Programmable Multi-Dimensional Table Filters for Line Rate Network Functions

Vishal Shrivastav
Purdue University
Evolution of Programmable Data Plane Hardware*

* Not an exhaustive list
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2013
RMT
[SIGCOMM’13]
Match-Action Tables

2016
Domino
[SIGCOMM’16]
Stateful Atoms

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PIFO
SIGCOMM’16
Push-In-First-Out Queue

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  - FlowBlaze [NSDI’19]
    - Finite State Machine

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  - Taurus [ASPLOS’22]
  - Map-Reduce
  - Thanos [SIGCOMM’22]
  - Multi-Dimensional Table Filtering

* Not an exhaustive list
Data Plane Filtering is Prevalent

Attributes

<table>
<thead>
<tr>
<th>Paths</th>
<th>Delay</th>
<th>Utilization</th>
</tr>
</thead>
</table>

Performance-aware Routing
Filter paths with delay < d and utilization < u. Choose a random path from the filtered set

Multi-dimensional Filtering
Data Plane Filtering is Prevalent

<table>
<thead>
<tr>
<th>Paths</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Congestion</td>
</tr>
</tbody>
</table>

Performance-aware Routing
Filter paths with delay < d and utilization < u. Choose a random path from the filtered set.

Congestion-aware Load Balancing
Filter path with minimum congestion.

Multi-dimensional Filtering
Data Plane Filtering is Prevalent

<table>
<thead>
<tr>
<th>Ports</th>
<th>Attributes</th>
<th>Queuing</th>
</tr>
</thead>
</table>

Performance-aware Routing
Filter paths with delay < d and utilization < u. Choose a random path from the filtered set.

Congestion-aware Load Balancing
Filter path with minimum congestion or
Filter d random egress ports. Choose the least queued port from those d ports.

Multi-dimensional Filtering
Data Plane Filtering is Prevalent

### Attributes

<table>
<thead>
<tr>
<th></th>
<th>mem</th>
<th>bw</th>
<th>cpu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servers</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
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#### Performance-aware Routing
Filter paths with delay < d and utilization < u. Choose a random path from the filtered set.

#### Congestion-aware Load Balancing
Filter path with minimum congestion or
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#### Resource-aware L4 Load Balancing
Filter servers with avail mem > m and avail bw > b. From the filtered set, choose server with least cpu utilization.

---

Multi-dimensional Filtering
Data Plane Filtering is Prevalent

### Performance-aware Routing
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### Data Plane Diagnosis
Filter switch ports with packet rate > t.

---

**Multi-dimensional Filtering**

<table>
<thead>
<tr>
<th>Ports</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
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</tr>
</tbody>
</table>
Data Plane Filtering is Prevalent

### Attributes

<table>
<thead>
<tr>
<th>Paths</th>
<th>A (0/1)</th>
<th>B (0/1)</th>
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</thead>
<tbody>
<tr>
<td></td>
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Filter switch ports with packet rate > t.

### Policy Compliance
From all available paths, filter the paths not carrying tenant A’s or B’s traffic. Choose a path at random from the filtered paths to route a new flow from tenant C.

### Multi-dimensional Filtering
Data Plane Filtering is Prevalent

**Performance-aware Routing**
Filter paths with delay < d and utilization < u. Choose a random path from the filtered set.

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Filter path with minimum congestion or Filter d random egress ports. Choose the least queued port from those d ports.

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Filter servers with avail mem > m and avail bw > b. From the filtered set, choose server with least cpu utilization.

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From all available paths, filter the paths not carrying tenant A's or B's traffic. Choose a path at random from the filtered paths to route a new flow from tenant C.

**Data Plane Diagnosis**
Filter switch ports with packet rate > t.

---

**Chained Multi-dimensional Filtering**
Data Plane Filtering is Prevalent

### Attributes

<table>
<thead>
<tr>
<th>Resources</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Performance-aware Routing
Filter paths with $\text{delay} < d$ and $\text{utilization} < u$.
Choose a random path from the filtered set.

#### Congestion-aware Load Balancing
Filter path with minimum congestion or
Filter $d$ random egress ports. Choose the least queued port from those $d$ ports.

#### Resource-aware L4 Load Balancing
Filter servers with $\text{avail mem} > m$ and $\text{avail bw} > b$.
From the filtered set, choose server with least cpu utilization.

#### Policy Compliance
From all available paths, filter the paths not carrying tenant A's or B's traffic.
Choose a path at random from the filtered paths to route a new flow from tenant C.

