Merlin: A Language for Provisioning Network Resources

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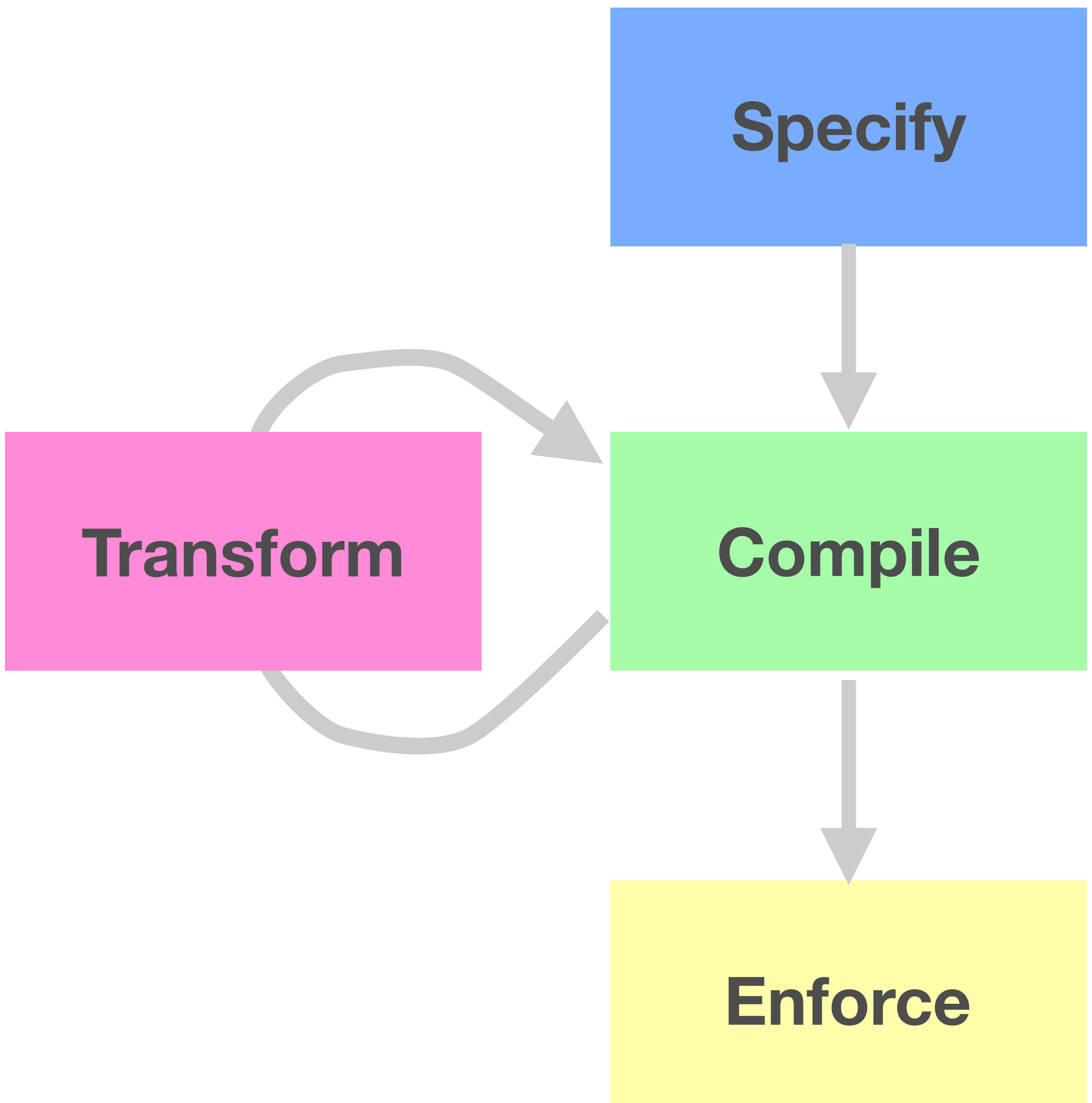
How to Program The Network?

- Existing SDN languages focus mostly on packet forwarding
- Ignore other vital network features like bandwidth, packet processing, etc.
- Network orchestration frameworks expose extremely simple APIs (if at all)

Merlin Approach



Specify global network policy in a **high-level declarative language**.

Map to a constraint problem. Provision network, select paths, and decide function placement.

Delegate to tenants for refinement. Verify that modifications conform to global policy. Re-solve if necessary.

Generate device-specific code and configuration to enforce policy.

Outline of This Talk

- Motivation
- **Policy Language**
- Compiler
- Dynamic Adaptation
- Evaluation
- Conclusions

Policy Language

Specify network behavior with high-level abstractions

Policy Basics

Informally: Ensure that HTTP traffic between two hosts is processed by NAT and DPI functions (in that order) and gets a guarantee of 100MB/s.

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} *Predicates identify which traffic*

} *Regular expressions for paths, functions*

} *Caps or guarantees for bandwidth*

Expressive Formulas

Informally: **Place an aggregate bandwidth cap on FTP data and control traffic. Data traffic must be processed by a DPI function.**

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```

} *FTP data*

} *FTP control*

} *Bandwidth constraints written as formulas*

Syntactic Sugar

Informally: Ensure that HTTP traffic between two hosts is processed by NAT and DPI functions (in that order) and gets a guarantee of 100MB/s (*again*).

```
srcs := {00:00:00:00:00:01}
dsts := {00:00:00:00:00:02}
foreach (s,d) in cross(srcs,dsts):
   tcp.dst = 80 ->
   ( .* nat .* dpi .*) at max(100MB/s)
```

