Modeling Complexity of Enterprise Routing Design

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Based on the paper of same title to be published in ACM CoNEXT 2012

Our Goal: Modeling Routing Design Complexity

- Existing work focused on developing complexity metrics
  - But does not answer how the metrics may be used to guide the design process
- We want to take it one step forward.
- Our goal: given a metric,
  - developing an analytic framework for modeling design complexity;
  - Integrating the complexity analysis into the design process to guide design.
- Focus on routing: many design choices possible
  - # of routing domains
  - Which subnets/routers to be placed in which domain?
  - How different domains are connected

What Do We Mean by “Complexity”?

- *Complexity Metric: configuration dependencies (measured as # of Referential Links)*

Router 1

1. interface GigabitEthernet 1/1 — *Define an interface*
2. ip address 10.1.0.1 255.255.255.252
3. !
4. router eigrp 10
5. distribute-list prefix TO-SAT out GigabitEthernet1/1 — *Install a route filter on an interface*
6. !
7. ip prefix-list TO-SAT seq 5 permit 192.168.1.0/24 — *Define a route filter*

Router 2

8. interface FastEthernet1/1
9. ip address 192.168.1.1 255.255.255.0 — *Define a subnet*
10. !

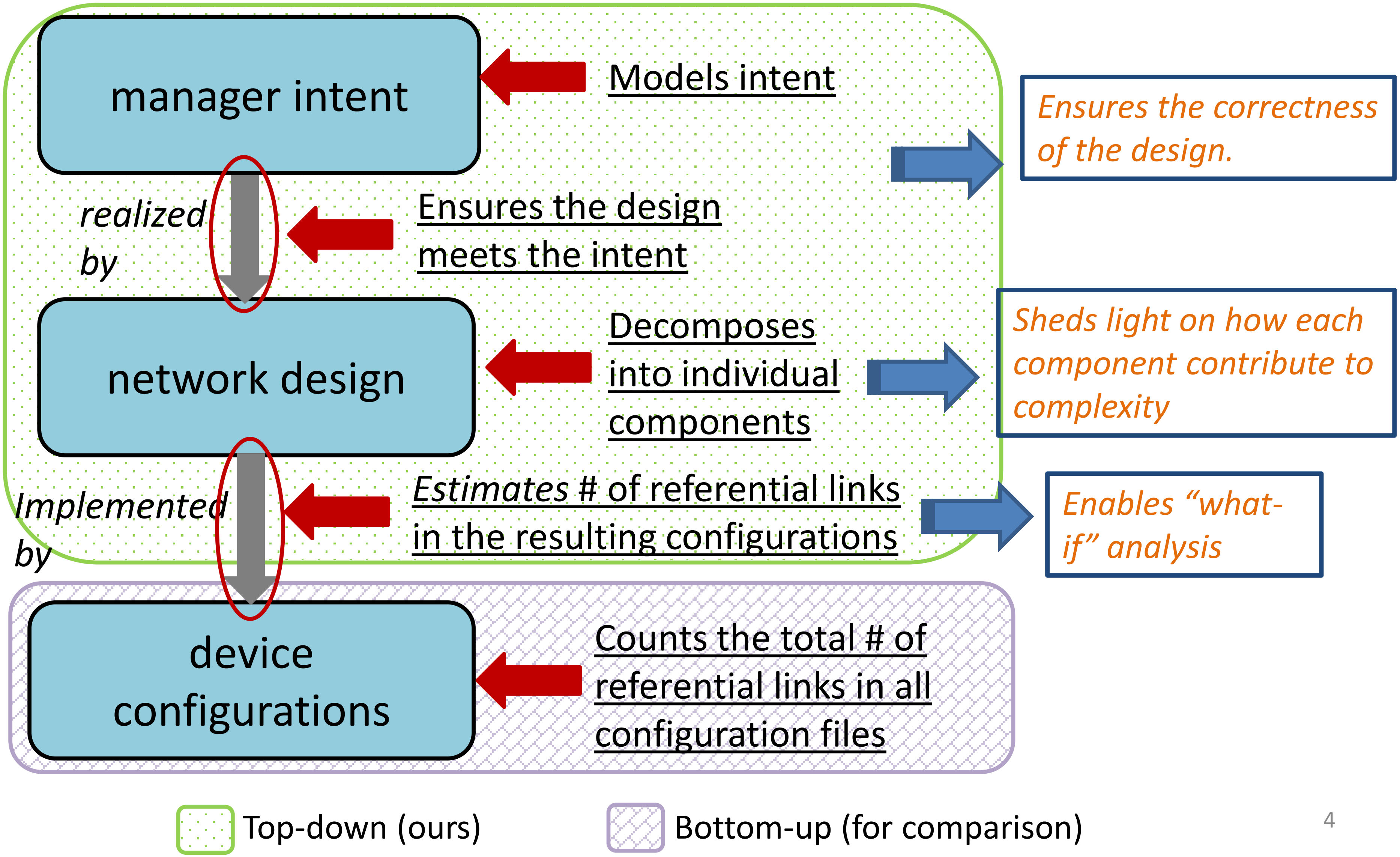
Definition of an object

Reference to an object

A referential link

“Unraveling the Complexity of Network Management”. Theophilus Benson, Aditya Akella and David Maltz. In Proc. USENIX NSDI 2009

