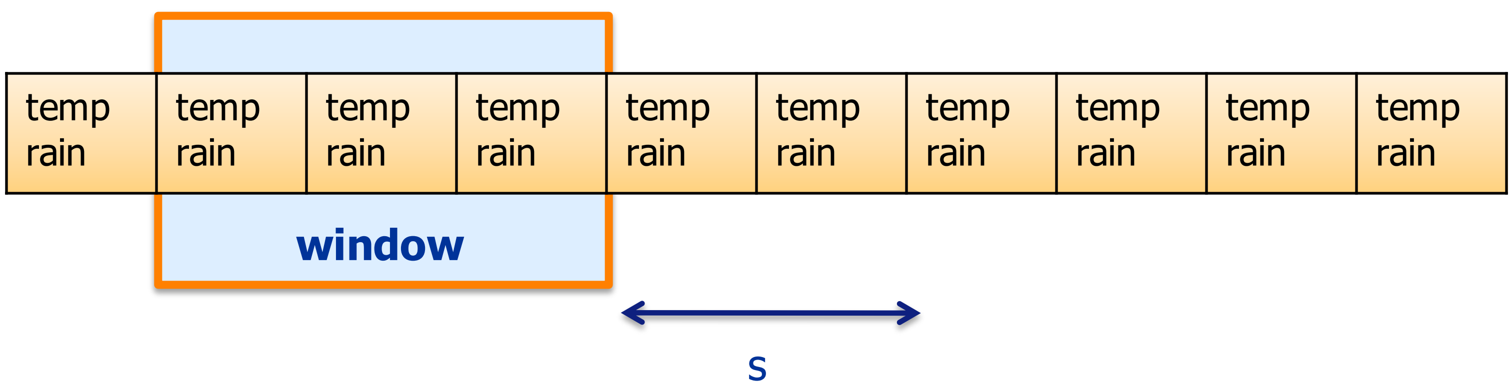
1. Output new result tuples as soon as available
   - Difficult to implement efficiently

2. Slide window by s seconds (or m tuples)

```
Sensors [Slide s seconds]
```

Sliding window: s < T

Tumbling window: s = T



Continuous Query Language (CQL)

Based on SQL with streaming constructs

- Tuple- and time-based windows
- Sampling primitives

```
SELECT temp
FROM Sensors [Range 1 hour]
WHERE temp > 42;
```

```
SELECT *
FROM S1 [Rows 1000],
     S2 [Range 2 mins]
WHERE S1.A = S2.A
   AND S1.A > 42;
```

Apart from that regular SQL syntax

Join Processing

Naturally supports joins over windows

```
SELECT *
FROM S1, S2
WHERE S1.a = S2.b;
```

Only meaningful with window specification for streams

- Otherwise requires unbounded state!

```
Sensors(time, id, temp, rain)          Faulty(time, id)
```

```
SELECT S.id, S.rain
FROM Sensors [Rows 10] as S, Faulty [Range 1 day] as F
WHERE S.rain > 10 AND F.id != S.id;
```

Converting Relations → Streams

Define mapping from relation back to stream

- Assumes discrete, monotonically increasing timestamps
  τ, $\tau+1$, $\tau+2$, $\tau+3$, ...

Istream(R)

- Stream of all tuples (r, τ) where $r \in R$ at time τ but $r \notin R$ at time $\tau-1$

Dstream(R)

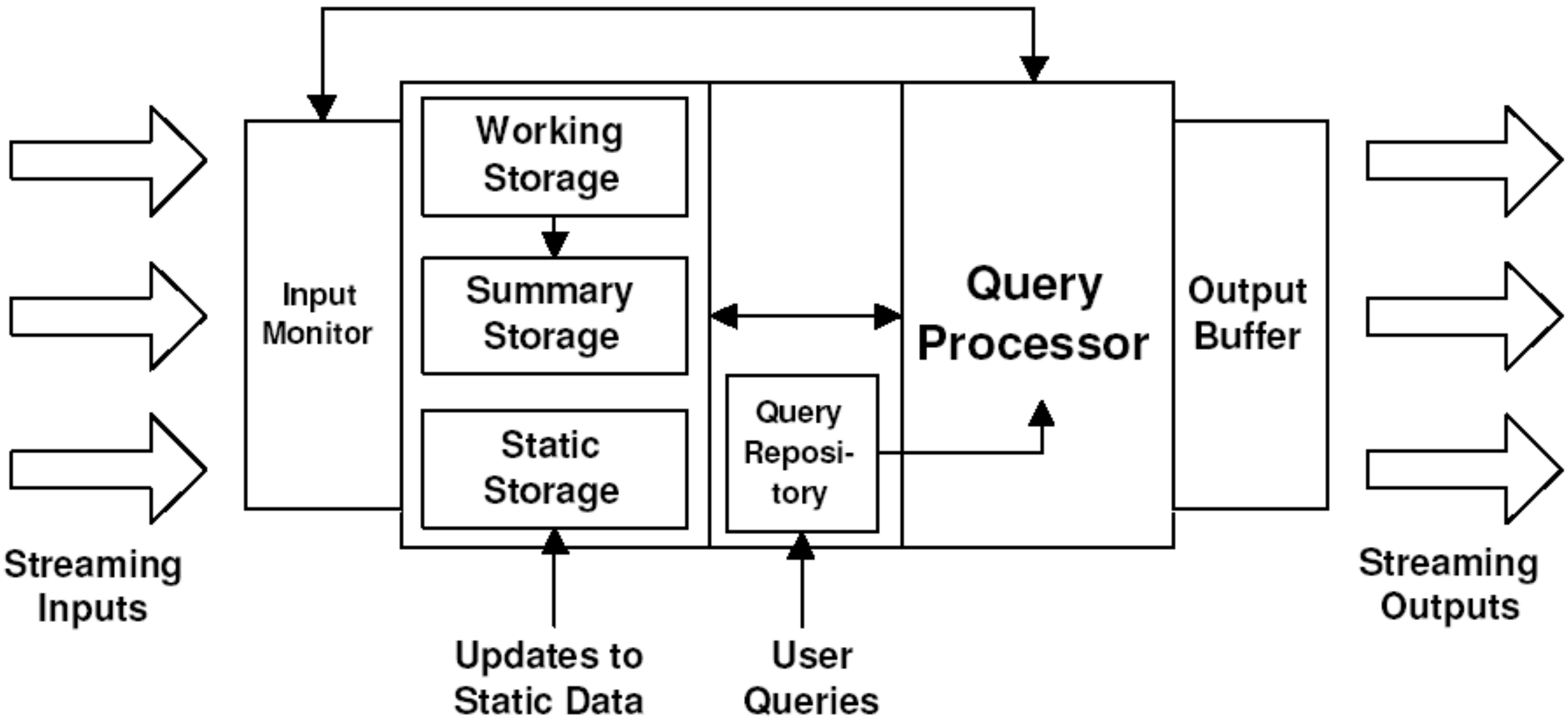
- Stream of all tuples (r, τ) where $r \in R$ at time $\tau-1$ but $r \notin R$ at time τ

Rstream(R)

- Stream of all tuples (r, τ) where $r \in R$ at time τ

Stream Processing Systems

General DSPS Architecture



Source: Golab & Ozsu 2003

Stream Query Execution

Continuous queries are long-running
➔ properties of base streams may change

- Tuple distribution, arrival characteristics, query load, available CPU, memory and disk resources, system conditions, ...

Solution: Use **adaptive query plans**

- Monitor system conditions
- Re-optimise query plans at run-time

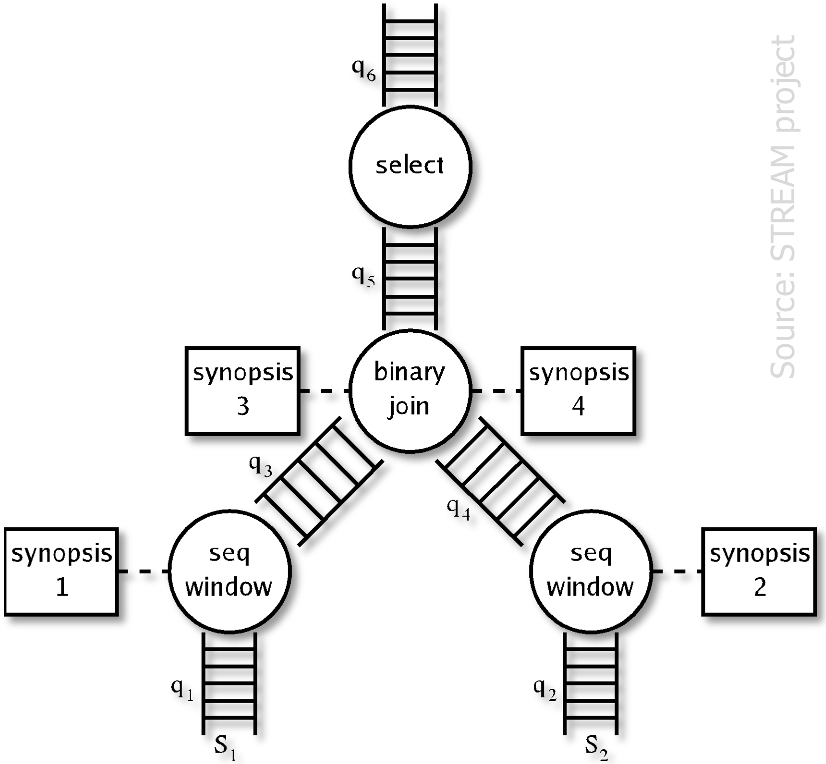
DBMS didn't quite have this problem...

Query Plan Execution

Executed query plans include:

- **Operators**
- **Queues** between operators
- **State**/"Synposis" (windows, ...)
- **Base streams**

```
SELECT *
FROM S1 [Rows 1000],
     S2 [Range 2 mins]
WHERE S1.A = S2.A
   AND S1.A > 42;
```



Source: STREAM project

Challenges

- State may get large (e.g. large windows)

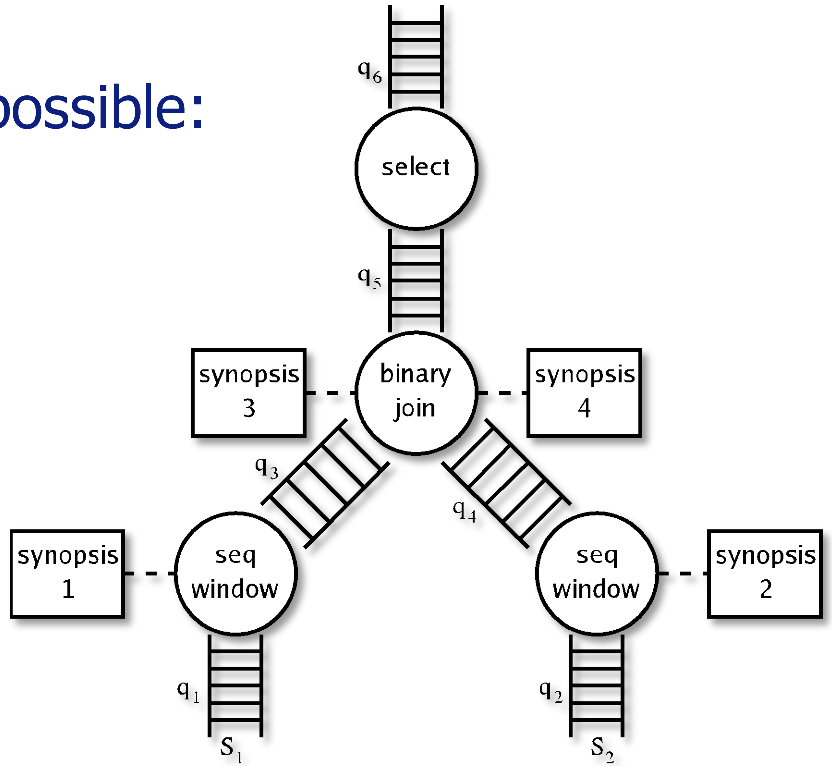
Operator Scheduling

Need scheduler to invoke operators (for time slice)

