Data Streams & Continuous Queries

The Stanford STREAM Project

stanfordstreamdatamanager

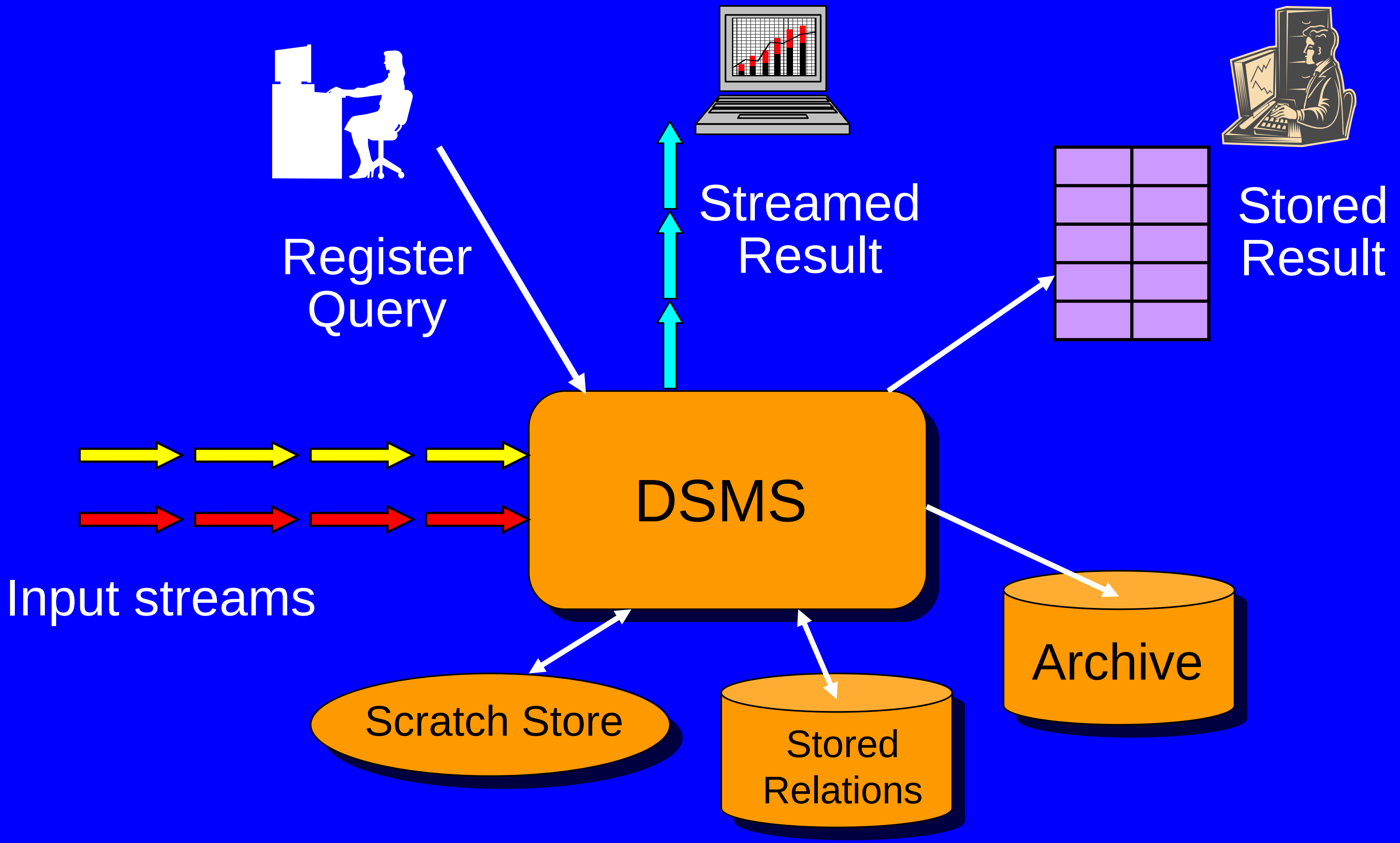
Data Streams

- Continuous streams of data elements (may be unbounded, rapid, time-varying)
- Occur in a variety of modern applications
  - Network monitoring and traffic engineering
  - Sensor networks, RFID tags
  - Telecom call records
  - Financial applications
  - Web logs and click-streams
  - Manufacturing processes
- DSMS = Data Stream Management System