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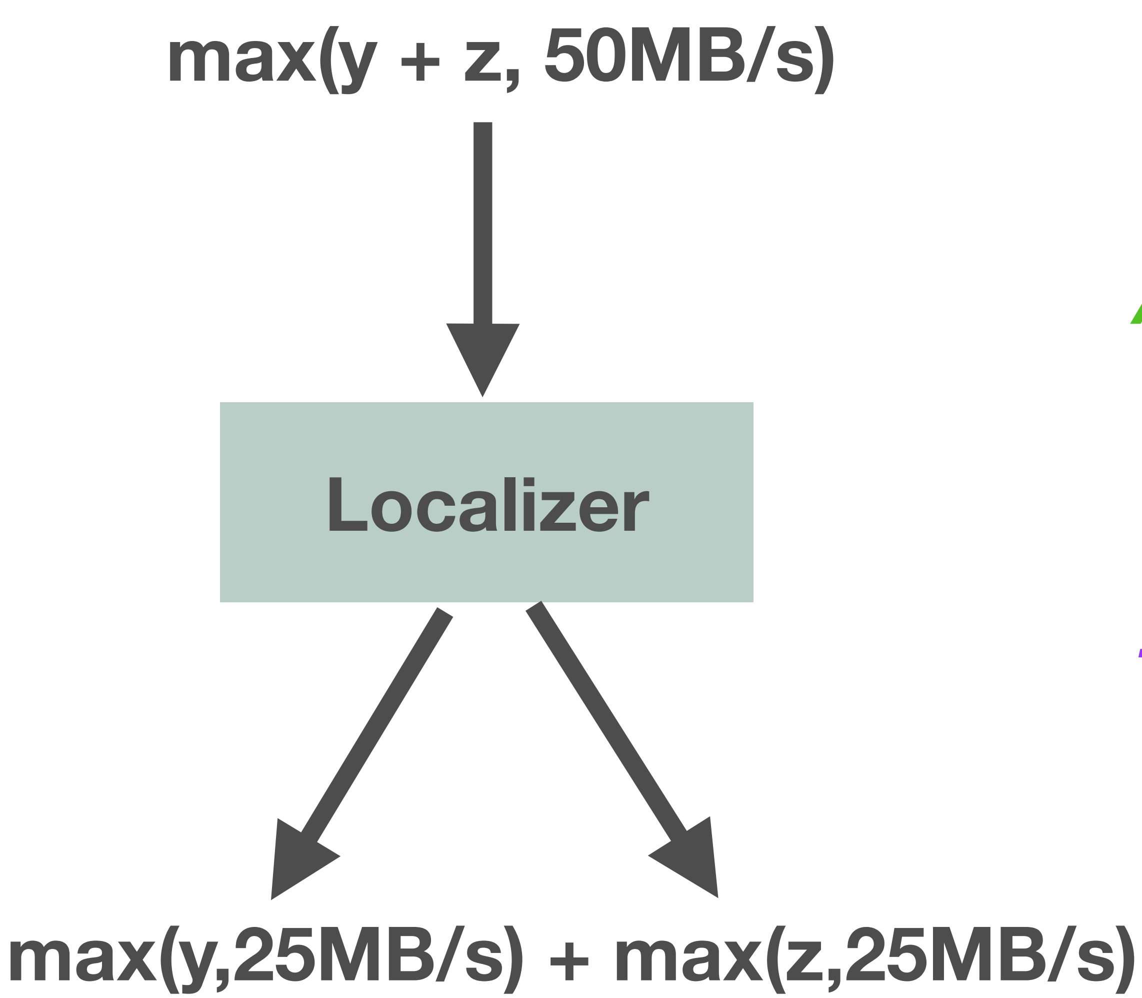
Merlin can concisely express a range of network policies. More examples in HotNets '13.

Compiler

Localize policies, allocate resources, and generate target code

Localization



Challenge:

Enforcing aggregate caps requires distributed state

Approach

- Re-write formulas so they can be locally enforced

Trade-off

- Increase scalability
- Risk underutilizing resource
- Run-time allows for dynamic adjustments