- Scheduling must be adaptive

Different scheduling disciplines possible:

1. Round-robin
2. Minimise queue length
3. Minimise tuple delay
4. Combination of the above



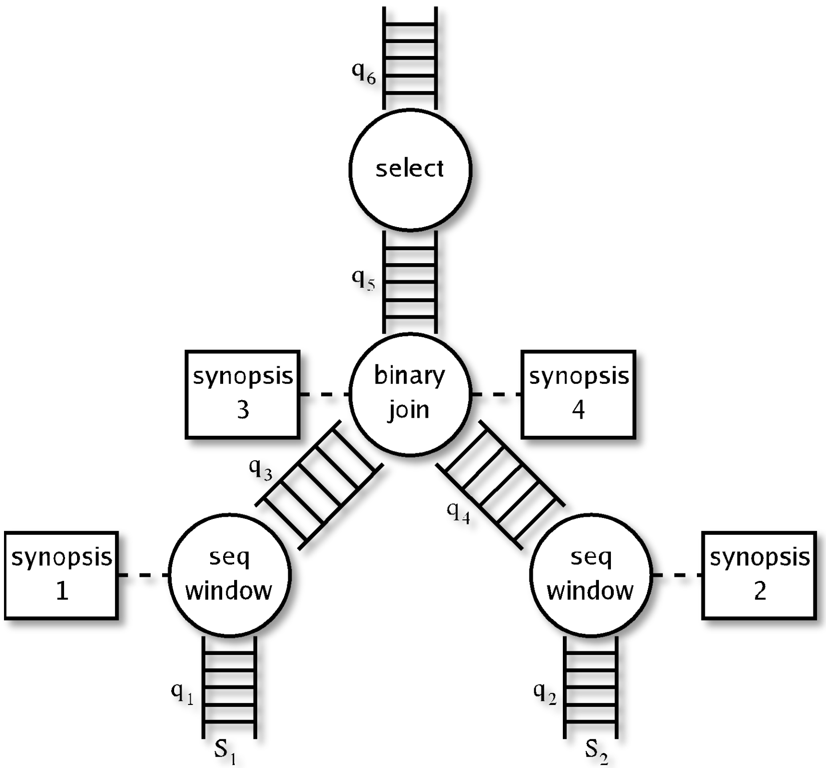
Load Shedding

DSMS must handle overload:
Tuples arrive faster than processing rate

Two options when overloaded:

1. **Load shedding**: Drop tuples
   - Much research on deciding which tuples to drop: c.f. result correctness and resource relief
   - e.g. sample tuples from stream

2. **Approximate processing**: Replace operators with approximate processing
   - Saves resources



Scalable Stream Processing

Big Data Centres + Big Data

Google: 20 data centre locations

- over 1 million servers
- 260 Megawatts
  (0.01% of global energy)
- 4.2 billion searches per day (2011)
- Exabytes (10^{18}) of storage

Assumptions:

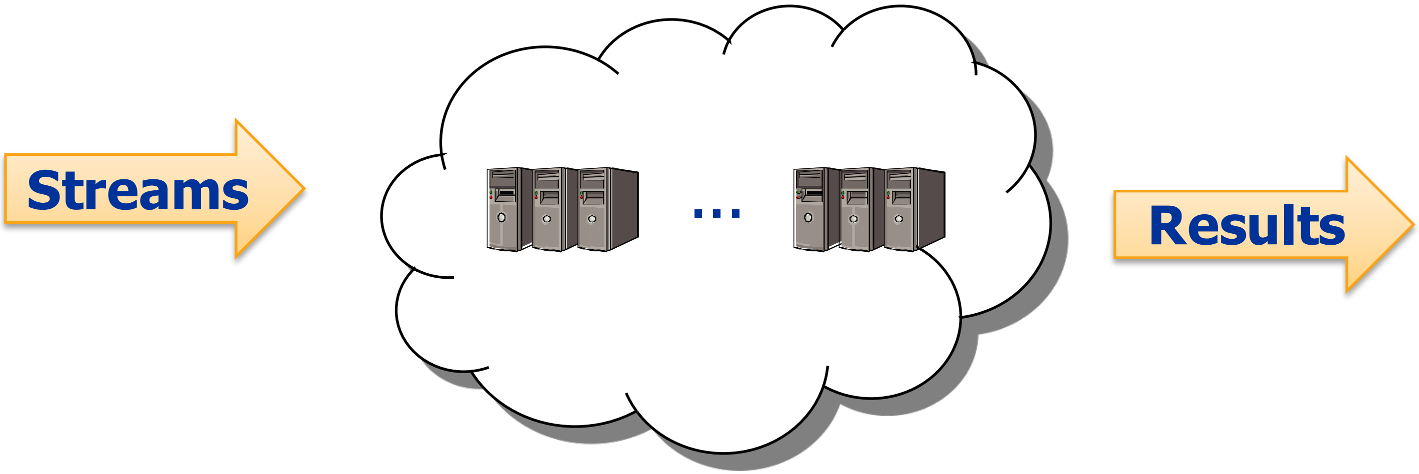
- **Scale out** and not scale up
  - Commodity servers with local disks
  - Data-parallelism is king
- Software designed for **failure**

Platforms for stream processing?

Stream Processing in the Cloud

Clouds provide virtually infinite pools of resources

- Fast and cheap access to new machines for operators



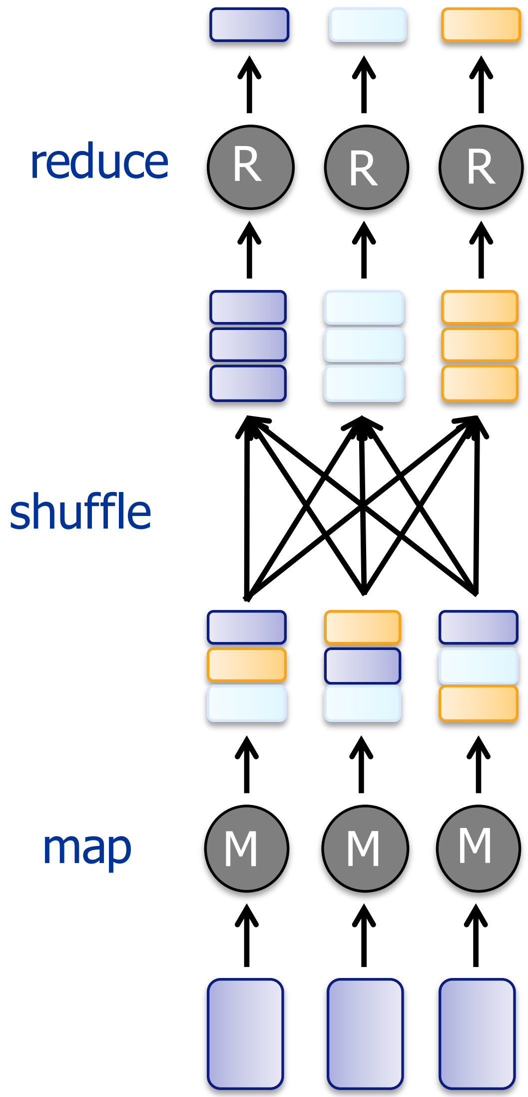
n virtual machines in cloud data centre

☛ How do you parallelise stream processing across VMs?

Google, USENIX OSDI'04

MapReduce: Distributed Dataflow

Sanjay Ghemawat   Jeff Dean



partitioned data on distributed file system

Data model: (key, value) pairs

Two processing functions:

$map(k_1,v_1) \rightarrow list(k_2,v_2)$

$reduce(k_2, list(v_2)) \rightarrow list(v_3)$

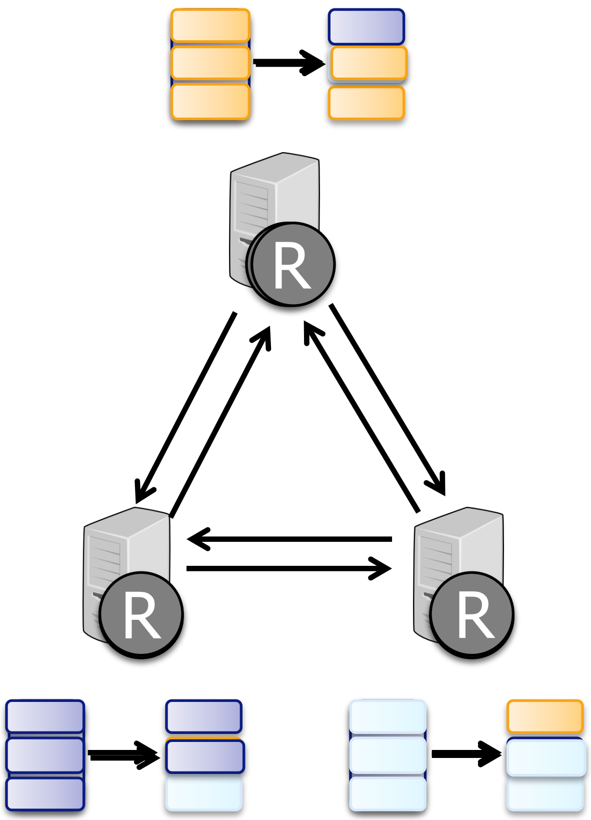
Benefits:

- Simple programming model
- Transparent parallelisation
- Fault-tolerant processing

hadoop

$2 billion market revenue (2013)

MapReduce Execution Model



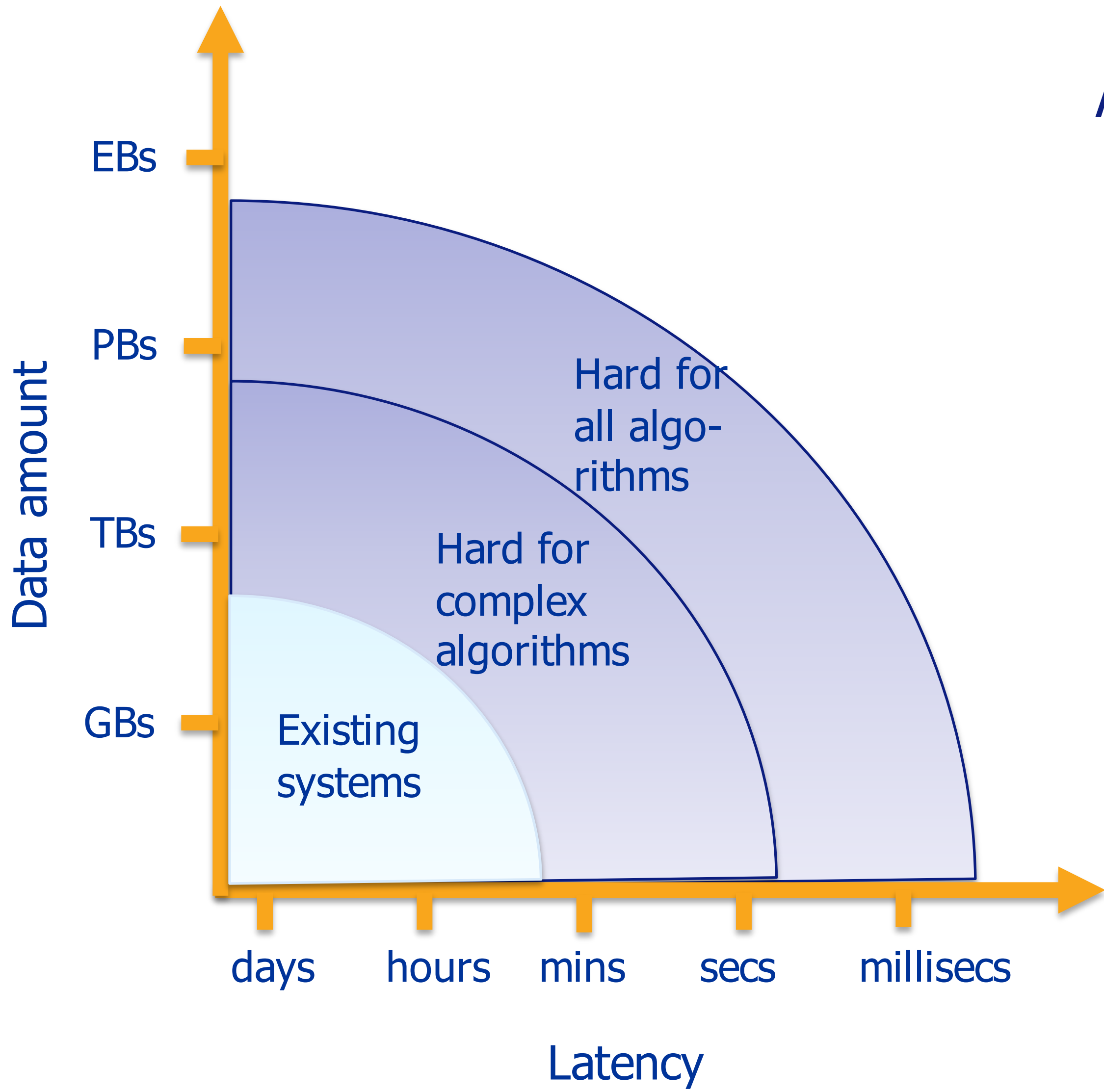
Map/reduce tasks scheduled across cluster nodes