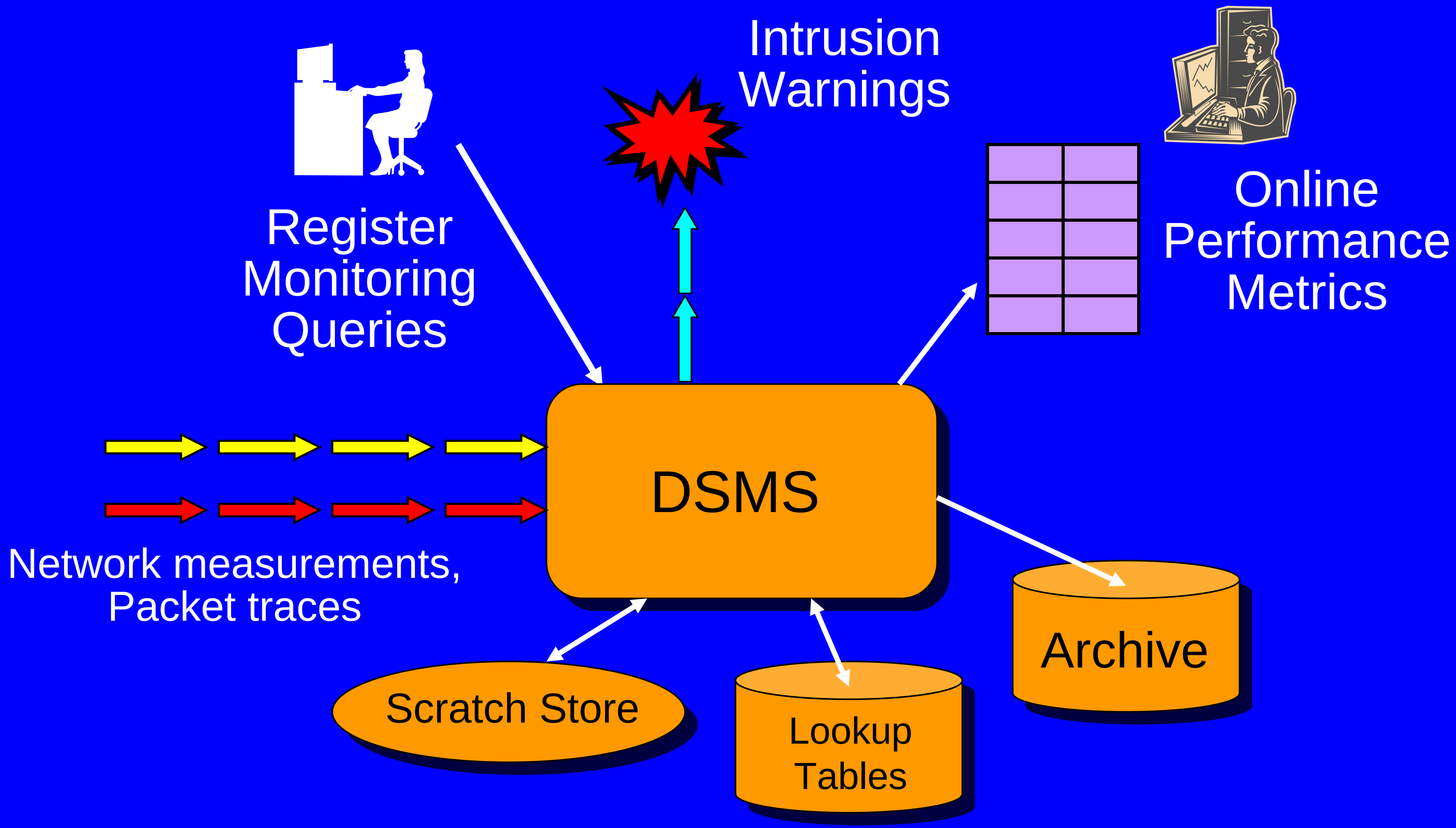
DBMS versus DSMS

DBMS	DSMS
Persistent relations	Transient streams (and persistent relations)
One-time queries	Continuous queries
Random access	Sequential access
Access plan determined by query processor and physical DB design	Unpredictable data characteristics and arrival patterns

The (Simplified) Big Picture



(Simplified) Network Monitoring



The STREAM System

- Data streams and stored relations
- SQL-based language for registering continuous queries
- Variety of query execution strategies
- Textual, graphical, and application interfaces
- Relational, centralized

Rest of This Lecture

- Query language
- System issues and overview (brief)
- Live system demonstration

