Sensor Database: Querying Sensor Networks

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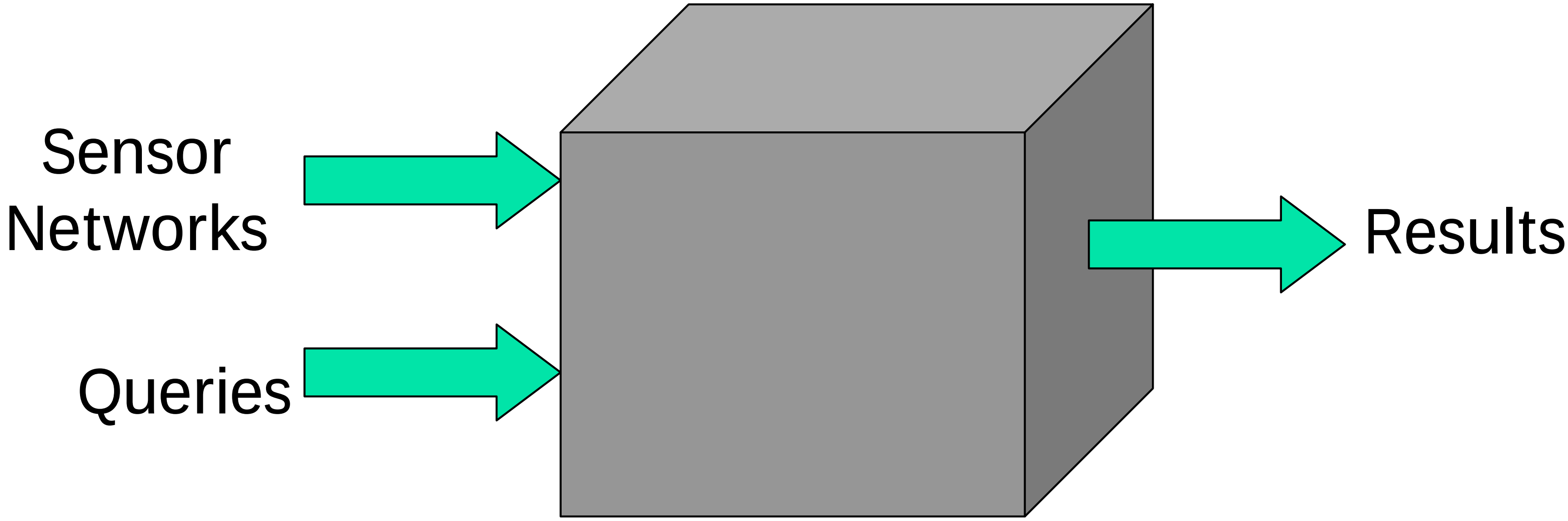
The Black Box



- Desirable Properties:
  - Good query interface
  - Power efficiency, long lifetime
  - Scalability
  - Adaptivity
  - Low response time (high throughput)

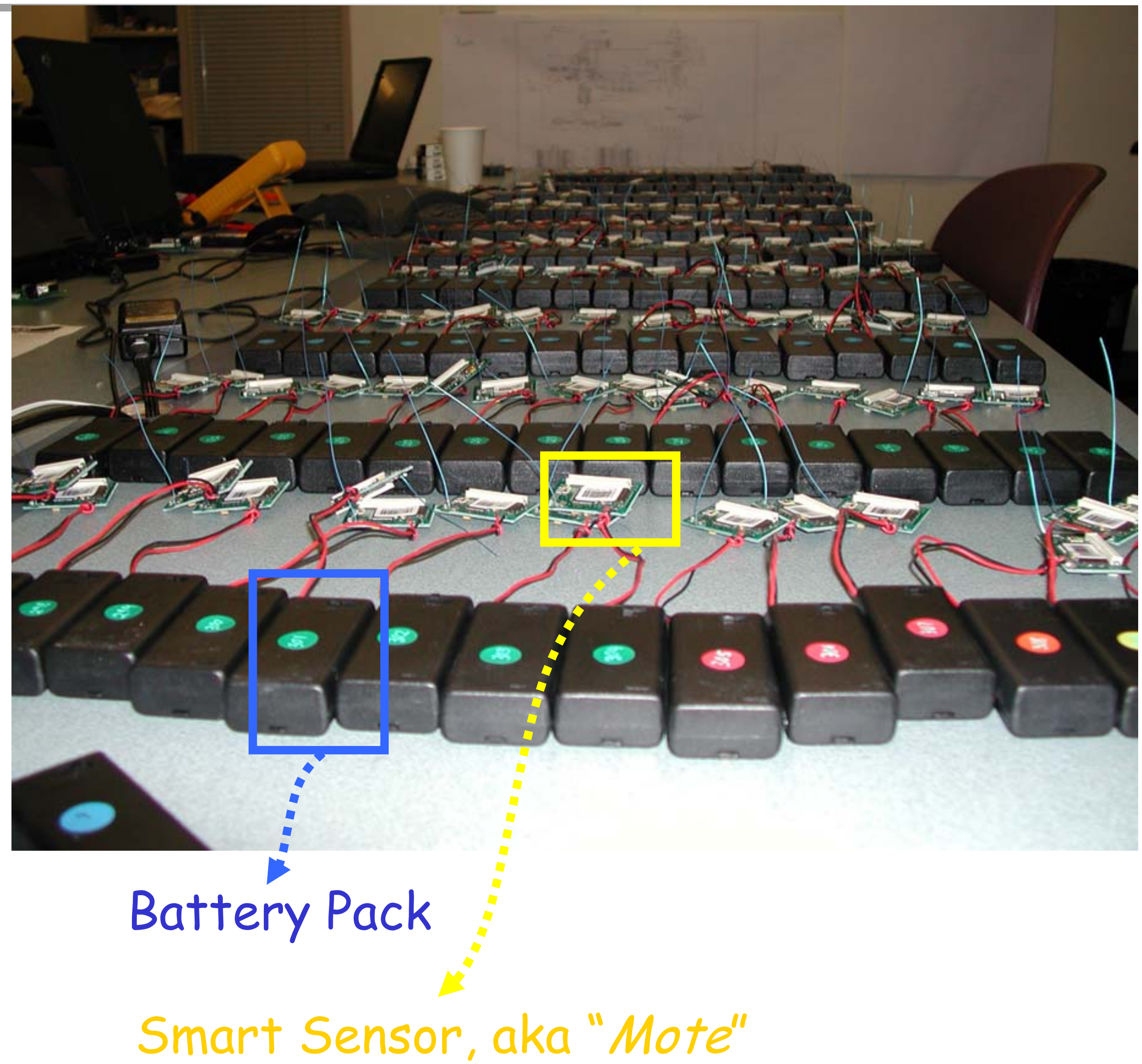
Outline

- Background and motivation
- Acquisitional query optimization
- Continuously adaptive continuous query optimization
- Summary
- Future work