Intermediate results persisted to local disks

- Restart failed tasks on another node
- Distributed file systems contains replicated data

But this is a batch processing model…

Design Space for Big Data Systems

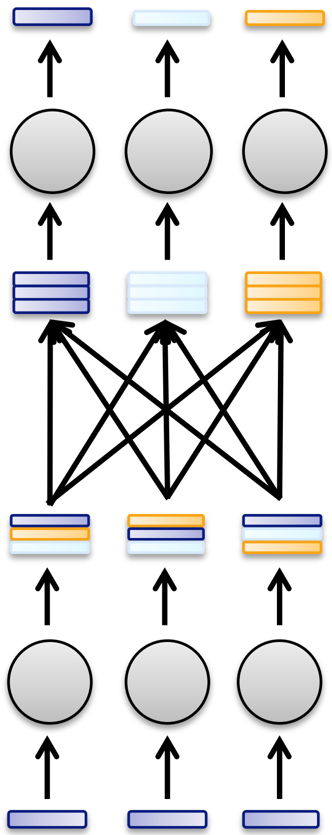


Volume and Velocity

Algorithmic complexity

- Arbitrary data transformation
- Iterative algorithms
- Large state as part of computation

Spark: Micro-Batching



RDD as discretised stream

Idea:
Reduce size of data partitons to produce up-to-date, incremental results

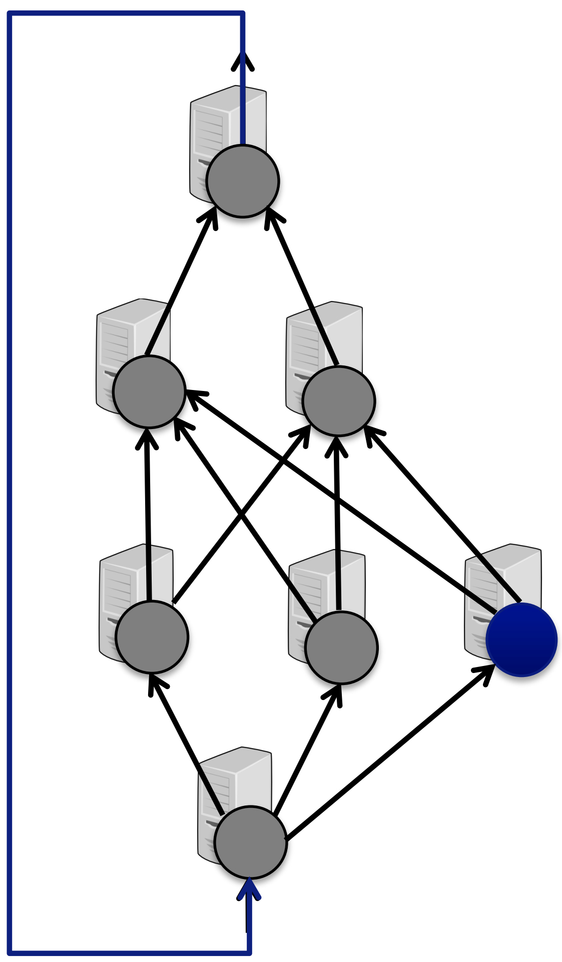
Micro-batching for data

- Window-based task semantics
- Parallel recomputation of RDDs

Challenge:
Need to control scheduling overhead

Imperial,
ACM SIGMOD'13

SEEP: Pipelined Dataflows



Idea:

Materialise dataflow graph to avoid scheduling overhead

Challenges:

1. Support for iteration
2. Resource allocation of tasks to nodes
3. Failure recovery

Cycles in graph for iteration

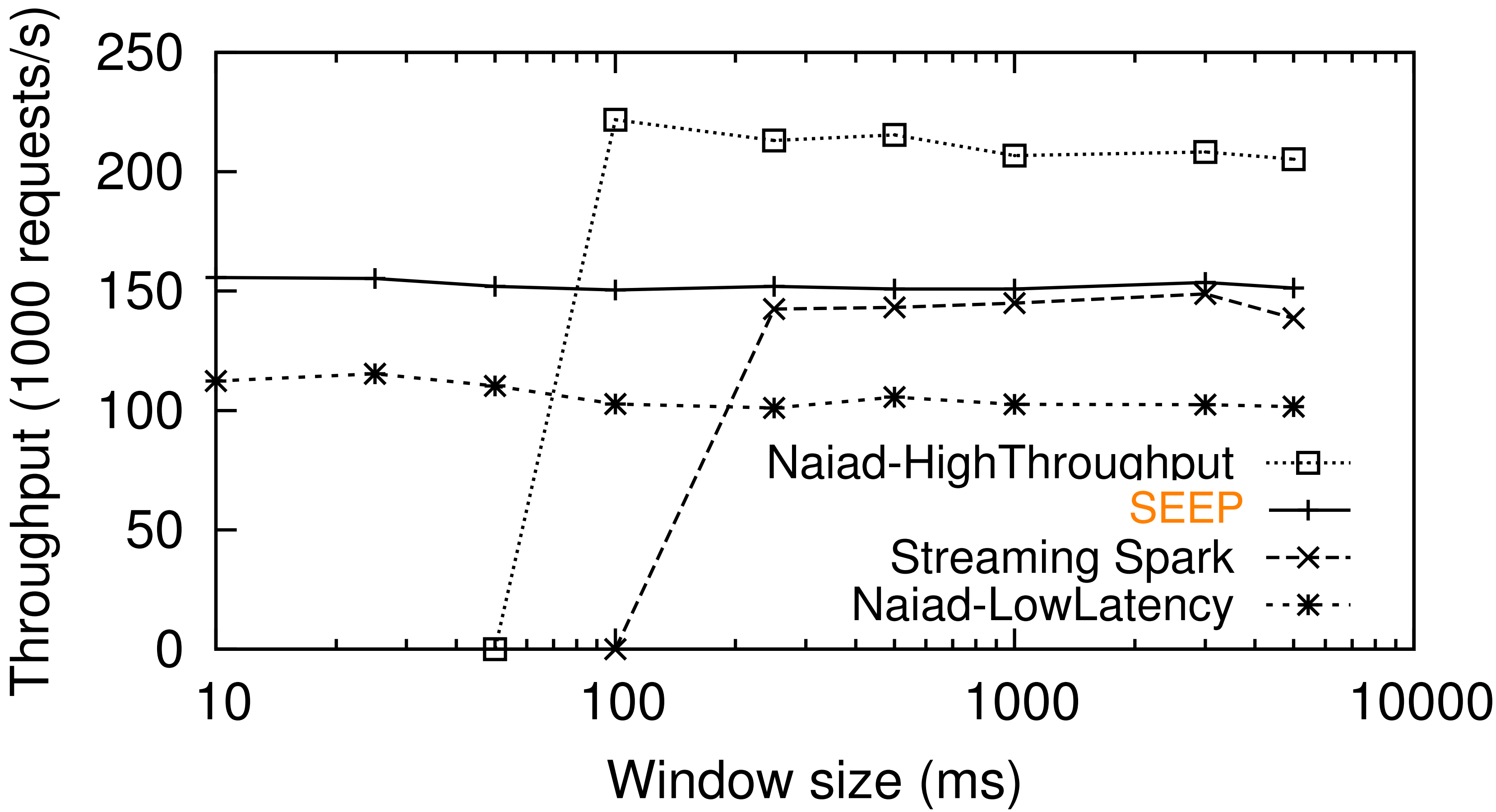
Dynamic scale out of tasks

Checkpoint-based recovery

SEEP: Low Latency Processing

Dataflow graph for window-based word count

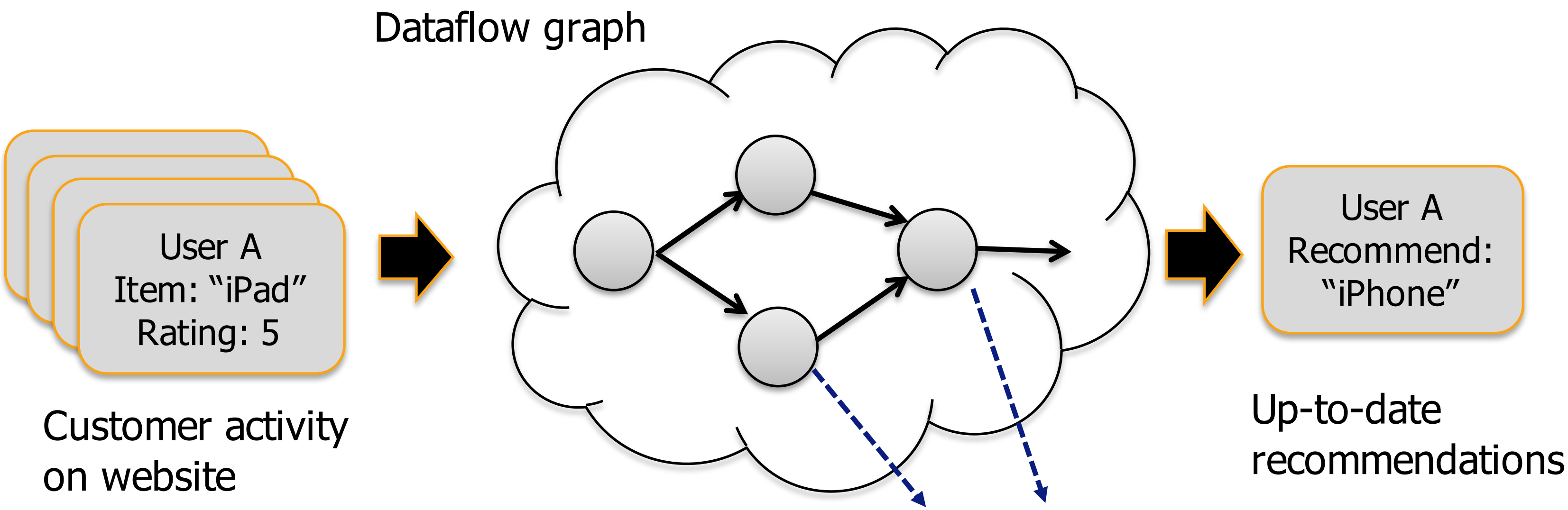
- Deployed on 4 nodes (4-core 3.4 Ghz Intel Xeon with 8GB RAM)



Scalable Stateful Stream Processing

What about Processing State?

