# Naiad: A Timely Dataflow System

Derek G Murray et al.

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Presentation by:
SB Ramalingam Santhanakrishnan
K Kleeberger
B Jain

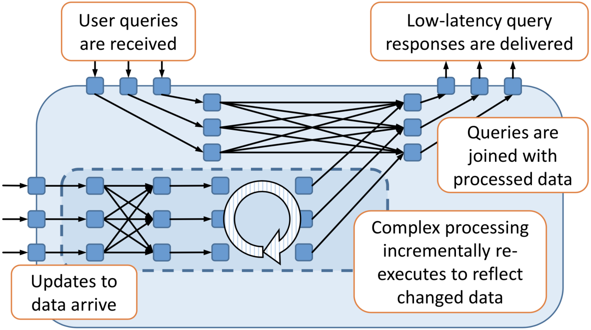
# Agenda

- Introduction
- Timely Data Flow

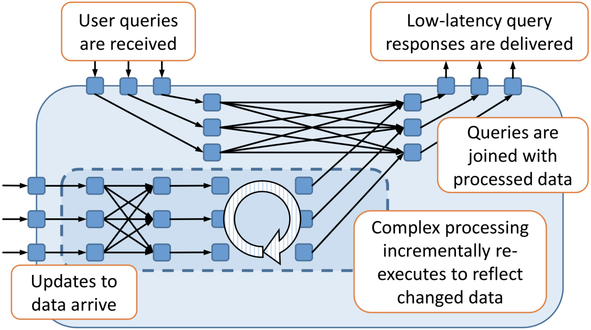
- Distributed Implementation
- Programming Model

- Performance Evaluation
- Real World Applications

# Introduction



# Introduction




**Batch**

- Iteration
- Consistency
- Poor latency

**Stream**

- No iteration
- No consistency
- Low latency

**Graph**

- Iteration
- Vertex-oriented Programming

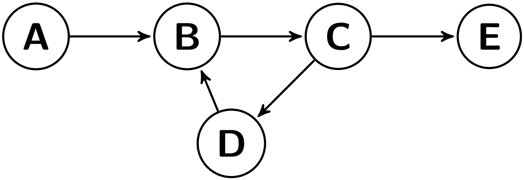
# Introduction

- General purpose system
- Support high-level programming models
- Iteration on real-time data
- Supports interactive queries on fresh, consistent view of results
- Low latency – specialized system performance

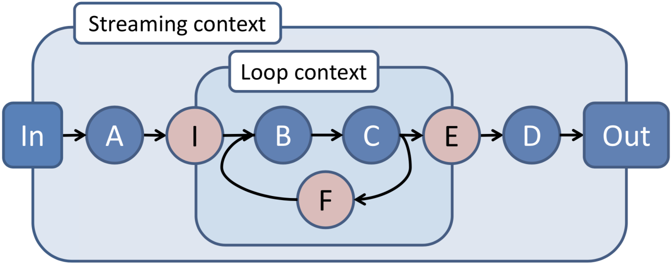
# *Timely* Dataflow

Dataflow programming primitives based on *time*

- Structured Loops
- Stateful vertices
- Notification for vertices on iteration completion

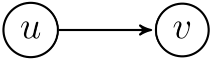


# Timely Dataflow - Graph Structure




- Time epoch on every input
- Streaming Context - Process data and pass
- Loop Context
  - Loop - Ingress (I) ⇒ Feedback (F) ⇒ Egress (E)
  - Monitors progress

# Timely Dataflow - Concurrency Primitives



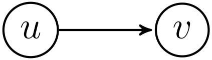

Vertices register callbacks

$v.\textsc{OnRecv}(e$: Edge, $m$: Message, $t$: Timestamp)
$v.\textsc{OnNotify}(t$: Timestamp)

Vertices generate events

$this.\textsc{SendBy}(e$: Edge, $m$: Message, $t$: Timestamp)
$this.\textsc{NotifyAt}(t$: Timestamp)