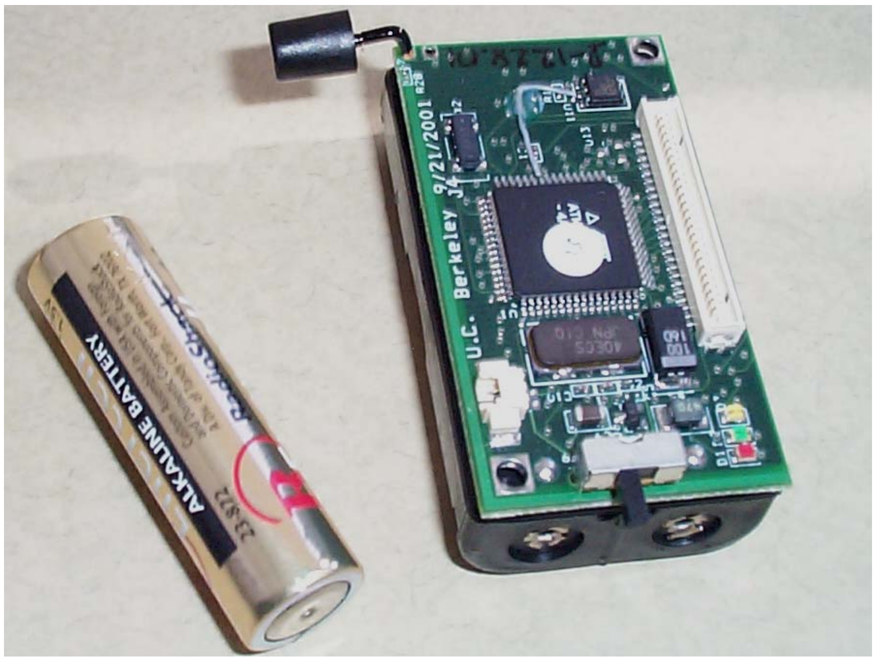
Sensor Networks

- Small computers with:
  - Radios
  - Sensing hardware
  - Batteries

- Remote deployments
  - Long lived
  - 10s, 100s, or 1000s



Mica Motes



4Mhz, 8 bit Atmel RISC uProc

40 kbit Radio

4 K RAM, 128 K Program Flash, 512 K Data Flash

AA battery pack

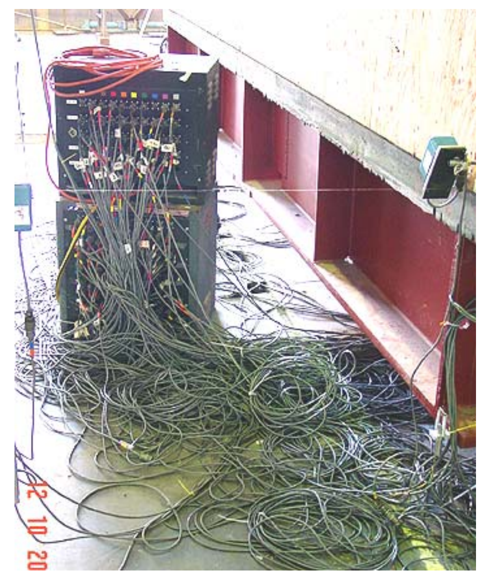
Based on TinyOS

Sensor Net Sample Apps

Habitat Monitoring: Storm petrels on Great Duck Island, microclimates on James Reserve.

Earthquake monitoring in shake-test sites.

Vehicle detection: sensors along a road, collect data about passing vehicles.



Traditional monitoring apparatus.

Sensor Database

- Sensors table is an unbounded, continuous data stream
  - Sensors viewed as a single table
  - Columns are sensor data
  - Rows are individual sensors
- Query processor-like interface
  - SQL-like queries in the form of SELECT-FROM-WHERE
- Operations such as sort and symmetric join are not allowed on streams, however, they are allowed on bounded subsets of the stream (windows)

Query Examples

"Find the sensors in bright nests."

- Example:

  SELECT nodeid, nestNo, light
  FROM sensors
  WHERE light > 400
  EPOCH DURATION 1s

Sensors

Epoch	Nodeid	nestNo	Light
0	1	17	455
0	2	25	389
1	1	17	422
1	2	25	405

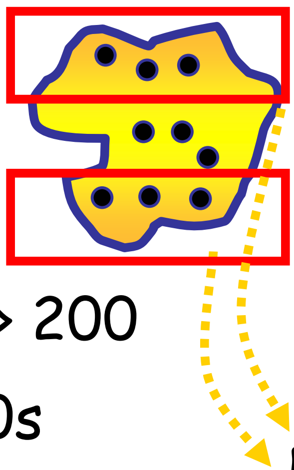
⋮ ⋮

Query Examples – *cont'd*

SELECT AVG(sound)
FROM sensors
EPOCH DURATION 10s

"Count the number occupied nests in each loud region of the island."

SELECT region, CNT(occupied)
AVG(sound)
FROM sensors
GROUP BY region
HAVING AVG(sound) > 200
EPOCH DURATION 10s



Epoch	region	CNT(...)	AVG(...)
0	North	3	360
0	South	3	520
1	North	3	370
1	South	3	520

Regions w/ AVG(sound) > 200

Continuous Query

- “Monitoring” queries look for recent events in data streams; We confine our view to queries over ‘recent-history’
    - Only tuples currently entering the system
    - Stored in in-memory data tables for time-windowed joins between streams
- Long running, “standing queries”, similar to trigger systems
- Installed; continuously produce results until removed

Continuous Query - *cont'd*

- Closed world assumption does not hold
  - Could generate an infinite number of samples
  - Traditional system: data is provided *a priori*
- Lots of queries, over the same data sources
  - In-network processing
  - Opportunity for work sharing!
  - Global query optimization problem (hard)
  - finding an optimal plan (adaptively)

Where are the problems?

- Radio consumes as much power as the CPU
- Transmitting one bit of data consumes as much energy as 1000 CPU instructions!
- Message overhead
- Sensing takes significant energy

Goals

- Provide a query processor-like interface to sensor networks
- Use some techniques to reduce power consumption compared to traditional passive systems

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Acquisitional Query Processing

- Provide a query processor-like interface to sensor networks
- Use Acquisitional techniques to reduce power consumption compared to traditional passive systems

Acquisitional Query Processing

- Traditional DBMS: processes data already in the system
- Acquisitional DBMS: generates the data in the system

- An Acquisitional query processor controls
  - When should samples for a particular query be taken?
  - What sensor nodes have data relevant to a particular query?
  - And with what frequency data is collected
- Versus traditional systems where data is provided ahead

What's the big deal? *(revisit)*

- Radio consumes as much power as the CPU
- Transmitting one bit of data consumes as much energy as 1000 CPU instructions!
- Message sizes in TinyDB are by default 48 bytes
- Sensing takes significant energy

Acquisitional Query Processing

- Basic Acquisitional Processing
  - Basic Language Features
  - Event-based Query and Lifetime-Based Query
- Power-aware Optimization
  - Ordering Sampling and Predicates
- Power-sensitive Dissemination
  - Semantic Routing Trees
- Processing Queries
  - Prioritizing Data Delivery
  - Adapting Rates and Power Consumption

Basic Language Features

- SQL-like queries in the form of SELECT-FROM-WHERE
- Support for selection, join, projection, and aggregation
- Also support for sampling, windowing, and sub-queries
- Not mentioned is the ability to log data and actuate physical hardware

Basic Language Features

Example:"Find the sensors in bright rooms"

```
SELECT nodeid, light, temp
FROM sensors
WHERE light > 400
SAMPLE INTERVAL 1s FOR 10s
```

- Queries posed from PC, distributed and executed in-network
- Sensors viewed as a single table
- Columns are sensor data
- Rows are individual sensors

Queries as a Stream

- Sensors table is an unbounded, continuous data stream
- Operations such as sort and symmetric join are not allowed on streams
- They are allowed on bounded subsets of the stream (windows)

Windows

- Windows in TinyDB are fixed-size materialization points
- Materialization points can be used in queries

- Example: “output a stream of counts indicating the number of recent light readings that were brighter than the current readings”

```
CREATE
       STORAGE POINT recentlight SIZE 8
       AS (SELECT nodeid, light FROM sensors
       SAMPLE INTERVAL 10s)

SELECT COUNT(*)
       FROM sensors AS s, recentlight AS r1
       WHERE r.nodeid = s.nodeid
       AND s.light < r1.light
       SAMPLE INTERVAL 10s
```

Temporal Aggregation

- *Temporal Aggregation* aggregates sensors values across multiple consecutive epochs from the same or different nodes
- *Temporal Aggregation* take two extra arguments: window_size, sliding_dist. For example, winavg(window_size, sliding_dist, arg)

- Example: "computes the 30-sample running average of light sensor readings"

```
SELECT WINAVG(30s, 5s, light)
FROM sensors
SAMPLE INTERVAL 1s
```

*Receive only 6 results from each sensor instead of 30

Event-Based Queries

- *Events* act as a mechanism for initiating data collection
- *Events* allow the system to be dormant until some external conditions occur

Example: “report the average light and temperature level at sensors near a bird nest where a bird has just been detected”

```
ON EVENT bird-detect(loc):
    SELECT AVG(light), AVG(temp), event.loc
    FROM sensors AS s
    WHERE dist(s.loc, event.loc) < 10m
    SAMPLE INTERVAL 2s FOR 30s
```