Goals in Language Design

1) Support continuous queries over multiple streams and updateable relations

2) Exploit existing relational semantics to the extent possible

3) Easy queries should be easy to write

4) Simple queries should do what you expect

Example Query 1

Two streams, contrived for ease of examples:

Orders (orderID, customer, cost)

Fulfillments (orderID, clerk)

Total cost of orders fulfilled over the last day by clerk “Sue” for customer “Joe”

```
Select  Sum(O.cost)
From Orders O, Fulfillments F [Range 1 Day]
Where O.orderID = F.orderID And F.clerk = “Sue”
  And O.customer = “Joe”
```

Example Query 2

Using a 10% sample of the Fulfillments stream, take the 5 most recent fulfillments for each clerk and return the maximum cost

```
Select F.clerk, Max(O.cost)
From Orders O,
     Fulfillments F [Partition By clerk Rows 5] 10% Sample
Where O.orderID = F.orderID
Group By F.clerk
```

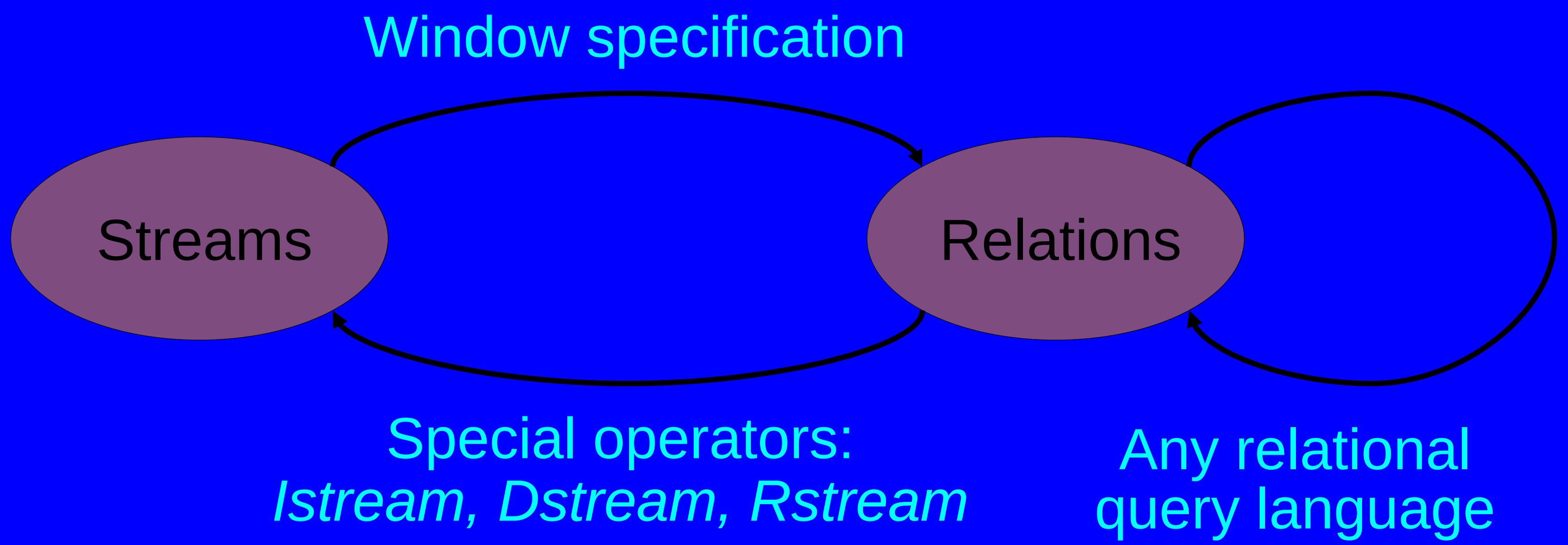
Next

- Formal definitions for relations and streams
- Formal conversions between them
- Abstract semantics
- Concrete language: CQL
- Syntactic defaults and shortcuts
- Equivalence-based transformations

Relations and Streams

- Assume global, discrete, ordered time domain
- Relation
  - Maps time *T* to set-of-tuples *R*
- Stream
  - Set of (*tuple,timestamp*) elements

Conversions



Conversion Definitions

- Stream-to-relation
  - $S\ [W\ ]$ is a relation — at time T it contains all tuples in window W applied to stream S up to T
  - When $W = \infty$, contains all tuples in stream S up to T