Allocate Resource: Map Policy to Constraints

```
[ x :
    (eth.src = 00:00:00:00:00:01 &
     eth.dst = 00:00:00:00:00:02 &
     tcp.dst = 80)
     -> .* nat *. dpi .*
], min(x,100MB/s)
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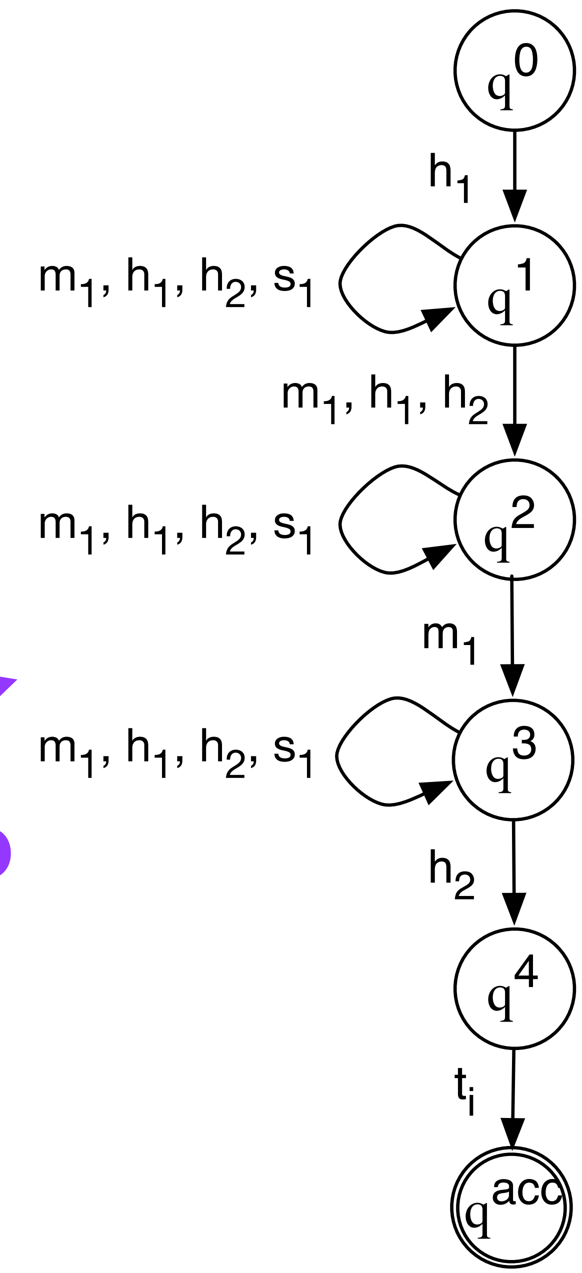
Convert to DFA



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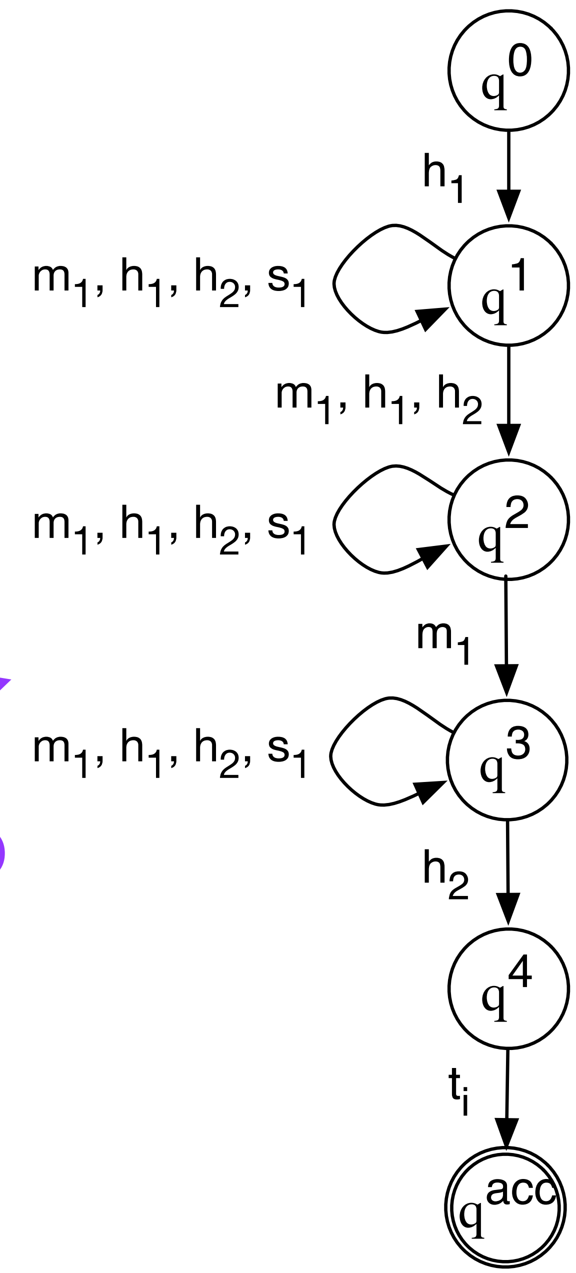
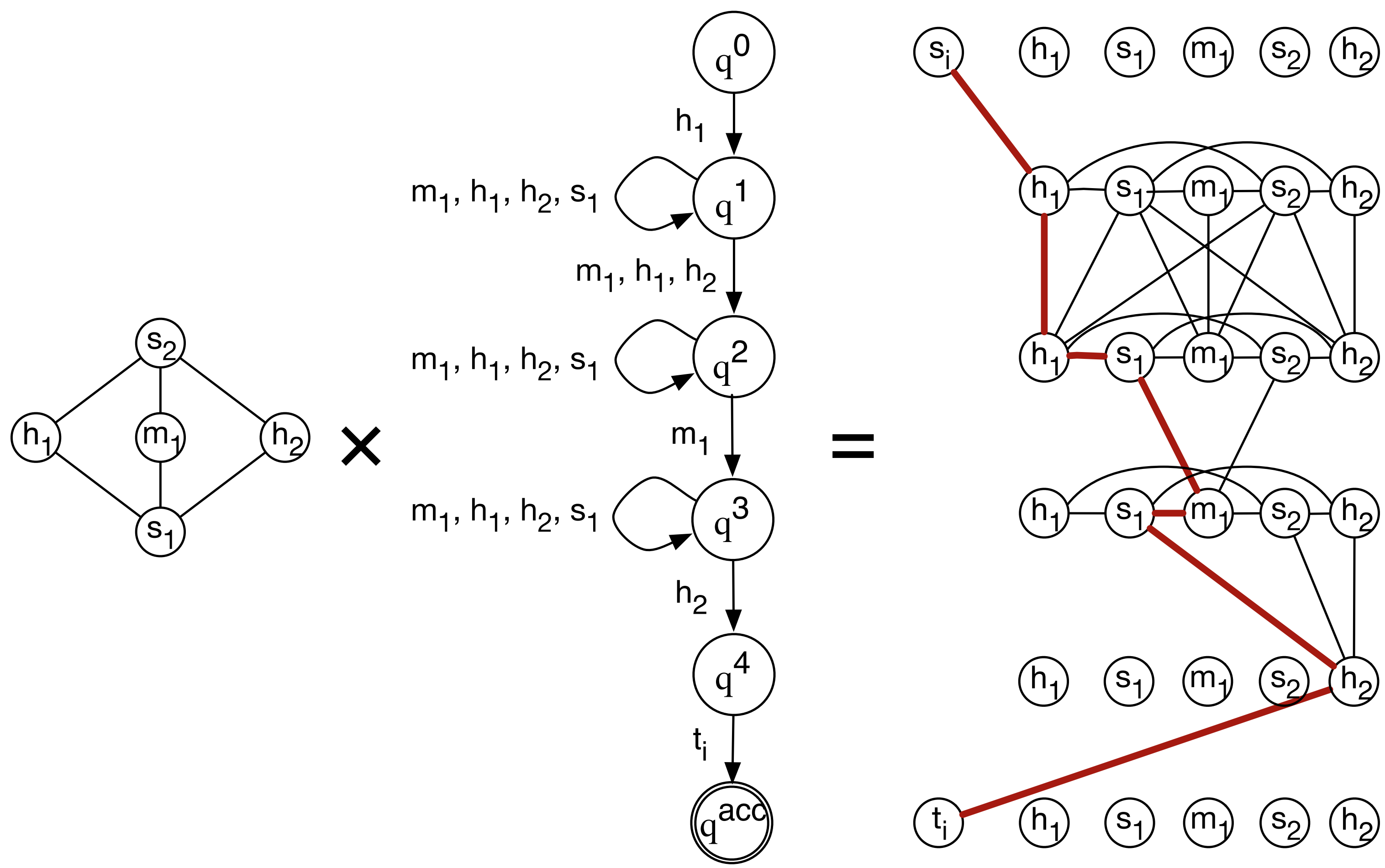
```

Convert to DFA

Note resource demands



Solve MIP to Determine Paths and Placement



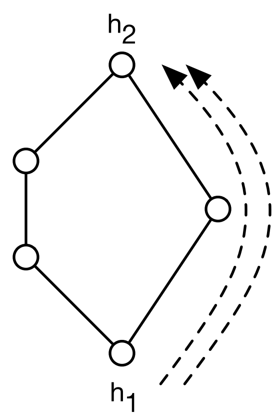
Physical topology with vertices V

Statement NFA with states Q_i

LP Graph G_i

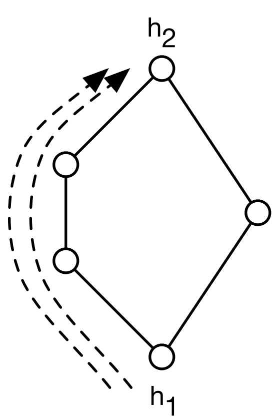
Encode with flow conservation and capacity constraints

Path Heuristics



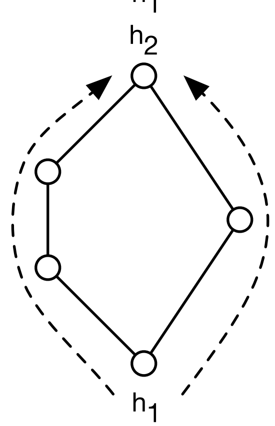
Weighted Shortest Path:

Minimizes total number of hops in assigned paths (standard)



Min-Max Ratio:

Minimizes the maximum fraction of reserved capacity (balance)



Min-Max Reserved:

Minimizes the maximum amount of reserved bandwidth (failures)