Lifetime-Based Queries

- Lifetime is a much more intuitive way for users to reason about power consumption
- To satisfy a lifetime clause, TinyDB performs lifetime estimation

$$T = p_h / e_s$$

T: maximum transmission rate; p_h: available power per hour; e_s: the energy to collect and transmit one sample

Example: "the network should run for at least 30 days"

```
SELECT nodeid, accel
FROM sensors
LIFETIME 30 days
```

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Optimization

- Three phases to queries
  - Creation of query
  - Dissemination of query
  - Execution of query
- TinyDB makes optimizations at each step

Ordering of Sampling And Predicates

SELECT light, mag
FROM sensors
WHERE pred1(mag)
AND pred2(light)
EPOCH DURATION 1s

- Power condition: sampling magnetometer is much more costly than sampling light
  - 1500uJ vs. 90uJ

- The correct order is pred2(light)→pred1(mag)
- At 1 sample/sec, total power savings could be ⩾3.5 mW, which is comparable with processor power

For Aggregate Queries

SELECT WINMAX(light, 8s, 8s)

FROM sensors

WHERE mag>X

EPOCH DURATION 1s

- The correct order is:
  - Sample light, light>MAX?
  - If so, sample mag, mag>X?
  - Report light

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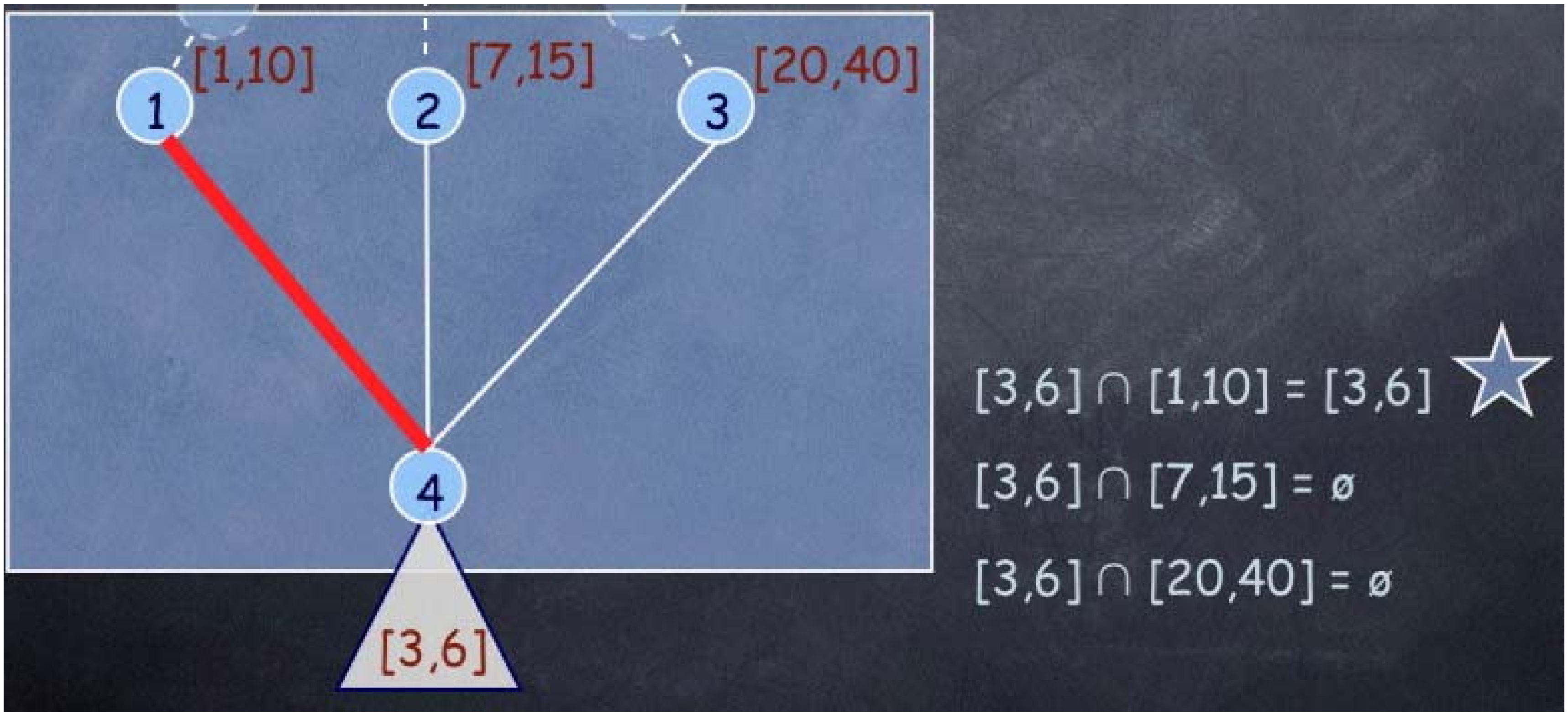
Semantic Routing Trees

- Co-acquisition: exploit correlations of sensors to reduce data dissemination
  - Queries are often constrained in a region
  - Avoid sending queries to non-involved sensors
- Rule: sensors that sample together route together
- Build semantic routing trees (SRT) to reduce data dissemination
  - SRT nodes choose parents based on semantic properties as well as link quality

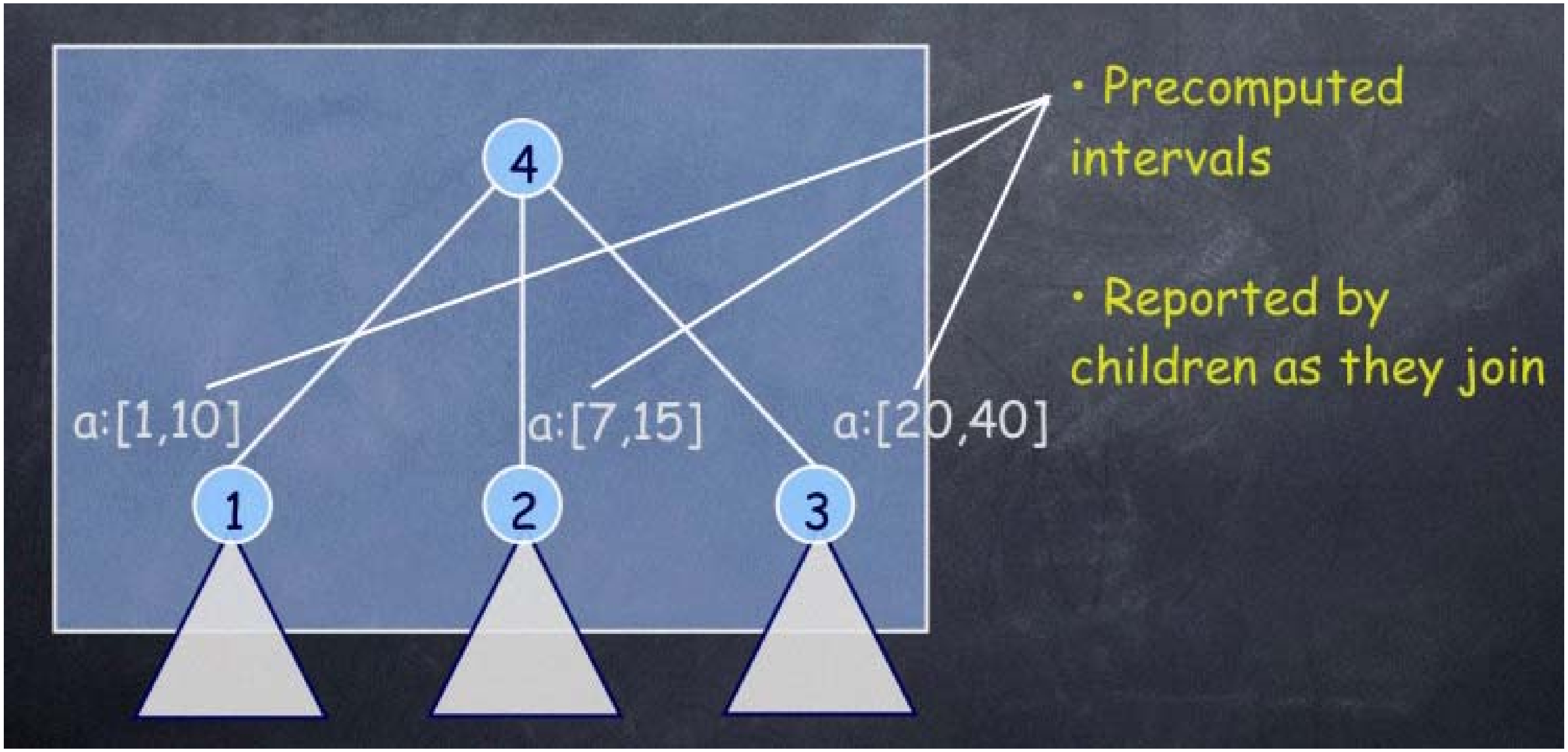
Semantic Routing Trees

- For node join, node picks parent whose ancestor's interval most overlap its descendants' interval