Online collaborative filtering:



User-item matrix

	Item 1	Item 2
User A	2	5
User B	4	1

GBs to TBs in size

State in Recommender Systems

```
Matrix userItem = new Matrix();
Matrix coOcc = new Matrix();

void addRating(int user, int item, int rating) {
    userItem.setElement(user, item, rating);
    updateCoOccurrence(coOcc, userItem);
}

Vector getRec(int user) {
    Vector userRow = userItem.getRow(user);
    Vector userRec = coOcc.multiply(userRow);
    return userRec;
}
```

Update with new ratings

User-Item matrix (**UI**)

	Item-A	Item-B
User-A	4	5
User-B	0	5

User-B	1	2

x

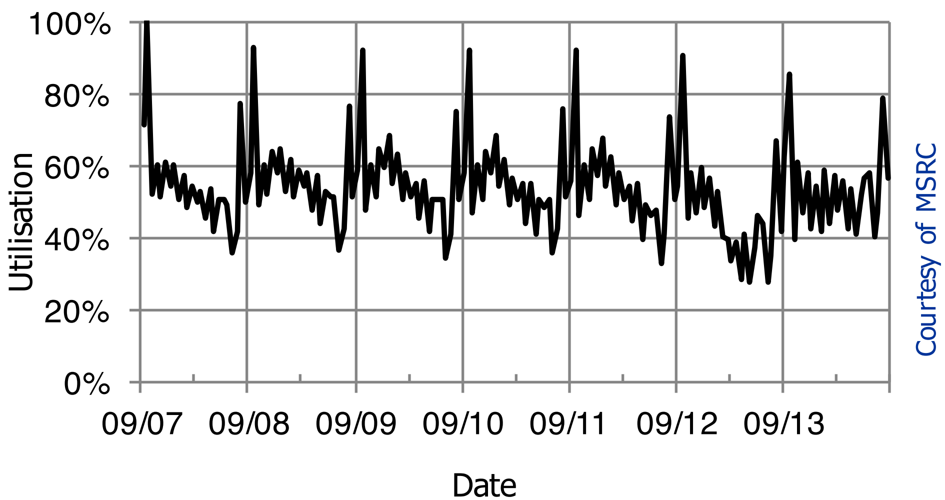
Co-Occurrence matrix (**CO**)

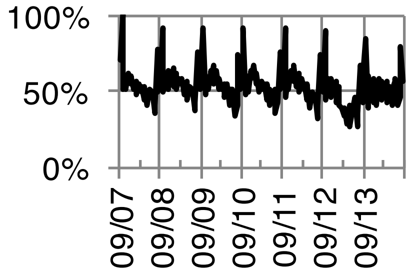
	Item-A	Item-B
Item-A	1	1
Item-B	1	2

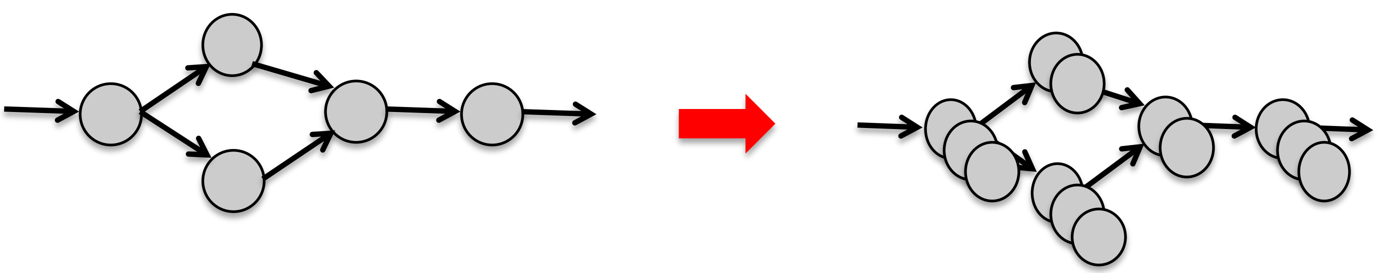
Multiply for recommendation

Challenge 1: Elastic Data-Parallel Processing

Typical stream processing workloads are bursty

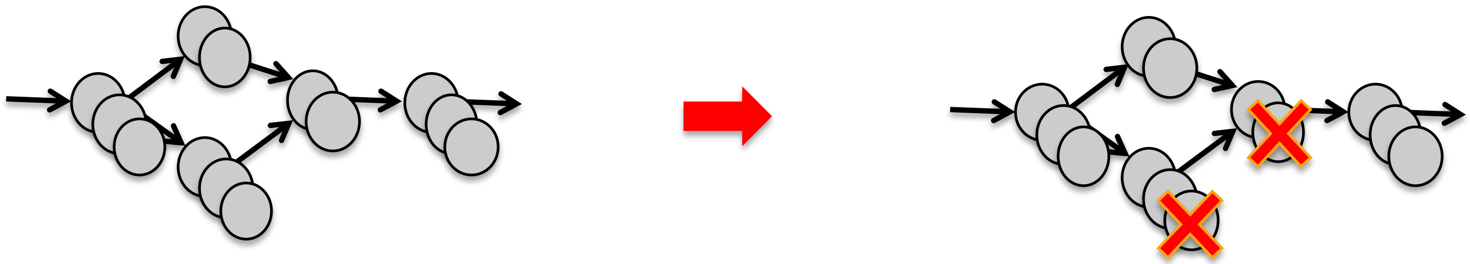






High + **bursty** input rates ➔ Detect **bottleneck** + **parallelise**

Challenge 2: Fault-Tolerant Processing



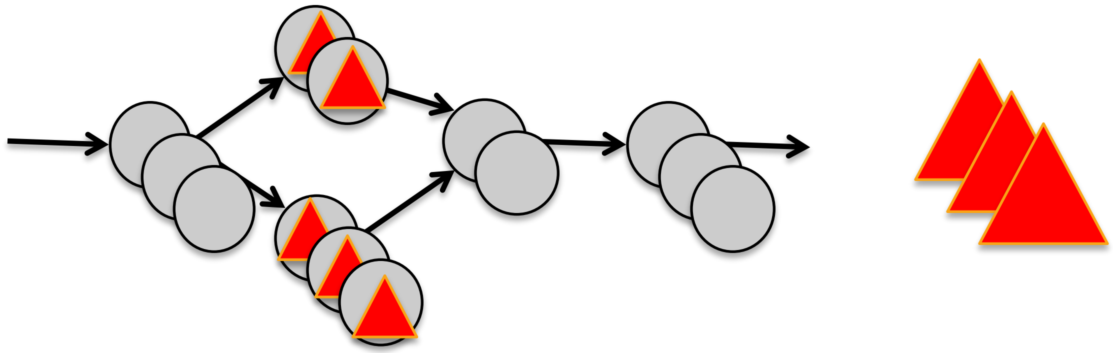
Large scale deployment ➔ Handle node **failures**

Failure is a common occurrence

- Active fault-tolerance requires 2x resources
- Passive fault-tolerance leads to long recovery times

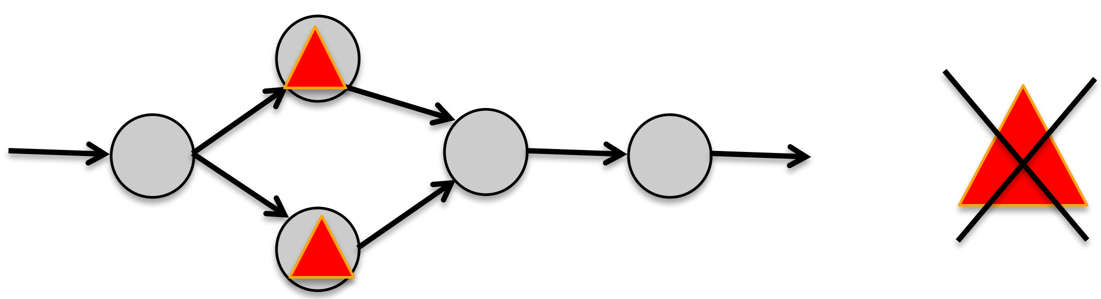
State Complicates Things…

1. Dynamic scale out impacts state



Partitioning of state

2. Recovery from failures

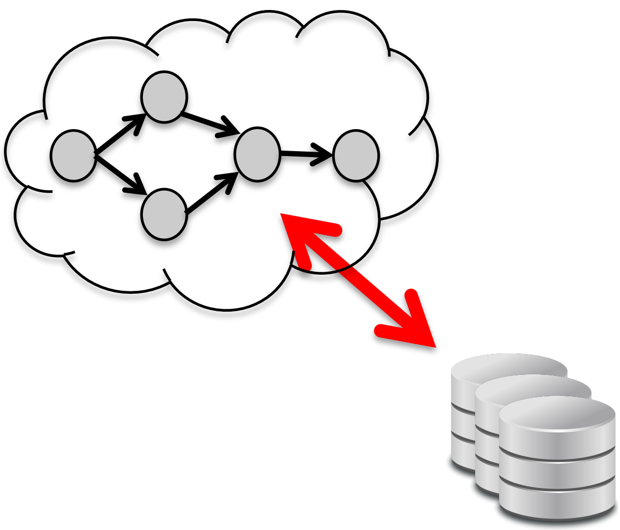


Loss of state after node failure

Current Approaches for Stateful Processing

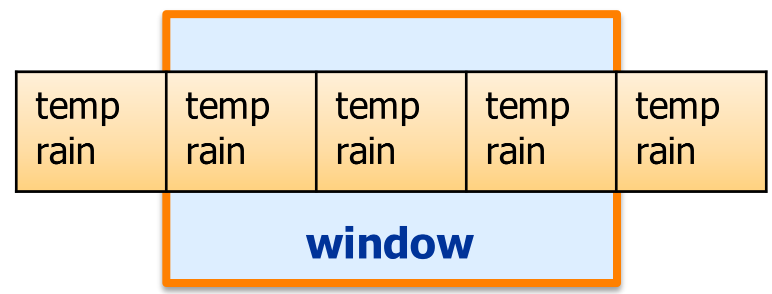
Stateless stream processing systems (eg Yahoo S4, Twitter Storm, …)

- **Developers manage state**
- Typically combine with external system to store state (eg Cassandra)
- Design complexity



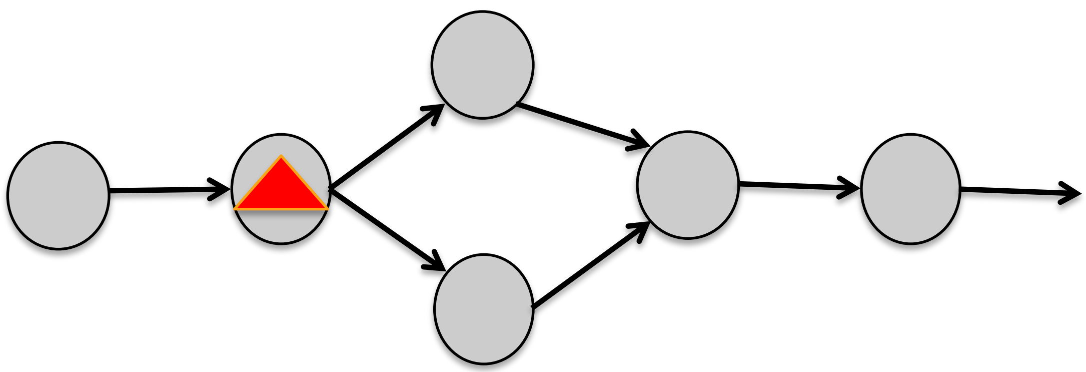
Relational stream processing systems (eg Borealis, Stream)

- State is **window** over stream
- No support for arbitrary state
- Hard to realise complex ML algorithms



