Enabling Signal Processing over Stream Data

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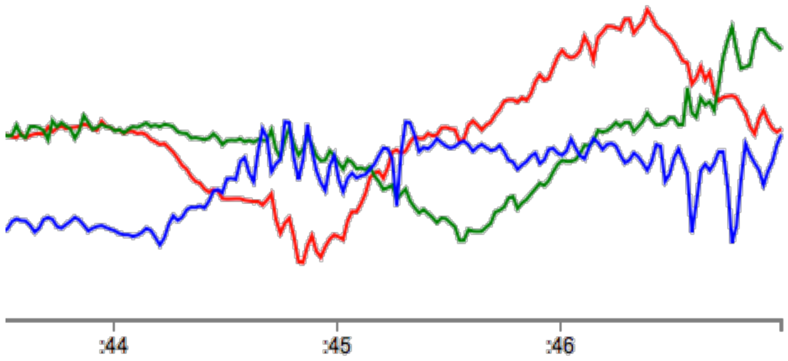
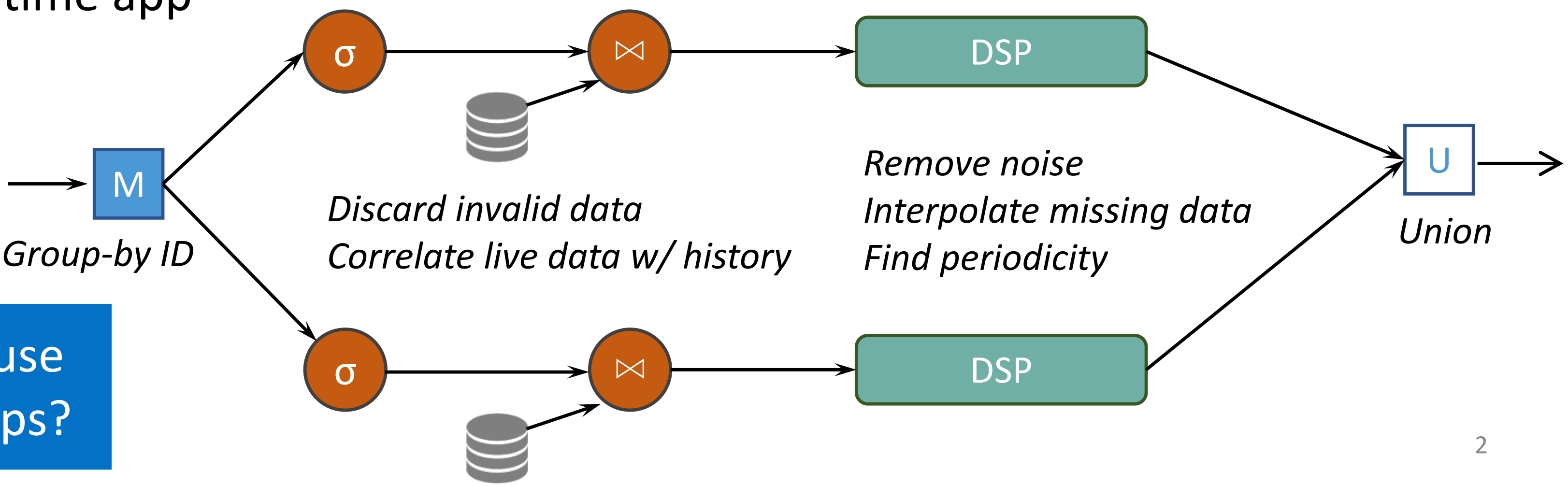
*Work performed during internship at MSR

Signals in Streams



- Lots of "signals" in stream data
  - Internet-of-things devices, app telemetry (e.g., ad clicks)
- IoT workflows combine relational & signal logic
  - Ex: Real-time app

ID	Time	Value
0	0:42:19	67
1	0:42:22	80
2	0:42:22	85



Which tools to use to build such apps?