Code Generation

	**Network Switches**	Encode paths using **NetCore** [POPL ’12] Generate tags for routing Install rules on **OpenFlow** switches
	**Middleboxes**	Translate function to **Click** [TOCS’00] Install on software middleboxes
	**End Hosts**	Generate code for Linux **tc** and **iptables** Experimental support for Merlin kernel module based on **netfilter**

Dynamic Adaptation

Enable policy delegation and verify refined policies

Runtime Component

- *Negotiators* are runtime component for dynamic adaptation
- Distributed hierarchically throughout network
- Exchange messages amongst themselves to:
    - Modify (i.e., refine) policies
    - Verify policy modifications

Refine Policies

Informally: **Ensure that traffic between two hosts has a bandwidth cap of 100MB/s.**

```
[x : (ip.src = 192.168.1.1 and
      ip.dst = 192.168.1.2) -> .*],
 max(x, 100MB/s)
```

Three Possible Transformations

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```
[x : (ip.src = 192.168.1.1 and
      ip.dst = 192.168.1.2 and
      tcp.dst = 22) -> .* ],
[y : (ip.src = 192.168.1.1 and
      ip.dst = 192.168.1.2 and
      tcp.dst = 80) -> .* log .* ],
[z : (ip.src = 192.168.1.1 and
      ip.dst = 192.168.1.2 and
      !(tcpDst=22|tcpDst=80)) -> .* dpi .*],
max(x, 50MB/s)
and max(y, 25MB/s)
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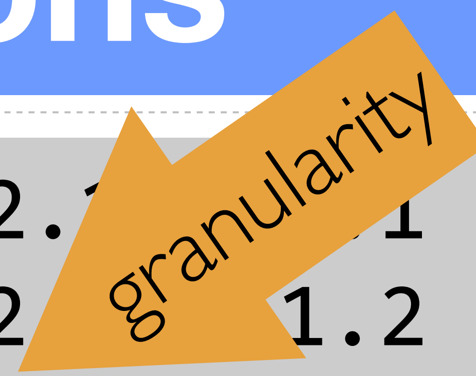
Three Possible Transformations

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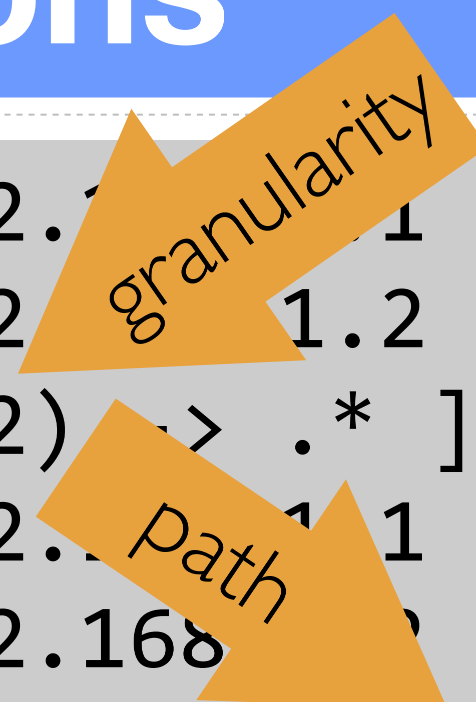

