Merlin: A Language For Provisioning Network Resources

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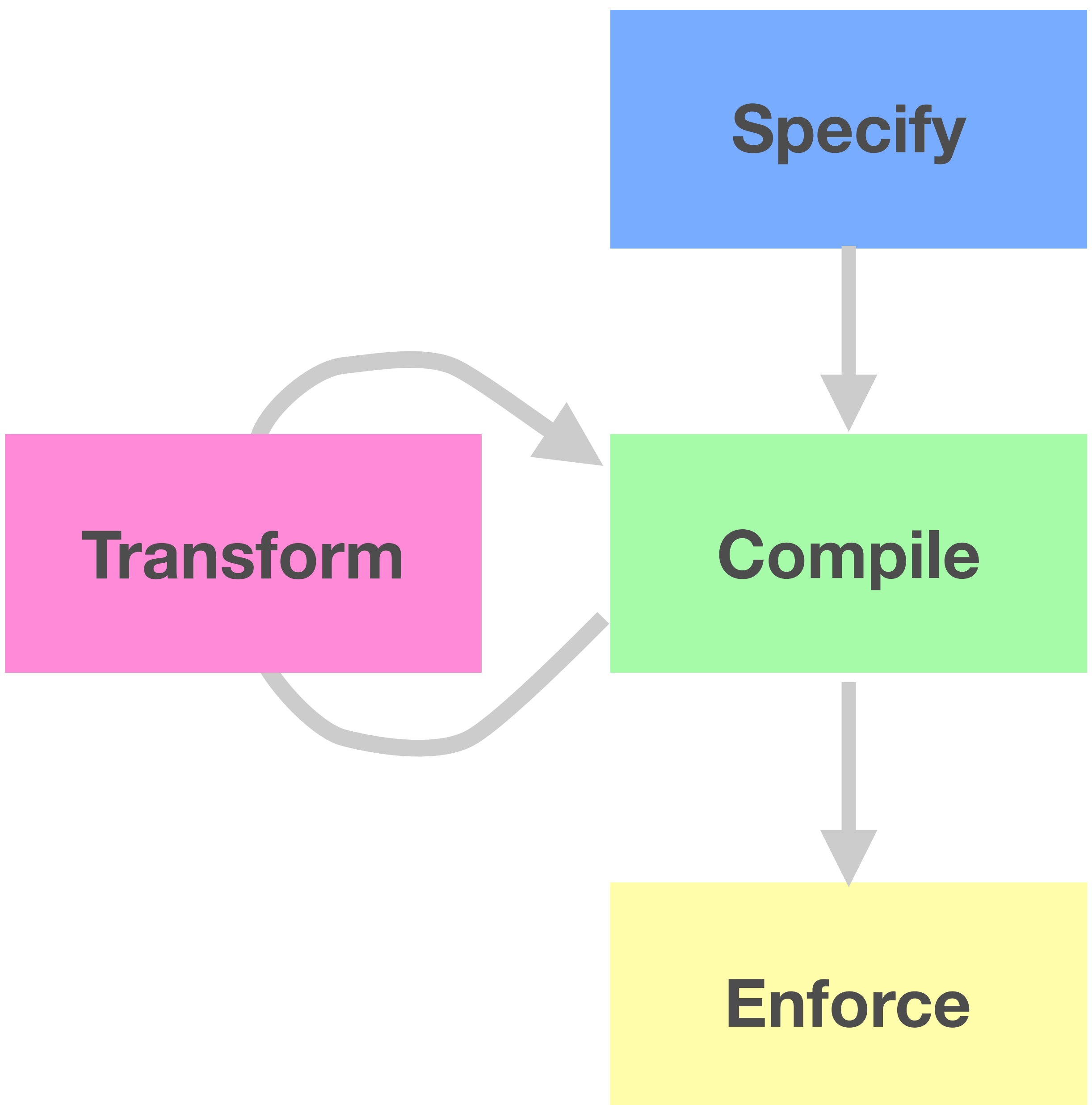
SDN Languages are Limited

- SDNs have simplified network management and increased programability
- But, existing SDN languages focus mostly on packet forwarding
- Network orchestration frameworks expose extremely simple APIs (if at all)

Need More Than Forwarding

- Support traffic engineering goals through bandwidth caps and guarantees
- Apply packet-processing functions such as NAT, DPI, load-balancers, etc.
- Provide an intuitive programming interface with compose-able policies

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

Basic Policy

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

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Regular expressions for paths, functions

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Caps or guarantees for bandwidth

Aggregate Policy

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max(y + z,50MB/s)
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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 := {192.168.1.1}
dsts := {192.168.1.2}
foreach (s,d) in cross(srcs,dsts):
   tcp.dst = 80 ->
   ( .* nat .* dpi .*) at min(100MB/s)
```

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} *Set operators and iterators*

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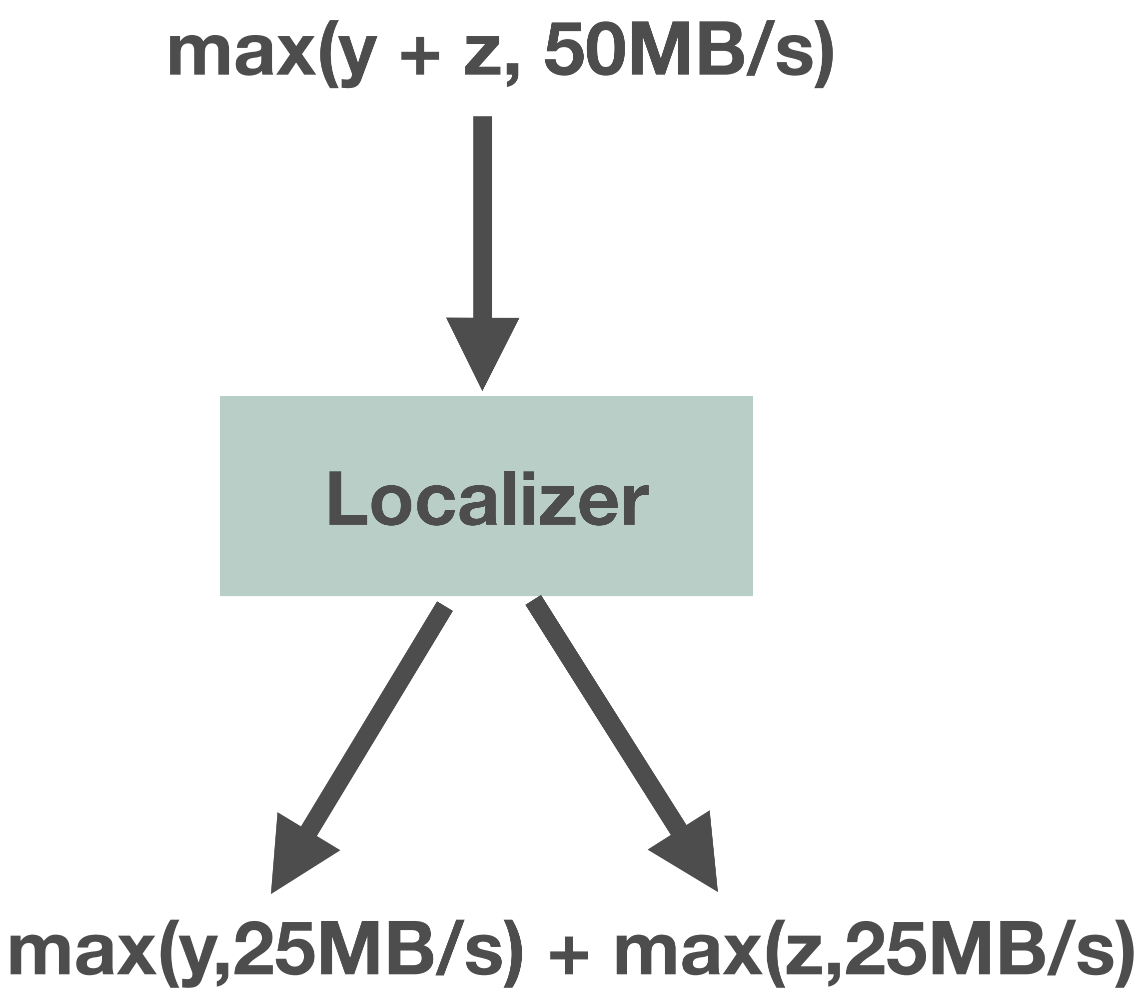
Merlin can concisely express a range of network policies. More examples in HotNets '13.