Data processing expert

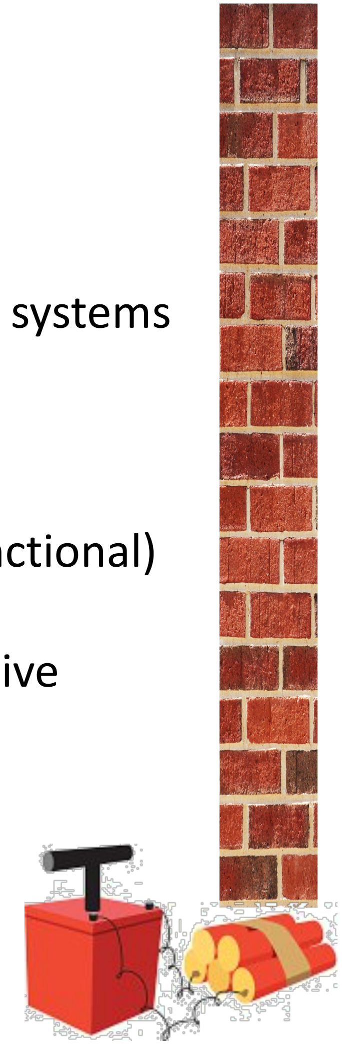
Engines: stream engines, DBMS, MPP systems

Data model: (tempo)-relational

Language: declarative (SQL, LINQ, functional)

Scenarios: real-time, offline, progressive

How to reconcile two worlds?



Digital signal processing expert

Engines: MATLAB, R

Data model: array

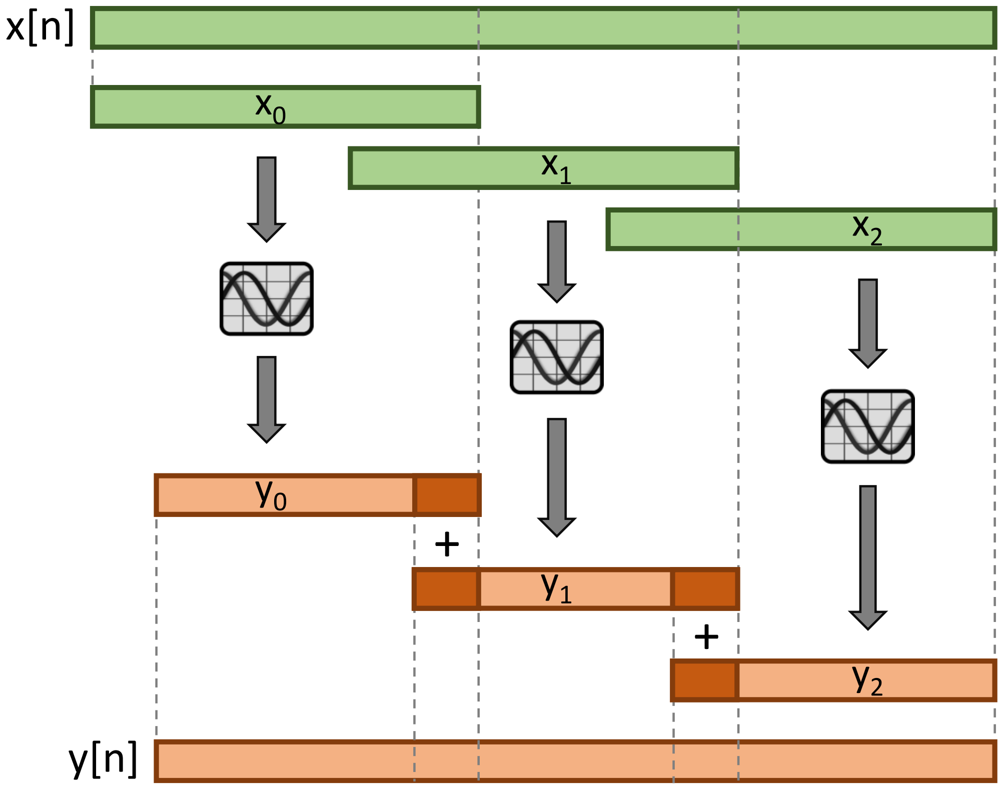
Language: imperative (array languages, C)

Scenarios: mostly offline, real-time

Our solution:

