Stream Processing Optimizations

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Agenda

- **9:00-10:30**
  - Overview and background (40 minutes)
  - Optimization catalog (50 minutes)

- **11:00-12:30**
  - SPL and InfoSphere Streams background (25 minutes)
  - Fission (40 minutes)
  - Open research questions (25 minutes)
DEBS’13 Tutorial: Stream Processing Optimizations

Scott Schneider, Martin Hirzel, and Buğra Gedik
Acknowledgements: Robert Soulé, Robert Grimm, Kun-Lung Wu

Part 1: Overview and Background
Stream Processing

- Streaming sources are plenty
  - Volume, Velocity, Variety
- Online analysis is paramount
  - Quickly process and analyze data, derive insights, and take timely action

Telco analyses streaming network data to reduce hardware costs by **90%**

Utility avoids power failures by analysing **10 PB** of data in minutes

Hospital analyses streaming vitals to detect illness **24 hours earlier**
Catalog of Streaming Optimizations

• Streaming applications: graph of streams and operators
• Performance is an important requirement
• Different communities → different terminology
  - e.g. operator/box/filter; hoisting/push-down
• Different communities → different assumptions
  - e.g. acyclic graphs/arbitrary graphs; shared memory/distributed
• Catalogue of optimizations
  - Uniform terminology
  - Safety & profitability conditions
  - Interactions among optimizations
Fission Optimization

• High throughput processing is a critical requirement
  - Multiple cores and/or host machines
  - System and language level techniques
• Application characteristics limit the speedup brought by optimizations
  - pipeline depth (# of ops), filter selectivity
• Data parallelism is an exception
  - number of available cores (can be scaled)
• Fission
  - Data parallelism optimization in streaming applications
  - How to apply transparently, safely, and adaptively?
Background

- **Operator graph**
  - Operators connected by streams

- **Stream**
  - A series of data items

- **Data item**
  - A set of attributes

- **Operator**
  - Generic data manipulator
  - Has input and output *ports*
  - Streams connect output ports to input ports
    - FIFO semantics
  - Source operator, no input ports
  - Sink operator, no output ports

- **Operator firing**
  - Perform processing, produce data items
State in Operators

- **Stateful operators**
  - Maintain state across firings
  - E.g., *deduplicate*: pass data items not seen recently

- **Stateless operators**
  - Do not maintain state across firings
  - E.g., *filter*: pass data items with values larger than a threshold

- **Partitioned stateful operators**
  - Maintain independent state for non-overlapping sub-streams
  - These sub-streams are identified by a *partitioning attribute*
  - E.g.: For each stock symbol in a financial trading stream, compute the volume weighted average price over the last 10 transactions. The partitioning attribute: stock symbol.
Selectivity of Operators

• Selectivity
  - the number of data items produced per data item consumed
  - e.g., selectivity=0.1 means
    • 1 data item is produced for every 10 consumed
  - used in establishing safety and profitability

• Dynamic selectivity
  - selectivity value is
    • not known at development time
    • can change at run-time
  - e.g., data-dependent filtering, compression, or aggregates on time-based windows
Selectivity Categories

- Selectivity categories (singe input/output operators)
  - *Exactly-once* (\(\geq 1\)): one in; one out [always]
  - *At-most-once* (\(\leq 1\)): one in; zero or one out [always]
  - *Prolific* (\(\geq 1\)): one in; one, or more out [sometimes]

- **Synchronous data flow (SDF) languages**
  - Assume that the selectivity of each operator is fixed and known at compile time
  - Provide good optimization opportunities at the cost of reduced application flexibility
  - Typically used for signal processing applications

- Unlike SDF, we assume dynamic selectivity
  - Support general-purpose streaming

- Selectivity categories are used to fine-tune optimizations
Streaming Programming Models

**Synchronous**
- Static selectivity
  - e.g., $1 : 3$
  
  ```python
  for i in range(3):
    result = f(i)
    submit(result)
  ```
  
  - In general, $m : n$ where $m$ and $n$ are statically known
  
  - Always has static schedule

**Asynchronous**
- Dynamic selectivity
  - e.g., $1 : [0,1]$
    
    ```python
    if input.value > 5:
      submit(result)
    ```
  
  - In general, $1 : *$
  
  - In general, schedules cannot be static
Flavors of Parallelism

- There are three main forms of parallelism in streaming applications
  - Pipeline, task, and data parallelism