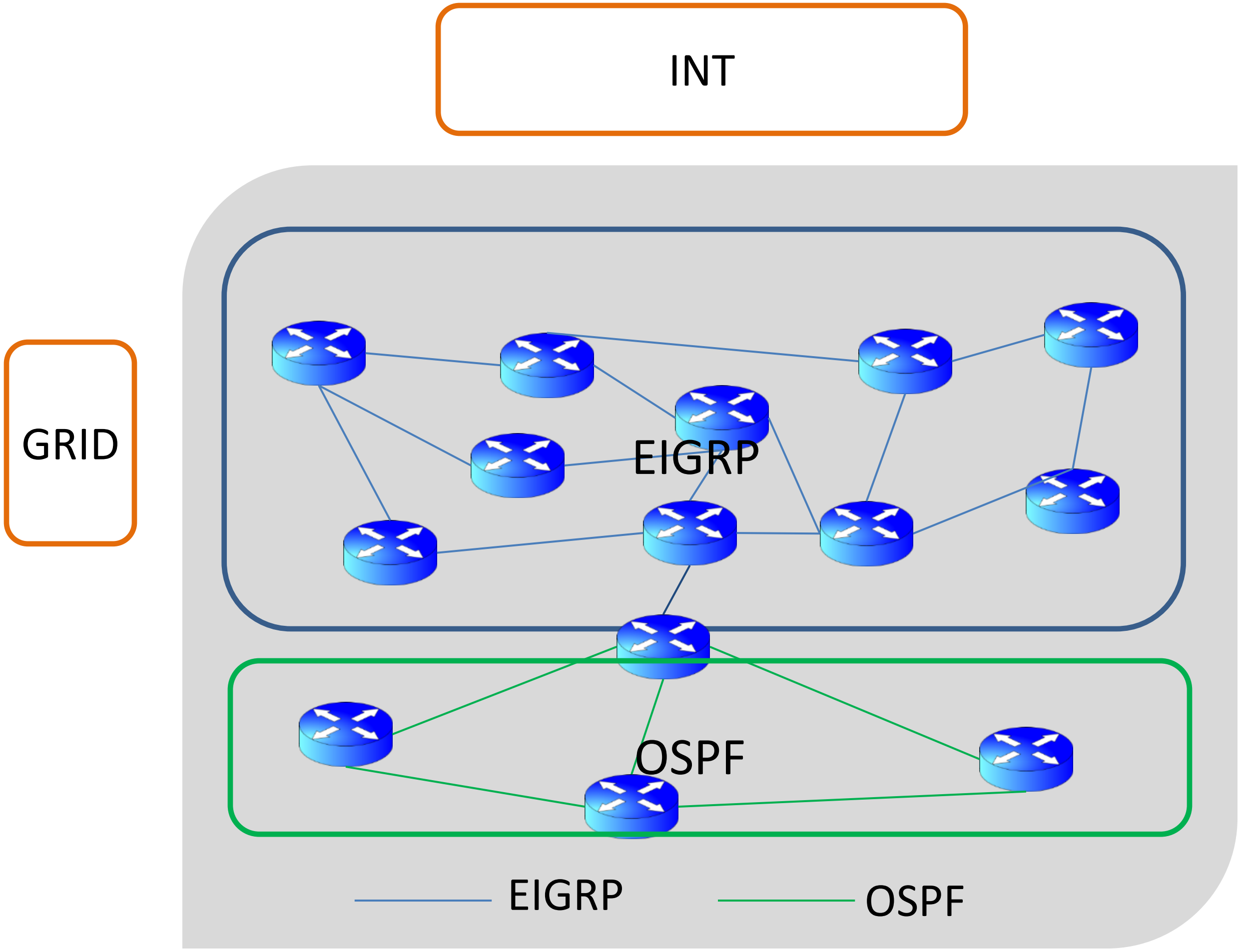
Overview of Our Top-Down Modeling Approach



Agenda

- Overview of our research goal & approach
- Abstractions we leveraged for..
  - decomposing routing design
  - capturing operators high-level intent
- Modeling details
- An evaluation study using the campus network of a large U.S. university

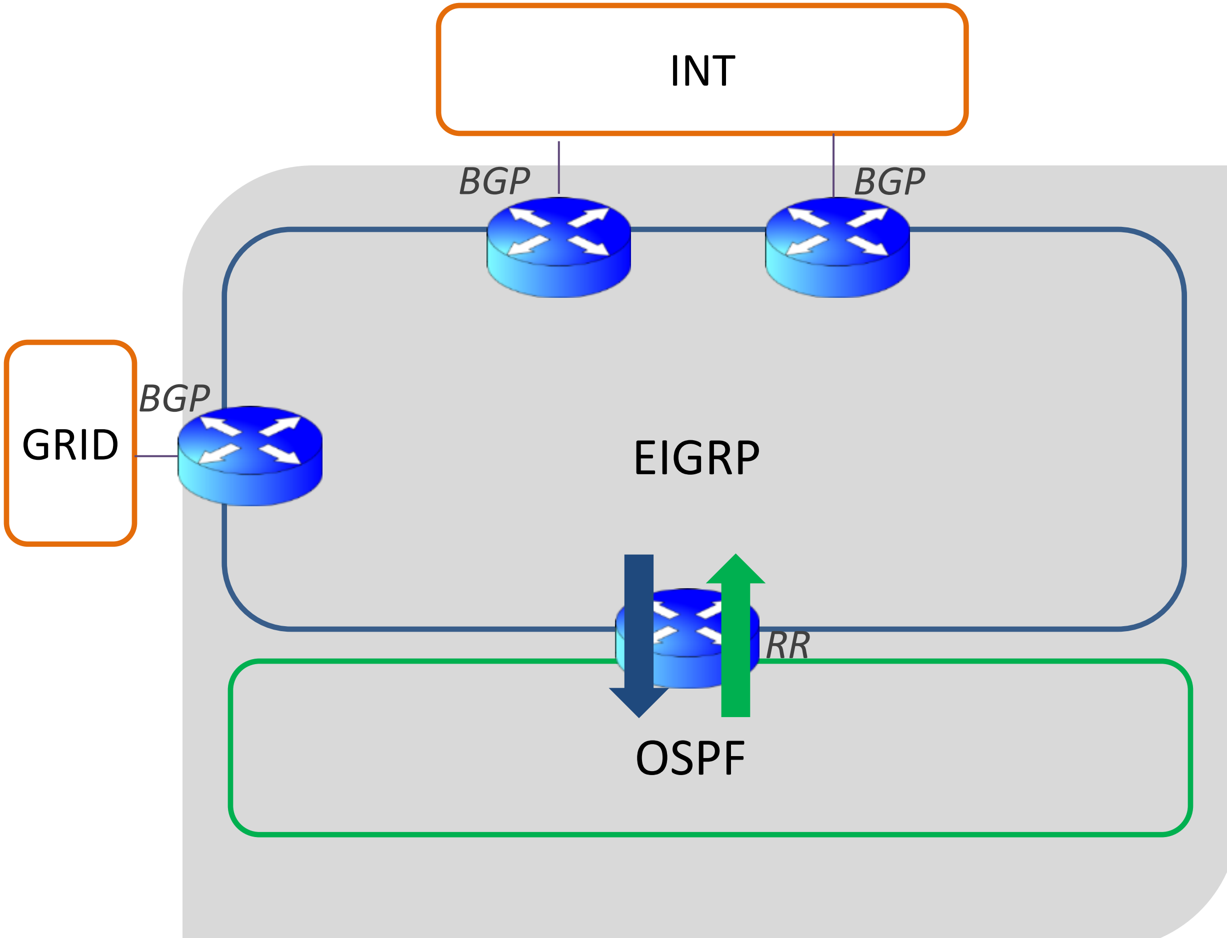
Decomposing Routing Design



- Routing Instance: a set of inter-connected routers that run the same instance of a routing protocol

D. Maltz, G. Xie, J. Zhan, H. Zhang, G. Hjalmtysson, and A. Greenberg, "Routing design in operational networks: A look from the inside," In Proc. ACM SIGCOMM, 2004.