- high-performance (2 OOM faster)
- one query language
- familiar abstractions to both worlds

Typical DSP Workflow



Equally-spaced samples stored in array

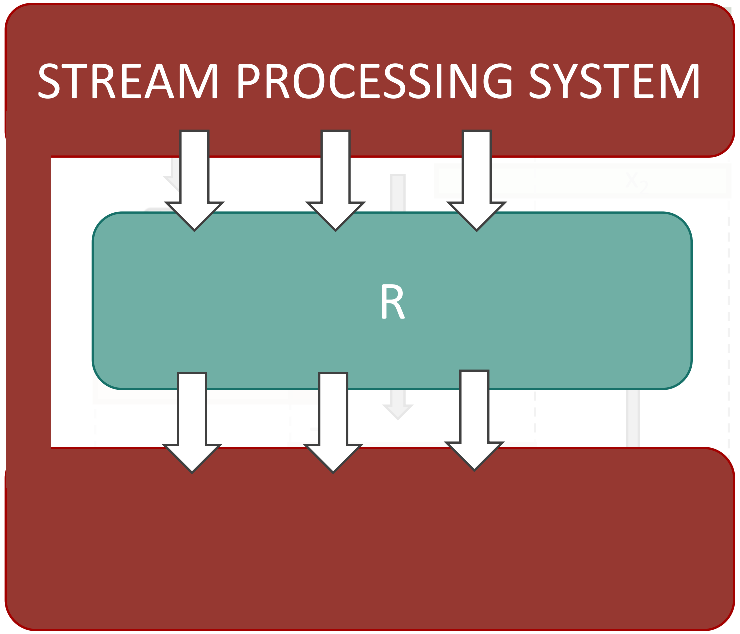
1. Window
   - window size & hop size
2. Per window: pipeline DSP ops
   - array to array
   - Example: spectral analysis

     FFT ➞ user-defined function ➞ IFFT
3. Unwindow
   - sum overlapping segments

Per device

Loose Systems Integration

Stream Processing Engine + R



- Stream engine for relational queries
  - Per-group computation, windowing, joins, etc.
- R for highly-optimized DSP operations
- Problem: impedance mismatch
  - High communication overhead (up to 95%)
  - Impractical for real-time analysis
  - Disparate query languages

Trill: Fast Streaming Analytics Engine

- Performance
  - 2-4 OOM faster than today's SPE
- Query model
  - Based on temporal query model (relational with time)
  - Real-time, offline, progressive queries
- Language integration
  - Built as .NET library
  - Works with arbitrary C# data-types