  **Pipeline**
  
an operator processes a data item at the same time its upstream operator processes the next data item

  **Task**
  
different operators process a data item produced by their common upstream operator, at the same time

- Pipeline and task parallelism are inherent in the graph
Data Parallelism

- Data parallelism needs to be extracted from the application
  - Morph the graph
    - Split: distribute to replicas
    - Replicate: do data parallel processing
    - Merge: put results back together
- Requires additional mechanisms to preserve application semantics
  - Maintaining the order of tuples
  - Making sure state is partitioned correctly

Different data items from the same stream are processed by the replicas of an operator, at the same time.
Safety and Profitability

- **Safety**: an optimization is *safe* if applying it is guaranteed to maintain the semantics
  - State (stateless & partitioned stateful)
    - Parallel region formation, splitting tuples
  - Selectivity
    - Result ordering, splitting and merging tuples

- **Profitability**: an optimization in profitable if it increases the performance (throughput)
  - Transparency: Does not require developer input
  - Adaptivity: Adapt to resource and workload availability
Adaptive Optimization

- When the workload increases, more resources should be requested
- In the context of data parallelism
  - How many parallel channels to use at a given time
- Maintaining SASO properties is a challenge
  - Stability: do not oscillate wildly
  - Accuracy: eventually find the most profitable operating point
  - Settling time: quickly settle on an operating point
  - Overshoot: steer away from disastrous settings
Publications


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Part 2: Optimization Catalog
Motivation

• Catalog = survey, but organized as easy reference

• Use cases:
  – User: understand optimized code; hand-implement optimizations
  – System builder: automate optimizations; avoid interference with other features
  – Researcher: literature survey (see paper); open research issues
Stream Optimization Literature

Conflicting terminology

- Operator = filter = box = stage = actor = module
- Data item = tuple = sample
- Join = relational vs. any merge
- Rate = speed vs. selectivity

Unstated assumptions

- Missing safety conditions
- Missing profitability trade-offs
- Any graph vs. forest vs. single-entry, single-exit region
- Shared-memory vs. distributed

DSP (digital signal processing)
Operating systems and networks
DB (databases)
CEP (complex event processing)
Optimization Name

Key idea.

Graph before ➔ Graph after

<table>
<thead>
<tr>
<th>Safety</th>
<th>Profitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Preconditions for</td>
<td>• Micro-benchmark</td>
</tr>
<tr>
<td>correctness</td>
<td>• Runs in SPL</td>
</tr>
<tr>
<td></td>
<td>• Relative numbers</td>
</tr>
<tr>
<td></td>
<td>• Error bars are standard</td>
</tr>
<tr>
<td></td>
<td>deviation of 3+ runs</td>
</tr>
<tr>
<td></td>
<td>Central trade-off factor</td>
</tr>
<tr>
<td>Variations</td>
<td>• How to optimize at runtime</td>
</tr>
<tr>
<td>• Most influential</td>
<td></td>
</tr>
<tr>
<td>published papers</td>
<td></td>
</tr>
</tbody>
</table>

Throughput (higher is better)
List of Optimizations

- Operator reordering
- Redundancy elimination
- Operator separation
- Fusion
- Fission

Graph changed

- Placement
- Load balancing
- State sharing
- Batching
- Algorithm selection
- Load shedding

Graph unchanged

Semantics unchanged

Semantics changed
Operator Reordering

Change the order in which operators appear in the graph.

Safety
- Commutative
- Attributes available

Profitability
- Selection Reordering
  - Not reordered
  - Reordered

Variations
- Algebraic
- Commutativity analysis
- Synergies, e.g. fusion, fission

Dynamism
- Eddy
Redundancy Elimination

Eliminate operators that are redundant in the graph.

- Same algorithm
- Data available

Variations

- Many-query optimization
- Eliminate no-op
- Eliminate idempotent operator
- Eliminate dead subgraph

Profitability

- In many-query case: share at submission time
Operator Separation
Separate an operator into multiple constituent operators.

\[
A_1(A_2(s)) = A(s)
\]

<table>
<thead>
<tr>
<th>Safety</th>
<th>Profitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Ensure ( A_1(A_2(s)) = A(s) )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variations</th>
<th>Dynamism</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Algebraic</td>
<td>• N/A</td>
</tr>
<tr>
<td>• Using special API</td>
<td></td>
</tr>
<tr>
<td>• Dependency analysis</td>
<td></td>
</tr>
<tr>
<td>• Enables reordering</td>
<td></td>
</tr>
</tbody>
</table>
Fusion

Fuse multiple separate operators into a single operator.