Decomposing Routing Design

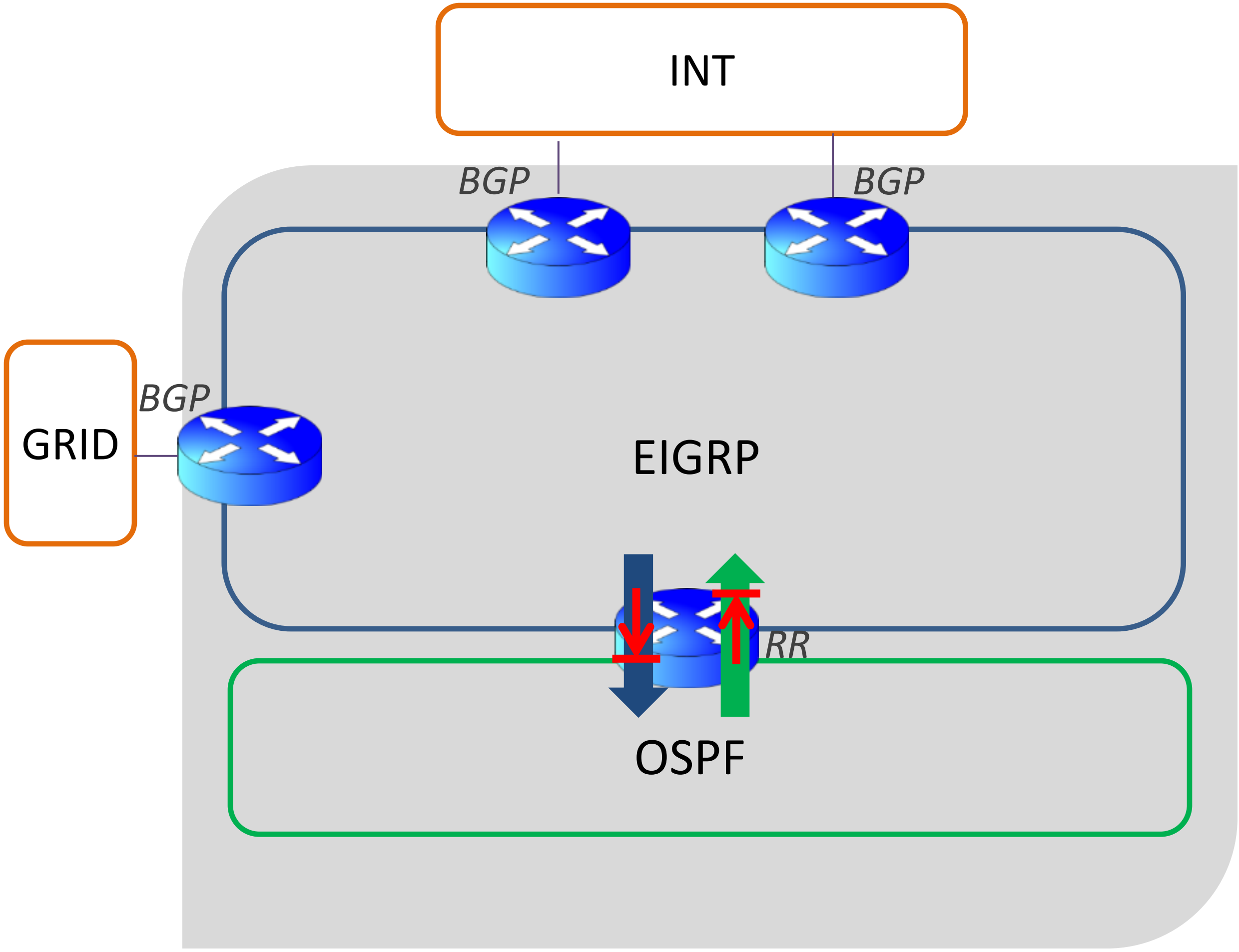


- Routing Instance: a set of inter-connected routers that run the same instance of a routing protocol

- Connecting primitive: enables different routing instances to exchange routes. (e.g., Route redistribution, BGP, static routes)
  - *Border router*

D. Maltz, G. Xie, J. Zhan, H. Zhang, G. Hjalmtysson, and A. Greenberg, "Routing design in operational networks: A look from the inside," In Proc. ACM SIGCOMM, 2004.

Decomposing Routing Design



- Routing Instance: a set of inter-connected routers that run the same instance of a routing protocol
- Connecting primitive: enables different routing instances to exchange routes. (e.g., Route redistribution, BGP, static routes)
  - *Border router*
- Route filter: restrict the set of routes to be advertised.

"Routing design in operational networks: A look from the inside". D. Maltz, G. Xie, J. Zhan, H. Zhang, G. Hjalmtysson, and A. Greenberg, In Proc. ACM SIGCOMM, 2004.

Abstracting High-Level Design Intents

- We abstracted correctness (in terms of reachability), and resiliency (in terms of # of border routers between each pair of routing instances)
- Reachability Matrix $\boldsymbol{M_R}$

	s1	s2	s3	s4	s5
s1	-	Y	Y	Y	N
s2	Y	-	Y	Y	N
s3	Y	N	-	N	Y
s4	Y	Y	N	-	Y
S5	Y	Y	N	Y	-

$\boldsymbol{M_R(i,j)}$:
whether *si* can reach *sj* ->
whether *si* should have the route to *sj*

- Border-router Matrix $\boldsymbol{M_B}$

	EIGRP	OSPF	GRID	INT
EIGRP	-	R1	R2	R3
OSPF	R1	-	-	-

$\boldsymbol{M_B(i,j)}$:
The set of border routers that instance *i* uses to connect to instance *j*

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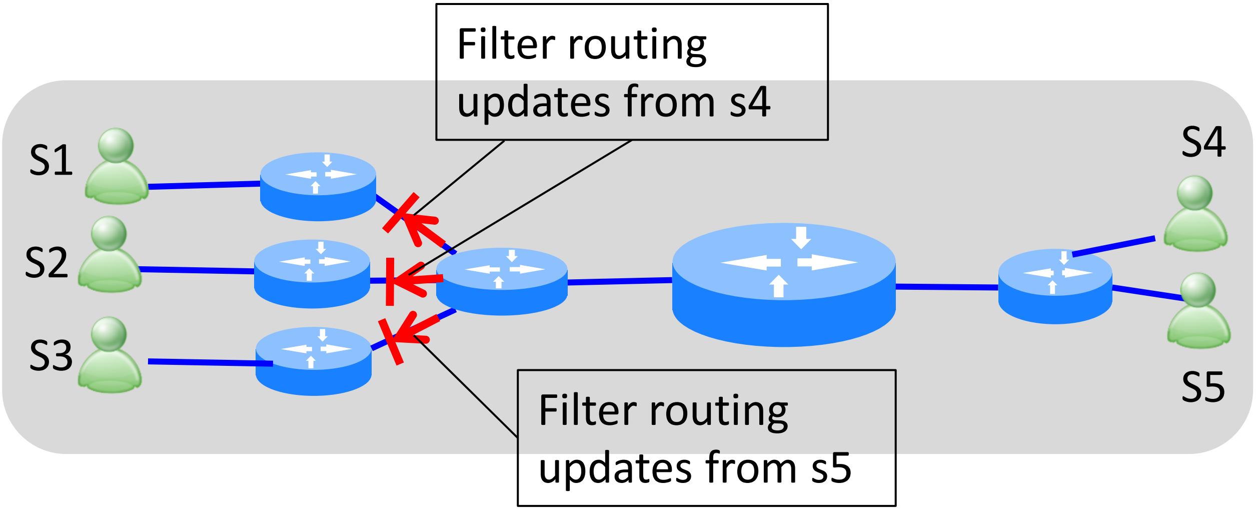
Model Inputs

- Router-level layer-3 topology
- Set of routing instances
- Reachability matrix
- Border-router matrix
- [Connecting primitive]

Modeling Single Instance Complexity

- Source of complexity: route filters to enforce reachability policy.