Compiler

Localize policies, allocate resources, and generate target code

Remove Distributed State



- Enforcing aggregate caps requires distributed state (e.g., FTP control and data traffic)
- Compiler re-writes formulas so that they only require local state
- There is an inherent trade-off: increased scalability vs. risk of under-utilization

Extract Policy Constraints

```
[ x :
    (eth.src = 192.168.1.1 and
     eth.dst = 192.168.1.2 and
     tcp.dst = 80)
     -> .* nat *. dpi .*
], min(x,100MB/s)
```

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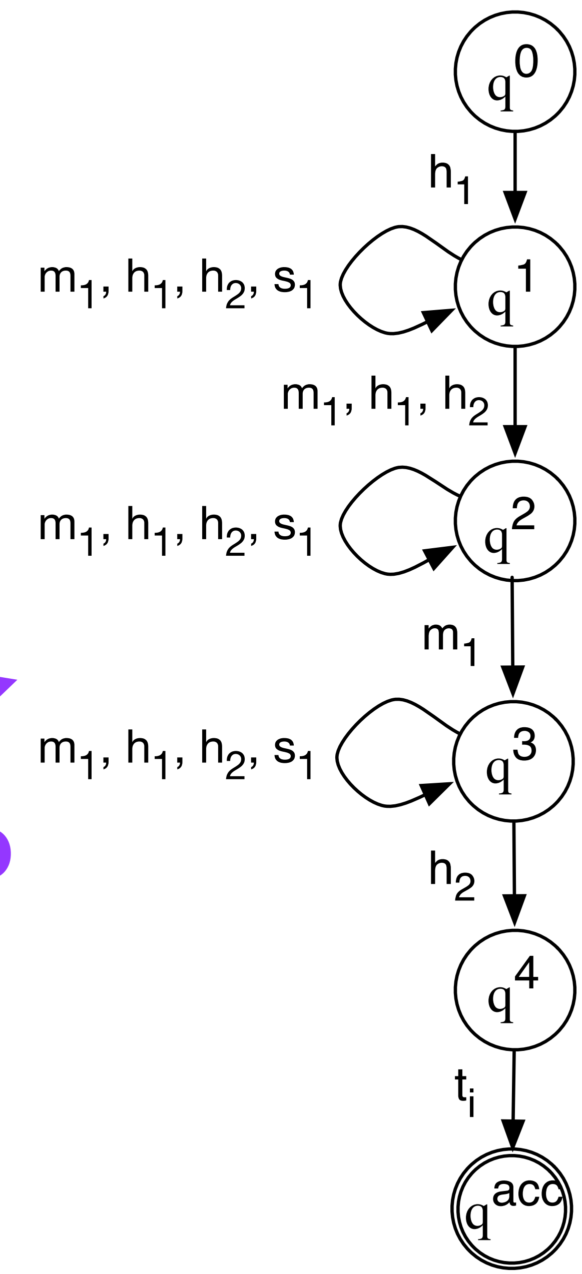
Convert to DFA