# Timely Dataflow - Concurrency Primitives




- $\textsc{OnRecv}$ and $\textsc{OnNotify}$ are queued, no strict ordering
- Notify guarantee:

  $v.\textsc{OnNotify}(t)$ is invoked only after no further invocations of $v.\textsc{OnRecv}(e, m, t')$, for $t' \leq t$
- Backward time constraint:

  Callback methods at $t$ should only call,
  $\textsc{SendBy}(t')$ and $\textsc{NotifyAt}(t')$
  such that $t' \geq t$

# Timely Dataflow - Timestamp

$$(e \in \mathbb{N}, \langle c_1, \dots, c_k \rangle \in \mathbb{N}^k)$$

Example: (epoch, counter) - $(1, \langle 0, 1, 2 \rangle)$

Vertex Behavior:

- Ingress - $\langle c_1, \dots, c_k \rangle \Rightarrow \langle c_1, \dots, c_k, 0 \rangle$
- Egress - $\langle c_1, \dots, c_k, c_{k+1} \rangle \Rightarrow \langle c_1, \dots, c_k \rangle$
- Feedback - $\langle c_1, \dots, c_k \rangle \Rightarrow \langle c_1, \dots, c_k, c_{k+1} \rangle$

Ordering:
$t_1 = (e_1, \vec{c_1}), t_2 = (e_2, \vec{c_2})$
$t_1 < t_2 \iff e_1 < e_2$ and $\vec{c_1} < \vec{c_2}$

# Timely Dataflow - Progress Tracking

Future timestamps constrained by,

- Unprocessed *events* (SendBy and NotifyAt)
- Graph structure

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for, $v.\textsc{SendBy}(e, m, t)$, pointstamp $= (t, e)$

for, $v.\textsc{NotifyAt}(t)$, pointstamp $= (t, v)$

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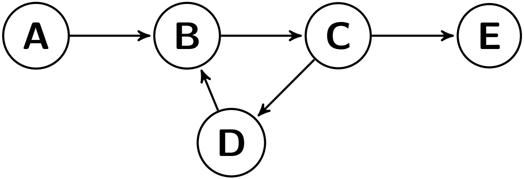
**Structure constraint induces ordering:**

$(t_1, l_1)$ *could-result-in* $(t_2, l_2) \iff \exists$ path $\psi = \langle l_1, \ldots, l_2 \rangle$

such that $t_1$ is adjusted by each I, E or F, satisfies $\psi(t_1) \leq t_2$.

# Timely Dataflow - could-result-in




Is there a path between D and E?

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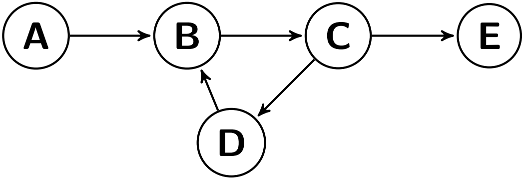


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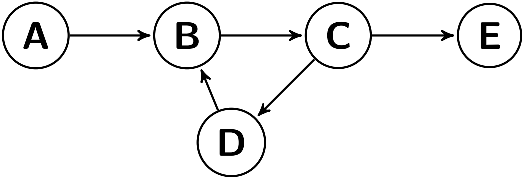
# Timely Dataflow - could-result-in

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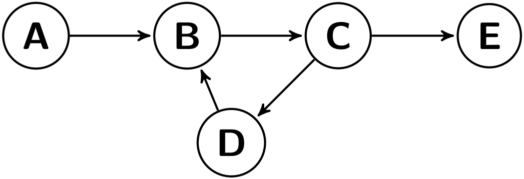


Is there a path between D and E?

$(1, A)$ *could-result-in* $(1, E)$ ?

$((1, 2), D)$ *could-result-in* $((1, 4), C)$ ?

$((3, 4), D)$ *could-result-in* $(2, E)$ ?