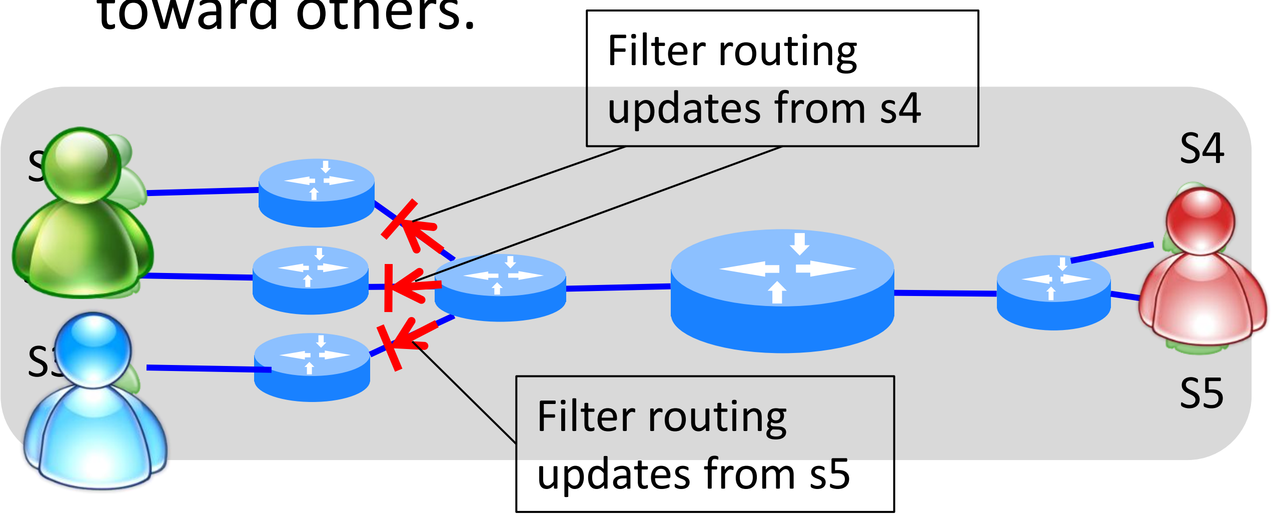


	s1	s2	s3	s4	s5
s1	-	Y	Y	N	Y
s2	Y	-	Y	N	Y
s3	Y	Y	-	Y	N
s4	Y	Y	Y	-	Y
S5	Y	Y	Y	Y	-

- Complexity depends on: (i) # of route filters, (ii) complexity of configuring each filter.

Modeling Single Instance Complexity

- Policy group: a set of subnets having the same reachability policy toward others.



	s1	s2	s3	s4	s5
s1	-	Y	Y	N	Y
s2	Y	-	Y	N	Y
s3	Y	Y	-	Y	N
s4	Y	Y	Y	-	Y
S5	Y	Y	Y	Y	-

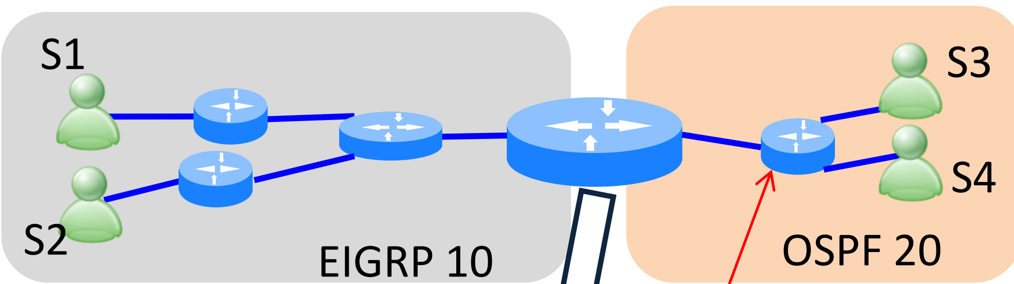
- # of route filters between a pair of policy groups:
  - Upper bound: # of all possible paths
  - Lower bound: Size of the smallest edge-cut set
    - Achievable on special topologies (details in paper)

Modeling Inter-Instance Complexity

- Source of complexity:
  - Configuring connecting primitive
  - Configuring route filters

- Connecting primitive considered
  - Route redistribution
  - BGP
  - Static routes and default routes

Route Redistribution (RR)




```
1.   router ospf 20
2.       redistribute eigrp 10
3.   !
4.   router eigrp 10
5.       redistribute ospf 20 route-map EIGRP2OSPF
6.   !
7.   route-map EIGRP2OSPF permit 10
8.       match ip address 1
9.   !
10. access-list 1 permit s4
11. !
```

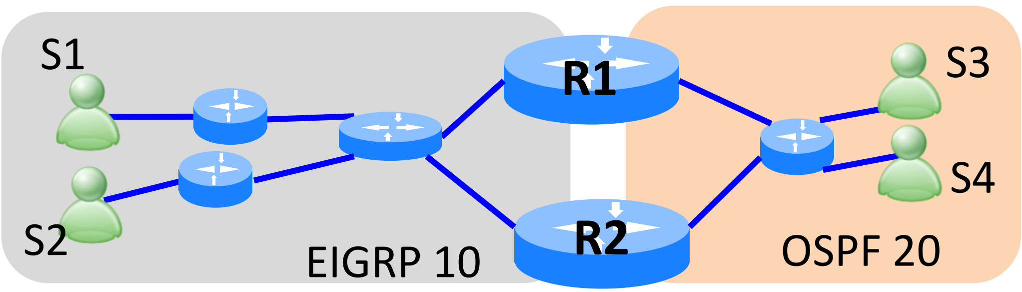
Instance-level reachability matrix

	OSPF	EIGRP
OSPF	-	all
EIGRP	s4	-

(i,j): the subnets in instance j that instance i can reach

- Total complexity (in one direction) =
  - complexity of configuring the RR itself +
  - Complexity of configuring the route filter (if needed)

More Complexity with Multiple Border Routers



- Route feedback could occur
  - May cause forwarding loop
  - Determining whether forwarding loop will occur is NP-hard. [*Understanding Route Redistribution, F. Le, G. Xie and H. Zhang, ICNP 2007*]
- Solution: using route filters on all the border routers to prevent feedback.
- We assume that route filters will always be used in this case.