#### Data Plane Diagnosis
Filter switch ports with packet rate $> t$.

---

**Chained Multi-dimensional Filtering at Line Rate**
State-of-the-Art

Current Programmable Switch Processing Pipeline

Match-Action

Does not support line rate multi-dimensional filtering
Thanos
Thanos

Thanos Switch Processing Pipeline

Match-Action

Programmable Filter Module
Thanos Switch Processing Pipeline

Match-Action

Multi-dimensional Table

Filter Processing Pipeline

Programmable Filter Module
Filter Abstractions and Primitives
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

```
UFPU: table → table
```

Filter a load balancing server at random

<table>
<thead>
<tr>
<th>Attributes (attr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
</tr>
<tr>
<td>-----</td>
</tr>
</tbody>
</table>

Servers

UFPU

random()
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table → table

\[
\begin{align*}
\text{random( )} \\
\text{predicate(attr \textit{relop} X)}
\end{align*}
\]

Filter load balancing servers with \textit{avail mem > X}

<table>
<thead>
<tr>
<th>ID</th>
<th>mem</th>
<th>bw</th>
<th>cpu</th>
<th># conn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

\textbf{Attributes (attr)}
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

\{
  \text{random( )}
  \text{predicate(attr relop X)}
  \text{weighted-round-robin(attr)}
\}

Filter load balancing servers in a \textit{round robin} manner weighted by \textit{avail bw}

### Attributes (attr)

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</tr>
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Servers

UFPU

w-rr(bw)
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

- random()
- predicate(attr $\ relop \ X$)
- weighted-round-robin(attr)
- min/max(attr)

Filter load balancing server with min cpu utilization

Attributes (attr)

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</tr>
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Servers

UFPU

min(cpu)
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

\[
\begin{align*}
\text{random( )} \\
\text{predicate(attr relop X)} \\
\text{weighted-round-robin(attr)} \\
\text{min/max(attr)}
\end{align*}
\]

Filter **N least cpu utilized** load balancing servers

or

Filter **N random** load balancing servers

Attributes (attr)

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Servers

A chain of N UFPU's

\[
I \rightarrow UFPU \rightarrow UFPU \rightarrow \cdots \rightarrow UFPU \rightarrow O_N = O
\]

\[
I = I_{N-1} - O_{N-1} \cup O_{N-1} \cup O_{N-1} \cup \cdots \cup O_{N-1} \cup O_N = O
\]
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table → table

\{
  \text{random( )},
  \text{predicate(attr relop X)},
  \text{weighted-round-robin(attr)},
  \text{min/max(attr)}
\}

Filter \textbf{N least cpu utilized} load balancing servers

or

Filter \textbf{N random} load balancing servers

Attributes (attr)

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A chain of \textbf{N} UFPU

\[ I \rightarrow I - O_1 \rightarrow I_{N-1} - O_{N-1} = O \]
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

$\{$
  random()
  predicate(attr $relop$ X)
  weighted-round-robin(attr)
  min/max(attr)
$\}$

Filter N least cpu utilized load balancing servers
or
Filter N random load balancing servers

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Servers

I $\rightarrow$ K-UFPU $\rightarrow$ O
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

\[
\begin{align*}
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Servers

K-UFPU comprises N UFPU

K specifies the length of chain (max N)

(by setting K=1, K-UFPU reduces to UFPU)
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

\{
  \begin{align*}
  \text{random}( ) \\
  \text{predicate} (\text{attr } \text{relop } X) \\
  \text{weighted-round-robin} (\text{attr}) \\
  \text{min/max} (\text{attr})
  \end{align*}
\}

Filter N least cpu utilized load balancing servers
or
Filter N random load balancing servers

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Servers

K-UFPU comprises N UFPU units and adds a new configurable parameter $K$

K specifies the length of chain (max N)
(by setting $K=1$, K-UFPU reduces to UFPU)

We use K-UFPU (instead of UFPU) as the basic computing unit
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table \rightarrow \text{table}

\{\}

- random(
- predicate(attr \; relop \; X)
- weighted-round-robin(attr)
- min/max(attr)

Binary Filter Processing Unit (BFPU)

BFPU: table, table \rightarrow \text{table}

\{\}

- union()
- intersection()
- difference()
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)
- $\text{UFPU: table } \rightarrow \text{table}$
  - $\text{random( )}$
  - $\text{predicate(attr relop } X)$
  - $\text{weighted-round-robin(attr)}$
  - $\text{min/max(attr)}$

Binary Filter Processing Unit (BFPU)
- $\text{BFPU: table, table } \rightarrow \text{table}$
  - $\text{union( )}$
  - $\text{intersection( )}$
  - $\text{difference( )}$

Filter all load balancing servers with $\text{avail mem} > X$ and $\text{avail bw} > Y$

<table>
<thead>
<tr>
<th>Attributes (attr)</th>
<th>ID</th>
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<th>bw</th>
<th>cpu</th>
<th># conn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servers</td>
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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