# Timely Dataflow - Single-Threaded Scheduler

- A set of *active pointstamps* (at least 1 unprocessed event).
- For each active poinstamp, maintains,
  - *occurrence count* - outstanding events.
  - *precursor count* - how many active poinstamps precede.
- Update *occurrence count* for each event.

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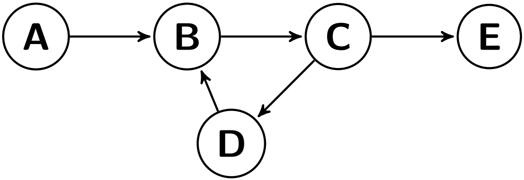
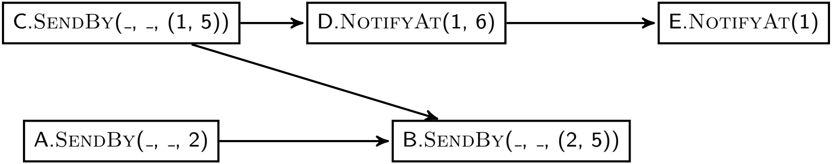
Scheduler is a simple message sorting function,
to deliver notifications

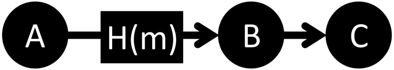
# Visualizing the scheduler



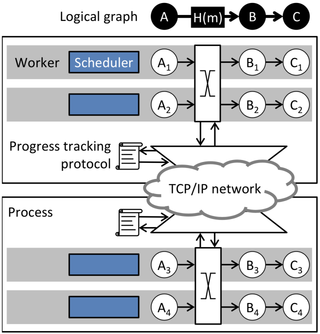
# Distributed Implemenation

*Naiad* is the distributed implementation of timely dataflow




- A program consists of logical stages (A, B, C)
- $H(m)$ – Partitioning function
- $H(m)$ controls exchange of data between stages

# Data Parallelism




- Physical graph represents the chosen amount of workers and distributed connected hosts
- Programmer can select which way a message should flow in the system stages
- Naiad always uses the logical graph as a decision base where data has to flow

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# Worker

Delivers messages (data) and notifications to vertices

- Tie-breaker – Always deliver messages before notifications
- Responsible for multiple vertices

Synchronization

- Communicate through shared queue
- Queue not necessary if $\mathrm{SEND}/\mathrm{RECV}$ are under same worker
- Re-entrancy due to loops – enqueue for later,
  coalesce incoming messages in $\textsc{OnRecv}$ to reduce memory.

# Progress tracking

- Local occurrence counter don't get updated directly
- Change of occurrence gets broadcasted
- Change gets queued and modified in FIFO order
- Therefore the local counter is never before the global counter

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Optimize broadcast

- Rely on the logical graph, not the physical
- Buffer before broadcast
- Optimistically first broadcast via UDP to reduce latency
- Wake up threads with either broadcast or unicast with programming primitives

# Fault tolerance and Availability

CHECKPOINT and RESTORE interface

- Vertex
  - Either log data or
  - Full checkpoint when requested
- Progress Tracking Protocol
  - Full checkpointing

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CHECKPOINT and RESTORE interface

- Vertex
  - Either log data or
  - Full checkpoint when requested
- Progress Tracking Protocol
  - Full checkpointing

Checkpointing

- Message delivery gets stopped
- Outstanding OnRecv Events get delivered
- Save to disk

Restoring

- Revert from the last checkpoint
- Vertexes of failed process get reassigned

# Micro Stragglers

Tiny latencies which can add up in a large system

Network

- Disable Nagle's algorithms
- Set smaller retry timeout for package loss
- Use different network protocols in datacenters for computing