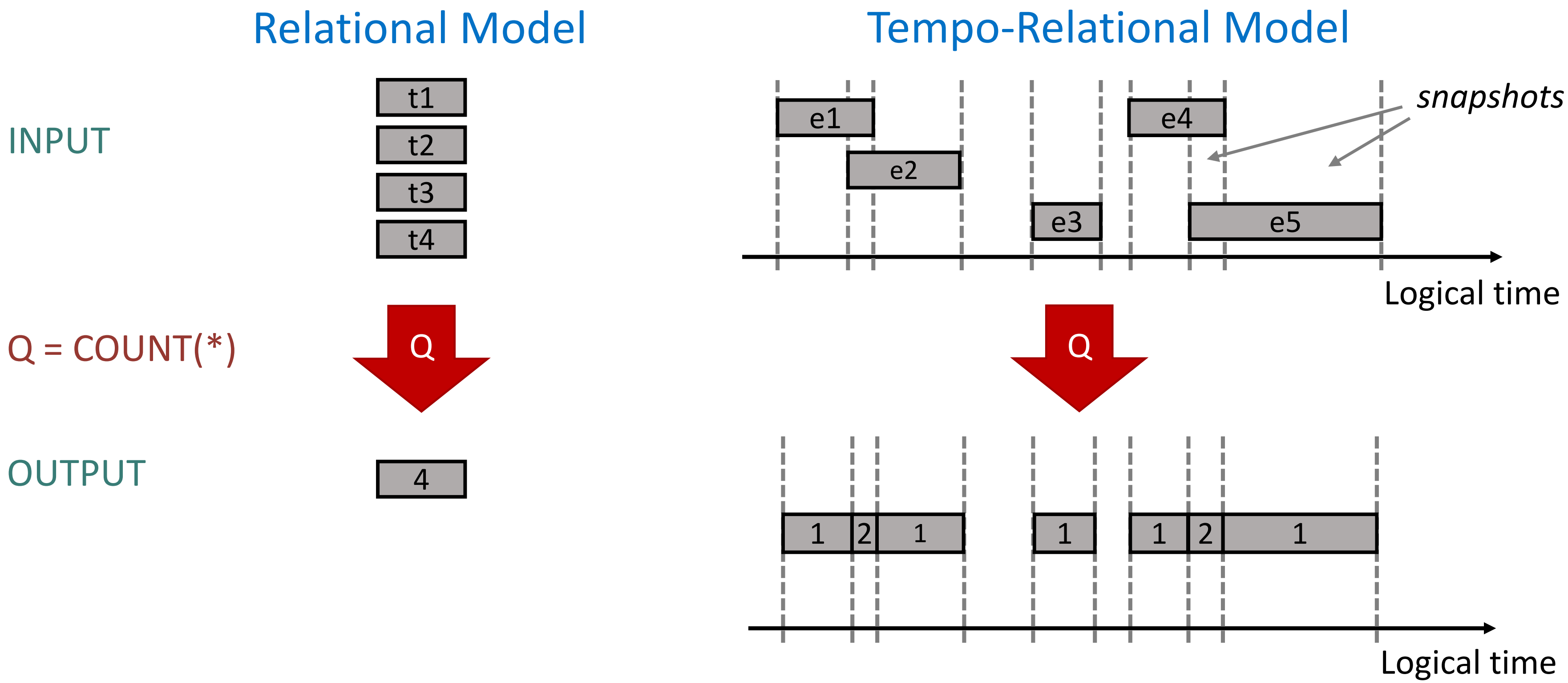
[VLDB 2014 paper]

DSP Library

- Unified query model
  - Non-uniform & uniform signals
  - Type-safe mix of stream & signal operators
- Array-based extensibility framework
  - DSP operator writer sees arrays
  - Supports incremental computation
- "Walled garden" on top of Trill
  - No changes in data model
  - Inherits Trill's efficient processing capability (e.g., grouped computation)

Tempo-Relational Model

- Uniformly represents offline and online datasets as stream data



Trill Example (Simplified)

- Define event data-type in C#

```
struct SensorReading { long SensorId; long Time; double Value; }
```

- Define ingress

Streamable — Application time

```
var str = Network.ToStream(e => e.Time);
```

- Write query (in C# app)

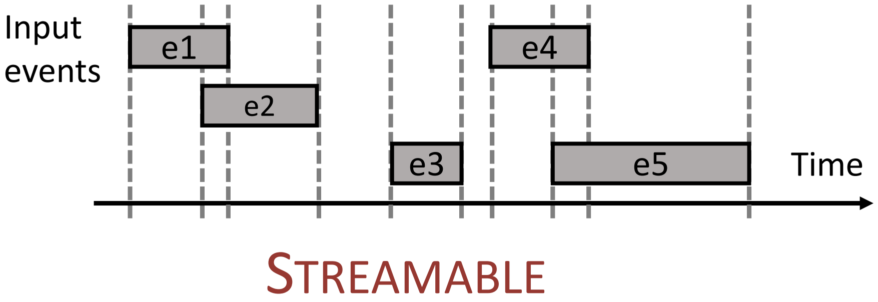
Operator — Lambda expression

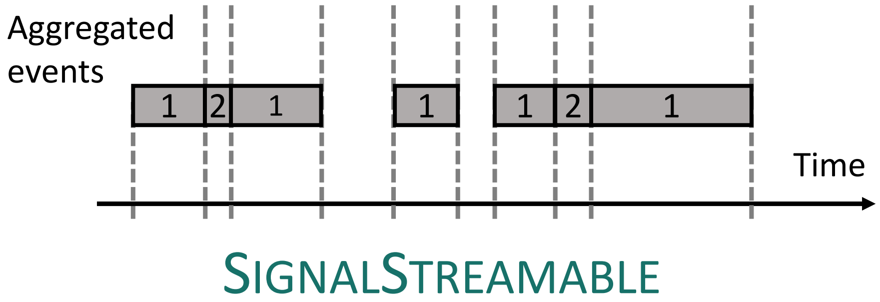
```
var query = str.Where(e => e.Value < 100)
               .Select(e => e.Value)
```