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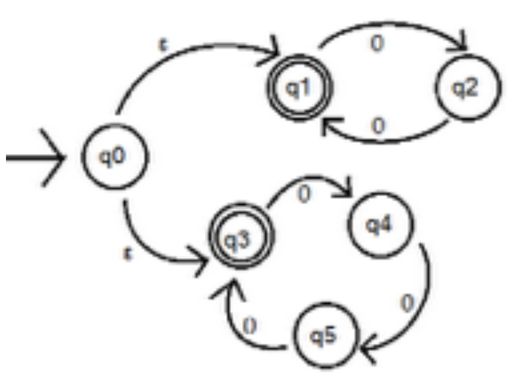
```

granularity

path

allocation

Automatic Verification



Essential operation:

policy inclusion (i.e., $P_1 \subseteq P_2$)

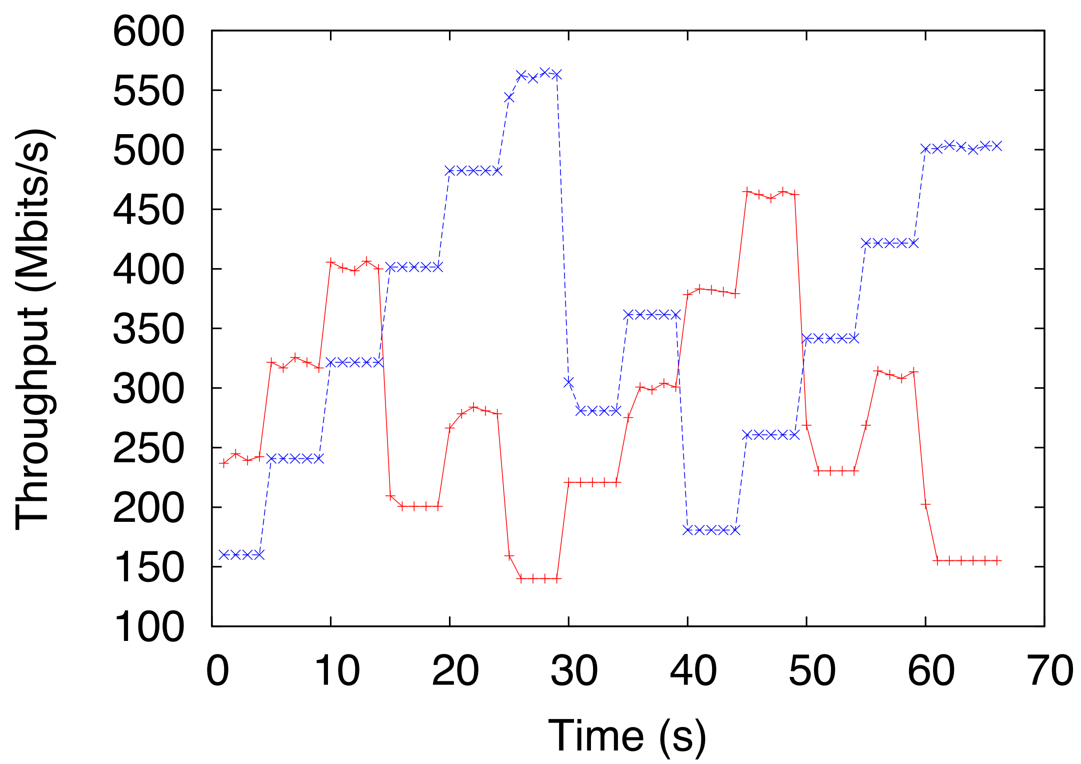
Algorithm

- Pair-wise comparison of statements
- Check for path inclusion in overlaps
- Aggregate bandwidth constraints

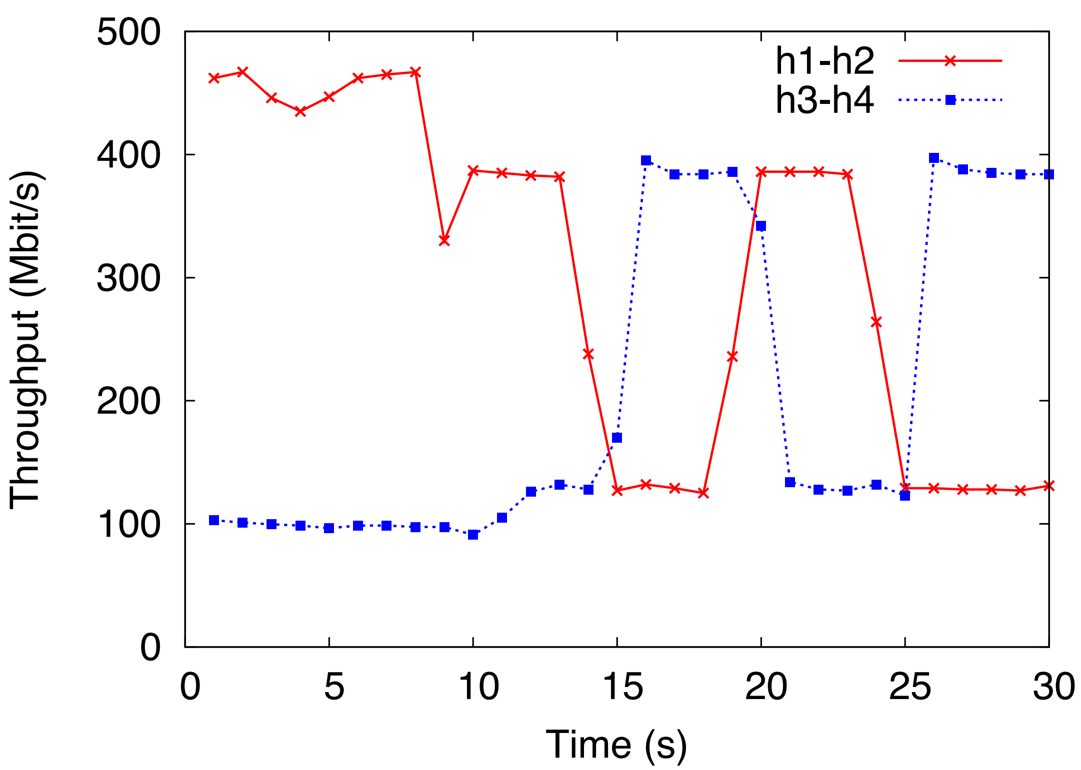
Implementation

- Decide predicate overlap using SAT
- Decide path inclusion using NFAs

Negotiator Implementations



Additive-Increase, Multiplicative-Decrease



Max-Min Fair Sharing

Evaluation

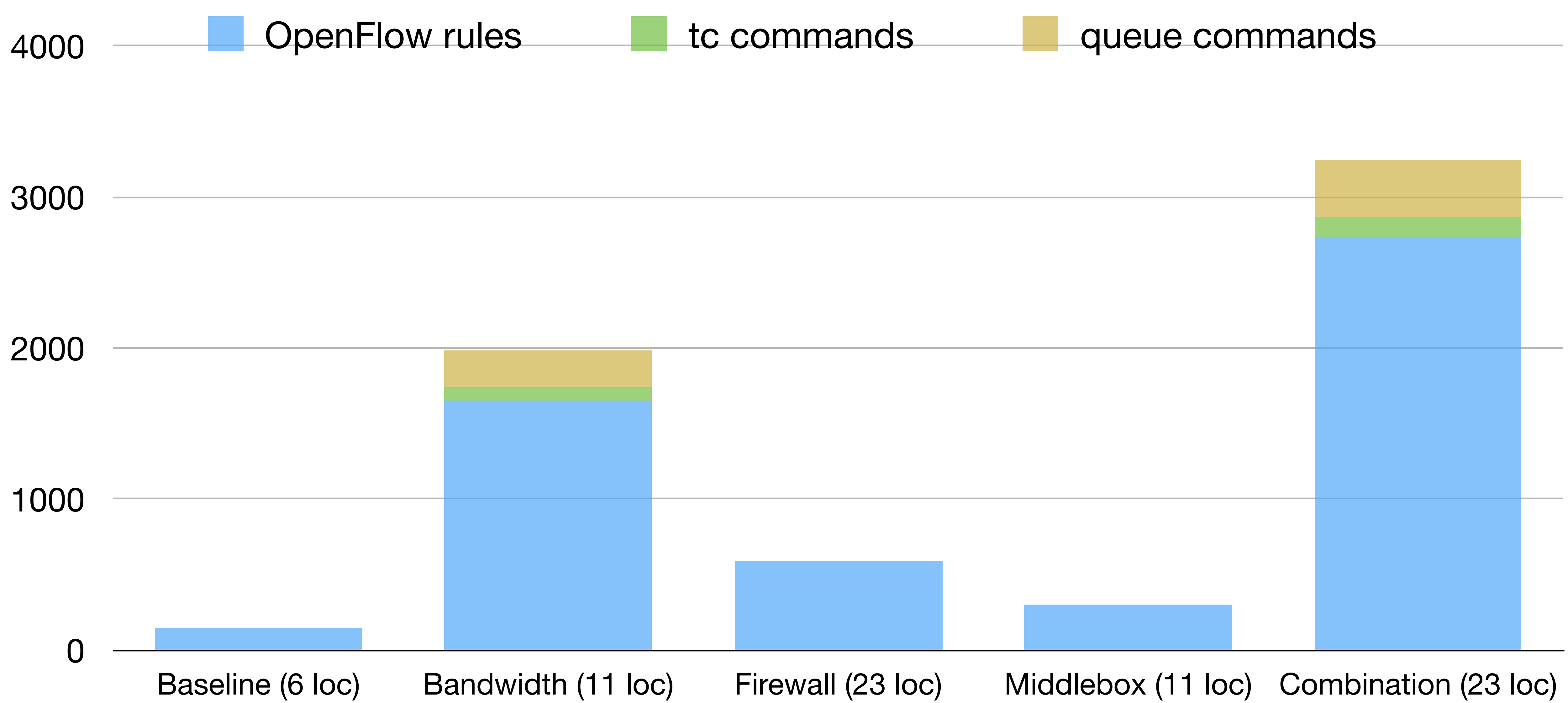
Demonstrating Merlin's expressiveness,
ability to manage the network, and scalability