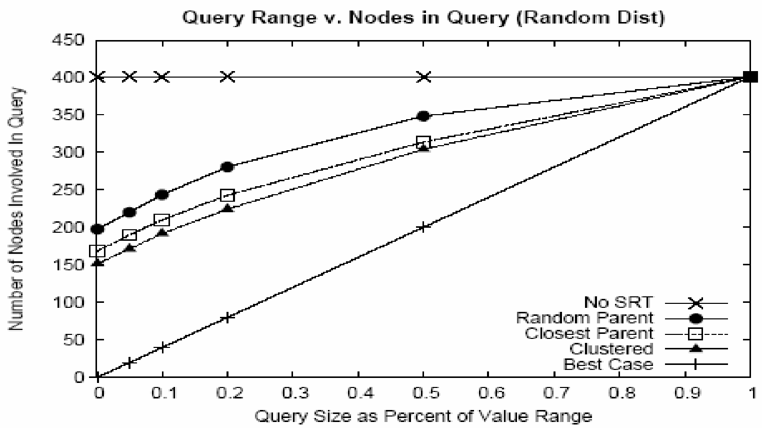
Semantic Routing Trees

- Parent nodes keep track of children's value range

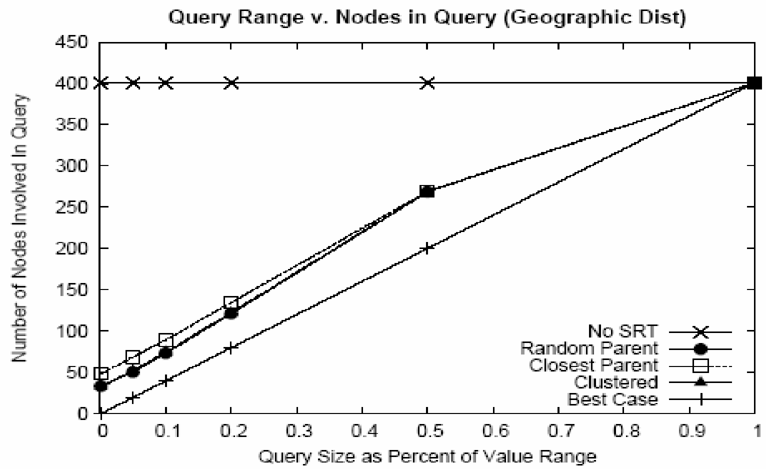


Performance Evaluation of SRT

- In the random distribution, each constant attribute value was randomly and uniformly selected from the interval [0, 1000]
- In the geographic distribution, sensor values were computed based on a function of sensor's x and y position in the grid.



(a)Random Distribution



(b)Geographic Distribution

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Processing Queries

- Queries have been optimized both locally and collaboratively in distribution. What more can we do?
- Enhance the channel utilization!
- Prioritize data that needs to be sent
  - Naive - FIFO
  - Winavg – Average top queue entries
  - Delta – Send result with most change
- Adapt data rates and power consumption

Prioritizing Data Delivery

- When aggregate sample rate > channel bandwidth, we can only transmit the most valuable data
- Data prioritization is domain dependent
  - E.g. largest, sharp, most frequently changing, ...
- use the delivery buffer
  - Out-of-order delivery

Discussion of ACQP

- TinyDB: a new way to the user interface for data collection in sensor network
  - Easier, faster, more general
  - Make people seek helps from the DB realm
- Acquisitonal query processing: addressing new issues that arise in sensor networks by adding new features to DB querying semantics
  - Lifetime and event based query
  - Power-aware optimization
  - Data dissemination in sensor networks
  - Runtime prioritization

Discussion of ACQP

- Is TinyDB the right way to look at the application of sensor networks
- Improve the semantic routing tree with more sophisticated methods
  - How about general routing issues when SRT is used? (e.g. load-balance, channel bandwidth). Can we benefit more from routing layer and geographic information in SRT?
- Data Prioritization is very important and need to be pursued
  - When query load is heavy, a sensor/channel will overload
  - Co-query prioritization is needed
  - A decentralized algorithm to make both emergent & less-emergent queries be satisfied, under resource constraints

Outline

- ✓ Background and motivation
- ✓ Acquisitional query (ACQP) optimization
- ➢ Continuously adaptive continuous query (CACQ) optimization
- Summary
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CACQ Introduction

- Proposed continuous query (CQ) systems are based on static plans
  - But, CQs are long running
  - Initially valid assumptions less so over time
  - Static optimizers at their worst!

- CACQ insight: apply continuous adaptivity to continuous queries
  - Dynamic operator ordering avoids static optimizer danger
  - Process multiple queries simultaneously
  - Interestingly, enables sharing of work & storage

Mission Accomplished:

- Efficient mechanism for processing multiple simultaneous monitoring queries over streaming data sources
  - Share work by processing all queries within a single eddy
- Continuous adaptivity to changing world
  - Queries come & go, but performance adapts without costly multiquery reoptimization
- Maximize ability to work share by explicitly encoding lineage
- Share selections via grouped filter

Approaches

- Adaptivity
  - Policies for continuous queries
  - Single eddy for multiple queries
- Tuple Lineage
  - Lineage capture a tuple's path through a single query, and concisely expresses a tuple's path through all queries in the system
  - In addition to **`ready`** and **`done`**, encode output history in tuple in **`queriesCompleted`** bits
    - Enables flexible sharing of operators between queries
- Grouped Filter
  - Efficiently compute selections over multiple queries