Agenda

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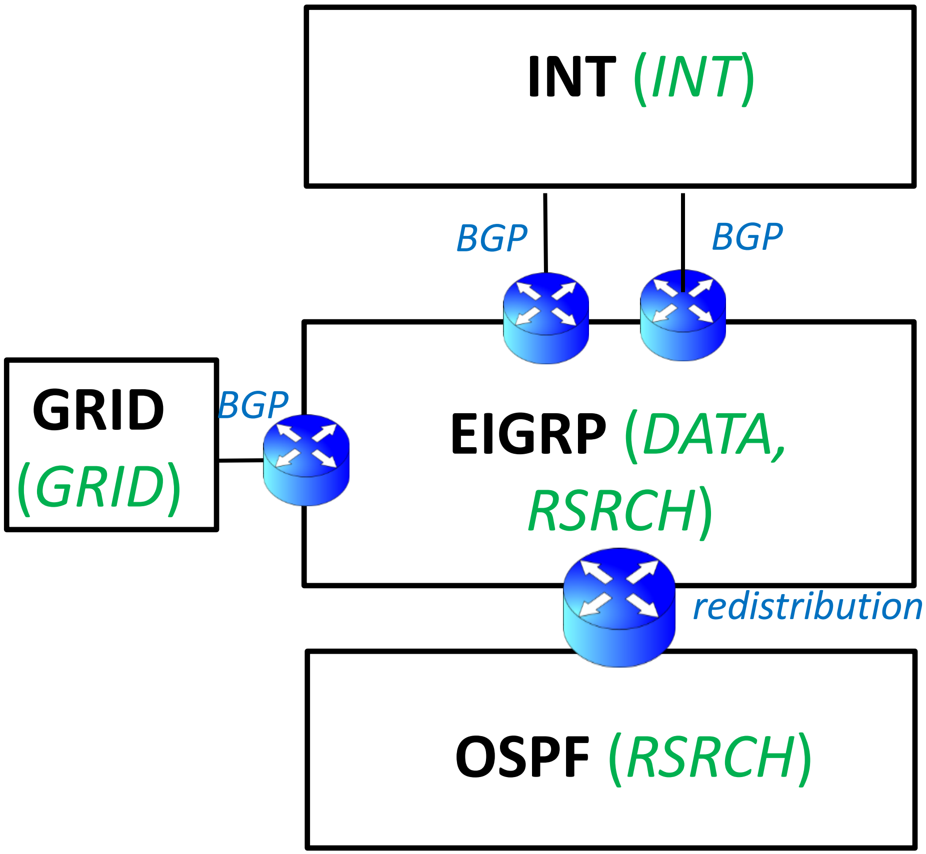
Evaluation Study Overview

- Data-set
  - Multiple configuration snapshots of a campus network
  - Physical topology data from CDP
  - ~100 routers, 1000 switches, 700 subnets (most /24)

- Evaluation methodology
  - Validate the accuracy of our framework in predicting routing design complexity
    - Compare the estimations with measured numbers from configuration files
  - Use the framework to evaluate a real-world routing redesign

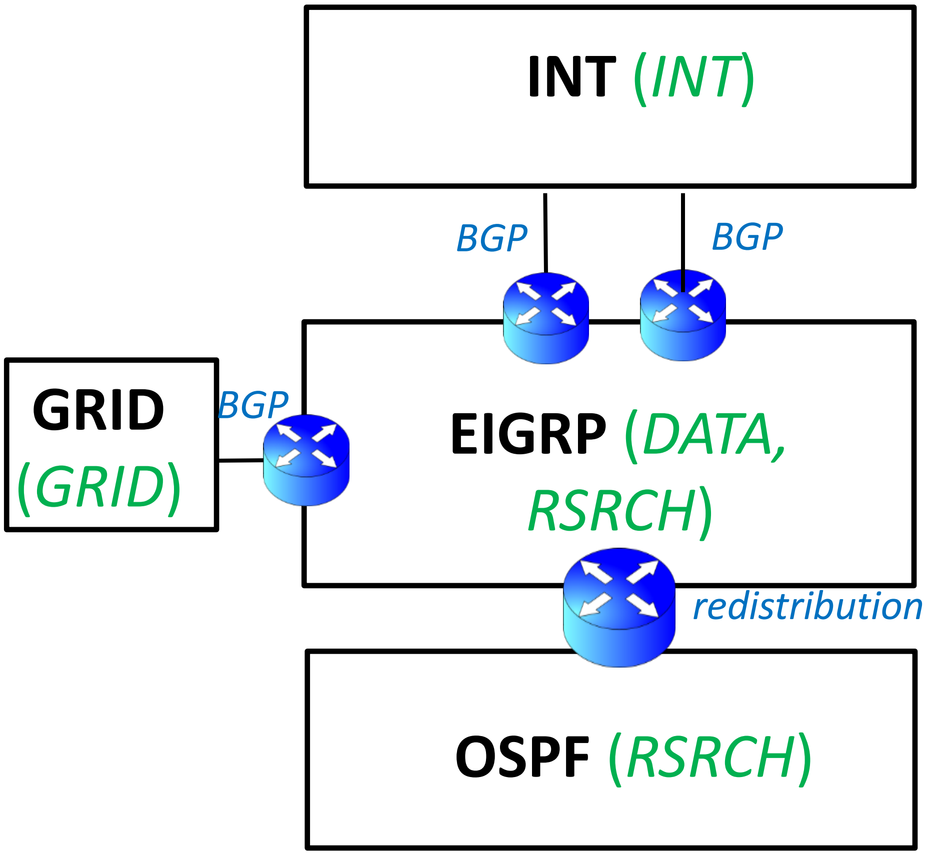
Inferring the Inputs



Reachability matrix

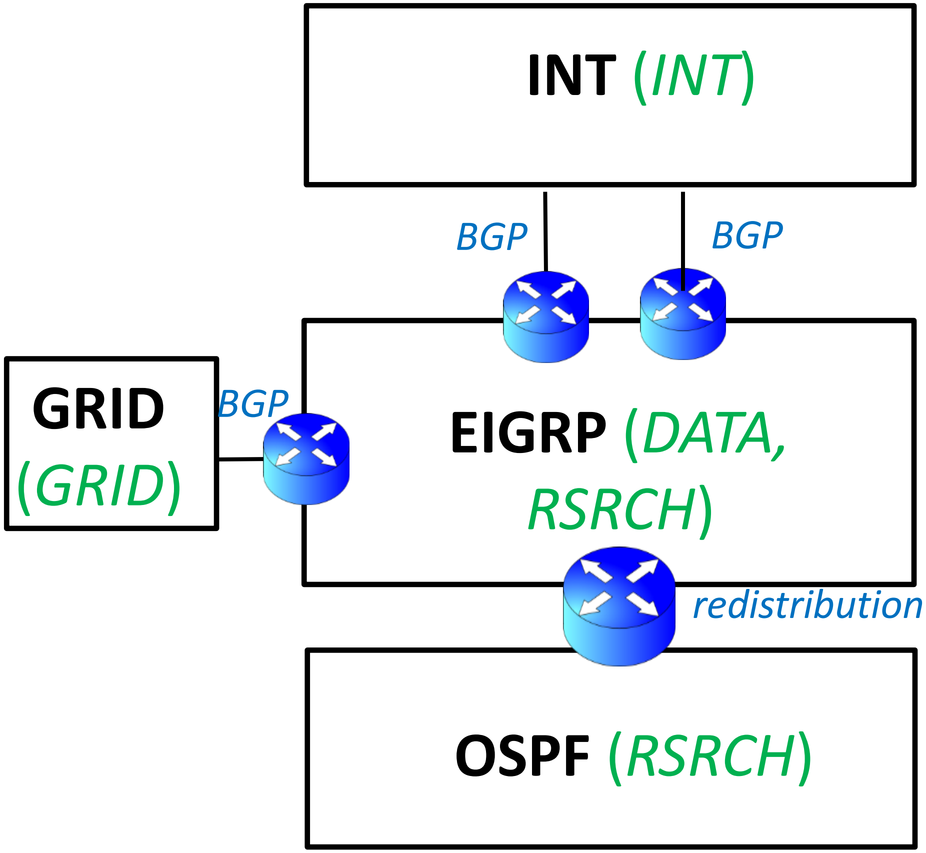
	DATA	RSRCH	GRID	INT
DATA	-	*(3)*	×	all
RSRCH	all	-	all	all
GRID	×	*(1)*	-	×
INT	*(7)*	*(1)*	×	-