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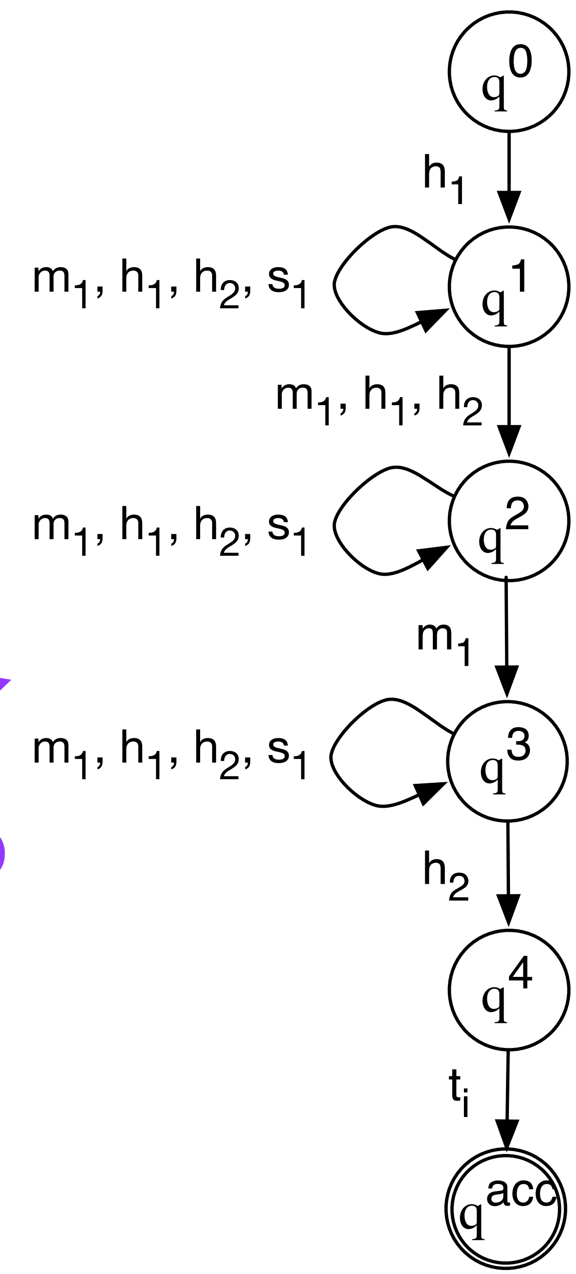
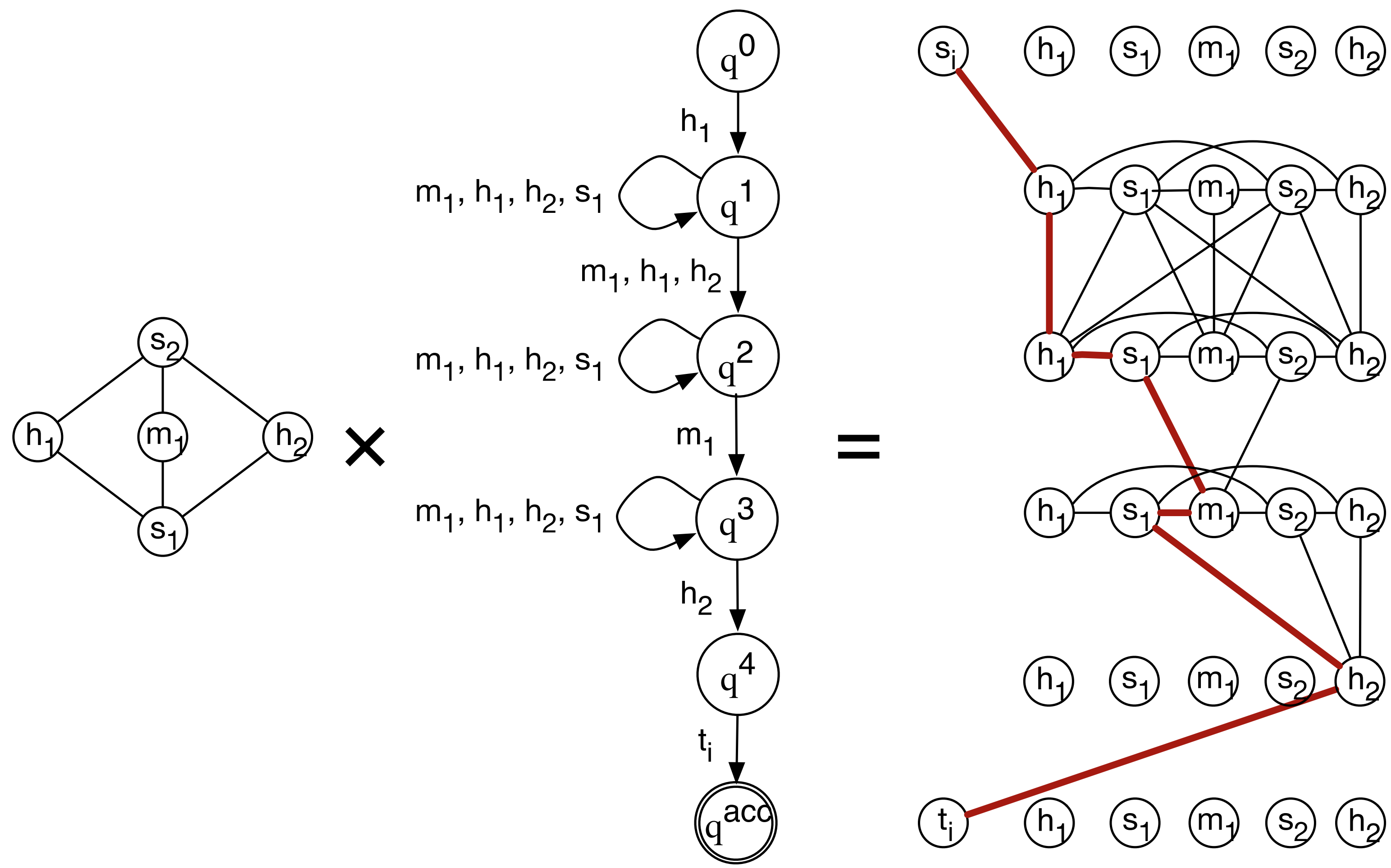
Convert to DFA

Note resource demands



Solve MIP For Paths and Placement



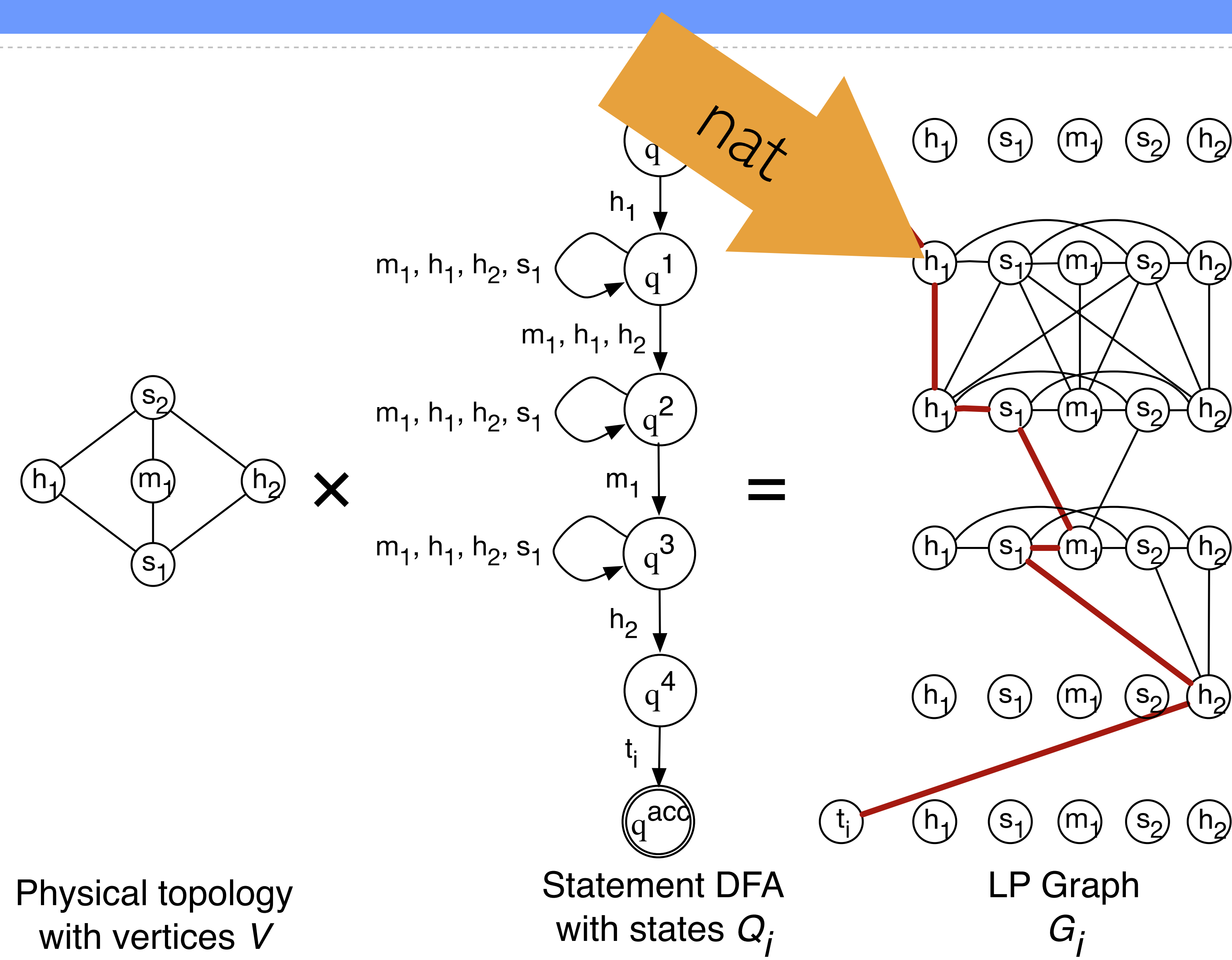
Physical topology with vertices V

Statement DFA with states Q_i

LP Graph G_i

Encode with flow conservation and capacity constraints

Solve MIP For Paths and Placement



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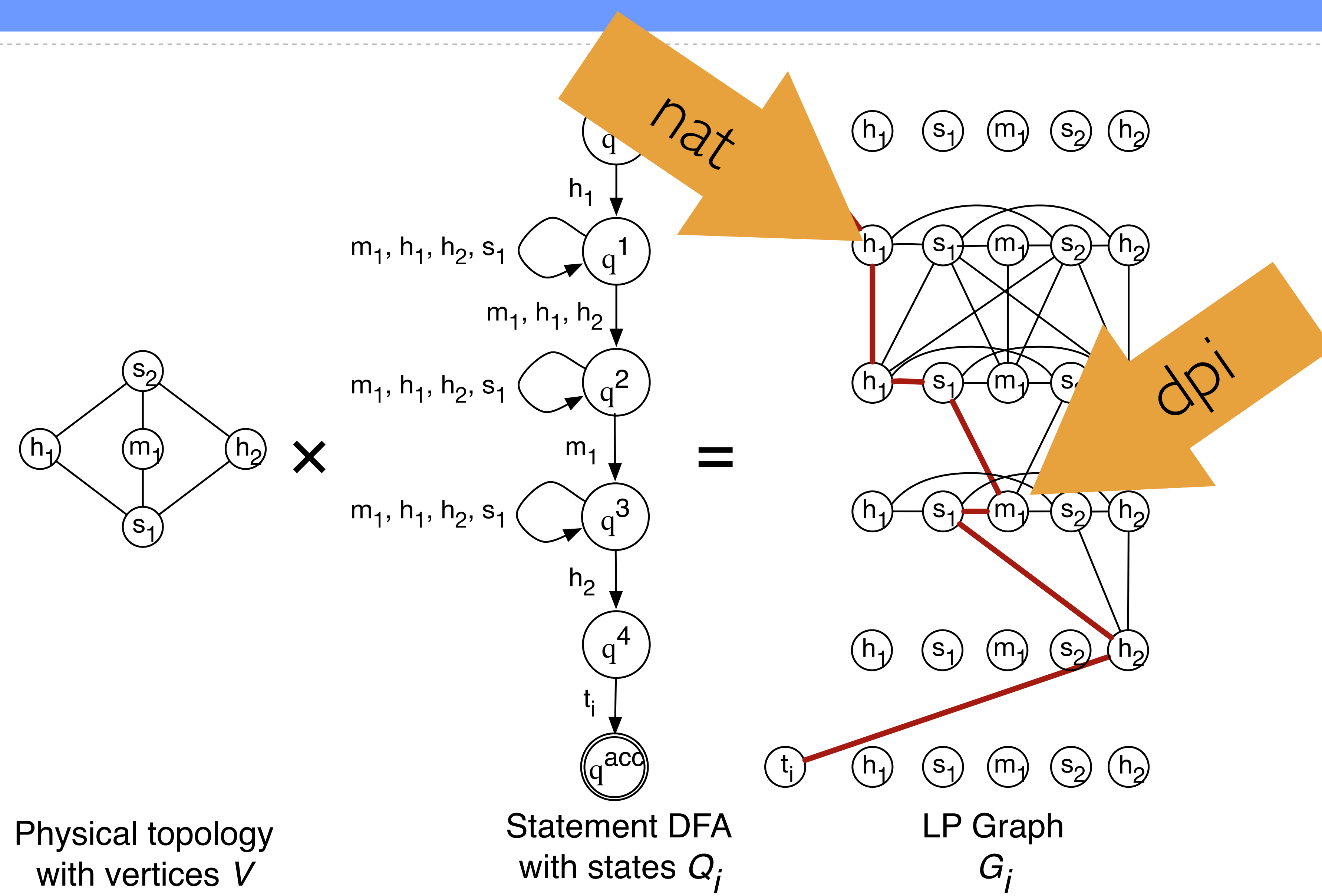
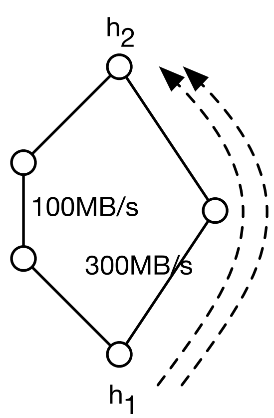


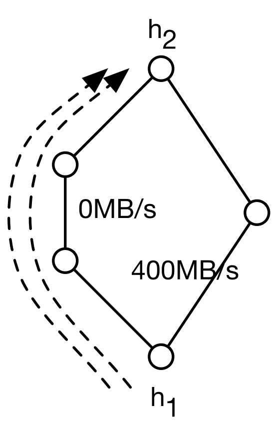