Safety
- Have right resources
- Have enough resources
- No infinite recursion

Profitability

Variations
- Single vs. multiple threads
- Fusion enables traditional compiler optimizations

Dynamism
- Online recompilation
- Transport operators
Fission

Replicate an operator for data-parallel execution.

Safety

- No state or disjoint state
- Merge in order, if needed

Profitability

- Elastic operators (learn width)
- STM (resolve conflicts)

Variations

- Round-robin (no state)
- Hash by key (disjoint state)
- Duplicate

Dynamism

Graph showing throughput vs. number of cores with different p/s/o configurations.
Placement

*Place the logical graph onto physical machines and cores.*

- Have right resources
- Have enough resources
- Obey license/security
- If dynamic, need migratability

**Safety**

**Profitability**

- Based on host resources vs. network resources, or both
- Automatic vs. user-specified

**Variations**

- Submission-time
- Online, via operator migration
Load Balancing

Avoid bottleneck operators by spreading the work evenly.

Safety
- Avoid starvation
- Ensure each worker is equally qualified
- Establish placement safety

Profitability

Variations
- Balancing work while placing operators
- Balancing work by re-routing data

Dynamism
- Easier for routing than placement
State Sharing

Share identical data stored in multiple places in the graph.

Safety

- Common access (usually: fusion)
- No race conditions
- No memory leaks

Profitability

![Graph showing State Sharing](image)

Variations

- Sharing queues
- Sharing windows
- Sharing operator state

Dynamism

- N/A
**Batching**

*Communicate or compute over multiple data items as a unit.*

- **Safety**
  - No deadlocks
  - Satisfy deadlines

- **Profitability**
  - Batching enables traditional compiler optimizations

- **Variations**
  - No deadlocks
  - Satisfy deadlines

- **Dynamism**
  - Batching controller
  - Train scheduling
Algorithm Selection

Replace an operator by a different operator.

\[ A_\alpha \rightarrow \rightarrow A_\beta \]

- Safety
  - \( A_\alpha(s) \equiv A_\beta(s) \)
  - May not need to be safe

- Profitability

- Variations
  - Algebraic
  - Auto-tuners
  - General vs. specialized

- Dynamism
  - Compile both versions, then select via control port
Load Shedding

*Degrade gracefully during overload situations.*

---

**Safety**

- By definition, not safe!
- QoS trade-off

**Variations**

- Filtering data items (variations: where in graph)
- Algorithm selection

**Profitability**

**Dynamism**

- Always dynamic
To Learn More

• DEBS’13 proceedings: “Tutorial: Stream Processing Optimizations”
DEBS’ 13 Tutorial: Stream Processing Optimizations

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Part 3: InfoSphere Streams
Background
Streams Programming Model

• Streams applications are data flow graphs that consist of:
  – **Tuples**: structured data item
  – **Operators**: reusable stream analytics
  – **Streams**: series of tuples with a fixed type
  – **Processing Elements**: operator groups in execution
Streams Processing Language

```java
composite Main {
    type
        Entry = int32 uid, rstring server, rstring msg;
        Sum = uint32 uid, int32 total;
    graph
        stream<Entry> Msgs = ParSource() {
            param servers: "logs.*.com";
            partitionBy: server;
        }
        stream<Sum> Sums = Aggregate(Msgs) {
            window Msgs: tumbling, time(5), partitioned;
            param partitionBy: uid;
        }
        stream<Sum> Suspects = Filter(Sums) {
            param filter: total > 100;
        }

    () as Sink = FileSink(Suspects) {
        param file: "suspects.csv";
    }
}
```
SPL: Immutable by Default

```java
stream<Data> Out = Custom(In) {
    logic state: int32 factor_ = 42;
    onTuple In: {
        submit({result=In.val*factor_}, Out);
    }
}
```