- Relation-to-stream
  - Istream(R) contains all $(r, T\ )$ where $r \in R$ at time T but $r \notin R$ at time $T–1$
  - Dstream(R) contains all $(r, T\ )$ where $r \in R$ at time $T–1$ but $r \notin R$ at time T
  - Rstream(R) contains all $(r, T\ )$ where $r \in R$ at time T

Abstract Semantics

- Take any relational query language
- Can reference streams in place of relations
  - But must convert to relations using any window specification language
    (default window = [∞])
- Can convert relations to streams
  - For streamed results
  - For windows over relations
    (note: converts back to relation)

Query Result at Time *T*

- Use all relations at time *T*
- Use all streams up to *T*, converted to relations
- Compute relational result
- Convert result to streams if desired

Abstract Semantics – Example 1

```
Select F.clerk, Max(O.cost)
From O [∞], F [Rows 1000]
Where O.orderID = F.orderID
Group By F.clerk
```

- Maximum-cost order fulfilled by each clerk in last 1000 fulfillments

Abstract Semantics – Example 1

```
Select F.clerk, Max(O.cost)
From O [∞], F [Rows 1000]
Where O.orderID = F.orderID
Group By F.clerk
```

- At time *T*: entire stream *O* and last 1000 tuples of *F* as relations
- Evaluate query, update result relation at *T*

Abstract Semantics – Example 1

Select Istream(F.clerk, Max(O.cost))
From O [∞], F [Rows 1000]
Where O.orderID = F.orderID
Group By F.clerk

- At time *T*: entire stream *O* and last 1000 tuples of *F* as relations
- Evaluate query, update result relation at *T*
- Streamed result: New element (<clerk,max>,T) whenever <clerk,max> changes from *T–1*

Abstract Semantics – Example 2

Relation CurPrice(stock, price)

```
Select stock, Avg(price)
From Istream(CurPrice) [Range 1 Day]
Group By stock
```

- Average price over last day for each stock

Abstract Semantics – Example 2

Relation CurPrice(stock, price)

```
Select stock, Avg(price)
From Istream(CurPrice) [Range 1 Day]
Group By stock
```

- *Istream* provides history of *CurPrice*
- Window on history, back to relation, group and aggregate

Concrete Language – CQL

- Relational query language: SQL
- Window specification language derived from SQL-99
  - Tuple-based windows
  - Time-based windows
  - Partitioned windows
- Simple "X% Sample" construct

CQL (cont'd)

- Syntactic shortcuts and defaults
  - *So easy queries are easy to write and simple queries do what you expect*
- Equivalences
  - Basis for query-rewrite optimizations
  - Includes all relational equivalences, plus new stream-based ones
- Examples: already seen some, more coming up

Shortcuts and Defaults

- Prevalent stream-relation conversions can make some queries cumbersome
  - *Easy queries should be easy to write*
- Two defaults:
  - Omitted window: Default [∞]
  - Omitted relation-to-stream operator: Default *Istream* operator on:
    - Monotonic outermost queries
    - Monotonic subqueries with windows

The Simplest CQL Query

Select ∗ From Strm

- Had better return *Strm* (It does)
  - Default [∞] window for *Strm*
  - Default *Istream* for result

Simple Join Query

Select $*$ From Strm, Rel Where Strm.A = Rel.B

- Default [∞] window on *Strm*, but often want Now window for stream-relation joins

Select Istream(O.orderID, A.City)
From Orders O, AddressRel A
Where O.custID = A.custID

Simple Join Query

Select $*$ From Strm, Rel Where Strm.A = Rel.B

- Default [∞] window on *Strm*, but often want Now window for stream-relation joins

Select Istream(O.orderID, A.City)
From Orders O [∞], AddressRel A
Where O.custID = A.custID

Simple Join Query

Select ∗ From Strm, Rel Where Strm.A = Rel.B

- Default [∞] window on *Strm*, but often want Now window for stream-relation joins

Select Istream(O.orderID, A.City)
From Orders O [Now], AddressRel A
Where O.custID = A.custID

- We decided against a separate default

Equivalences and Transformations

- All relational equivalences apply to all relational constructs directly
  - Queries are highly relational
- Two new transformations
  - Window reduction
  - Filter-window commutativity

Window Reduction

Select Istream(L) From S [∞] Where C

is equivalent to

Select Rstream(L) from S [Now] Where C

- Question for class
  - Why *Rstream* and not *Istream* in second query?
- Answer: Consider stream **<5>, <5>, <5>, <5>, …**

Window Reduction (cont'd)

Select Istream(L) From S [∞] Where C

is equivalent to

Select Rstream(L) from S [Now] Where C

- First query form is very common due to defaults
- In a naïve implementation second form is much more efficient

Filter-Window Commutativity

- Another question for class

  When is

  Select L From S [window] Where C

  equivalent to

  Select L From (Select L From S Where C) [window]

- Is this transformation always advantageous?