Encode with flow conservation and capacity constraints

Choose Path Heuristic



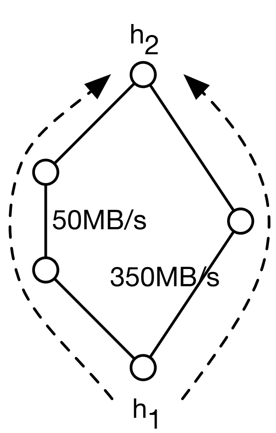
Weighted Shortest Path:

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)

Generate Code

	**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

Delegate 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)
```

Transform Policies

Transform Policies

```
[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
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      tcp.dst = 80) -> .* log .* ],
[z : (ip.src = 192.168.1.1 and
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Transform Policies

granularity

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granularity

path

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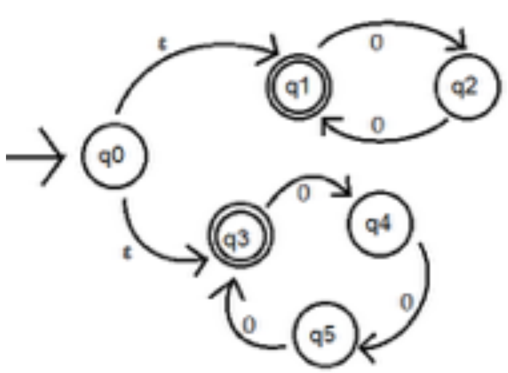
granularity

path

allocation

Verify Transformed Policies



Essential operation:

Ensure that new policy implies the old (i.e., $P_1 \subseteq P_2$)

Algorithm

- Perform pair-wise comparison of statements
- Check for path inclusion in overlaps
- Check aggregate bandwidth constraints

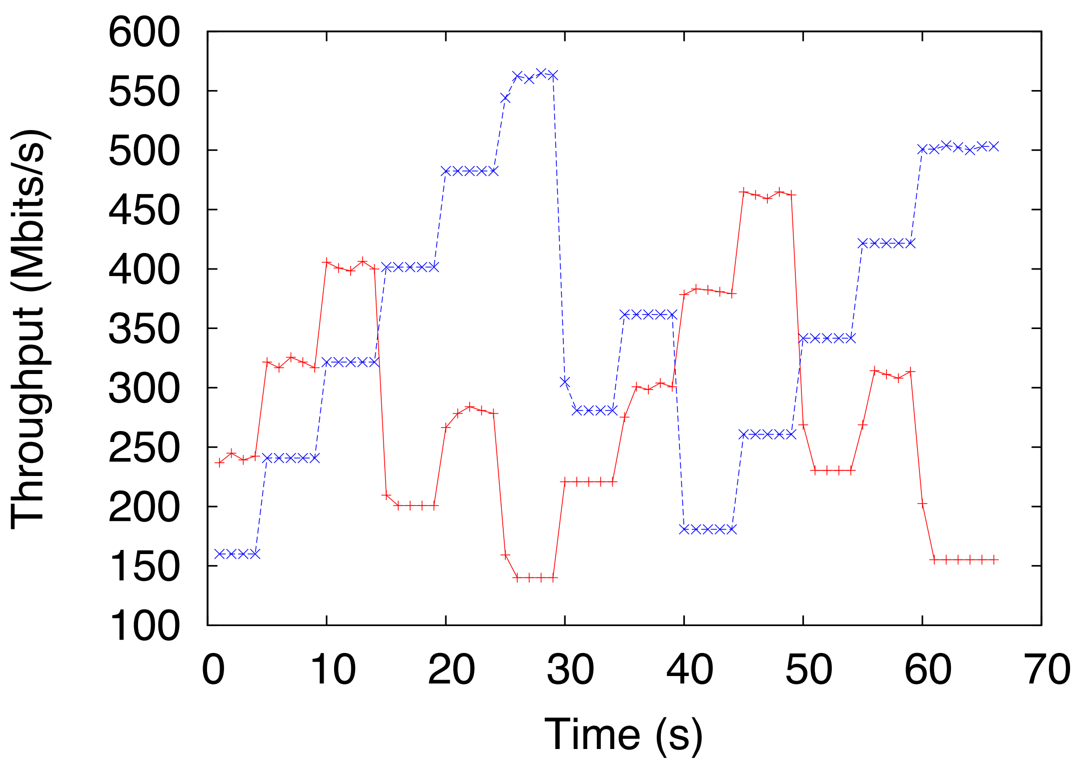
Implementation

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

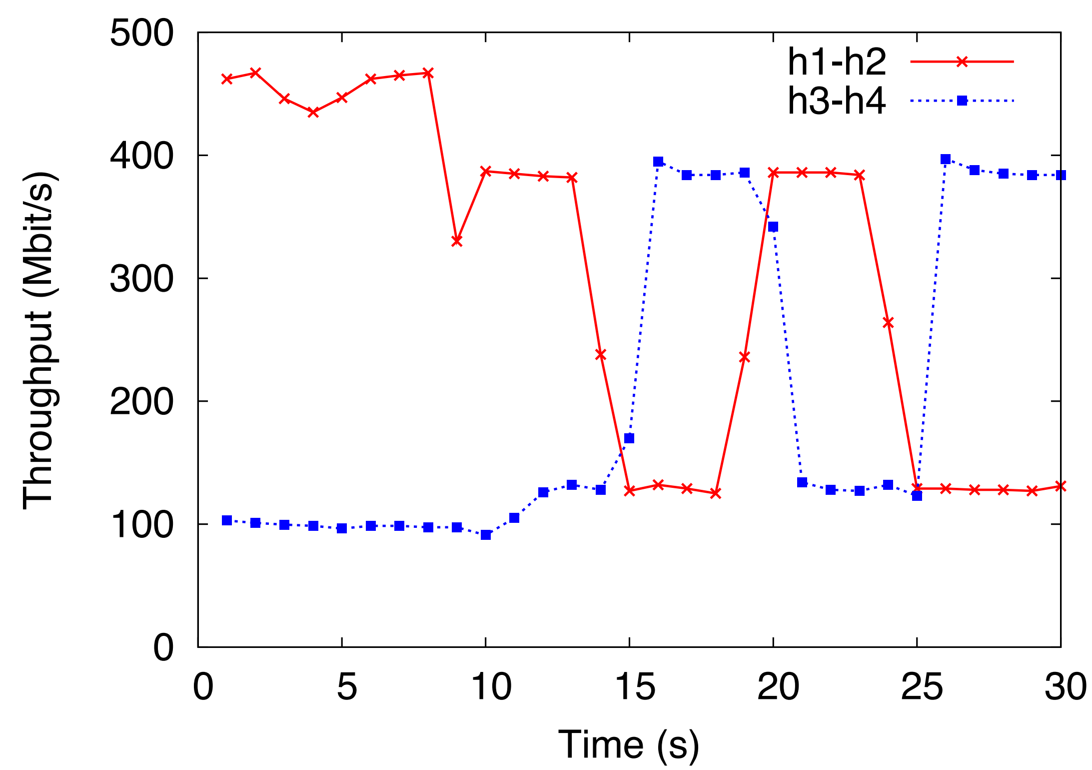