Idea: State as First Class Citizen

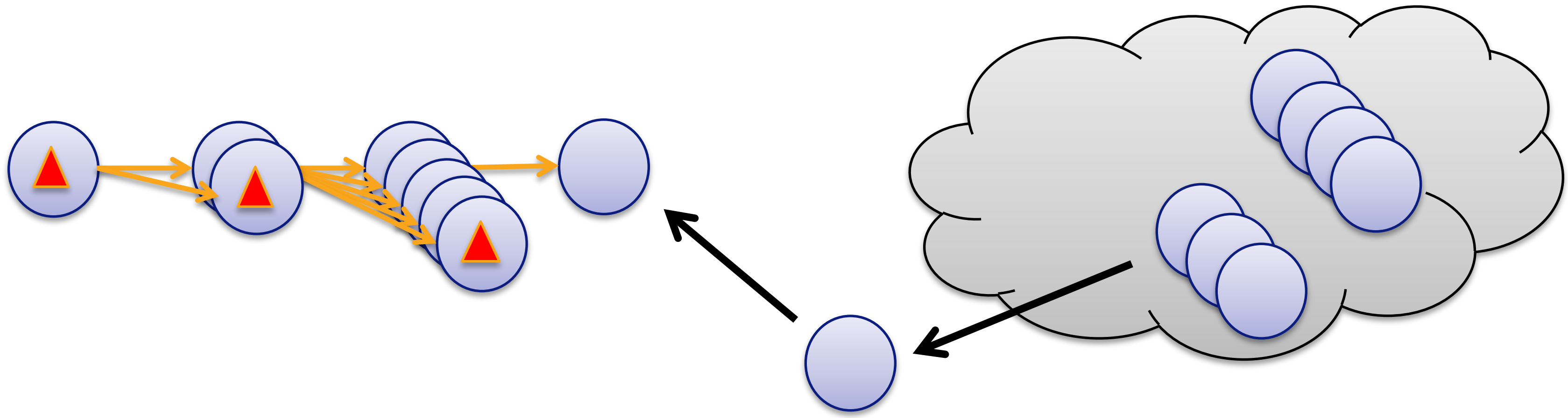
☛ Expose operator state as external entity so that it can be managed by stream processing system



Operators have direct access to state

System manages state

Stateful Stream Processing



Operators can maintain **arbitrary state**

State management primitives to:

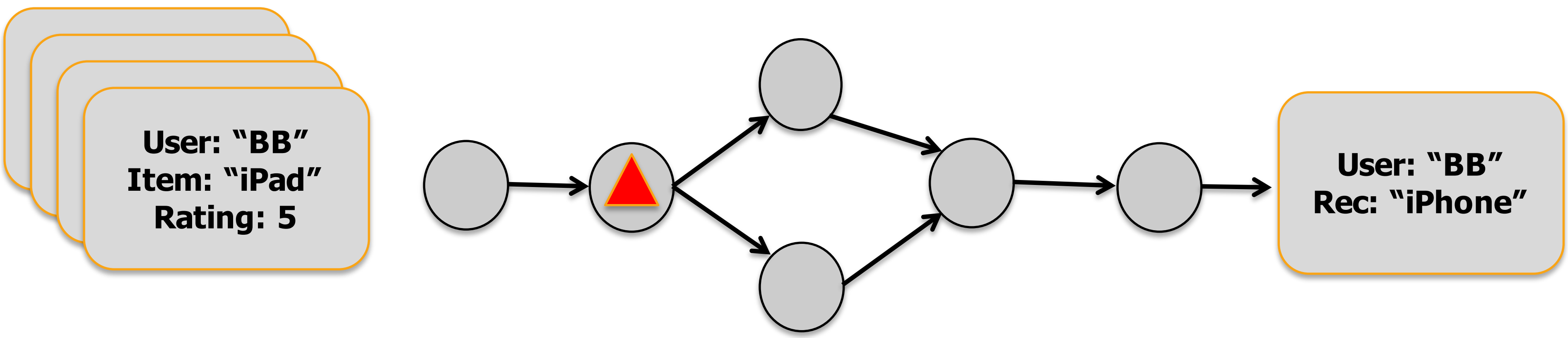
- Backup and recover state
- Partition state

Integrated mechanism for scale out and failure recovery

- Operator recovery and scale out equivalent from state perspective

Raul Castro Fernandez, Matteo Migliavacca, Evangelia Kalyvianaki, and Peter Pietzuch, **"Integrating Scale Out and Fault Tolerance in Stream Processing using Operator State Management"**, ACM International Conference on Management of Data (**SIGMOD'13**), June 2013

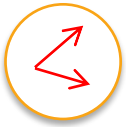
Example: Streaming Recommender Application



What is State?

Processing state

	Item 1	Item 2
User A	2	5
User B	4	1

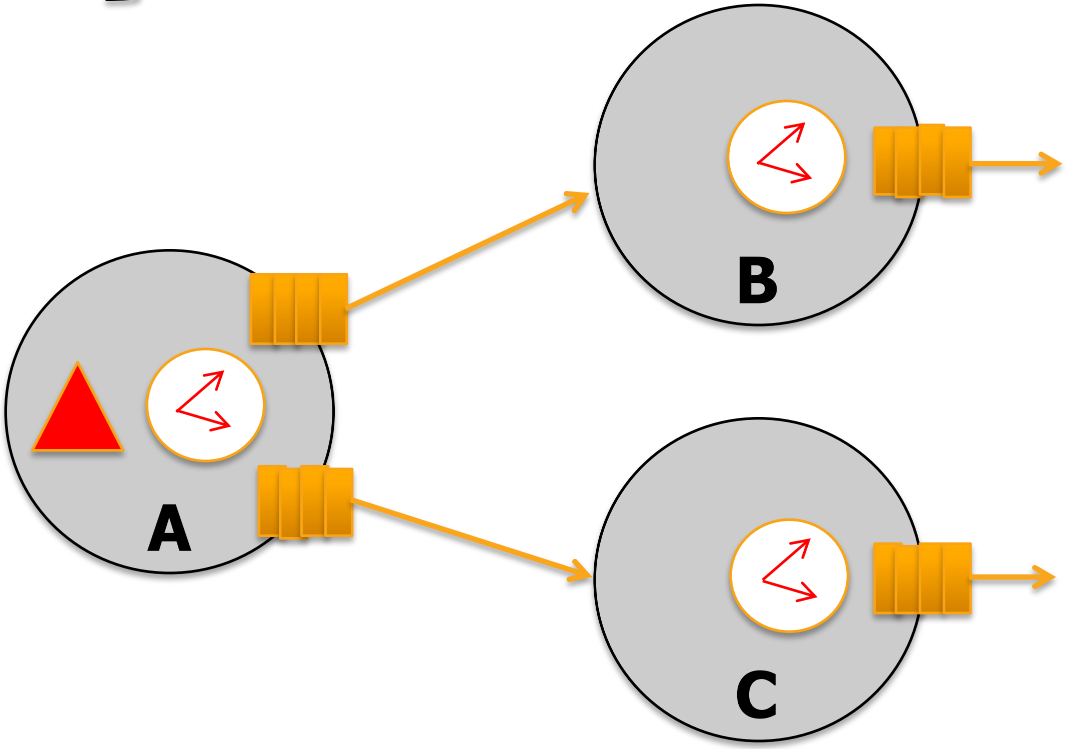


Routing state

Dynamic data flow graph:
Based on data, A ➔ B or A ➔ C

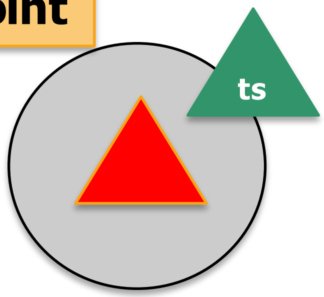
Buffer state

Data ts1	Data ts2	Data ts3	Data ts4



State Management Primitives

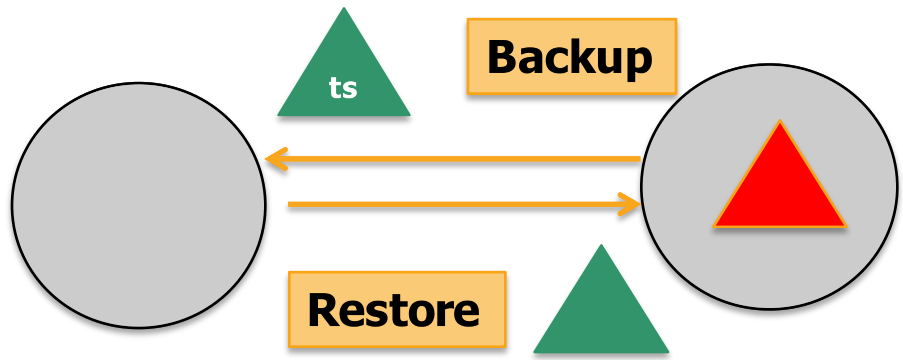
Checkpoint



- Makes state available to system
- Attaches **last processed tuple timestamp**

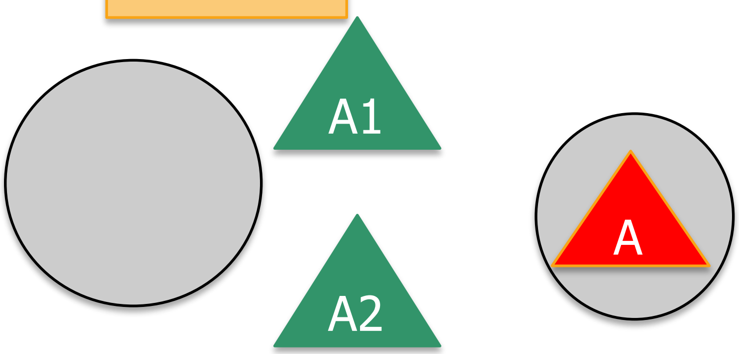
Backup

Restore



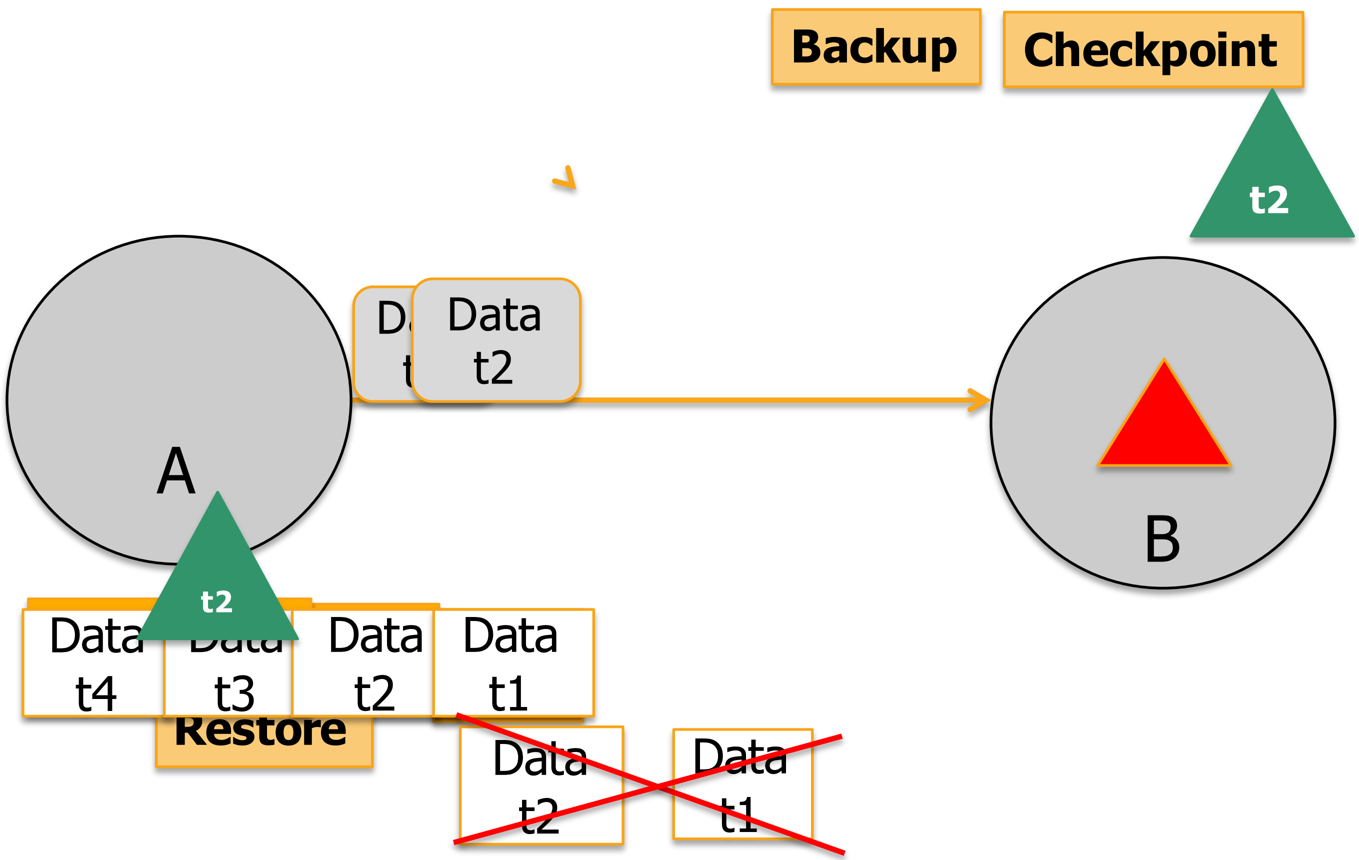
- Moves copy of state from one operator to another