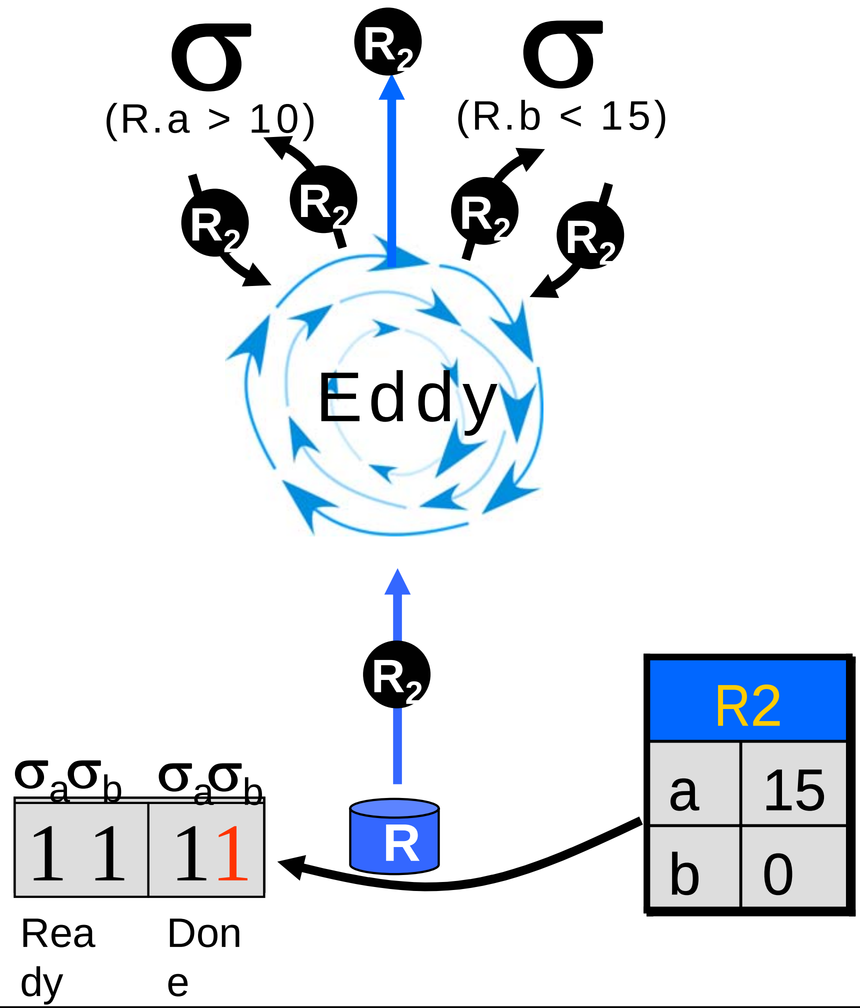
Tuple Lineage

- **`Ready`** bit vector
  - Where it must go next
  - set if the operator can be applied to this tuple
- **`Done`** bit vector
  - Where it has been
  - Set if the operator to which a tuple has already been routed
- **`QueriesCompleted`** bit vector
  - where it may still be output
  - set if this tuple has already been output or rejected by the query

Single Query, Single Source

```
SELECT *
FROM R
WHERE R.a > 10 AND R.b < 15
```

- Use ready bits to track what to do next
  - All 1's in single source
- Use done bits to track what has been done
  - Tuple can be output when all bits set