Validating Our Framework



	EIGRP	OSPF	GRID	INT
EIGRP	7	1	1	2
OSPF	1	0	0	-
GRID	6	-	-	-
INT	30	-	-	-

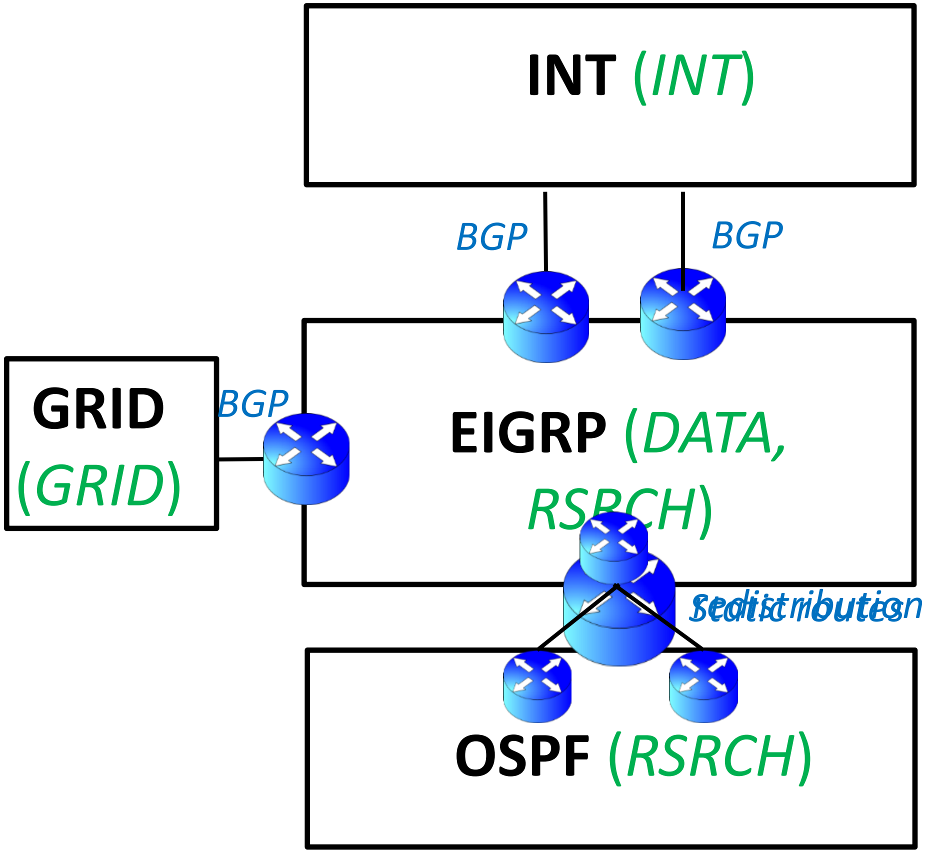
Validating Our Framework



	EIGRP	OSPF	GRID	INT
EIGRP	7	1	1 (ε=-3)	2
OSPF	1	0	0	-
GRID	6 (ε=-6)	-	-	-
INT	30	-	-	-

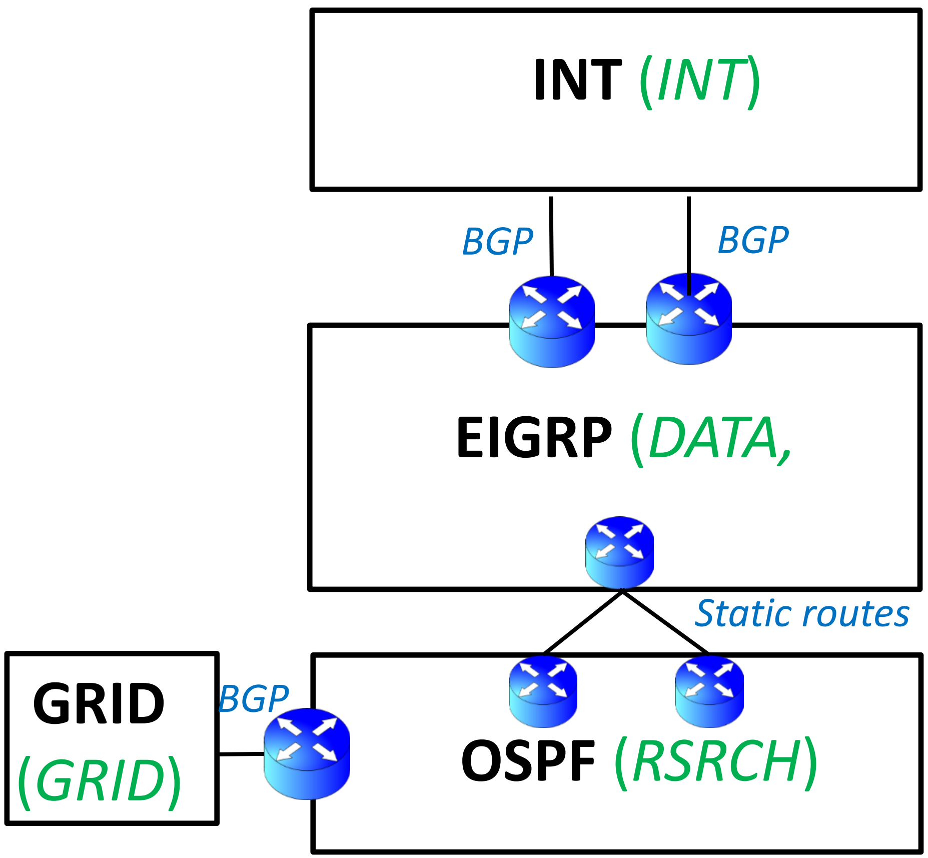
ε: estimated - measured

Case Study of a Redesign



- Move *RSRCH* to OSPF
- OSPF now has two border routers
- Uses static routes instead
- Grid now peers with OSPF