Partition



- Splits state to scale out an operator

State Primitives: Backup and Restore

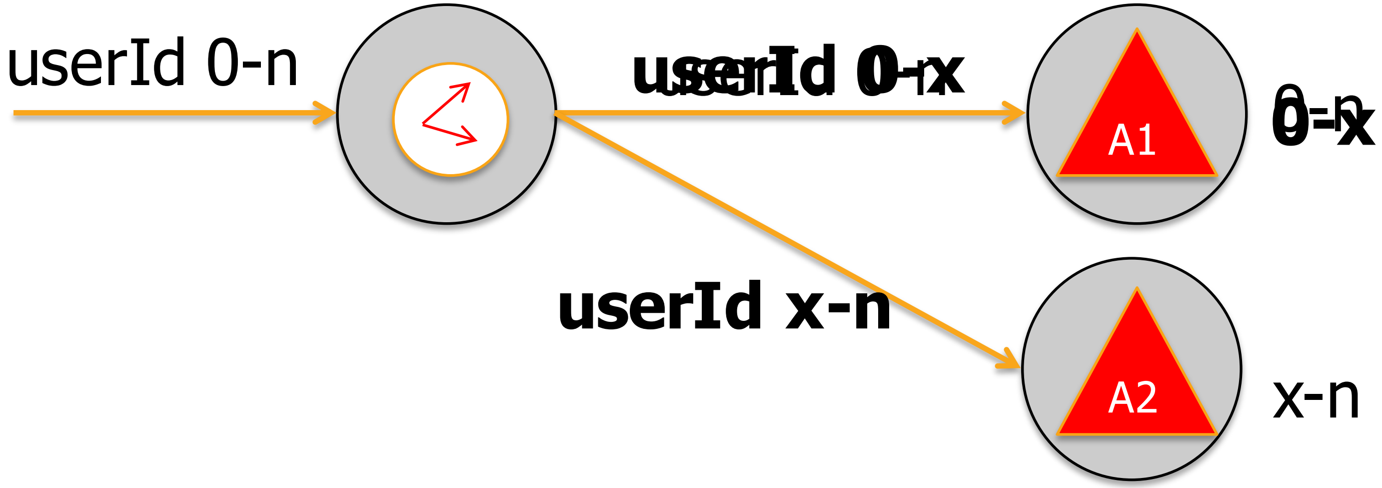


State Primitives: Partition

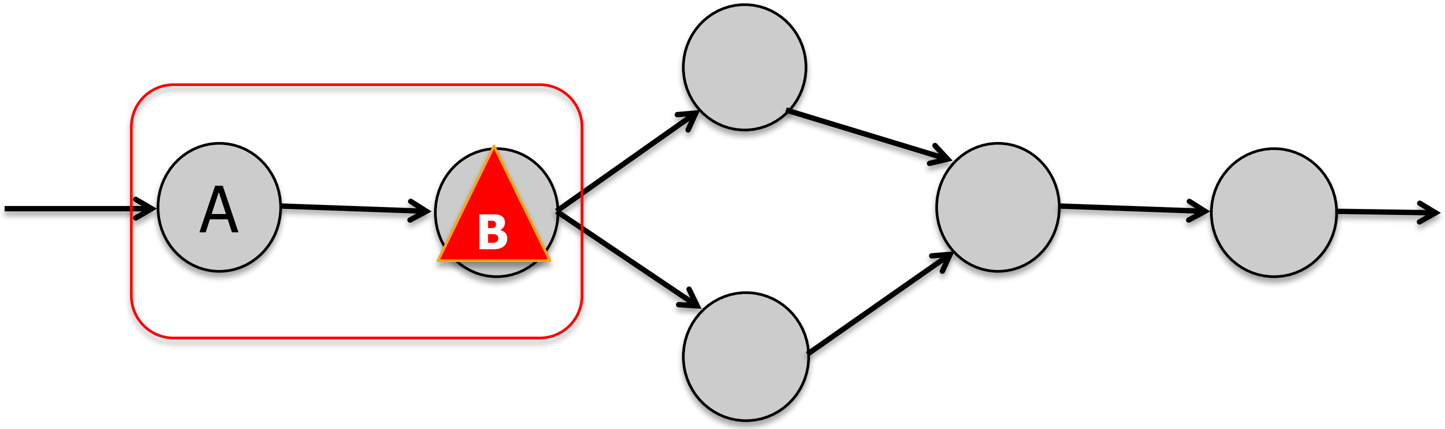
Processing state modeled as (key, value) dictionary

State partitioned according to **key** *k* of tuples

- Same key used to partition streams



Failure Recovery and Scale Out



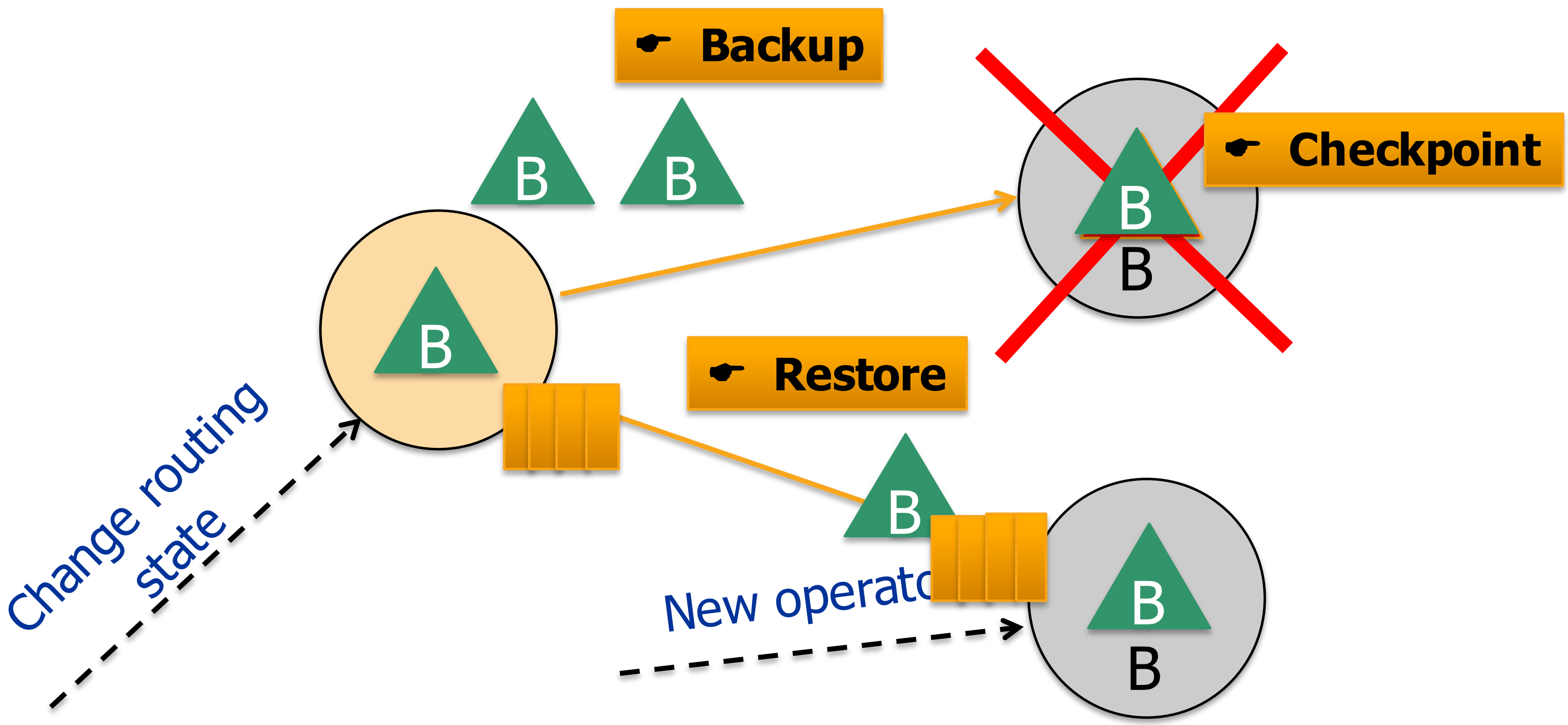
Two cases:

- Operator B **fails** ➔ **Recover**
- Operator B becomes **bottleneck** ➔ **Scale out**

Recovering Failed Operators

Periodically, stateful operators checkpoint and back up state to designated **upstream backup node**

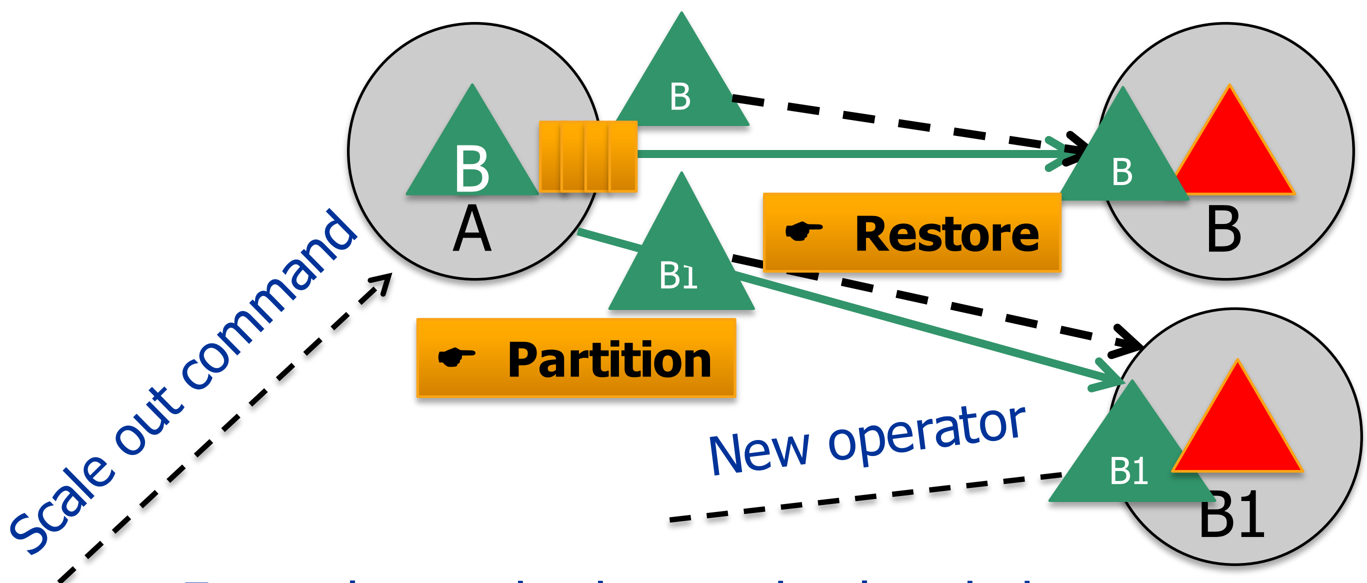
Use backed up state to recover quickly



State restored and unprocessed tuples replayed from buffer

Scaling Out Stateful Operators

Finally, upstream operators replay unprocessed tuples to update checkpointed state