Multiple Queries

SELECT *
FROM R
WHERE R.a > 10
AND R.b < 15

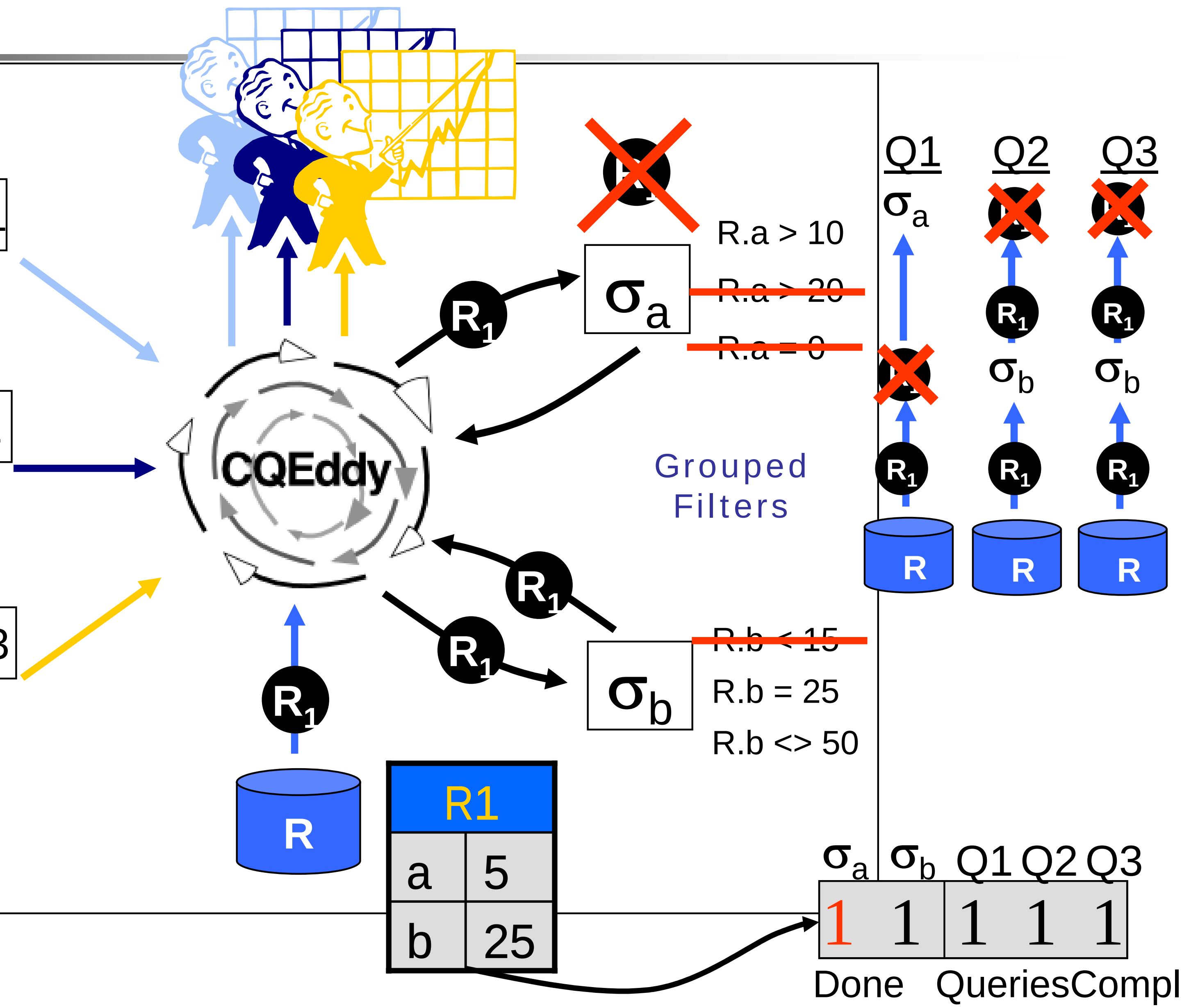
Q1

SELECT *
FROM R
WHERE R.a > 20
AND R.b = 25

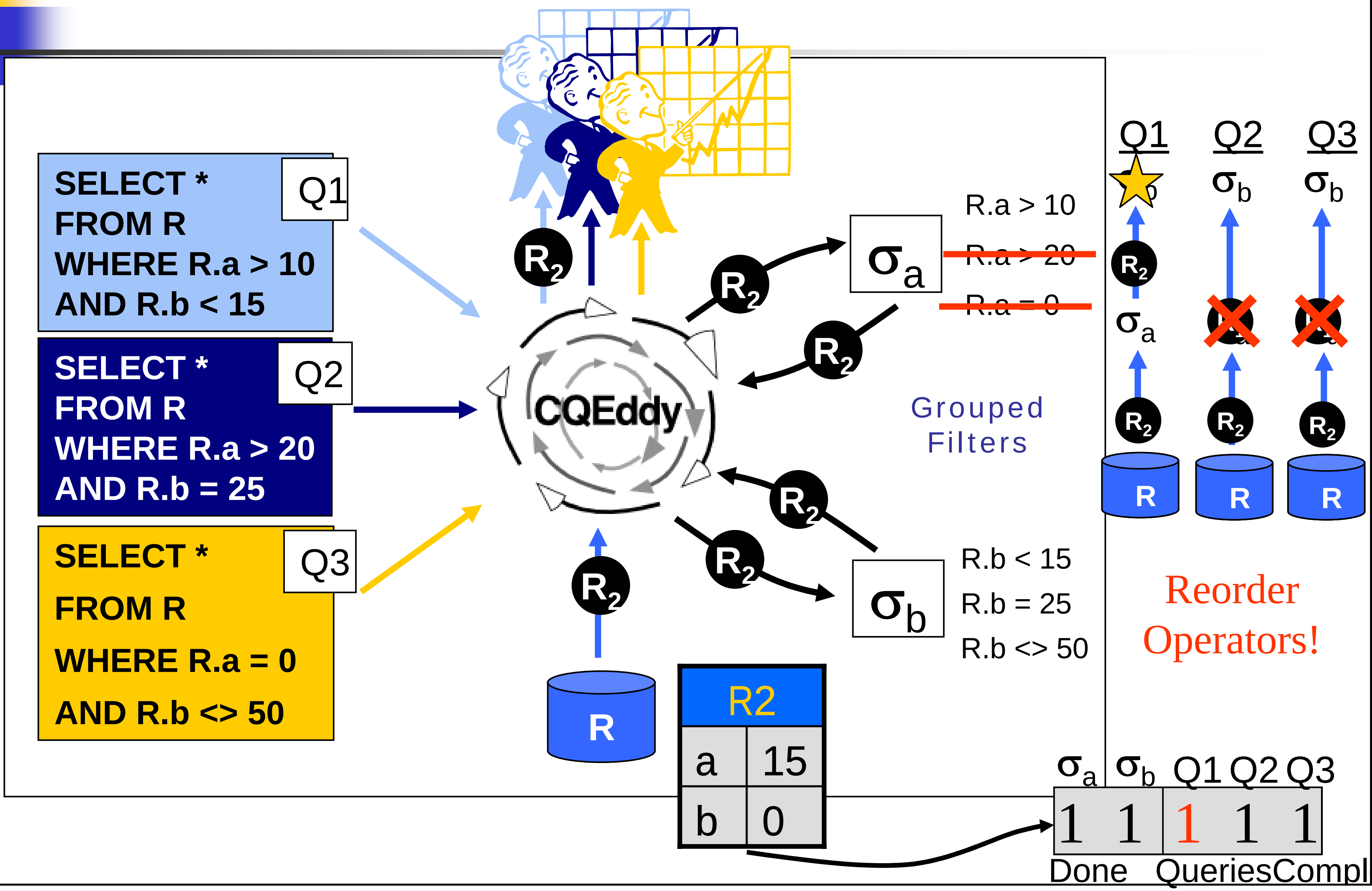
Q2

SELECT *
FROM R
WHERE R.a = 0
AND R.b <> 50

Q3



Multiple Queries



Outputting Tuples

- Store a completionMask bitmap for each query
  - One bit per operator
  - Set if the operator in the query
- To determine if a tuple t can be output to query q:
  - Eddy ANDs q's completionMask with t's done bits