Adapt to Network Changes

- A small runtime component, called a *negotiator,* is distributed in a hierarchical overlay of the network
- Negotiators exchange messages amongst themselves to:
    - Modify (i.e., refine) policies
    - Verify policy modifications
- They can be instantiated with different adaptation schemes

Negotiator Implementations



Additive-Increase, Multiplicative-Decrease



Max-Min Fair Sharing

Evaluation

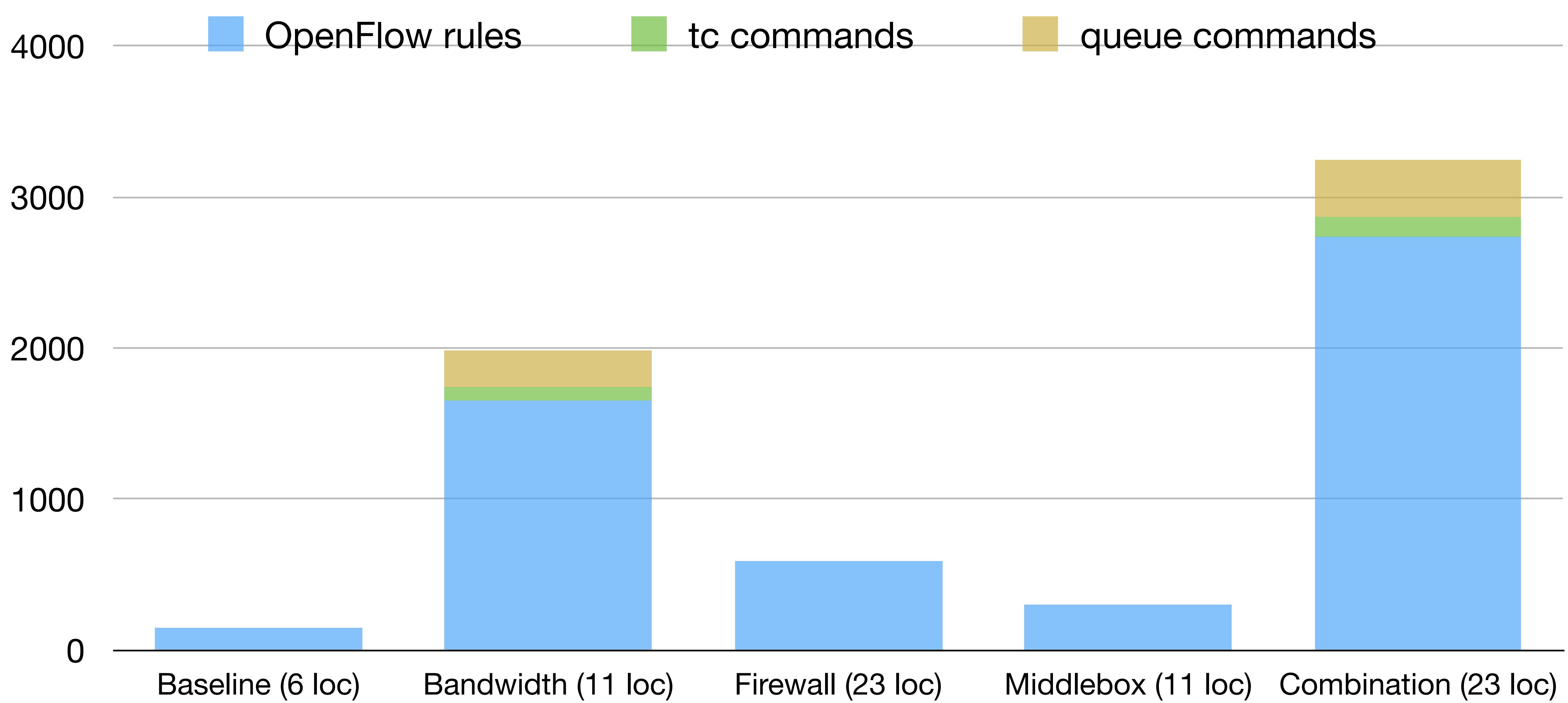
Demonstrating Merlin's expressiveness, ability to manage the network, and scalability

Example Network Policies

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