Constraint-Based Transformations

- Recall first example query (simplified)

  Select Sum(O.cost)
  From Orders O, Fulfillments F [Range 1 Day]
  Where O.orderID = F.orderID

- If orders always fulfilled within one week

  Select Sum(O.cost)
  From Orders O [Range 8 Days],
  Fulfillments F [Range 1 Day]
  Where O.orderID = F.orderID

- Useful constraints: keys, stream referential integrity, clustering, ordering

STREAM System

- First challenge: basic functionality from scratch

- Next steps – cope with :
  - Stream rates that may be **high**, variable, **bursty**
  - Stream data that may be unpredictable, variable
  - Continuous query loads that may be **high**, variable

➢ **Overload**

➢ Changing conditions

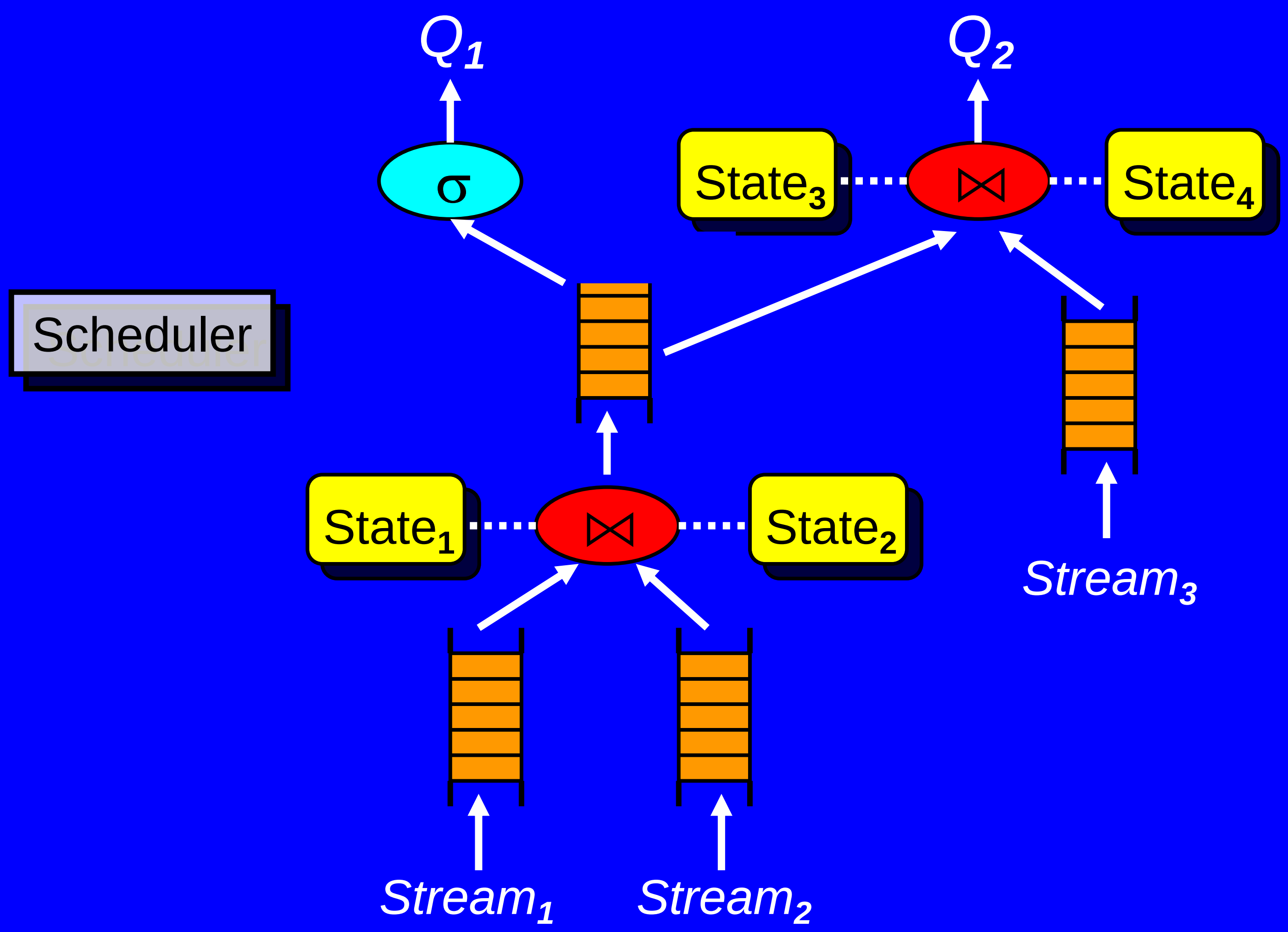
System Features

- Aggressive sharing of state and computation among registered queries
- Careful resource allocation and use
- Continuous self-monitoring and reoptimization
- Graceful approximation as necessary

Query Execution