Case Study of a Redesign

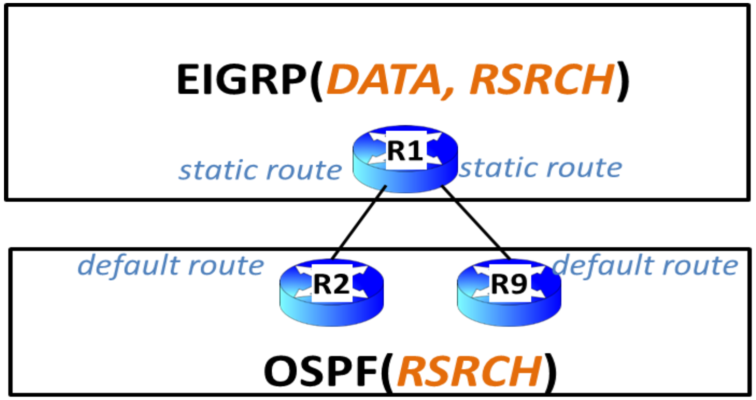


	EIGRP	OSPF	GRID	INT
EIGRP	Δ=-7	Δ=29	Δ=-1	Δ=0
OSPF	Δ=1	Δ=0	Δ=1	-
GRID	Δ=-6	Δ=6	-	-
INT	Δ=0	-	-	-

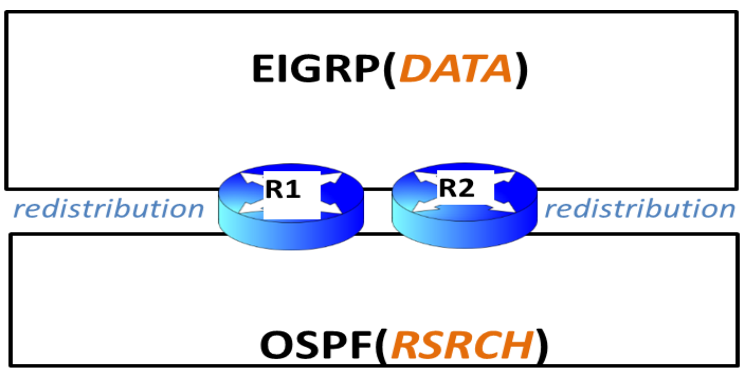
Δ: new - old

- Complexity shifted from intra-EIGRP to EIGRP-OSPF
- Total complexity increases
- Are there better alternative designs?

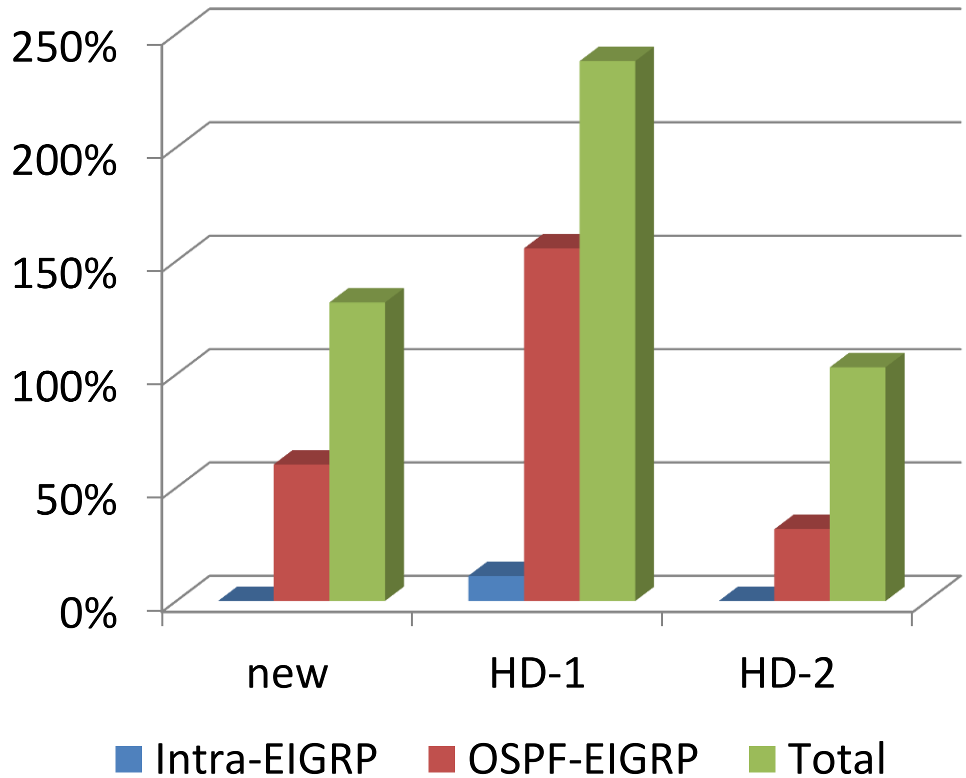
Are There Better Alternatives?



Alternative design 1 (HD-1)
(Differ in the grouping scheme)



Alternative design 2 (HD-2)
(Differ in the connecting primitive)



Each bar is shown as a percentage of the total complexity of the old design.

Summary

- First top-down framework for modeling complexity
  - Models individual design components
  - Models high-level intent
- Advantages
  - Does not require configuration files
  - Can guide the design process, enable “what-if” analysis
  - Ensures correctness of design
- Demonstrated feasibility on an operational campus network.

Future Directions

- Complexity-aware top-down routing design
  - By leveraging the models developed here to guide the search
- Taking into account other design objectives (costs, performance, etc.) and design constraints (hardware capacity, etc.)
- Jointly optimize across multiple design tasks
  - VLANs, packet filters, etc.
- Emerging architectures and configuration languages.

Thank you!