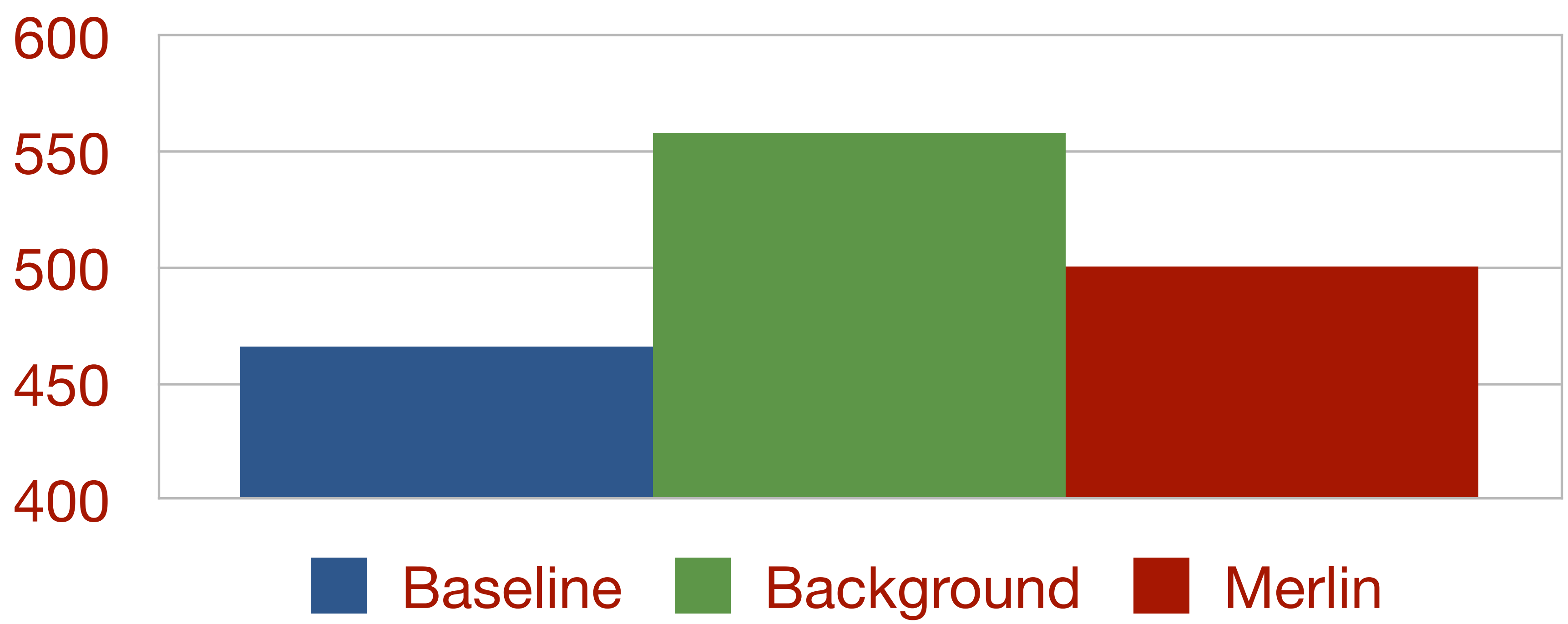
Policies to manage Stanford network topology

Merlin Is Expressive



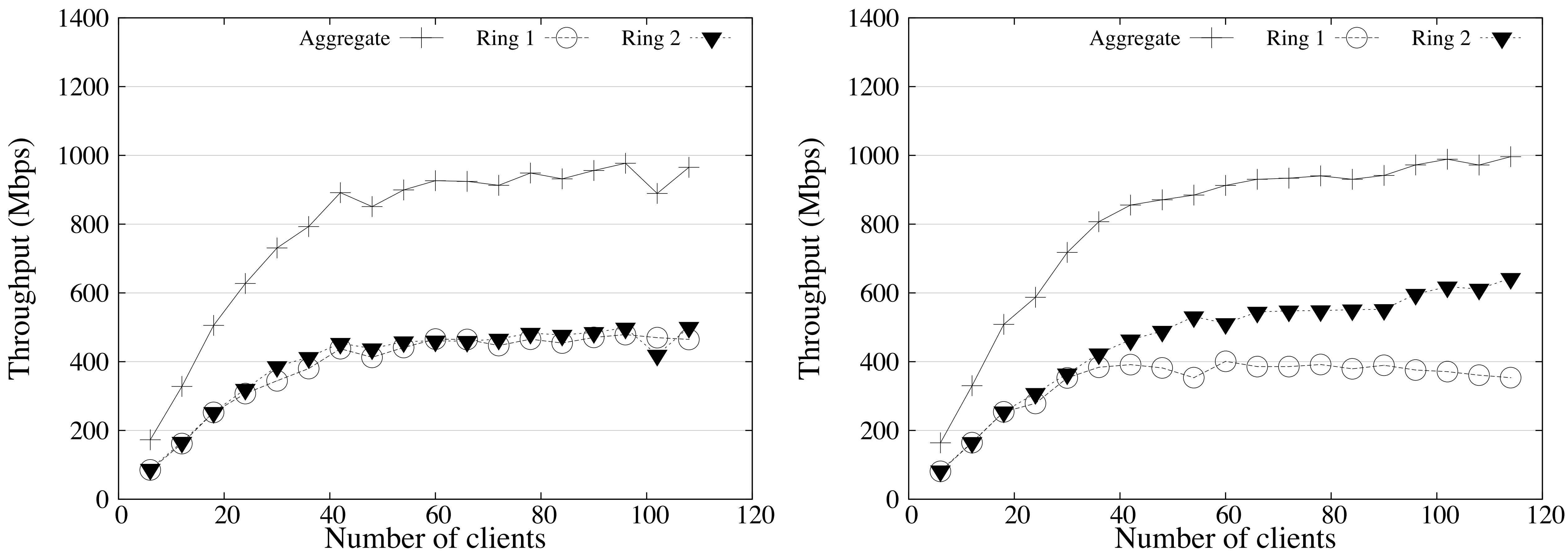
Merlin Managing Hadoop

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



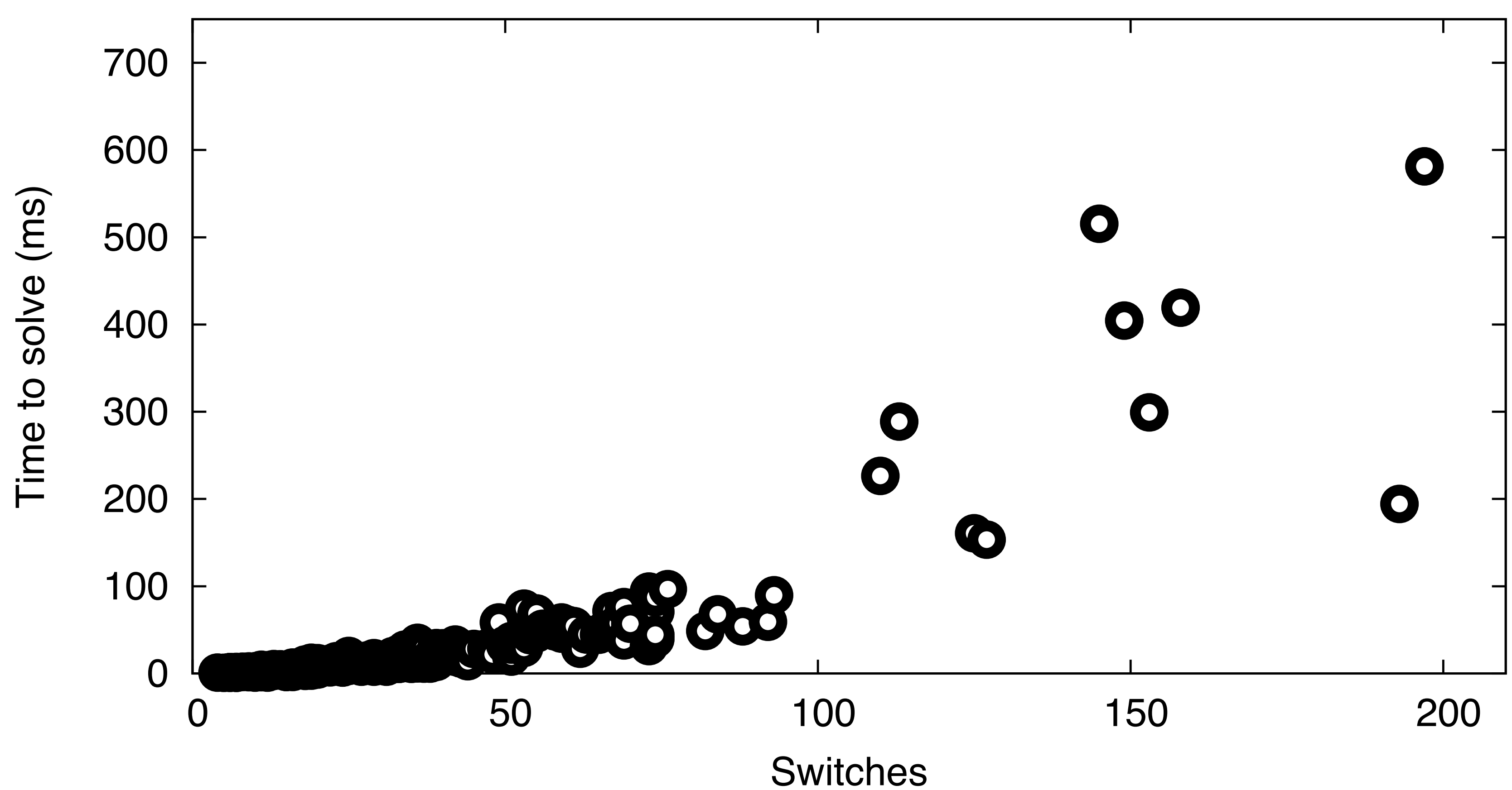
Merlin Managing Ring Paxos

- Measured throughput for co-located key-value stores backed by state machine replication
- Merlin prioritizes traffic for one service



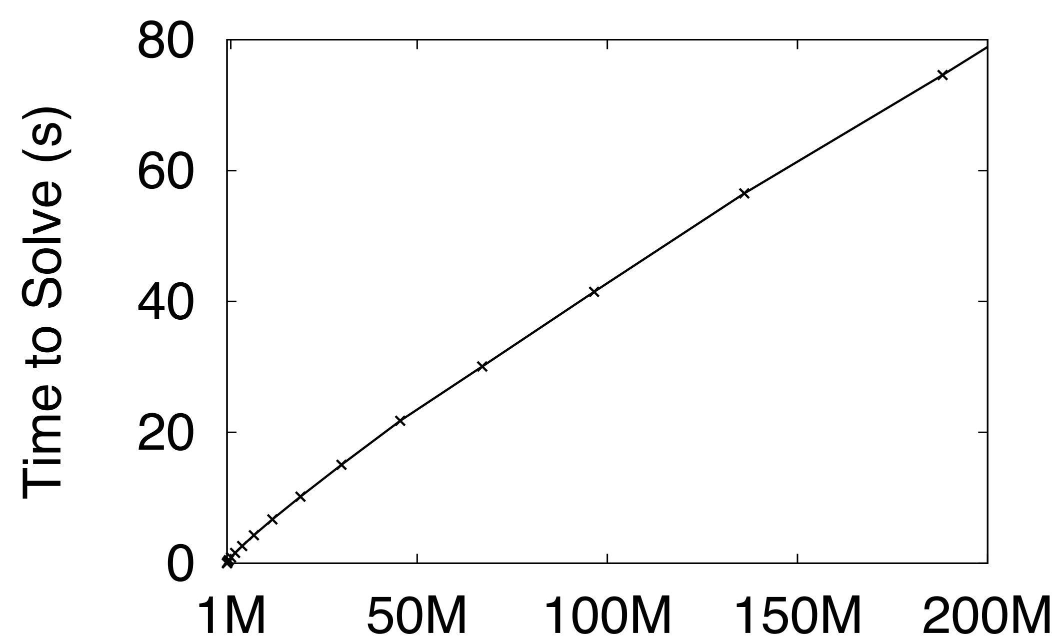
Compilation Is Fast For Basic Connectivity

- Measured compilation time for all-pairs connectivity on Internet Topology Zoo dataset