Data structure contention

- solved by smaller clock granularity

Garbage Collection

- avoid object allocation
- use buffer pools
- use value types

# Naiad Program

- Provides public API with primitives
- Higher Level APIs
  - LINQ
  - MapReduce
  - Pregel
- Examples do not support coordination
  - to improve performance
  - concat, distinct, select
- Generic API for vertex programming
  - First define the behavior dataflow vertices
  - Second define the topology

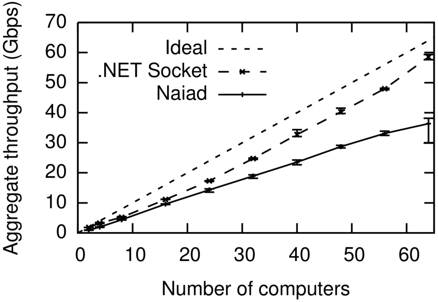
# Prototype Program

```
// 1a. Define input stages for the dataflow.
var input = controller.NewInput<string>();

// 1b. Define the timely dataflow graph.
// Here, we use LINQ to implement MapReduce.
var result = input.SelectMany(y => map(y))
                  .GroupBy(
                     y => key(y),
                     (k, vs) => reduce(k, vs)
                  );

// 1c. Define output callbacks for each epoch
result.Subscribe(result => { ... });

// 2. Supply input data to the query.
input.OnNext(/* 1st epoch data */);
input.OnNext(/* 2nd epoch data */);
input.OnNext(/* 3rd epoch data */);
input.OnCompleted();
```

# Performance Evaluation

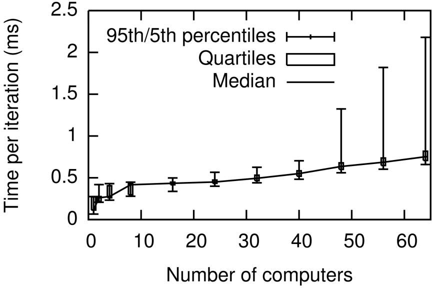
# Performance Evaluation - Throughput

- Cyclic dataflow that repeatedly performs all-to-all data exchange of a fixed number of records.
- Ideal aggregate throughput based on Ethernet Bandwidth.
- .NET Socket demonstrates achievable throughput given network topology, TCP overheads and .NET API costs.
- Naiad throughput scales linearly.



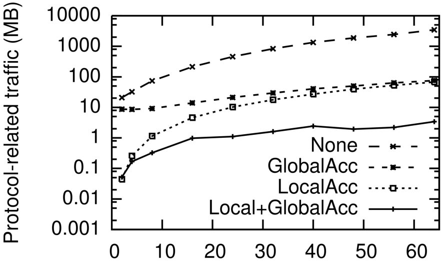
# Performance Evaluation - Latency

- Minimal time required for Global Coordination.
- Request and receive completeness notifications.
- Median time per iteration small at 753$\mu$s for 64 computers.
- 95th percentile results - adverse impact of micro-stragglers.



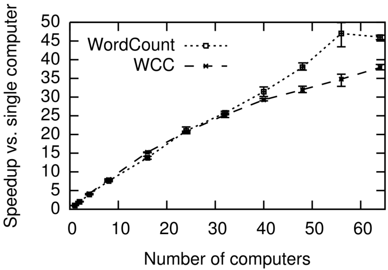
# Performance Evaluation - Protocol Optimizations

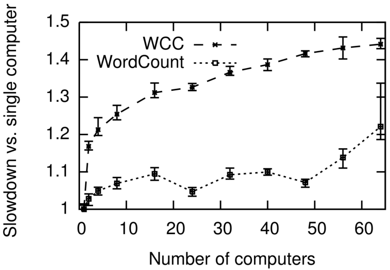
- Weakly Connected Components Computation (WCC) on random graph of 300 edges ( 2.2GB of raw input).
- Reduction in volume of protocol traffic depending on level of accumulation.
- In practice, reduction in messages from local accumulation is sufficient.