Merlin Network Management

Baseline	Basic all-pairs connectivity between hosts
Bandwidth	10% of traffic classes get a guarantee of 1Mbps, and a cap of 1Gbps
Firewall	All packets with tcp.dst = 80 are routed through a firewall
Middlebox	Hosts are partitioned into two sets (trusted and untrusted). Inter-set traffic must pass through a middle box.
Combination	All of the above

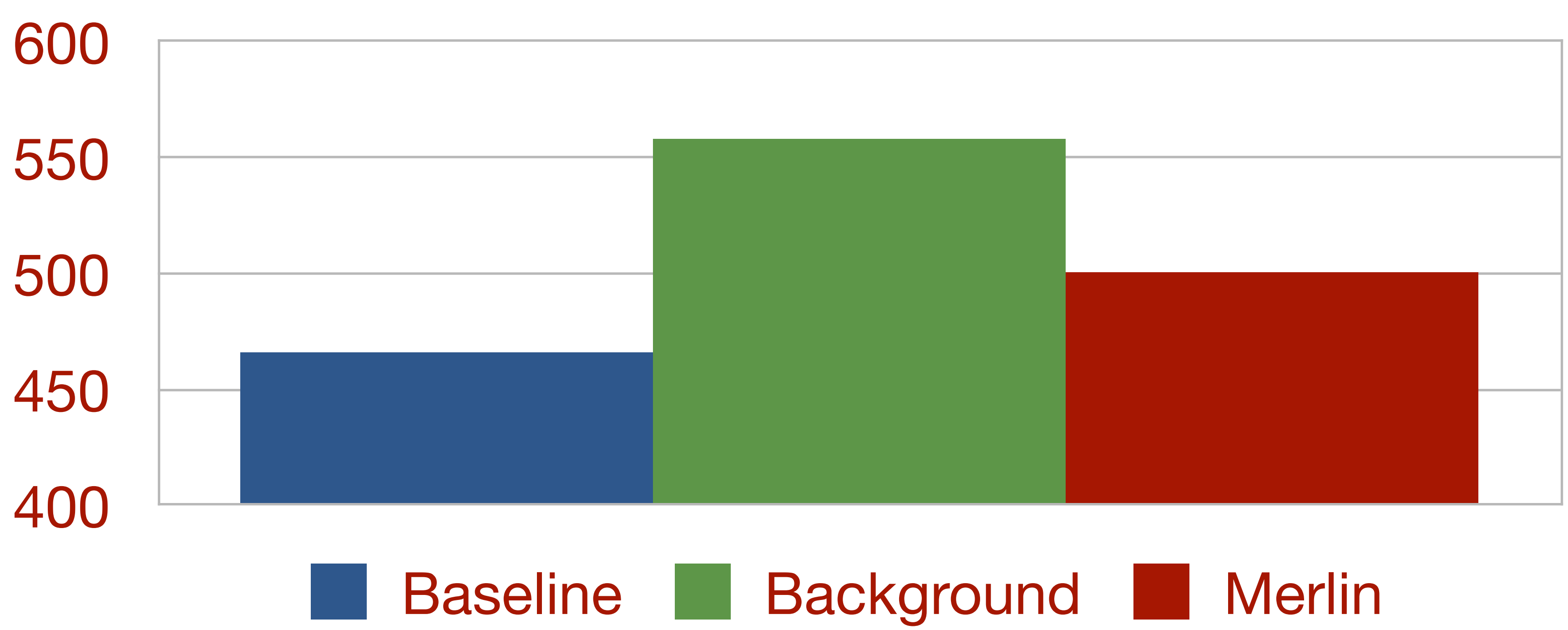
Policies to manage Stanford network topology

Merlin Reduces Management Effort



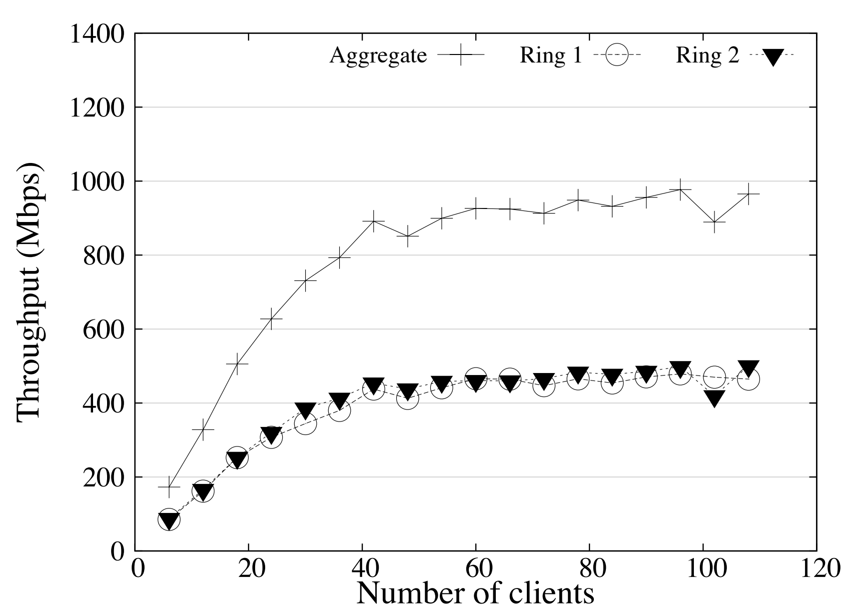
Merlin Managing Hadoop

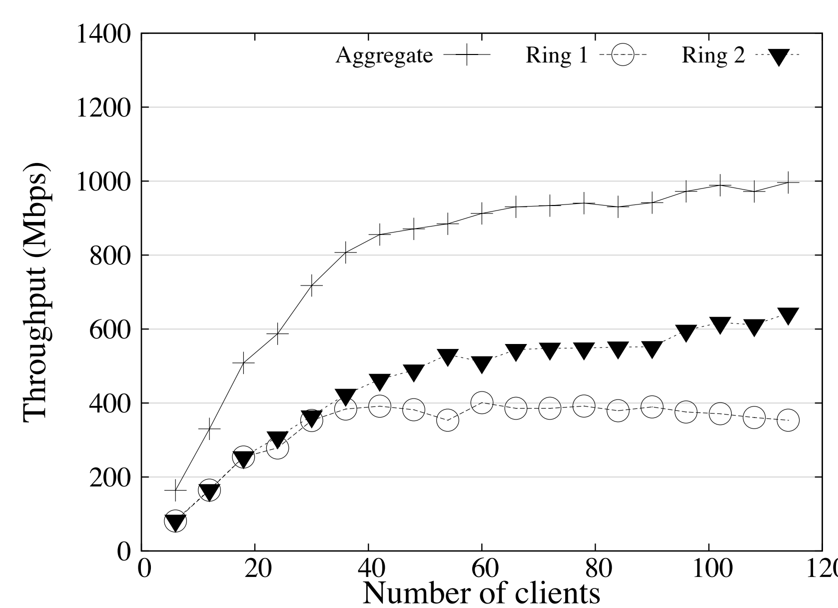
- Measured completion time for word count:
    1. Without background traffic
    2. With background traffic