- Majority of topologies completed in <50ms

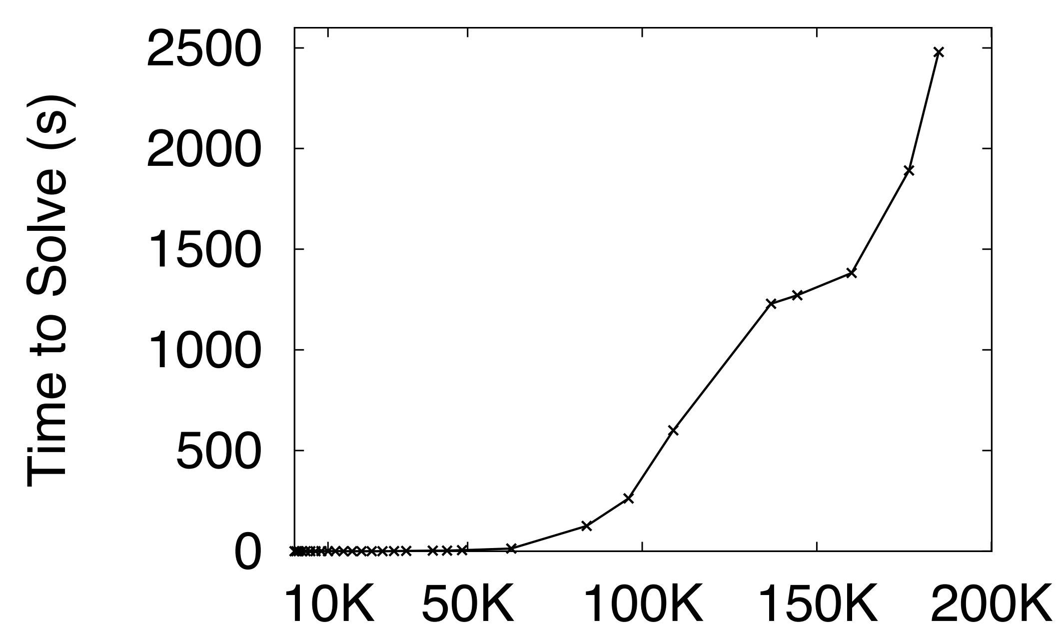


Solver Adds Reasonable Overhead

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



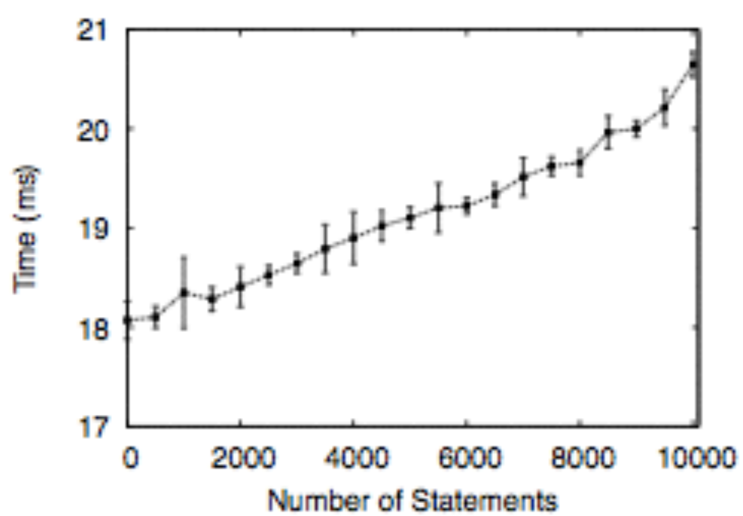
All-pairs connectivity



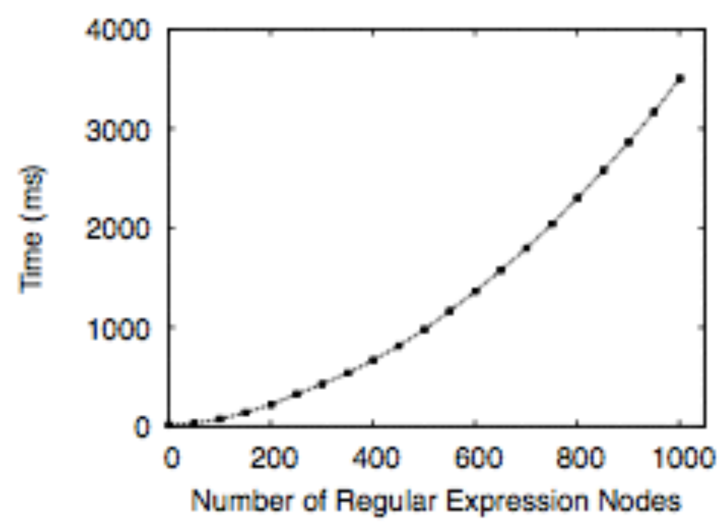
5% of traffic with bandwidth guarantees

Verification Is Very Fast

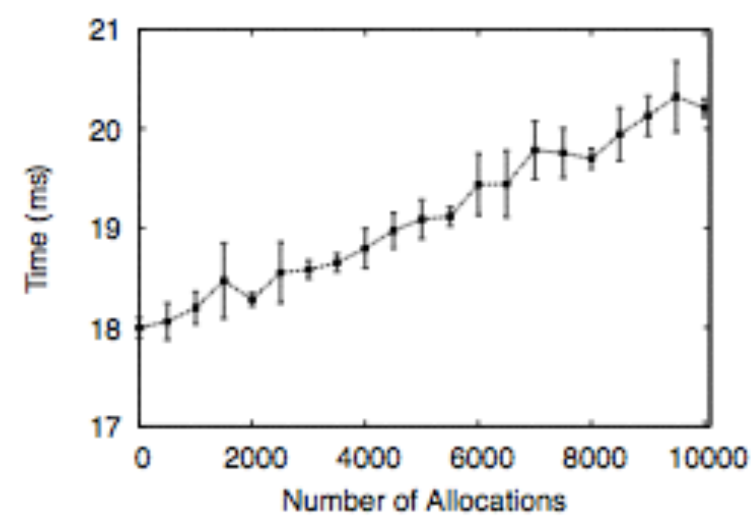
- 10,000 statements verified in less than 21ms
- Verifying resource allocations is very fast
- Verifying paths scales with complexity of the expression



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