- Subscribe to result

```
query.Subscribe(e => Console.Write(e));   // write results to console
```

Signal = stream w/o overlapping events



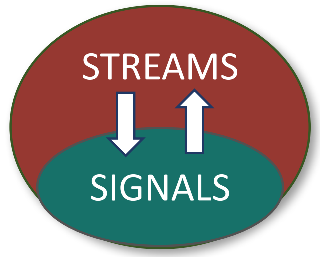


- Transition to signal domain
  - E.g., result of an aggregate query

```
var signal = stream.Where(e => e.Value < 100).Count()
```

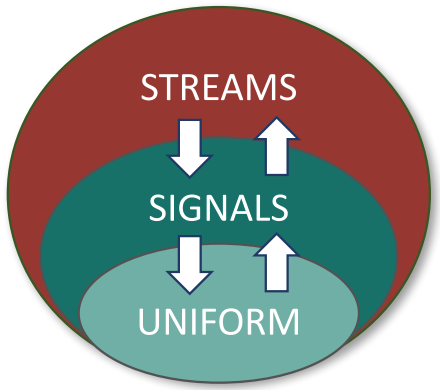
- Using stream operators to build signal operators
  - E.g., adding two signals as a temporal join of two streams

```
left.Join(right, (l, r) => l + r)
```



Type-safe operations

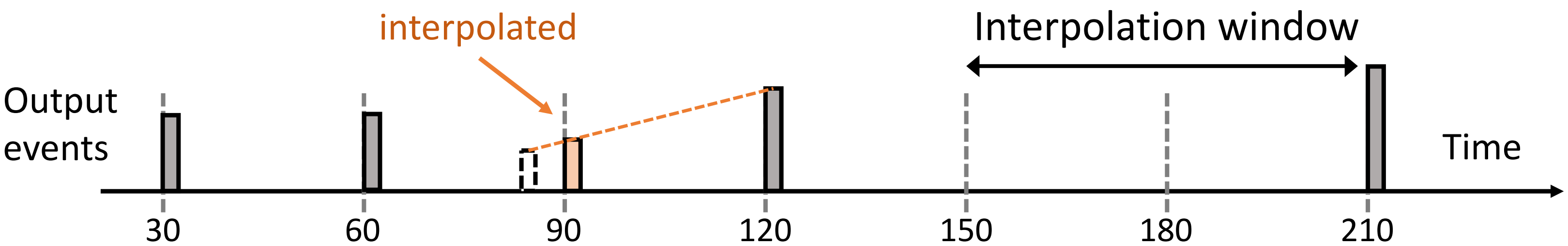
Uniformly-sampled signals



- Sampling with interpolation

Period, offset, interpolation policy

```
var uniformSignal = signal.Sample(30, 0, ip => ip.Linear(60));
```

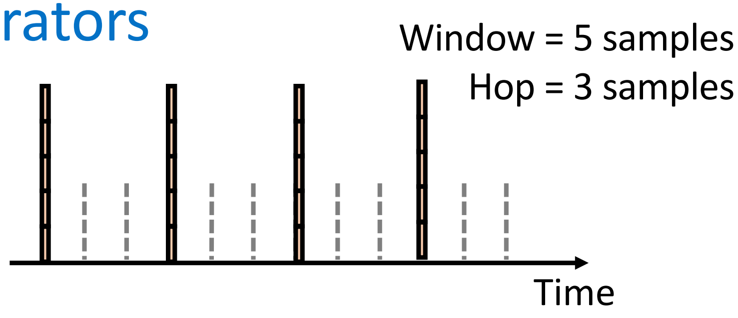


Bringing Array Abstractions to DSP Users

- Initial idea: Window & Unwindow sample operators
  - `Window()` creates a stream of arrays

    ```
    var s = uniformSignal.Window(5,3).FFT()…
    ```

  - `Unwindow()` projects arrays back in time



- Performance problems
  - Creates dependencies between window semantics and system performance
  - No data sharing across overlapping arrays
- Unclear language semantics
  - e.g., stream of arrays: is it a signal or not?