$K=1, \text{mem} > X$
$K=1, \text{bw} > Y$
intersect
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

- random( )
- predicate(attr $\_\_rellop\_\_X$)
- weighted-round-robin(attr)
- min/max(attr)

filter all load balancing servers with $\text{avail mem} > X$ and $\text{avail bw} > Y$ and $\#\text{ conn} < Z$
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table \( \rightarrow \) table

\{
\begin{align*}
\text{random(~)} \\
\text{predicate(attr \ relop \ X)} \\
\text{weighted-round-robin(attr)} \\
\text{min/max(attr)}
\end{align*}
\}

Filter all load balancing servers with \text{avail mem > X and avail bw > Y and # conn < Z}

Filter \text{m} load balancing servers at \text{random}

Binary Filter Processing Unit (BFPU)

BFPU: table, table \( \rightarrow \) table

\{
\begin{align*}
\text{union(~)} \\
\text{intersection(~)} \\
\text{difference(~)}
\end{align*}
\}

Attributes (attr)

<table>
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<tr>
<th>ID</th>
<th>mem</th>
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<th>cpu</th>
<th># conn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td></td>
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<tr>
<td>2</td>
<td></td>
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<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Servers

K-UFPU

K=1, \text{bw > Y}

BFPU

intersect

K-UFPU

K=1, \text{mem > X}

BFPU

intersect

K-UFPU

K=1, \text{# conn < Z}

BFPU

K=m, \text{random(~)}
Abstractions and Primitives

Unary Filter Processing Unit (UFPU)

UFPU: table $\rightarrow$ table

- random() 
- predicate(attr relop X)
- weighted-round-robin(attr)
- min/max(attr)

Binary Filter Processing Unit (BFPU)

BFPU: table, table $\rightarrow$ table

- union()
- intersection()
- difference()

Filter all load balancing servers with `avail mem > X and avail bw > Y and # conn < Z`

Filter `m` load balancing servers at random:

Filter load balancing server with `min cpu util`

Attribute table:

<table>
<thead>
<tr>
<th>ID</th>
<th>mem</th>
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<th># conn</th>
</tr>
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</tbody>
</table>

Diagram:

- UFPU: table $\rightarrow$ table
  - K-UFPU $K=1$, bw > Y
  - K-UFPU $K=1$, mem > X
  - K-UFPU $K=1$, # conn < Z
- BFPU: table, table $\rightarrow$ table
  - BFPU intersect
  - BFPU intersect
  - BFPU intersect
  - K-UFPU $K=m$, random()
  - K-UFPU $K=1$, min(cpu)
## Abstractions and Primitives

### Unary Filter Processing Unit (UFPU)

UFPU: \( \text{table} \rightarrow \text{table} \)

- \( \text{random}(\) \)
- \( \text{predicate(attr relop X)} \)
- \( \text{weighted-round-robin(attr)} \)
- \( \text{min/max(attr)} \)

### Binary Filter Processing Unit (BFPU)

BFPU: \( \text{table, table} \rightarrow \text{table} \)

- \( \text{union()} \)
- \( \text{intersection()} \)
- \( \text{difference()} \)

### A 5-stage serial chain filter pipeline

(outputs from stage \( i \) are inputs to stage \( i+1 \))

<table>
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</table>

Servers:

- Stage 1: K-UFPU
- Stage 2: BFPU
- Stage 3: BFPU
- Stage 4: K-UFPU
- Stage 5: K-UFPU
From Abstractions to Hardware Design
Two Hardware Components

Attributes (attr)

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Stage 1: K-UFPU
Stage 2: BFPU
Stage 3: BFPU
Stage 4: K-UFPU
Stage 5: K-UFPU

Servers
Hardware Component # 1

1. Multi-dimensional Table
Hardware Component # 2

2. Programmable Filter Pipeline
How to design an efficient data structure for a multi-dimensional relational table?

Should allow line rate read, write, update!
Multi-Dimensional Table Data Structure

Limitations of Classic Data Structures

No universal data structure

- Range trees / B-Trees for range filtering
- Heap for min/max filtering
- Disjoint Set Data Structure for set operations
- Either compromise on performance of certain operations or pay the cost of maintaining multiple data structures over the same data

Hierarchical Structure

- Fundamental $O(\log(N))$ latency
- Hard to pipeline

Multi-Dimensional Table Data Structure

Our Solution:

Sorted Multidimensional Bidirectional Map (SMBM)
Multi-Dimensional Table Data Structure

Our Solution:

Sorted Multidimensional Bidirectional Map (SMBM)

<table>
<thead>
<tr>
<th>ID</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

Example Table
SMBM Property # 1

Our Solution:
Sorted Multidimensional Bidirectional Map (SMBM)

Example Table

<table>
<thead>
<tr>
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<td>19</td>
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<td>8</td>
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</tbody>
</table>

Store each dimension as flat list of flip-flops
Allows parallel access and processing
SMBM Property # 2

Our Solution:

Sorted Multidimensional Bidirectional Map (SMBM)

Example Table

<table>
<thead>
<tr>
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</tr>
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<td>4</td>
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<td>8</td>
</tr>
</tbody>
</table>

Each list is kept sorted

Allows fast max/min filter operations
Sorted Multidimensional Bidirectional Map (SMBM)

Our Solution:

Each dimension is stored as an independent list.