immutable by default

```java
stream<Data> Out = Custom(In) {
    logic state: mutable int32 count_ = 0;
    onTuple In: {
        ++count_;
        submit({count=count_}, Out);
    }
}
```

explicitly mutable

straight-forward to statically determine this is a stateless operator

straight-forward to statically determine this is a stateful operator
SPL: Generic Primitive Operators

an Aggregate invocation

```
stream<Sum> Sums = Aggregate(Msgs) {
    window Msgs: tumbling, time(5), partitioned;
    param partitionBy: uid;
}
```

the Aggregate operator model

```
{Aggregate
    {parameters {groupBy optional Expression}
        {partitionBy optional Expression}}
    {inputPorts 1 required windowed}
    {outputPorts 1 required}
}
```
Source ➔ Compilation ➔ Execution

- SPL source
- SPL compiler
- Streams Runtime
- x86 host
- x86 host
- x86 host
- x86 host
- x86 host
Source ➔ Compilation ➔ Execution
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Part 4: Fission Deep Dive
Fission Overview

composite Main {
  type
    Entry = int32 uid, rstring server,
         rstring msg;
  Sum = uint32 uid, int32 total;
  graph
    stream<Entry> Msgs = ParSource() {
      param servers: "logs.*.com";
      partitionBy: server;
    }

    stream<Sum> Sums = Aggregate(Msgs) {
      window Msgs: tumbling, time(5),
               partitioned;
      param partitionBy: uid;
    }

    stream<Sum> Suspects = Filter(Sums) {
      param filter: total > 100;
    }

    () as Sink = FileSink(Suspects) {
      param file: "suspects.csv";
    }
}
Technical Overview

Compiler:
• Apply parallel transformations
• Pick routing mechanism (e.g., hash by key)
• Pick ordering mechanism (e.g., seq. numbers)

Runtime:
• Replicate segment into channels
• Add split/merge/shuffle as needed
• Enforce ordering
# Transformations

<table>
<thead>
<tr>
<th>Parallelize non-source/sink</th>
<th>Parallelize sources and sinks</th>
<th>Combine parallel regions</th>
<th>Rotate merge and split</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Examples:
- OPRA source
- Database sink

Also known as “shuffle”

Do all of the above as much as possible, wherever it is safe to do so.
Core Challenges

• State
  – **Problem:** No shared memory between channels (partitioned local state)
  – **Solution:** Only parallelize if stateless or partitioned (i.e., separate state into channels by keys)

• Order
  – **Problem:** Race conditions between channels (independent threads of control)
  – **Solution:** Only parallelize if merge can guarantee same tuple order as without parallelization
# Safety Conditions

<table>
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<tr>
<th>Parallelize non-source/sink</th>
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</tr>
</tbody>
</table>

- **stateless or partitioned state**
- **simple chain**

- **stateless or partitioned state**

- **stateless**
  - compatible keys
  - forwarding

- **incompatible keys**
  - selectivity $\leq 1$
• Can't parallelize
  – Operators with >1 fan-in or fan-out
  – Punctuation dependency later on

• Can't add operator to parallel segment if
  – Another operator in segment has co-location constraint
  – Keys don't match
Constraints & Fusion

Infer partition colocation → Select parallel segments → Fusion

Compile-time

Expand parallel segments → Check placement constraints → Place partitions on hosts

Submission-time

ADL
Compiler to Runtime

- **Compile-time**
  - Compiler
    - Graph + unexpanded parallel regions
  - Fully expanded graph
    - Runtime graph fragment
      - PE
    - Runtime graph fragment
      - PE
    - Runtime graph fragment
      - PE

- **Submission-time**
  - Fully expanded graph

- **Run-time**
## Runtime

<table>
<thead>
<tr>
<th></th>
<th>state</th>
<th>selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gaps</td>
<td>dups</td>
</tr>
<tr>
<td>round-robin</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>seqno</td>
<td>partitioned</td>
<td>✗</td>
</tr>
<tr>
<td>strict seqno &amp; pulse</td>
<td>partitioned</td>
<td>✓</td>
</tr>
<tr>
<td>relaxed seqno &amp; pulse</td>
<td>partitioned</td>
<td>✓</td>
</tr>
</tbody>
</table>

Operators in parallel segments:
- Forward seqno & pulse

Split:
- Insert seqno & pulse
- Routing

Merge:
- Apply ordering policy
- Remove seqno (if there) and drop pulse (if there)
Merger Ordering