Windowing Operator for DSP Users

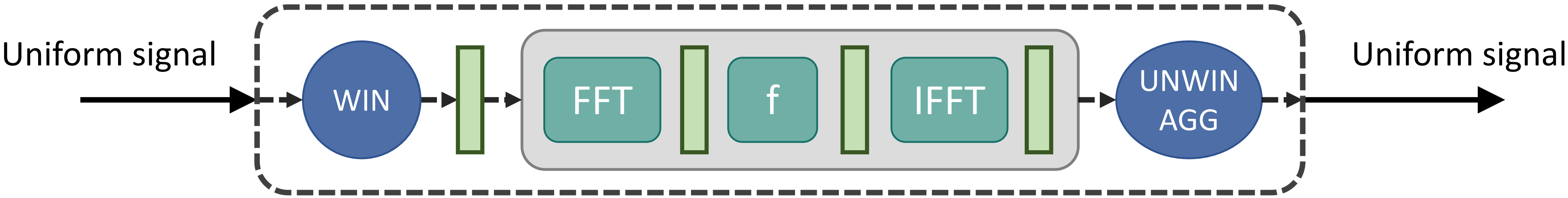
- Expose arrays only inside the windowing operator

```
var query = uniformSignal
  .Window(512, 256,
     w => w.FFT().Select(a => f(a)).IFFT(),
     a => a.Sum())
  )
```

Create array, fill it incrementally

Invoke user logic on full window

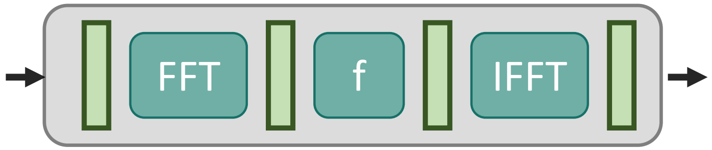
Unwindow & aggregate



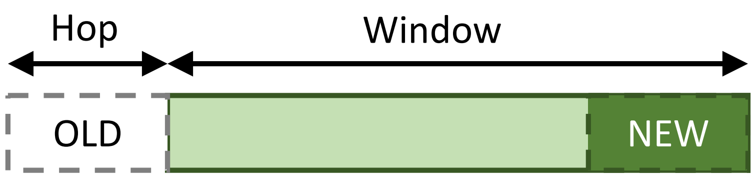
- DSP pipeline & arrays instantiated only once ➞ better data management

User-Defined Operator Framework

- DSP experts write array-array operators
  - Matches their expectations
  - Allows optimized array-based logic (e.g., SIMD)



- Incremental DSP operators
  - Framework uses circular arrays to avoid data copying with hopping windows
  - New & old data available for incremental computation