    3. With background traffic + Merlin reserve 90% capacity



Merlin Managing Ring Paxos

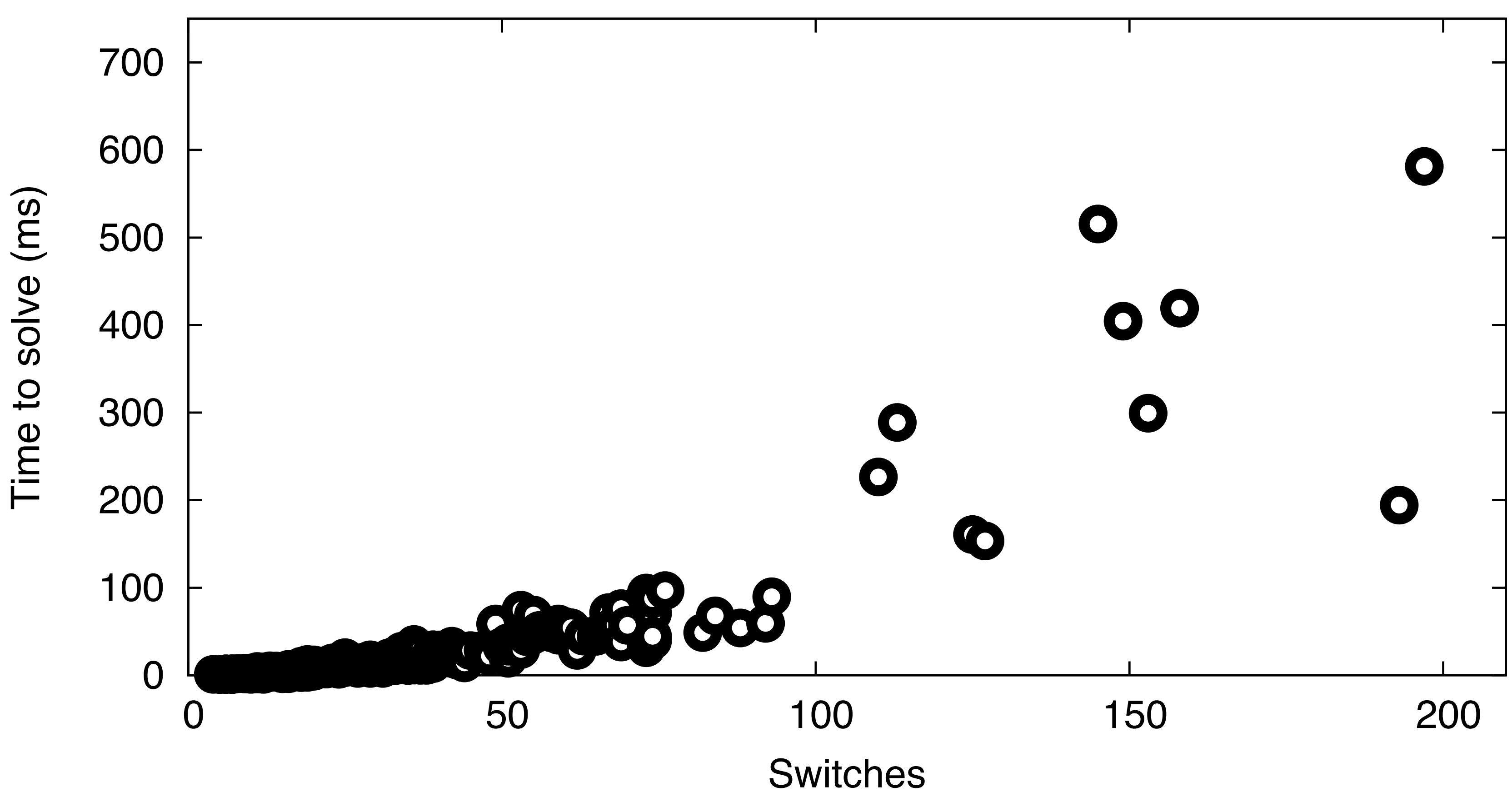
- State machine replication (SMR) is fundamental approach for fault-tolerant services
- Measure throughput for co-located key-value store service backed by SMR
- Merlin prioritizes traffic for one service





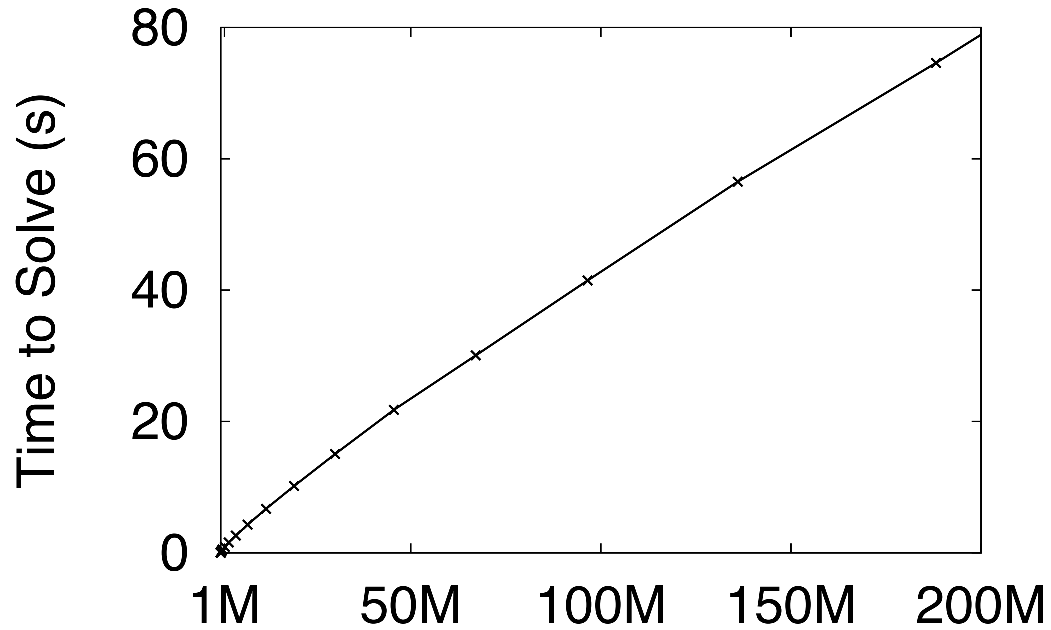
Compilation is Fast For Basic Connectivity

- All-pairs connectivity for Internet Topology Zoo dataset
- Majority of topologies completed in <50ms

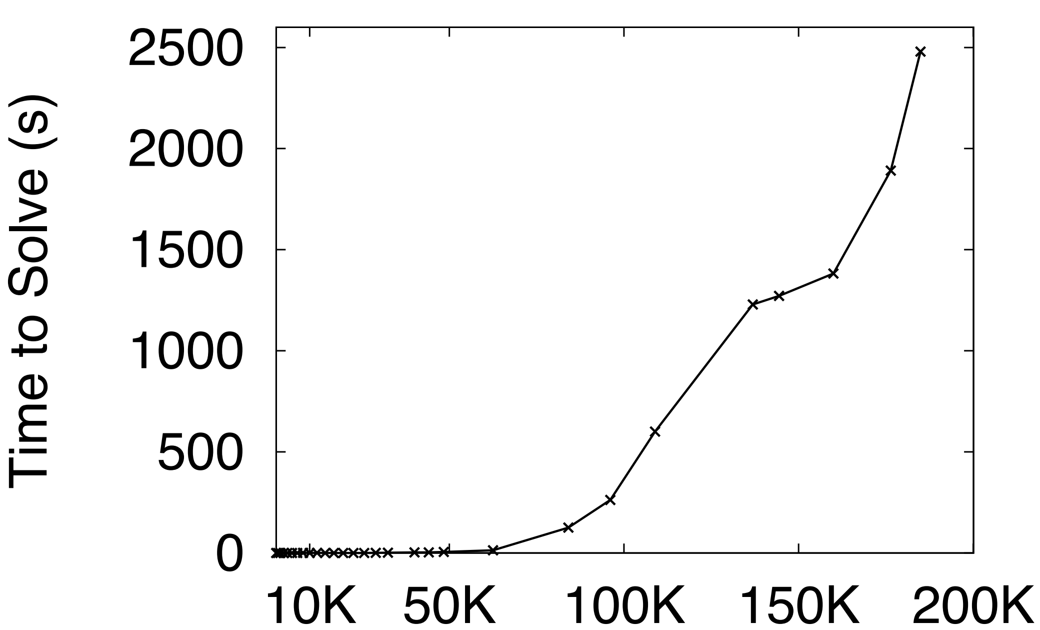


Solver Adds Reasonable Overhead

- Measured compilation time for fat tree topologies for an increasing number of traffic classes
- 100 traffic classes for 125 switch network in 5 sec