Round-Robin

Sequence Numbers

Strict Sequence Number & Pulses

Relaxed Sequence Number & Pulses
Application Kernel Performance

- **Network monitoring**
- **Twitter NLP**
- **PageRank**
- **Twitter CEP**
- **Finance**

**Legend:**

- Speedup vs. 1 channel
- Number of parallel channels

**Diagram:**

- (a) Network monitoring
- (b) PageRank
- (c) Twitter NLP
- (d) Twitter CEP
- (e) Finance

**Notes:**

- Trade-off between speedup and scalability
- Multi-threading and parallel processing
• What is $N$? We want to:
  – find it dynamically, at runtime
  – automatically, with no user intervention
  – in the presence of stateless and partitioned stateful operators
  – maximize throughput
Elasticity: Solution Sketch

local control, adaptation

global storage, synchronization
Part 6: Open Research Questions
Programming Model Challenges

High-level
- Easy to use
- Optimizable

CEP patterns
- StreamDatalog
- StreamSQL
- StreamIt (MIT)
- Graph GUI

SPL
- Java API
- Annotated C
- C/Fortran

Low-level
- General
- Predictable

Other challenges
- Foreign code
- Familiarity
Interaction of SPL and C++

- Application source code (SPL)
  - SPL Compiler
    - Operator model (XML)
  - Application model (XML)
- Operator instance model (XML)
- Operator code generator
- At compile time
- At run time
- Stream of input data items
- Stream of output data items
- Streaming platform

Operator code generator

Operator instance (C++)
Optimization Combination

- Operator reordering
- Redundancy elimination
- Placement
- State sharing
- Operator separation
- Fission
- Fusion
- Load balancing
- Batching
- Algorithm selection
- Load shedding

Challenges
- If separate: order
- If combined: profitability model
Interaction with Traditional Compiler Analysis

- Operator reordering
- Operator separation
- Algorithm selection
- Load shedding
- Redundancy elimination
- Placement
- Fusion
- Load balancing
- State sharing
- Batching

Challenges:
- State
- Ordering
- Selectivity
- Key forwarding
Interaction with Traditional Compiler Optimizations

- Operator reordering
- Operator separation
- Algorithm selection
- Redundancy elimination
- Fission
- Load shedding
- Placement
- Load balancing
- State sharing
- Batching
- Challenges:
  - Inlining
  - Loop unrolling
  - Deforestation
  - Scalarization

Traditional compiler analyses:
- Traditional compiler optimizations
## Dynamic Optimization

**Compile time** | **Submission time** | **Runtime discrete** | **Runtime continuous**
---|---|---|---
Operator separation | Redundancy elimination | Load balancing | Operator reordering
Fusion | Fission | | Batching
State sharing | Placement | | Load shedding
Algorithm selection | | | Other challenges:

- **Settling**
- **Accuracy**
- **Stability**
- **Overshoot**
Dynamic Operator Reordering

Approach: Emulate graph change via data-item routing. Example: Eddies [Avnur, Hellerstein SIGMOD’00]
Wish List
• Representative
  – … of real code
  – … of real inputs
• Fast enough to conduct many experiments
• Fully automated / scripted
• Self-validating
• Open-source with industry-friendly license

Literature
• LinearRoad [Arasu et al. VLDB’04]
• BiCEP [Mendes, Bizarro, Marques TPC TC’09]
• StreamIt [Thies, Amarasinghe PACT’10]
Generality of Optimizations

Challenges
- Expand “Supported”
- In the right direction
Generality of Fission

- Safe
- Supported
- Profitable and/or common

<table>
<thead>
<tr>
<th>State</th>
<th>Ordering</th>
<th>Topology</th>
<th>User code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stateless</td>
<td>Static selectivity</td>
<td>Single operator</td>
<td>Built-in operators</td>
</tr>
<tr>
<td>Partitioned stateful</td>
<td></td>
<td>Simple pipeline</td>
<td>Streaming language</td>
</tr>
<tr>
<td>Arbitrary stateful</td>
<td>Dynamic selectivity</td>
<td>Arbitrary subgraph</td>
<td>Foreign language</td>
</tr>
</tbody>
</table>

Challenges
- Expand "Supported"
- In the right direction