Allows parallel filters operations on multiple dimensions.
SMBM Property # 4

Our Solution:
Sorted Multidimensional Bidirectional Map (SMBM)

Example Table

<table>
<thead>
<tr>
<th>ID</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>8</td>
</tr>
</tbody>
</table>

Stored as

Bidirectional mapping between ID and attributes
SMBM Property # 4

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Bidirectional mapping between ID and attributes
Forward map keeps track of which attributes belong to which ID

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Bidirectional mapping between ID and attributes
Forward map keeps track of which attributes belong to which ID
Reverse map allows fast mapping of filtered attributes to their respective IDs
Our Solution:
Sorted Multidimensional Bidirectional Map (SMBM)

Can read the entire data structure in parallel in 1 clock cycle
Add and Delete can be issued every clock cycle with a latency of 2 cycles
Filter Pipeline

How to design a fully reconfigurable and fast filter pipeline?

Can express any arbitrary chain of filter operation with chain length $\leq k$ on the $n$ input lines

Runs at line rate
Filter Pipeline Layout
Reconfigurable Pipeline

In each stage:
1. Ability to apply any filter operation to an input (or pair of input) line
2. Ability to connect the output of a filter operation to any output line

Sufficient condition for full reconfigurability
Pipeline Stage Design

Naive design with both K-UFPUs and BFPUs

Input lines: $n = 4$

Output lines: $n = 4$

$n \times 2n$ Crossbar

$n/2 \times n$ Crossbar
Pipeline Stage Design

Naive design with both K-UFPUs and BFPUs

High overhead

n X 2n Crossbar

n/2 X n Crossbar

n = 4 Input lines

n = 4 Output lines
Pipeline Stage Design

Our design with both K-UFPUs and BFPUs

Cell

n = 4
Input lines

Cell

n X n
Crossbar

n = 4
Output lines
Example Configuration

Apply a UFPU op on Input 1 and connect to Output 3

Input lines

Output lines

n = 4

Cell

Cell

n X n Crossbar
Apply a UFPU op on Input 1 and connect to Output 3

Example Configuration

n = 4

Input lines

Cell

BFPU

K-UFPU

Cell

BFPU

K-UFPU

n X n

Crossbar

n = 4

Output lines

no-op
Example Configuration

Apply a BFPU op on Input 1 and 3 connect to Output 2

Cell

Input lines

Output lines

n X n Crossbar

n = 4

K-UFPU

BFPU

K-UFPU

BFPU

K-UFPU

BFPU

n = 4
Example Configuration

Apply a BFPU op on Input 1 and 3 and connect to Output 2

Cell

Input lines

Output lines

n = 4

n X n Crossbar

n = 4

K-UFPU

BFPU

no-op

K-UFPU

BFPU

K-UFPU

BFPU
Filter Pipeline Performance

- Filter pipeline can process a new filter request every clock cycle
- Our implementation runs at clock speeds in excess of 1 GHz
  - 1 GHz is the typical clock speed of today’s switches
- However, scalability is limited to a few 1000s of table entries
  - …beyond that the clock speed falls below 1 GHz
  - Still sufficient for many applications where table entries include network paths, switch ports, servers in a cluster, etc.
Load balancing client requests

**Policy 1.** Select a server uniformly at random.

**Policy 2.** Select a server uniformly at random from the set of servers with CPU utilization $< X$ and available memory $> Y$ and available bandwidth $> Z$. If the filtered set is empty, select a server uniformly at random from the entire set.

1.7x—1.3x better response time for 70% of client requests
Application Performance
Application Performance

In-network caching of relational graph filter queries

4x—2.8x better response time for cached filter queries

Response time with caching normalized w.r.t. no caching
Summary
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- **Thanos** extends programmable switches with the ability to do programmable line rate filtering over a multi-dimensional table.

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- Evaluations show up to 1.7x improvement in performance of key network functions, such as routing and load balancing.
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• Evaluations show up to 1.7x improvement in performance of key network functions, such as routing and load balancing

• **Overall, advances the current state of in-network computing**
  • enables **richer** algorithms for existing in-network applications
  • enables **new** in-network applications, e.g., caching of relational queries
Thank you!