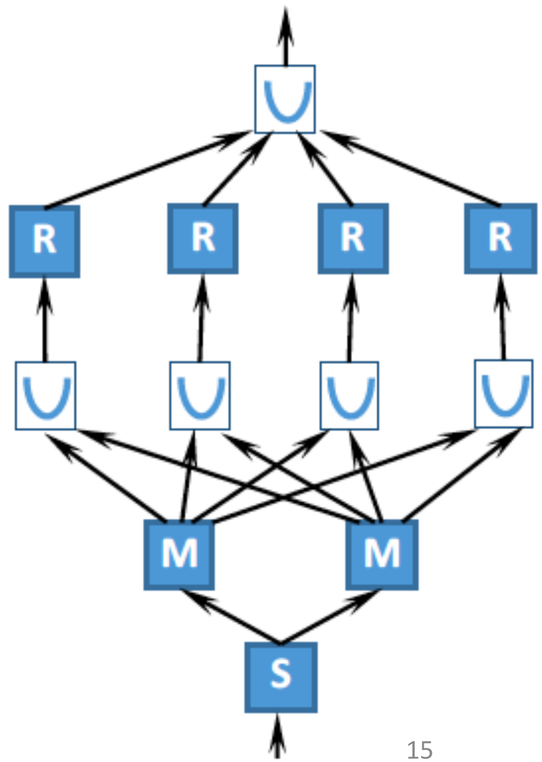
Grouped Computation

- Group-aware operators
  - Online processing of intertwined signals
  - One state per each group
    - E.g., interpolator keeps a history of samples for each group
- Streaming MapReduce in Trill
  - Parallel execution on each sub-stream corresponding to a distinct grouping key

Grouping key selector

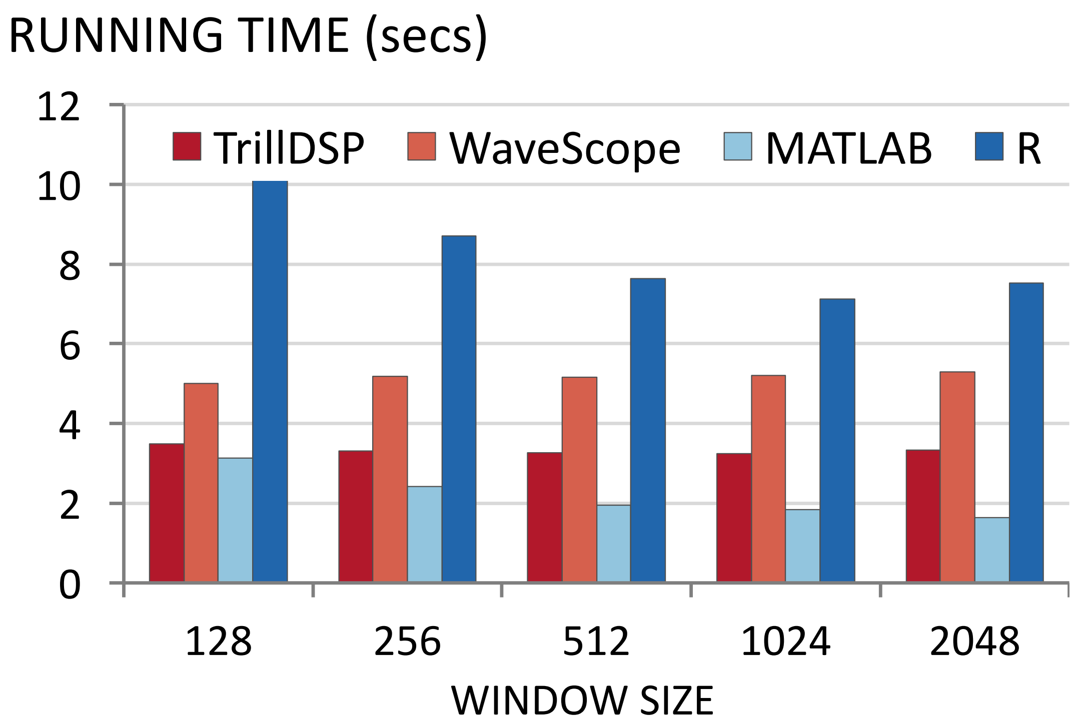
```
var q = signal
    .Map(s => s.Select(e => e.Value), e => e.SensorId)
    .Reduce(s => s.Window(512, 256,
                w => w.FFT().Select(a => f(a)).IFFT(),
                a => a.Sum()))
```