  - Output only if q's bit not set in t's queriesCompleted bits
- Every time a tuple returns from an operator

completionMasks

Q1: 1100 & **Done** == 1100 && **QueriesCompleted[0]** == 0

Q2: 0111 & **Done** == 0111

Query 1

SELECT * FROM R
WHERE R.a > 10
AND R.b < 15

Query 2

SELECT * FROM R
WHERE R.b < 15
AND R.c <> 5 AND R.d = 10

completionMasks

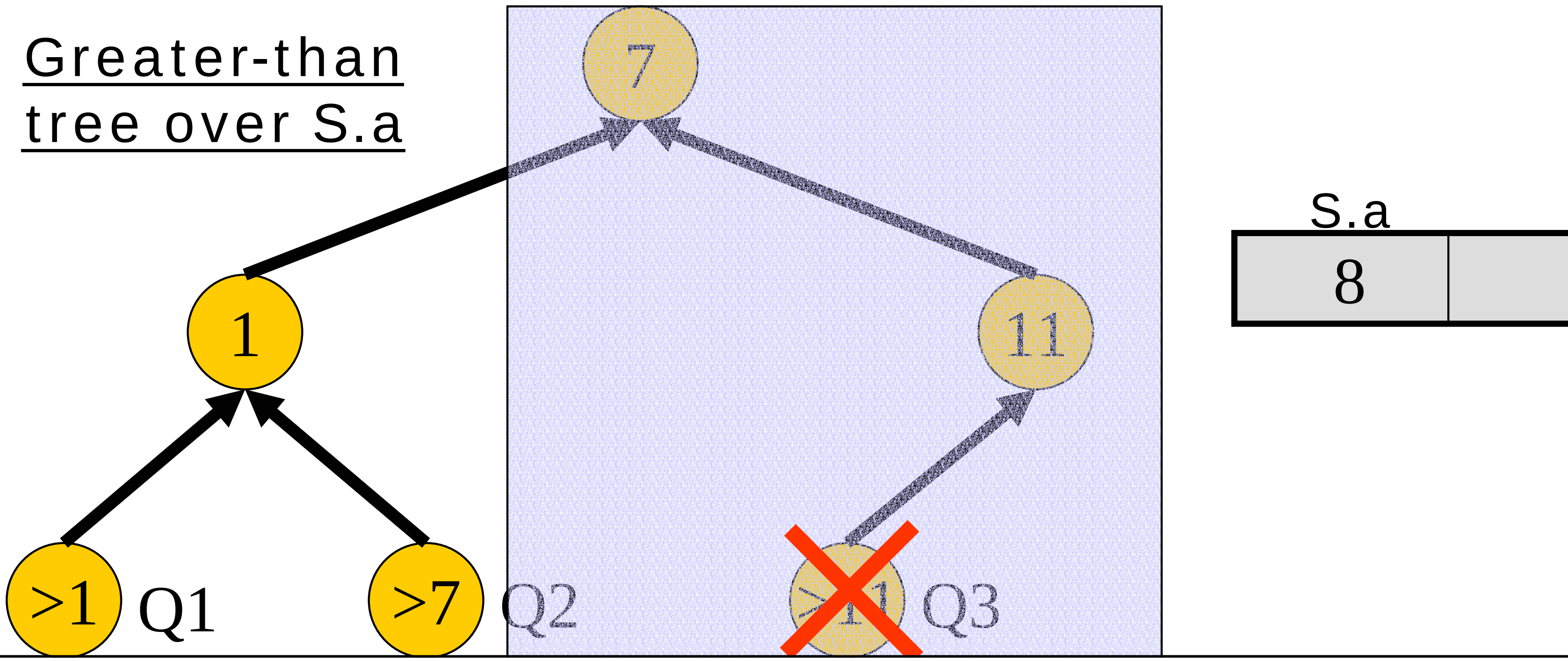
σ	a	b	c	d
Q1	1	1	0	0
Q2	0	1	1	1

Tuple

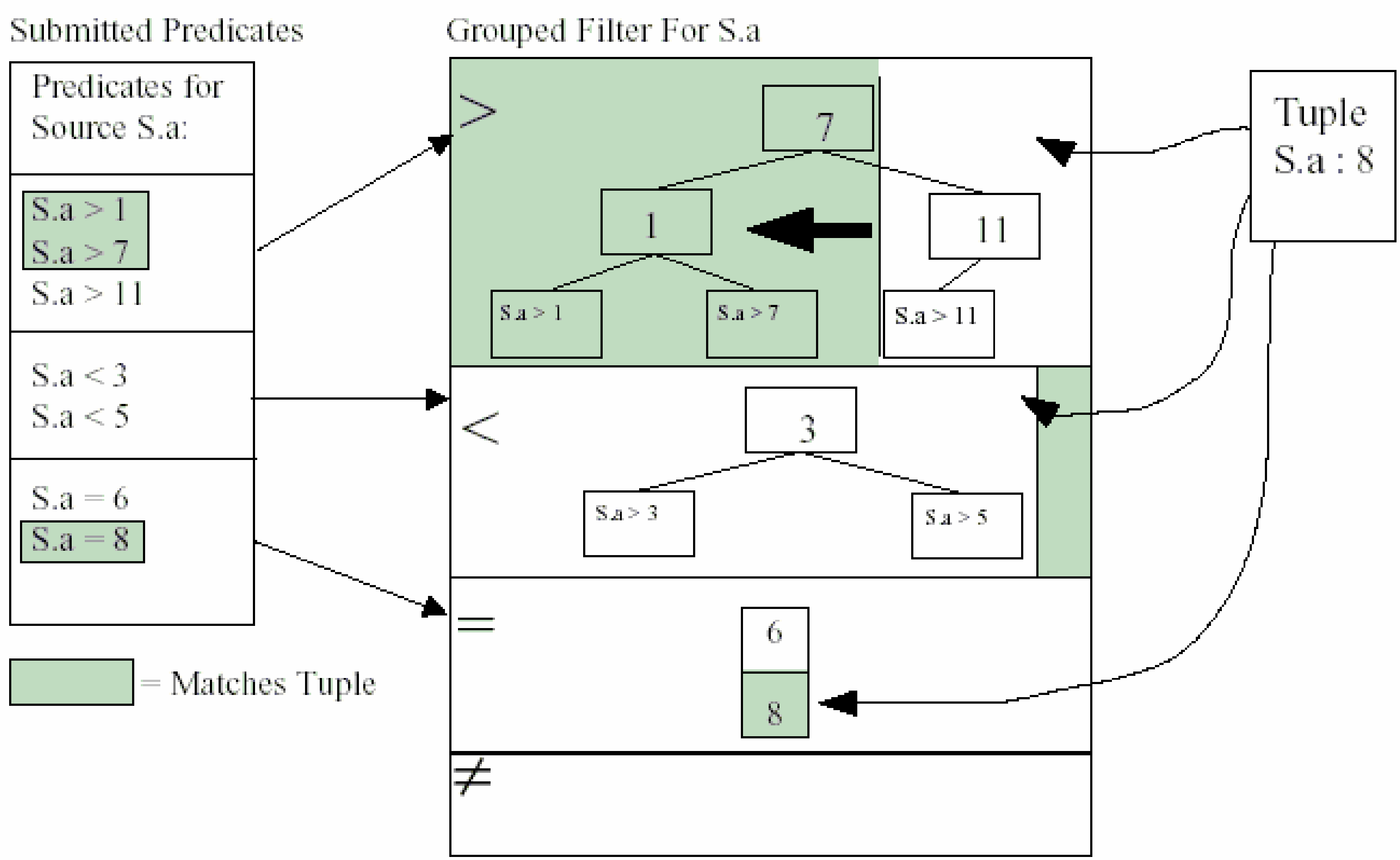
σ_a	σ_b	σ_c	σ_d	Q1	Q2
1	1	0	0	1	0
Done				QC	