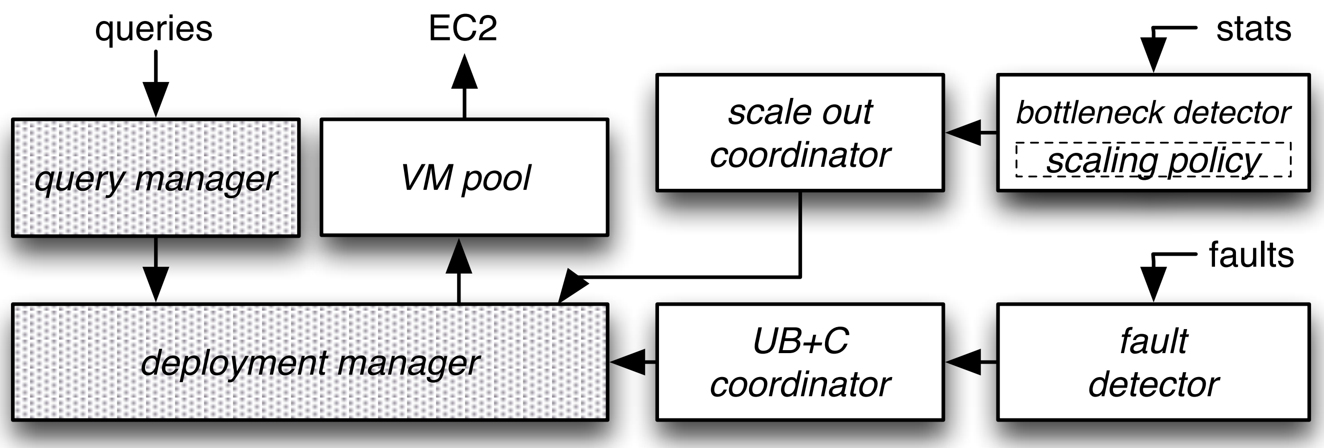
For scale out, backup node already has state of operator to be parallelised

SEEP Stream Processing System

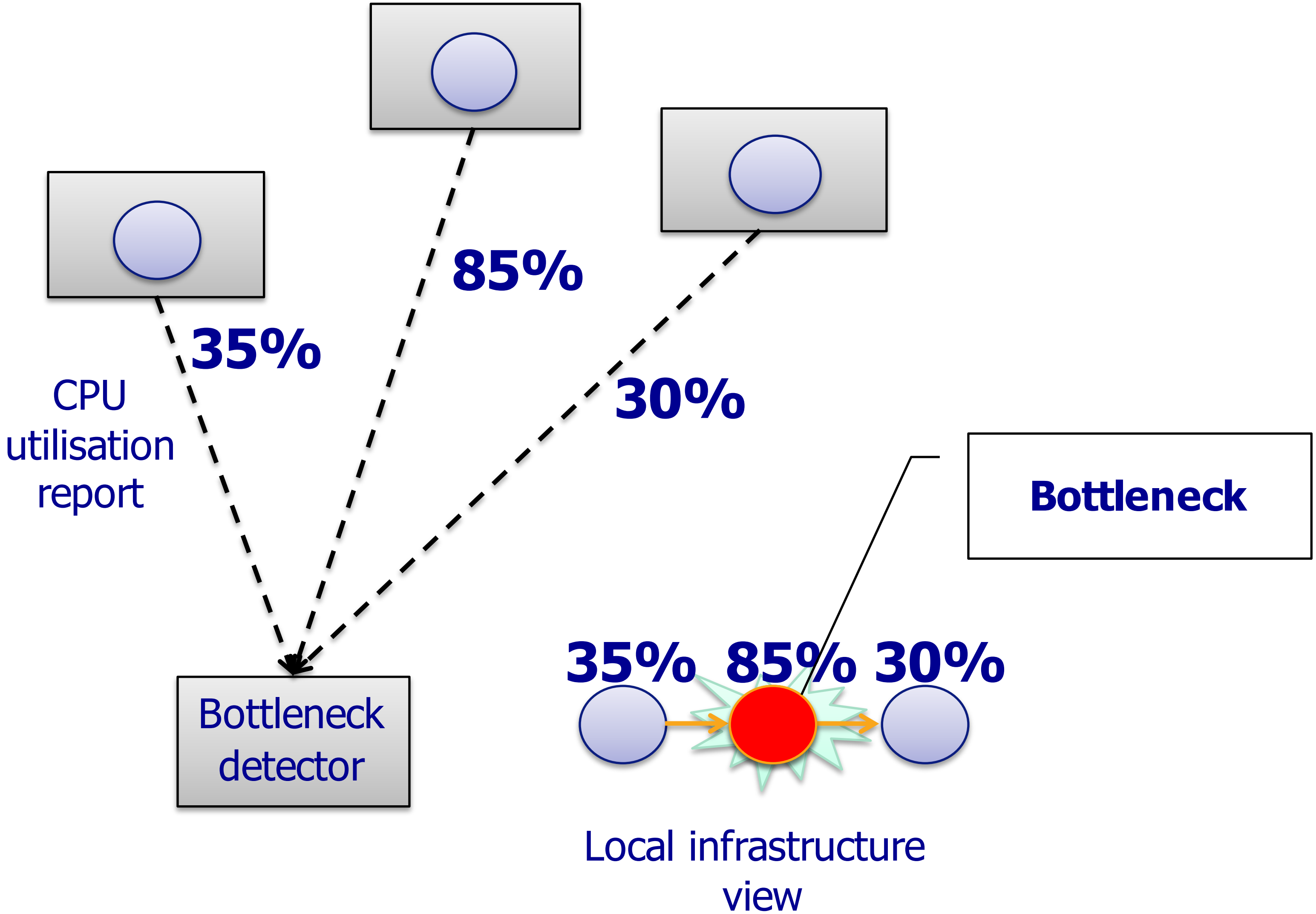
Experimental stateful stream processing platform

Implements dynamic scale out and recovery

- Detect failed or overloaded operators
- Have fast access to new VMs

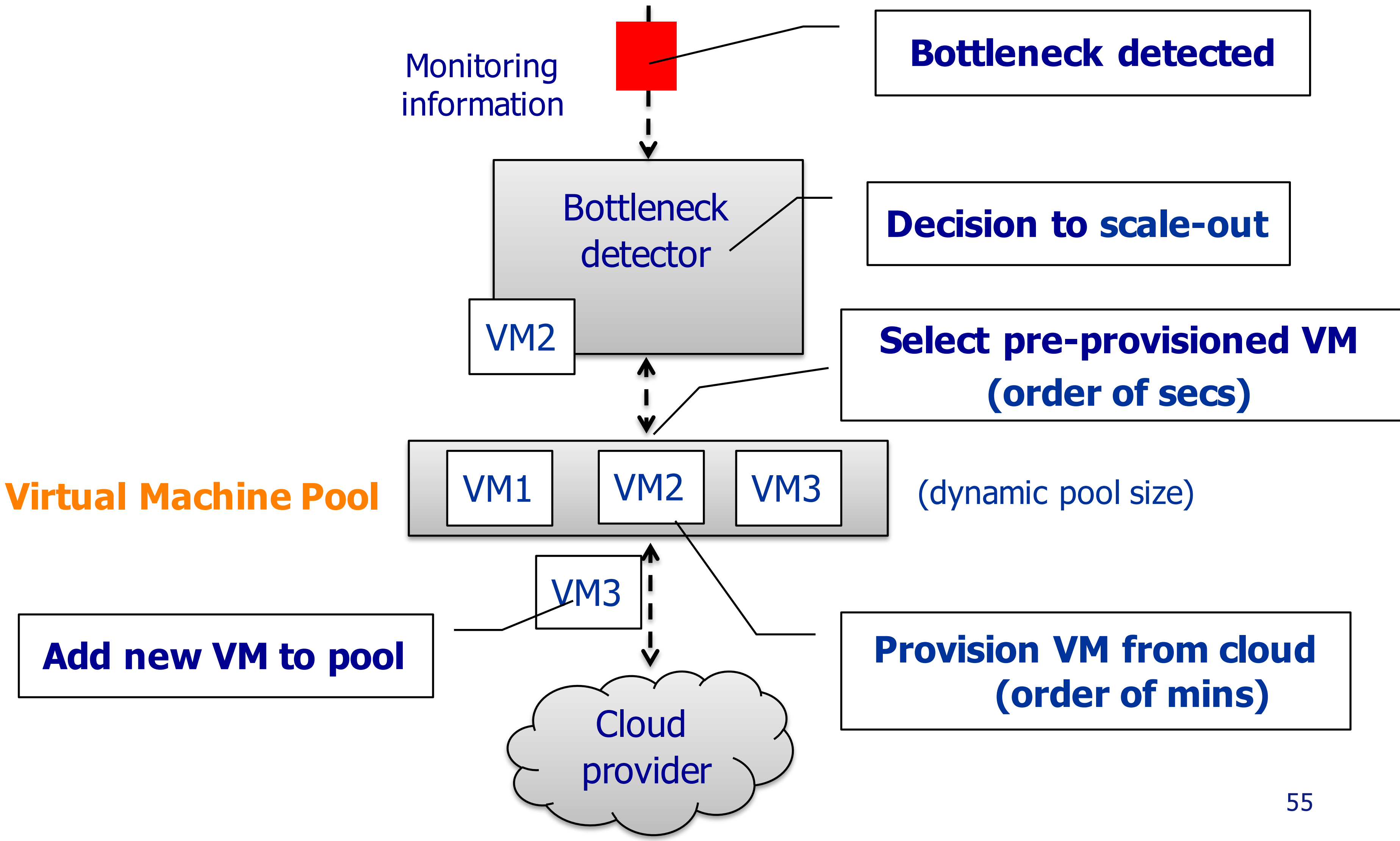


Detecting Bottlenecks



VM Pool for Adding Operators

Problem: Allocating new VMs takes minutes...

