The Raindrop Engine: Continuous Query Processing at WPI

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This talk is based on joint work with students at DSRG lab.

Invited Talk at Database Seminar Series @ Univ. of Waterloo, Canada.
Monitoring Applications

- Monitor troop movements during combat and warn when soldiers veer off course
- Send alert when patient’s vital signs begin to deteriorate
- Monitor incoming news feeds to see stories on “Iraq”
- Scour network traffic logs looking for intruders (this is our focus in Raindrop)
Properties of Monitoring Applications

- Queries and monitors run continuously, possibly unending
- Applications have varying service preferences:
  - Patient monitoring only wants freshest data
  - Remote sensors have limited memory
  - News service wishes maximal throughput
  - Taking 60 seconds to process vital signs and sound an alert may be too long
Properties of Streaming Data

- Possibly never ending stream of data
- Unpredictable arrival patterns:
  - Network congestion
  - Weather (for external sensors)
  - Sensor moves out of range
DBMS Approach to Continuous Queries

- Insert each new tuple into the database, encode queries as triggers [MWA03]

Problems:
- High overhead with inserts [CCC02]
- Triggers do not scale well [CCC02]
- Uses static optimization and execution strategies that cannot adapt to unpredictable streams
- System is less utilized if data streams arrive slowly
- No means to input application service requirements
Hence, New Class of Query Systems

- CQ Systems emerged recently (Aurora, Stream, NiagaraCQ, Telegraph, et al.)
- Generally work as follows:
  - System subscribes to some streams
  - End users issued continuous queries against streams
  - System processes queries continuously
  - System returns the results to the user as a stream
- All CQ systems use adaptive techniques to cope with unpredictability of streams and environment
### Overview of Adaptive Techniques in CQ Systems

<table>
<thead>
<tr>
<th>Research Work</th>
<th>Technique(s)</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurora [CCC02]</td>
<td>Load shedding, batch tuple processing to reduce context switching</td>
<td>Maintain high quality of service</td>
</tr>
<tr>
<td>STREAM [MWA03]</td>
<td>Adaptive scheduling algorithm (Chain) [BBM03], Load shedding</td>
<td>Minimize memory requirements during periods of bursty arrival</td>
</tr>
<tr>
<td>NiagaraCQ [CDT00]</td>
<td>Generate near-optimal query plans for multiple queries</td>
<td>Efficiently share computation between multiple queries, highly scalable system, maximize output rate</td>
</tr>
<tr>
<td>Eddies [AH00] (Telegraph)</td>
<td>Dynamically route tuples among Joins</td>
<td>Keep system constantly busy, improve throughput</td>
</tr>
<tr>
<td>XJoin [UF00]</td>
<td>Break Join into 3 stages and make use of memory and disk storage</td>
<td>Keep Join and system running at full capacity at all times</td>
</tr>
<tr>
<td>[UF01]</td>
<td>Schedule streams with the highest rate</td>
<td>Maximize throughput to clients</td>
</tr>
<tr>
<td>Tukwila [IFF99] [UF98]</td>
<td>Reorganize query plans on the fly by using using synchronization packets to tell operators to finish up their current work.</td>
<td>Improve ill-performing query plans</td>
</tr>
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</table>
The WPI Stream Project: Raindrop
Raindrop Project Goal

- Our goal is to bring adaptability into all components of the system;
- Without reneging on the requested accuracy of answer;
- While optimizing for a given set of quality of service requirements.

- Quality of service requirements are multi-faceted, such as memory usage, timeliness, output rate, etc., and can even be modified at run-time.
- Plus, we support self-inspection of components to observe the effect of their actions on environment, and respond appropriately.
Adaption in All Components

- Scalable Query Operators (Punctuations)
- Cooperative Plan Optimization
- Adaptive Operator Scheduling
- On-line Query Plan Migration
- Distributed Plan Execution
Adaption in All Components

- **Scalable Query Operators (Punctuations)**
  - Adapt and select among tasks such as memory purging, stream reading, memory-to-disk shuffling, punctuation propagation, etc.

- **Cooperative Plan Optimization**
  - Operators request and selectively provide punctuations (meta-knowledge) to improve their performance

- **Adaptive Operator Scheduling**
  - Selector scores alternate scheduling algorithm based on their effect on QoS requirements, and selects candidate.

- **On-line Query Plan Migration**
  - On-line plan restructuring and then online migration to the new plan even for stateful operators.