# Performance Evaluation - Scaling

- Strong scaling  Adding compute resources with fix input size.
- Weak scaling  Adding compute resources and increasing input.
- Word Count  128GB uncompressed corpus.
- WCC  Random Graph of 200M edges.



# Real World Applications

# Real World Applications - Batch Iterative Graph Computation

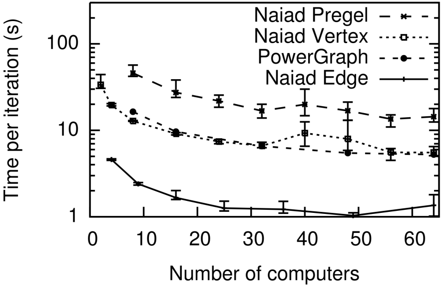
- Graph Computation on Large scale real world datasets.
- PDW – Distributed Database
- DryadLINQ – General Purpose Batch Processor
- SHS – Purpose Built Distributed Graph Store
- Speedups demonstrate the power of being able to maintain application-specific state in memory between iterations.

| Algorithm | PDW | DryadLINQ | SHS | Naiad |
|---|---|---|---|---|
| PageRank | 156,982 | 68,791 | 836,455 | **4,656** |
| SCC | 7,306 | 6,294 | 15,903 | **729** |
| WCC | 214,479 | 160,168 | 26,210 | **268** |
| ASP | 671,142 | 749,016 | 2,381,278 | **1,131** |

Running time in seconds

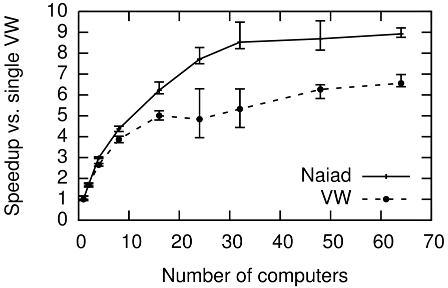
# Batch Iterative Graph Computation

- Several systems have adopted the computation of PageRank on a Twitter follower graph as a standard benchmark.
- Naiad Vertex – Partitions edges by source vertex.
- Naiad Edge – Partitions edges using a space-filling curve.



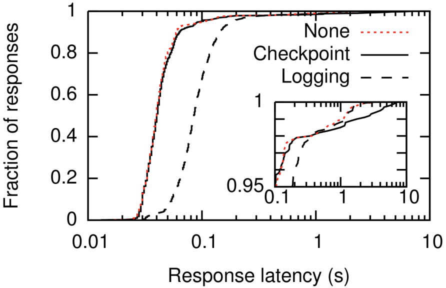
# Batch Iterative Machine Learning

- Vowpal Wabbit (VW) – open-source distributed machine learning library
- Modified VW –
  first and second phases run inside a Naiad vertex,
  third phase uses Naiad implementation of the AllReduce.



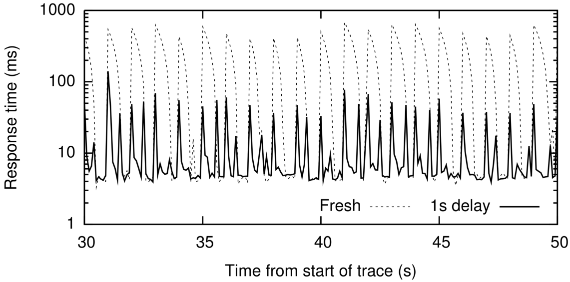
# Streaming Acyclic Computation

- Kineograph ingests arriving graph data, takes regular snapshots for data parallel computation, and produces consistent results.
- The system is partitioned into ingest nodes and compute nodes.
- k-exposure metric for identifying controversial topics on Twitter.



# Streaming Iterative Graph Analytics

- There are two input stages: stream of tweets and requests, specified by a user name and query identifier.
- "Fresh" – queries being delayed behind tweet processing
- "1s delay" – the benefit of querying stale but consistent data.
- Naiads support for overlapped computation by trading off responsiveness for staleness.



# Thank you

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