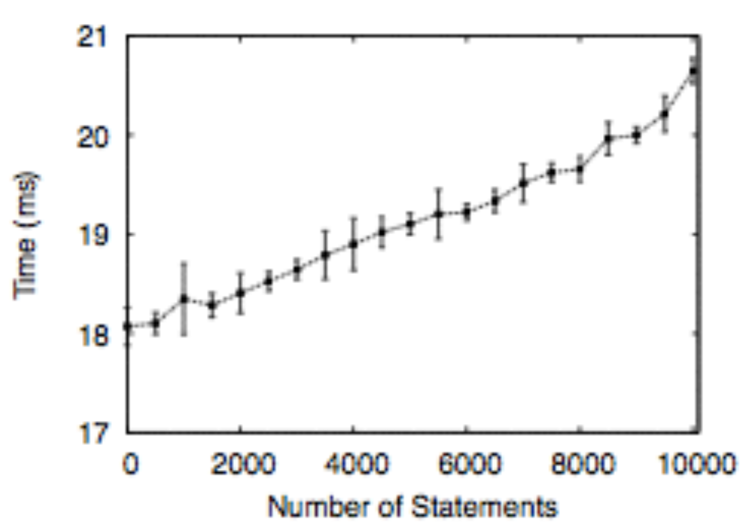
All-pairs connectivity



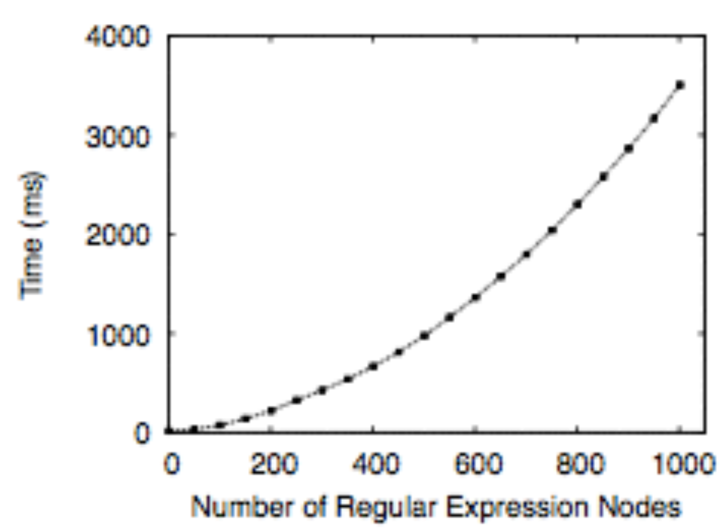
5% of traffic with bandwidth guarantees

Verification is Very Fast

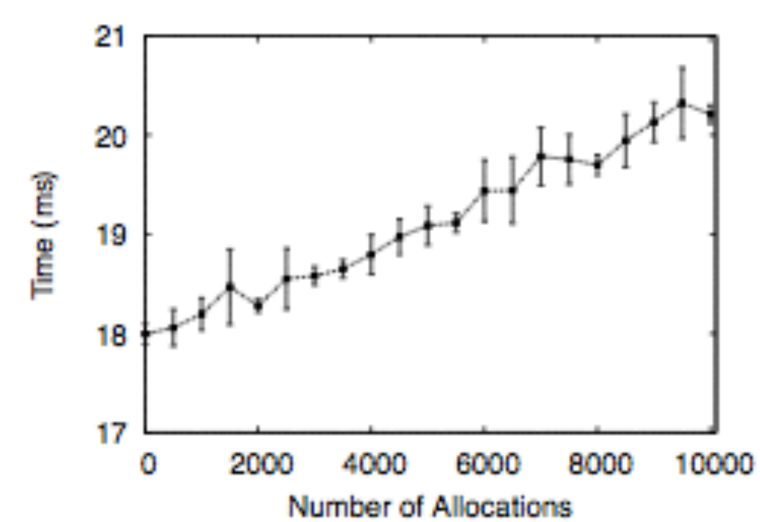
- 10,000 statements verified in less than 21ms
- Verifying resource allocations is very fast
- Verifying paths scales with complexity of the expression



Increasing Statements



Increasing Path Expressions



Increasing Bandwidth Constraints

Conclusion

- Merlin dramatically simplifies network management
- It provides abstractions that:
  - Let developers program the network as a unified entity
  - Allow mapping to a constraint problem for provisioning
  - Enable delegation and automatic verification

http://frenetic-lang.org/merlin