- **Distributed Plan Execution**
  - Adaptively distribute computations across multiple machines to optimize QoS requirements without information loss
Topics Studied in Raindrop Project

- PLUS, Bring XML into Stream Engine (!?)
- Scalable Query Operators (Punctuations)
- Cooperative Plan Optimization
- Adaptive Operator Scheduling
- On-line Query Plan Migration
- Distributed Plan Execution
Let’s now focus on putting XML into Raindrop, as each of the other topics is a separate story to be told at another time.
PART II: XQueries on XML Streams
(Automaton Meets Algebra)

Based on CIKM’03 and ER’03
Joint work with Hong Su and Jinhui Jian
What’s Special for XML Stream Processing?

```xml
<Biditems>
  <book year="2001">
    <title>Dream Catcher</title>
    <author><last>King</last><first>S.</first></author>
    <publisher>Bt Bound</publisher>
    <price>30</price>
  </book>
  ...
</Biditems>
```

**Token-by-Token access manner**

```
$\text{FOR } b \text{ in stream(biditems.xml) //book}
LET $p := b/price$
$\text{WHERE } p < 20$
RETURN $<\text{Inexpensive}> t </\text{Inexpensive}>$
```

- Token: not a direct counterpart of a tuple

<table>
<thead>
<tr>
<th>year</th>
<th>title</th>
<th>last</th>
<th>first</th>
<th>publisher</th>
<th>price</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>Dream</td>
<td>King</td>
<td>S.</td>
<td>Bt Bound</td>
<td>30</td>
</tr>
</tbody>
</table>

**Pattern retrieval** + **Filtering** + **Restructuring**

**Pattern Retrieval on Token Streams**
Two Computation Paradigms

- **Automata-based** [yfilter02, xscan01, xsm02, xsq03, xpush03…]
- **Algebraic** [niagara00, …]

*This Raindrop framework intends to integrate both paradigms into one*
Automata-Based Paradigm

FOR $b$ in stream(biditems.xml) //book
LET $p := $b/price
$t := $b/title
WHERE $p < 20
Return <Inexpensive> $t </Inexpensive>

Auxiliary structures for:
1. Buffering data
2. Filtering
3. Restructuring

…
Algebraic Computation

FOR $b$ in stream(biditems.xml) //book
LET $p := \$b/price$
$\$t := \$b/title$
WHERE $p < 20$
Return <Inexpensive> \$t </Inexpensive>
Observations

<table>
<thead>
<tr>
<th><strong>Automata Paradigm</strong></th>
<th><strong>Algebra Paradigm</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Good for pattern retrieval on tokens</td>
<td>Does not support token inputs</td>
</tr>
<tr>
<td>Need patches for filtering and restructuring</td>
<td>Good for filtering and restructuring</td>
</tr>
<tr>
<td>Present all details on same low level</td>
<td>Support multiple descriptive levels (declarative-&gt;procedural)</td>
</tr>
<tr>
<td>Little studied as query processing paradigm</td>
<td>Well studied as query process paradigm</td>
</tr>
</tbody>
</table>

Either paradigm has deficiencies
Both paradigms complement each other
How to Integrate Two Paradigms
How to Integrate Two Models?

- Design choices
  - Extend algebraic paradigm to support automata?
  - Extend automata paradigm to support algebra?
  - Come up with completely new paradigm?

- Extend algebraic paradigm to support automata
  - Practical
    - Reuse & extend existing algebraic query processing engines
  - Natural
    - Present details of automata computation at low level
    - Present semantics of automata computation (target patterns) at high level
Raindrop: Four-Level Framework

- Semantics-focused Plan
- Stream Logic Plan
- Stream Physical Plan
- Stream Execution Plan

Abstraction Level

High (Declarative)

Low (Procedural)
Level I: Semantics-focused Plan [Rainbow-ZPR02]

- Express query semantics regardless of stored or stream input sources
- Reuse existing techniques for stored XML processing
  - Query parser
  - Initial plan constructor
  - Rewriting optimization
    - Decorrelation
    - Selection push down
    - ...
Example Semantics-focused Plan

FOR $b$ in stream(biditems.xml) //book
LET $p := $b/price
    $t := $b/title
WHERE $p < 20
Return <Inexpensive> $t </Inexpensive>
Level II: Stream Logical Plan

- Extend semantics-focused plan to accommodate tokenized stream inputs
  - New input data format: 
    - contextualized tokens
  - New operators: 
    - StreamSource, Nav, ExtractUnnest, ExtractNest, StructuralJoin
  - New rewrite rules: 
    - Push-into-Automata
One Uniform Algebraic View

Algebraic Stream Logical Plan

- Tuple-based plan
- Token-based plan (automata plan)
- Tuple stream
- XML data stream

Query answer
Modeling the Automata in Algebraic Plan: Black Box[XScan01] vs. White Box

FOR $b$ in stream(biditems.xml) //book
LET $p := $b/price
   $t := $b/title
WHERE $p < 20
Return <Inexpensive> $t </Inexpensive>
Example Uniform Algebraic Plan

FOR $b$ in stream(biditems.xml) //book
LET $p := $b/price
    $t := $b/title
WHERE $p < 30
Return <Inexpensive> $t </Inexpensive>

Tuple-based plan

Token-based plan
(automata plan)
Example Uniform Algebraic Plan

FOR $b$ in stream(biditems.xml) //book
LET $p := $b/price
   $t := $b/title
WHERE $p < 30
Return <Inexpensive> $t </Inexpensive>