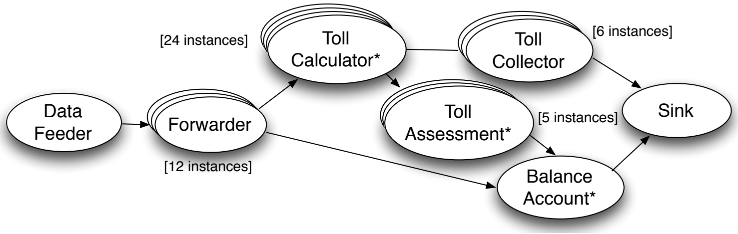


Evaluation

SEEP: Scalability on Amazon EC2

Linear Road Benchmark [VLDB'04]

- Network of toll roads of size L
- Input rate increases over time
- Dataflow graph with 5 operators; SLA: results < 5 secs

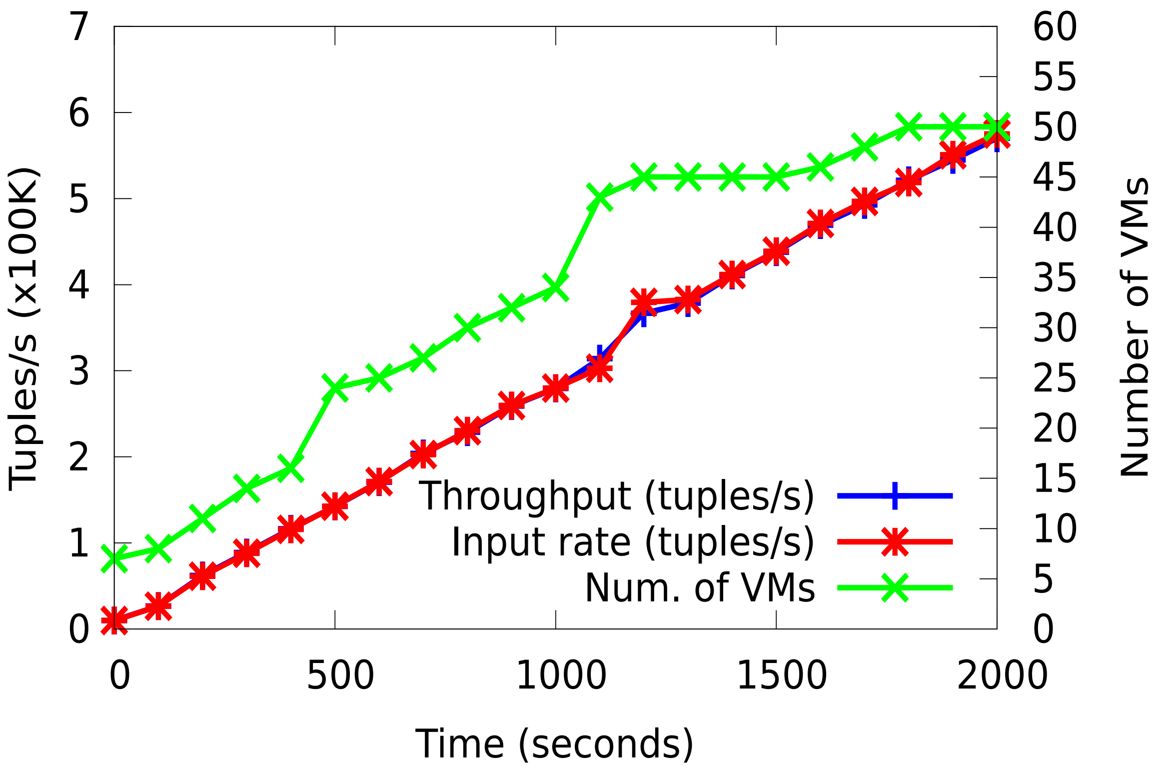


SEEP deployed on Amazon EC2

- Scales to 60 VMs (small instances with 2GB RAM)

Achieves L=350

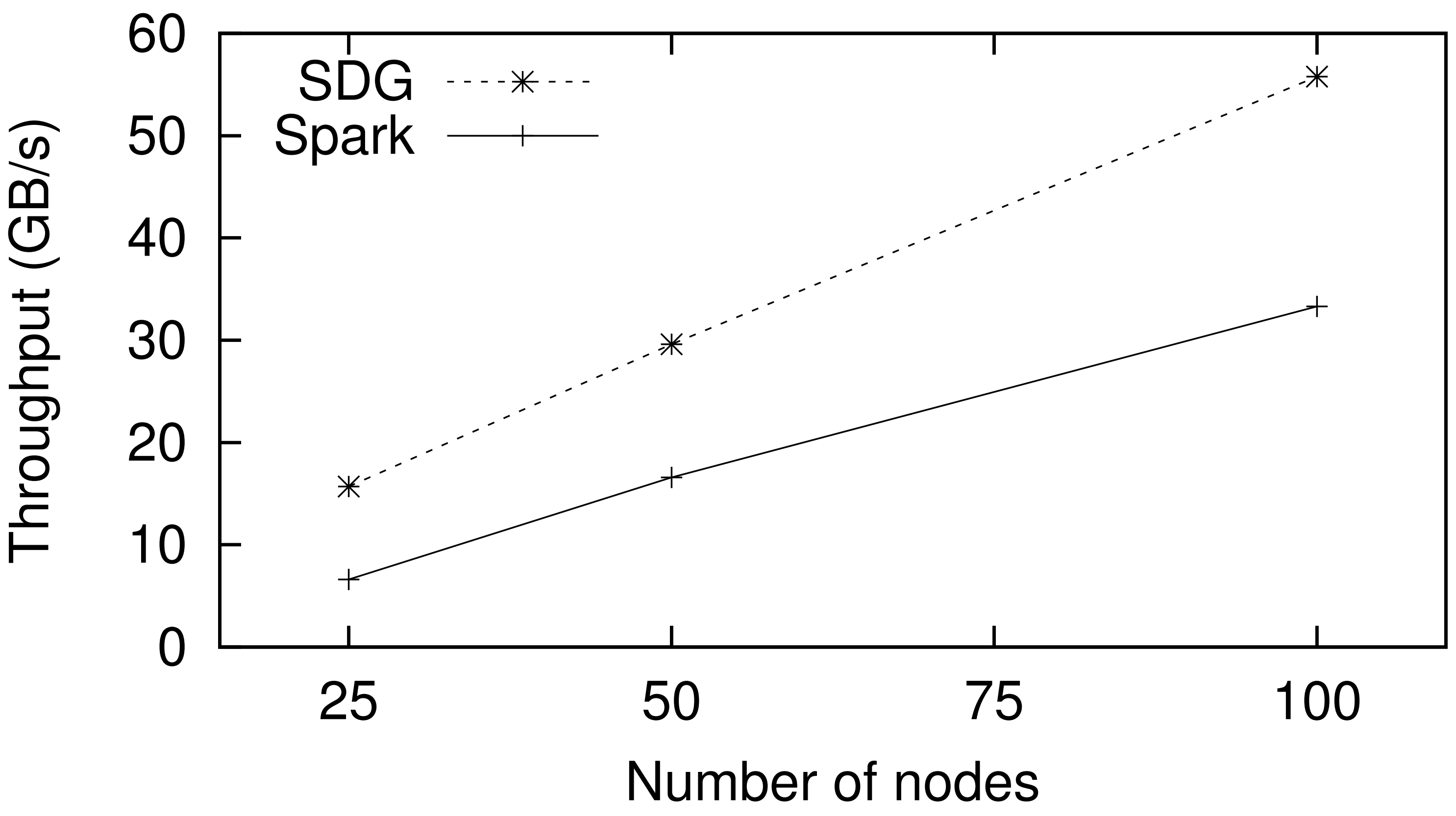
- L=512 highest reported result in literature [VLDB'12]



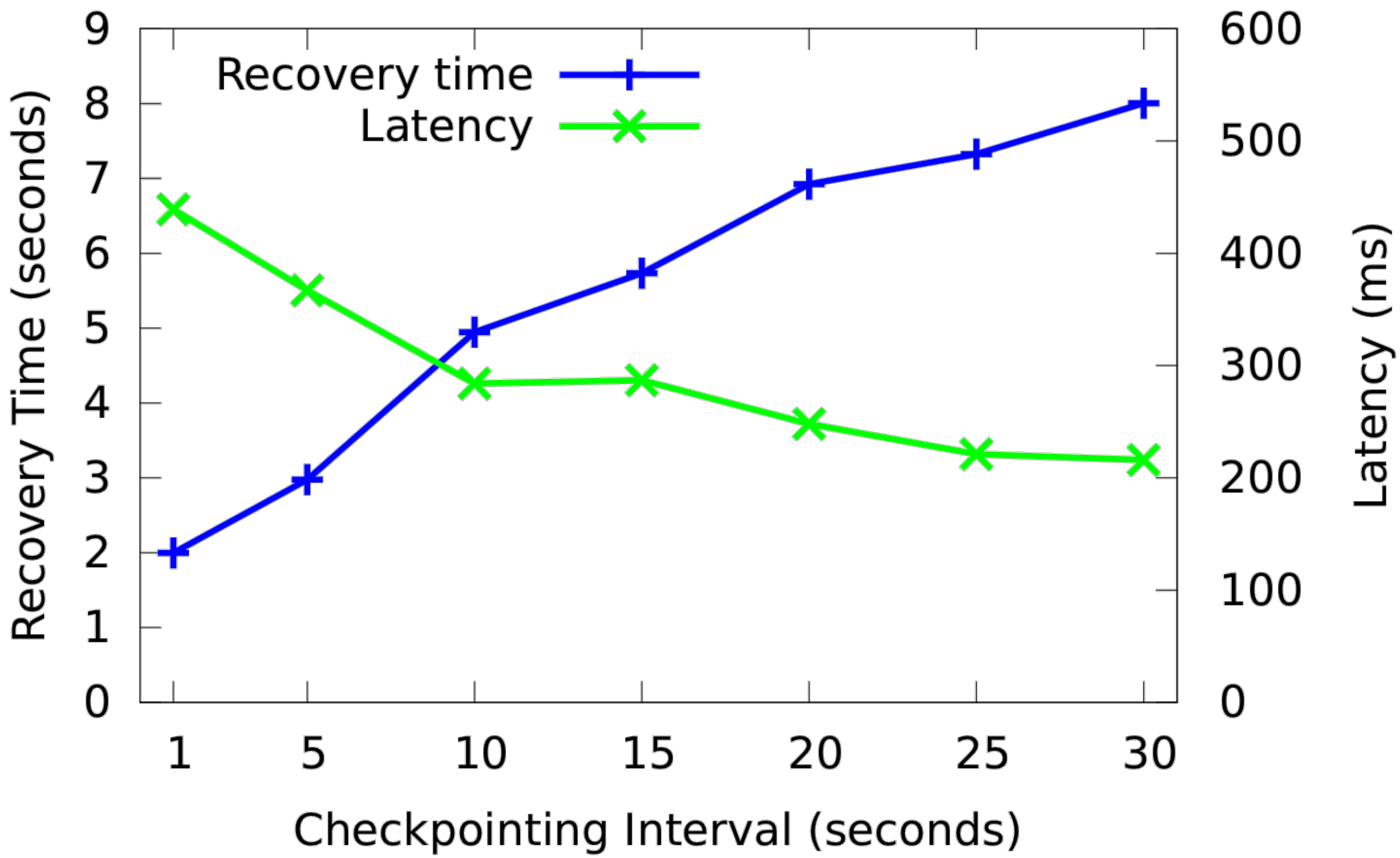
Performance of SEEP

Logistic regression

- Deployed on Amazon EC2 (“m1.xlarge” VMs with 4 vCPUs and 16 GB RAM)
- 100 GB dataset



Overhead of Checkpointing



☛ **Tradeoff between latency and recovery time**

Related Work

Scalable stream processing systems

- **Twitter Storm, Yahoo S4, Nokia Dempsey, Apache Samza**
  Exploit operator parallelism mainly for stateless queries

Distributed dataflow systems

- **MapReduce, Dryad, Spark, Apache Flink, Naiad, SEEP**
  Shared nothing data-parallel processing on clusters

Elasticity in stream processing

- **StreamCloud** [TPDS'12]
  Dynamic scale out/in for subset of relational stream operators
- **Esc** [ICCC'11]
  Dynamic support for stateless scale out

Resource-efficient fault tolerance models

- **Active Replication at (almost) no cost** [SRDS'11]
  Use under-utilized machines to run operator replicas
- **Discretized Streams** [HotCloud'12]
  Data is checkpointed and recovered in parallel in event of failure

Summary

Stream processing grows in importance

- Handling the data deluge
- Enables real-time response and decision making

Principled models to express stream processing semantics

- Window-based declarative query languages
- What is the right programming model for machine learning?

Stateful distributed dataflows for stream processing

- High stream rates require data-parallel processing
- Fault-tolerant support for state important for many algorithms
- Convergence of batch and stream processing

Thank You! Any Questions?

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