Grouped sub-query



Performance: FFT with tumbling window

Window ➞ FFT ➞ Unwindow



Pre-loaded datasets in memory

Pure DSP task

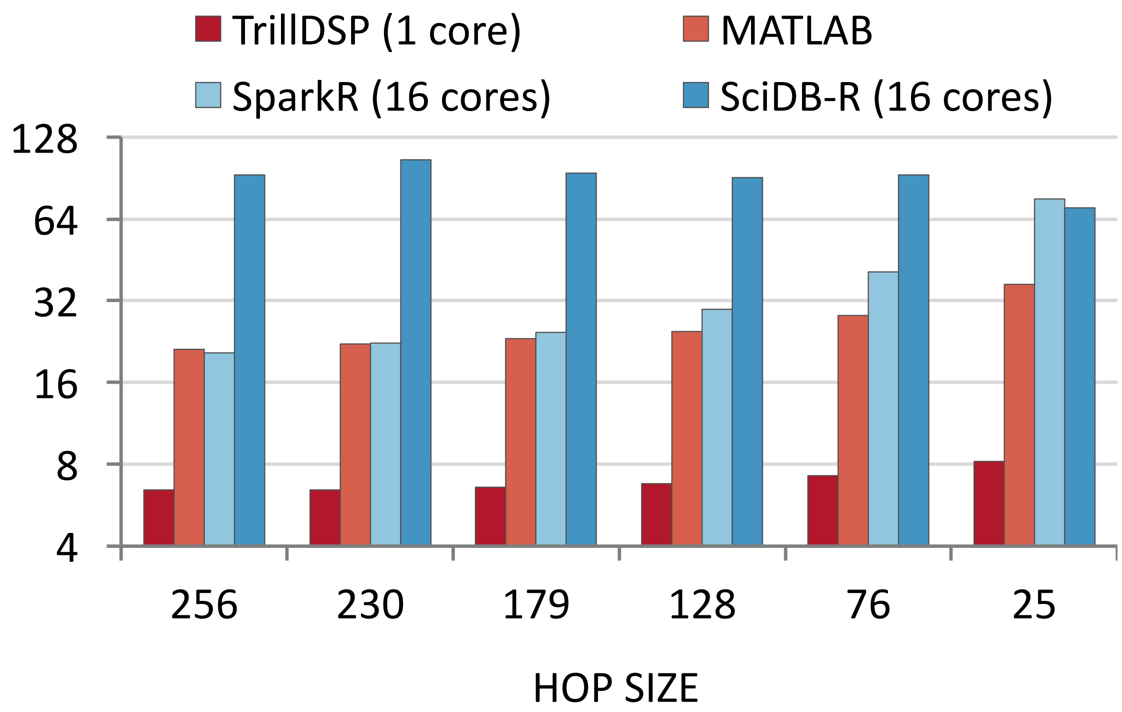
- TrillDSP uses FFTW library

Comparable to best DSP tools

Performance: Grouping + DSP

Per sensor: Windowed FFT ➞ Function ➞ Inverse FFT ➞ Unwindow

NORMALIZED TIME TO TRILLDSP ON 16 CORES



Pre-loaded datasets in memory

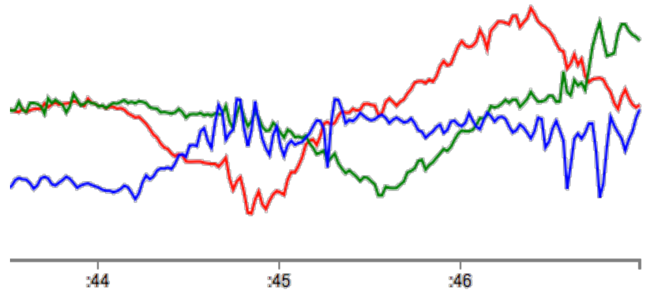
- 100 groups in stream

Up to 2 OOM faster than others

Performance benefits from:

- Efficient group processing, group-aware DSP windowing
- Using circular arrays to manage overlapping windows
- TrillDSP uses FFTW library

Conclusion



- Apps mix relational & signal logic
  - Per device: find periodicity in signals, interpolate missing data, recover noisy data
  - Different data models: relational vs. array
- Existing query processors integrated with R
  - Impedance mismatch → high performance overhead → not suitable for real-time
- TrillDSP = Relational processing + Signal processing
  - Unified query model for relational and signal data, for both real-time and offline
  - Gives users the view they are comfortable with
  - Avoids impedance mismatch between components

Up to 2 OOM faster than systems integrated w/ R