Tuple-based plan

- **StructuralJoin**
  - $b$

- **ExtractNest**
  - $b, p$

- **ExtractNest**
  - $b, t$

- **Navigate**
  - $b, /price->$p

- **Navigate**
  - $b, /title->$t

- **Navigate**
  - $S1, //book ->$b
Example Uniform Algebraic Plan

FOR $b$ in stream(biditems.xml) //book
LET $p := b/price$
    $t := b/title$
WHERE $p < 30$
Return <Inexpensive> $t </Inexpensive>
From Semantics-focused Plan to Stream Logical Plan

- **NavUnnest**: $S1, //book ->$b
- **NavNest**: $b, /price/text() ->$p
- **NavNest**: $b, /title ->$t
- **NavNest**: $b, /title ->$t
- **ExtractNest**: $b, $p
- **ExtractNest**: $b, $t
- **Select**: $p<30
- **Tagger**: “Inexpensive”, $t->$r
- **StructuralJoin**: $b
- **Apply “push into automata”**
- **Apply “push into automata”**
Level III: Stream Physical Plan

- For each stream logical operator, define how to generate outputs when given some inputs
  - Multiple physical implementations may be provided for a single logical operator
  - Automata details of some physical implementation are exposed at this level
    - Nav, ExtractNest, ExtractUnnest, Structural Join
One Implementation of Extract/Structural Join

```
<biditems> <book> <title> Dream Catcher </title> ... </book> ...
```

Diagram:
- SJoin //book
- ExtractNest $b, $t
- ExtractNest /$b, $p
- Nav $b, /price->$p
- Nav $b, /title->$t
- Nav .. //book ->$b

Diagram nodes:
1. *book
2. title
3. price
4. ..
Level IV: Stream Execution Plan

- Describe coordination between operators regarding when to fetch the inputs
  - When input operator generates one output tuple
  - When input operator generates a batch
  - When a time period has elapsed
  - ...

- Potentially unstable data arrival rate in stream makes fixed scheduling strategy unsuitable
  - Delayed data under scheduling may stall engine
  - Bursty data not under scheduling may cause overflow
Raindrop: Four-Level Framework (Recap)

Express the semantics of query regardless of input sources

Accommodate tokenized input streams

Describe how operators manipulate given data

Decides the Coordination among operators

Semantics-focused Plan

Stream Logic Plan

Stream Physical Plan

Stream Execution Plan
Optimization Opportunities
Optimization Opportunities

- General rewriting (e.g., selection push down)
- Physical implementations choosing
- Execution strategy choosing
- Break-linear-navigation rewriting
From Semantics-focused to Stream Logical Plan: In or Out?

Tuple stream

XML data stream

Token-based plan (automata plan)

Pattern retrieval in Semantics-focused plan

Apply “push into automata”

Tuple-based Plan

Query answer
Plan Alternatives

**In**

- **Tagger**
- **Select**
  - price < 30

**SJoin**

- **ExtractNest**
  - $b, $t
  - **Nav**
    - $b, /title->$t

- **ExtractNest**
  - $b, $p
  - **Nav**
    - $b, /price->$p

**Out**

- **Tagger**
- **Select**
  - $p<30

- **NavNest**
  - $b, /title->$t
- **NavNest**
  - $b, /price->$p

- **NavUnnest**
  - $S1, //book ->$b

- **Navigate**
  - book/title
  - **Select**
    - price<30

- **Navigate**
  - /price
  - **ExtractNest**
    - $S1, $b
  - **Nav**
    - $S1, //book->$b
Experimentation Results

Execution Time on 85M XML Stream Under Various Selectivity

Execution Time (ms) vs. Selectivity of Selection

- 1 Nav
- 2 Navs
- 3 Navs
- 4 Navs
- 5 Navs

Graph shows the execution time in milliseconds for different selectivities under various navigation counts.
Contributions Thus Far

- Combined automata and algebra based paradigms into one uniform algebraic paradigm
- Provided four layers in algebraic paradigm
  - Query semantics expressed at high layer
  - Automata computation on streams hidden at low layer
- Supported optimization at an iterative manner (from high abstraction level to low abstraction level)
- Illustrated enriched optimization opportunities by experiments
Automaton Meets Algebra: On-Going Issues To be Tackled

- Exploit XML schema constraints for query optimization
- Costing/query optimization of plans
- On-the-fly migration into/out of automaton
- Physical implementation strategies of operators
- Load-shedding from an automaton
Plus, Other Topics in Raindrop

- Bring XML into Stream Engine
- Scalable Query Operators (Punctuations)
- Cooperative Plan Optimization
- Adaptive Operator Scheduling
- On-line Query Plan Migration
- Distributed Plan Execution

To be told on another day …
Overall Blizz . . .

- Many interesting problems arise in this new stream context
- There is room for lot’s of fun research
http://davis.wpi.edu/dsrg/raindrop/

Here you can find Project Overview, Publications, and Talks

Email: raindrop@cs.wpi.edu