Grouped Filter

- Use binary trees to efficiently index range predicates
  - Two trees (LT & GT) per attribute
  - Insert constant
- When tuple arrives
  - Scan everything to right (for GT) or left (for LT) of the tuple-attribute in the tree
  - Those are the queries that the tuple does not pass
- Hash tables to index equality, inequality predicates

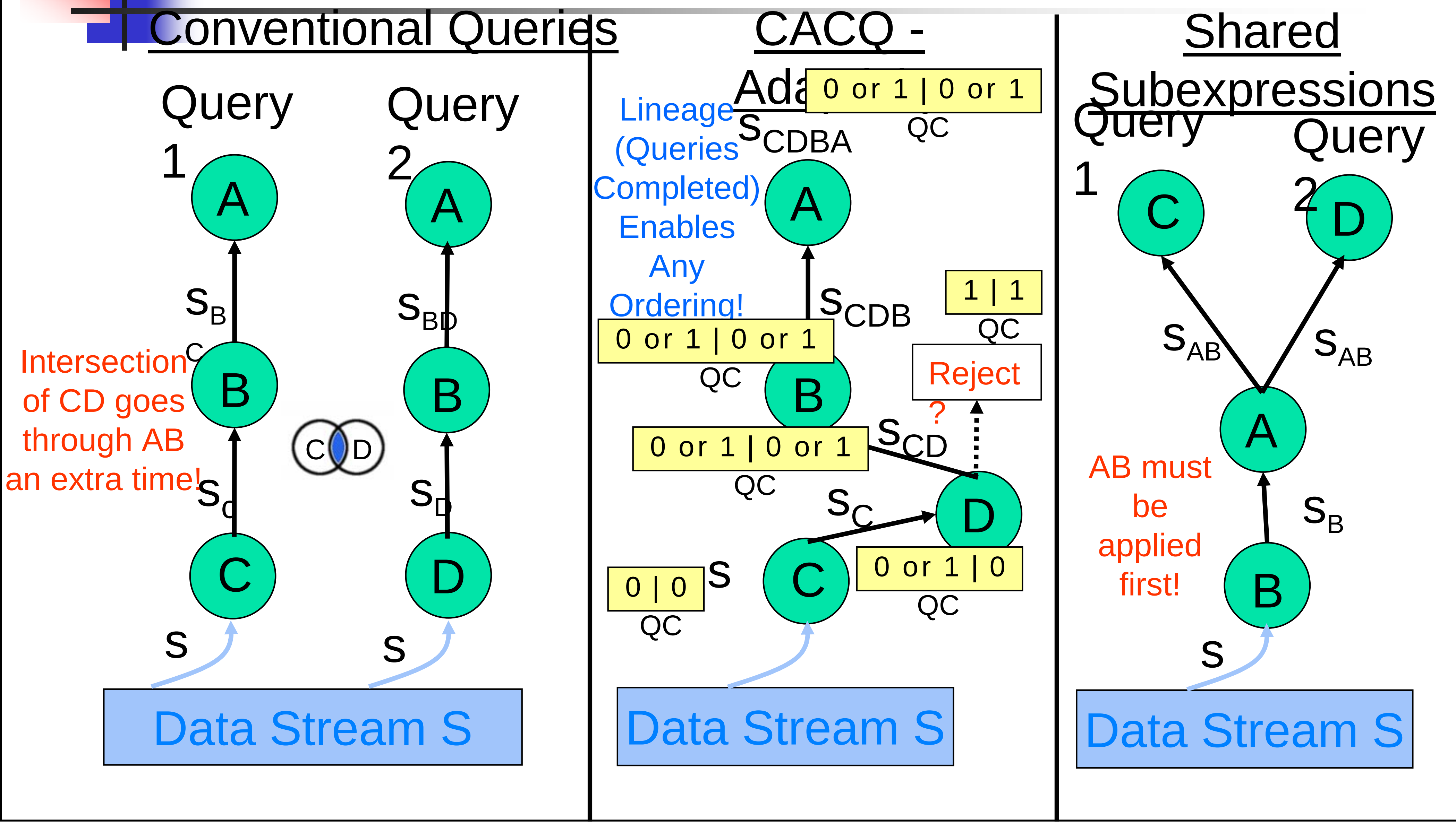


Grouped Filter – *cont'd*



Work Sharing via Tuple Lineage

Q1: SELECT * FROM s WHERE A, B, C   Q2: SELECT * FROM s WHERE A, B, D



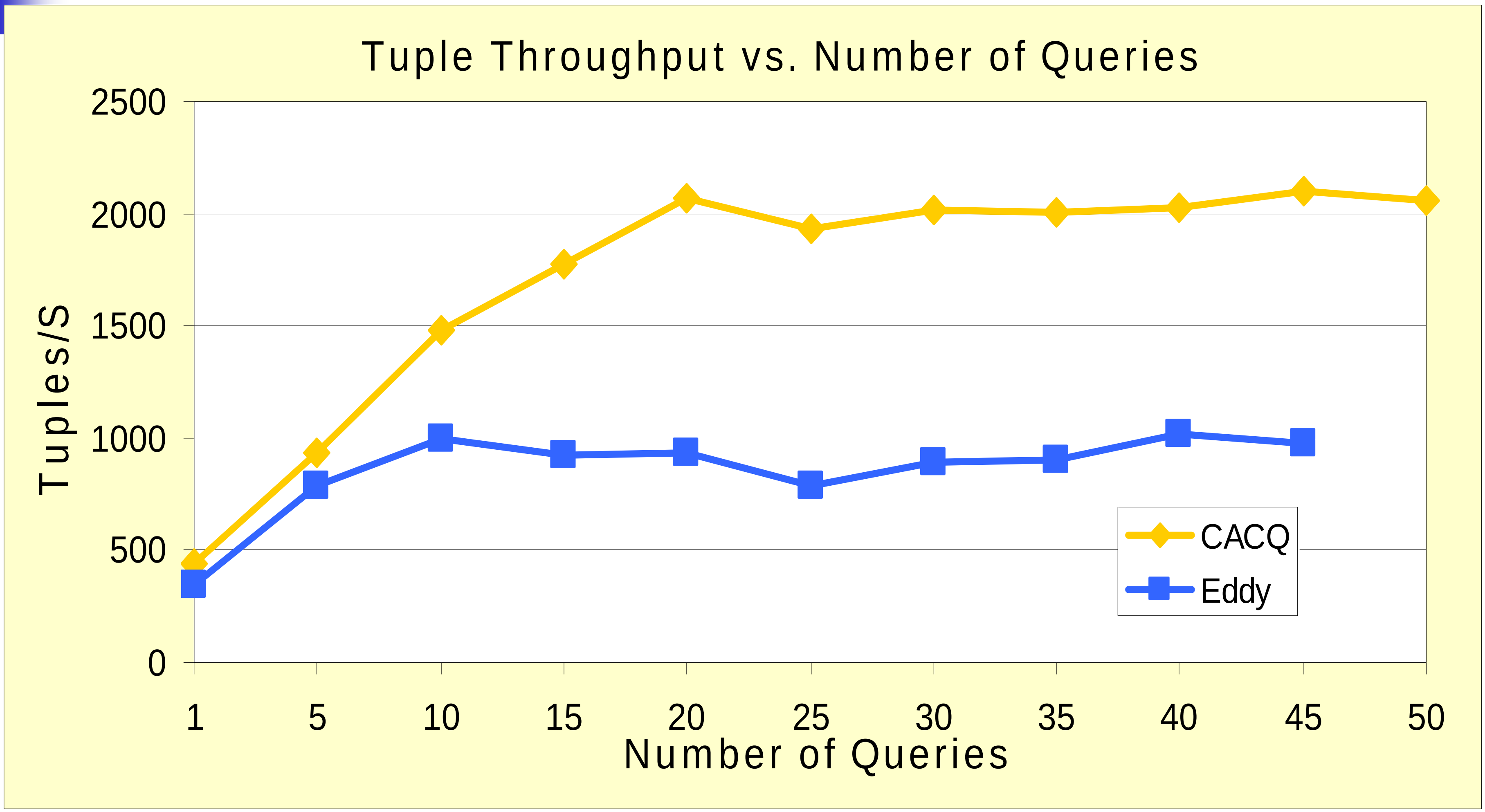
Tradeoff: Overhead vs. Shared Work

- Overhead in additional bits per tuple
  - Experiments studying performance, size in paper
  - Bit / query / tuple is most significant
- Trading accounting overhead for work sharing
  - 100 bits / tuple allows a tuple to be processed once, not 100 times
- Reduce overhead by not keeping state about operators tuple will never pass through

Evaluation

- Real Java implementation on top of Telegraph QP
  - 4,000 new lines of code in 75,000 line codebase
- Server Platform
  - Linux 2.4.10
  - Pentium III 733, 756 MB RAM
- Queries posed from separate workstation
  - Output suppressed
- Lots of experiments in paper, just a few here

Performance: Increased Scalability

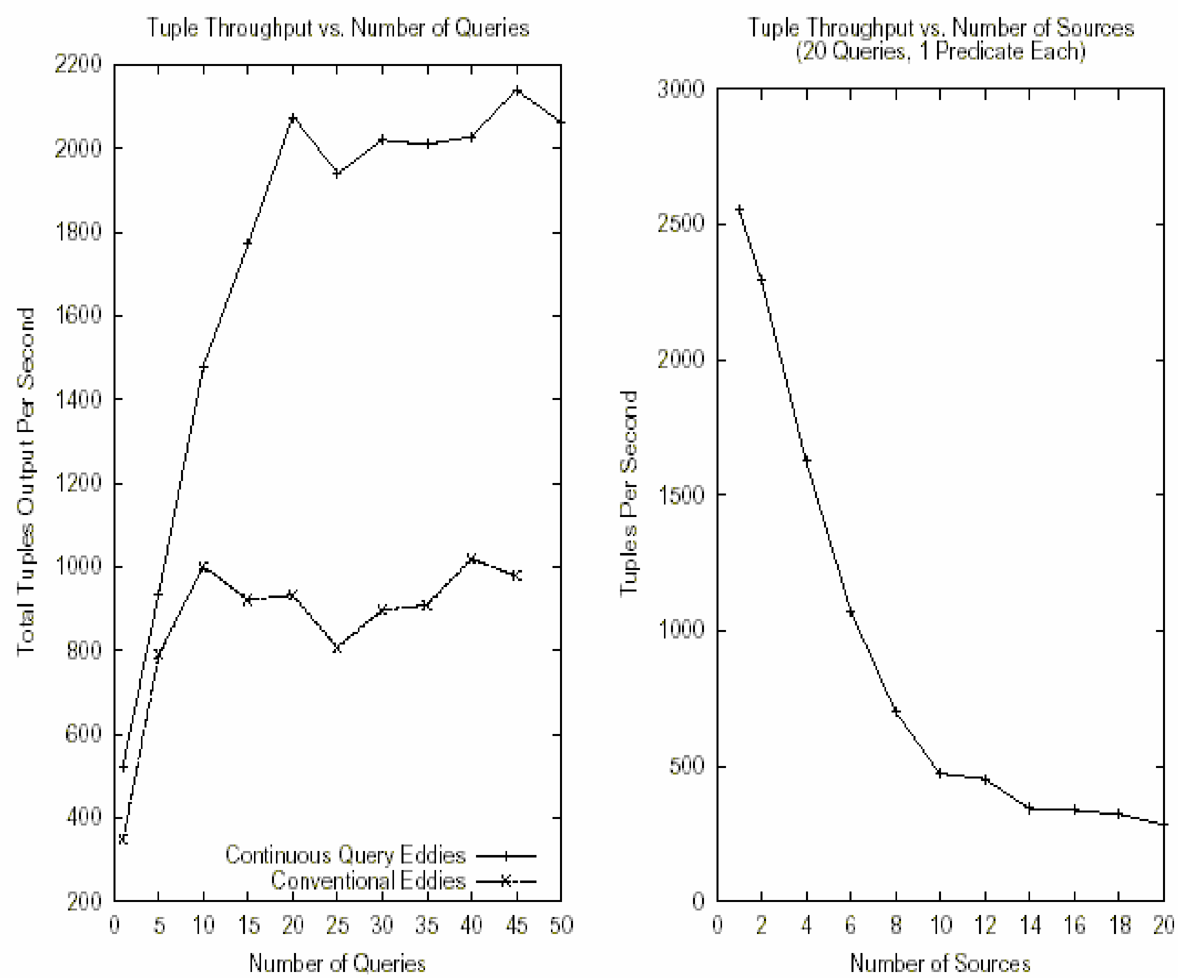


Workload, Per Query: 1-5 randomly selected range predicates of form 'attr > x' over 5 attributes. Predicates from the uniform distribution [0,100]. 50% chance of predicate over each attribute.

Performance – *cont'd*

- Continuous query has about double throughput compared to conventional query

- Additional sources decrease throughput
  - Many more scan operators that must be scheduled
  - Many more filter-operators are created and a larger number of predicates evaluated (filters of indep. Streams cannot be combined)



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Summary: ACQP

- ACQP: controls when, where, and with what frequency data is collected
  - Question: *Is this the best way (right way?) to look at a sensor network?*

- Four related questions
  - When should samples be taken?
  - What sensors have relevant data?
  - In what order should samples be taken?
  - Is it worth it?

Summary: ACQP – *cont'd*

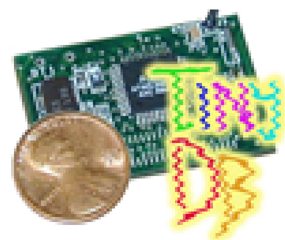
- How should the query be processed?
  - Sampling as a first class operation
  - Event – join duality
- How does the user control acquisition?
  - Rates or lifetimes
  - Event-based triggers
- Which nodes have relevant data?
  - Index-like data structures
- Which samples should be transmitted?
  - Prioritization, summary, and rate control

Summary: CACQ

- CACQ: sharing and adaptivity for high performance monitoring queries over data streams
- Features
  - Adaptivity
    - Adapt to changing query workload without costly multi-query reoptimization
  - Work sharing via tuple lineage
    - Without constraining the available plans
  - Computation sharing via grouped filter

Future Work

- Expressing lossiness
- Batching & query grouping
- Additional Operations
  - Joins
  - Signal Processing



- Integration with Streaming DBMS
  - In-network vs. external operations
- Heterogeneous Nodes and Operators
- Real Deployments