- When a continuous query is registered, generate a query plan
  - New plan merged with existing plans
  - Users can also create & manipulate plans directly
- Plans composed of three main components:
  - Operators
  - Queues (input and inter-operator)
  - State (windows, operators requiring history)
- Global scheduler for plan execution

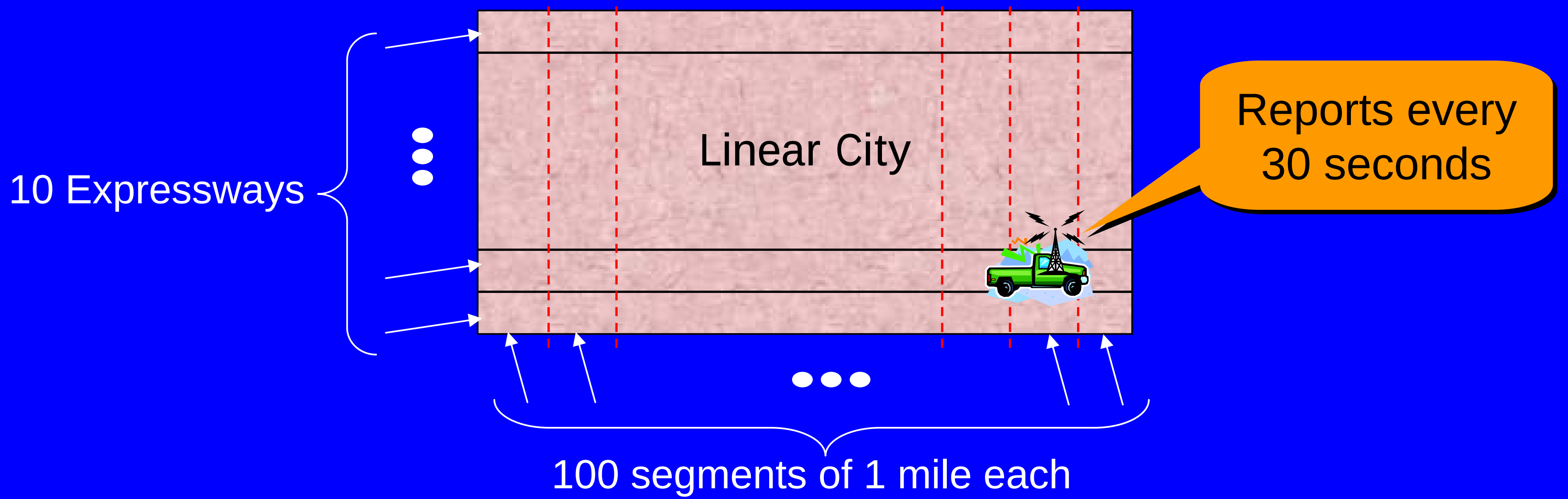
Simple Query Plan



System Status

- System is “complete”
  - 30,000 lines of C++ and Java
  - Multiple Ph.D. theses, undergrad and MS projects
- Source is available and system is being used
- Can also use system over internet

Stream System Benchmark: "Linear Road"



Main Input Stream: Car Locations **(CarLocStr)**

car_id	speed	exp_way	lane	x_pos
1000	55	5	3 (Right)	12762
1035	30	1	0 (Ramp)	4539
...	...	...	...	...

STREAM System Demo

- Incoming data streams
- Continuous queries executing over streams
- Query plan visualizer
- System monitoring via “introspection” queries
- Benchmark execution