- Modeling

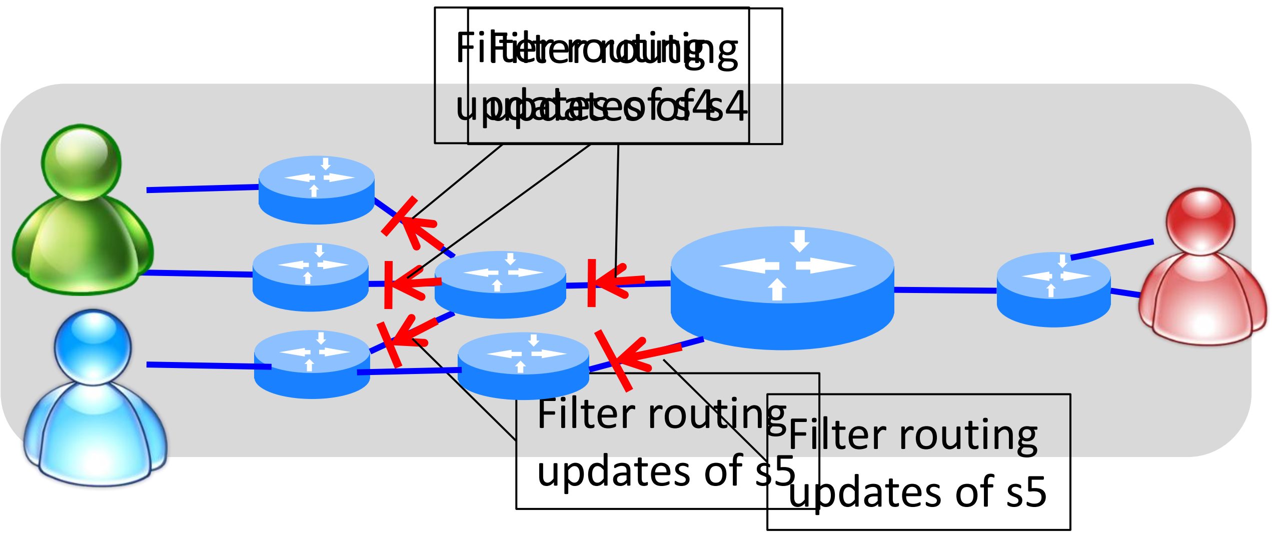
Existing Work: Bottom-Up Modeling

- Focused on characterizing the device configuration files.
  - But did not model the high-level intent, or the design itself.
- Proposed a couple metrics to measure complexity
  - The primary one is "# of referential links in the configuration files"
- Established correlation between the metrics and the difficulty level of managing the network.

"Unraveling the Complexity of Network Management". Theophilus Benson, Aditya Akella and David Maltz. In Proc. USENIX NSDI 2009

Modeling Single Instance Complexity

- Policy group: a set of subnets having the same reachability policy.



	s1	s2	s3	s4	s5
s1	-	Y	Y	N	Y
s2	Y	-	Y	N	Y
s3	Y	Y	-	Y	N
s4	Y	Y	Y	-	Y
S5	Y	Y	Y	Y	-

- # of route filters between a pair of policy groups:
  - Upper bound: # of all possible paths
  - Lower bound: Size of the smallest edge-cut set
  - focused on a special "hub-and-spike" type topology → details in paper.

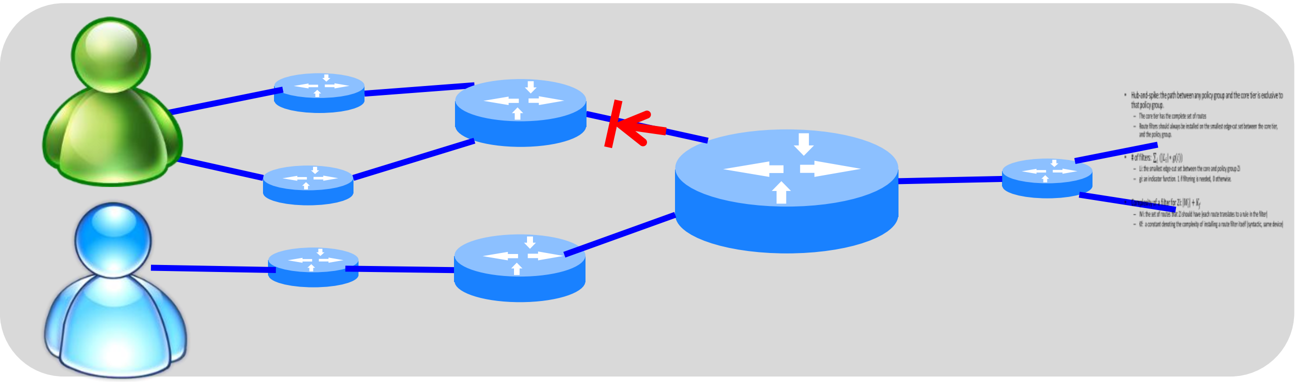
- # of referential links introduced by a route filter
  - Depends on the # of routes to allow/deny -> # of filter rules

Focusing on "Hub-and-Spike" Topology

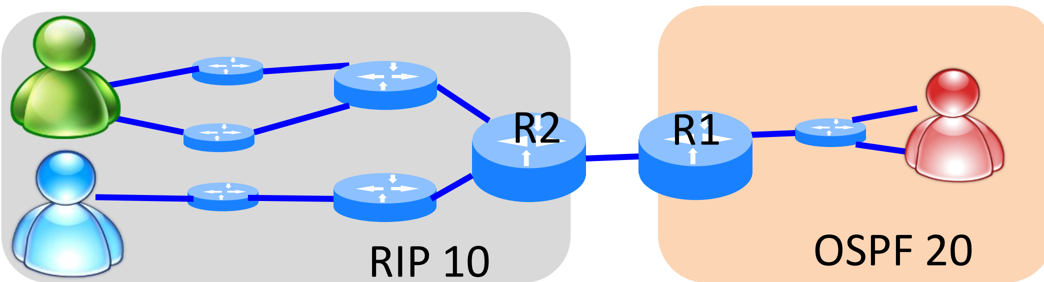
- Hub-and-spike: the path between any policy group and the core tier is exclusive to that policy group.
  - The core tier has the complete set of routes
  - Route filters should always be installed on the smallest edge-cut set between the core tier, and the policy group.

- # of filters: $\sum_i (|L_i| * g(i))$
  - Li: the smallest edge-cut set between the core and policy group Zi
  - gi: an indicator function. 1 if filtering is needed, 0 otherwise.

- Complexity of a filter for Zi: $|W_i| + K_f$
  - Wi: the set of routes that Zi should have (each route translates to a rule in the filter)
  - Kf: a constant denoting the complexity of installing a route filter itself (syntactic, same device)



Static Routes and Default Routes



$$C_{sr}(i,j) = \underbrace{|W_{ij}| * K_{sr}}_{\text{static route}} \underbrace{+ K'_{rr}}_{\text{RR}}$$

$$C_{dr}(i,j) = K_{dr} + K'_{rr}$$

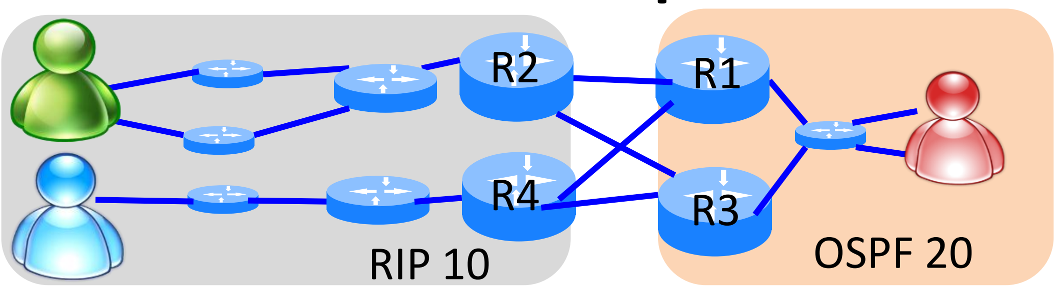
<u>R1</u>

1. ip route *s1-ip R2-ip*
2. ip route *s2-ip R2-ip*
3. !
4. router rip 10
5. redistribute static
6. !

<u>R2</u>

1. ip route *0.0.0.0 0.0.0.0 R1-ip*
2. !
3. router ospf 20
4. redistribute static
5. !

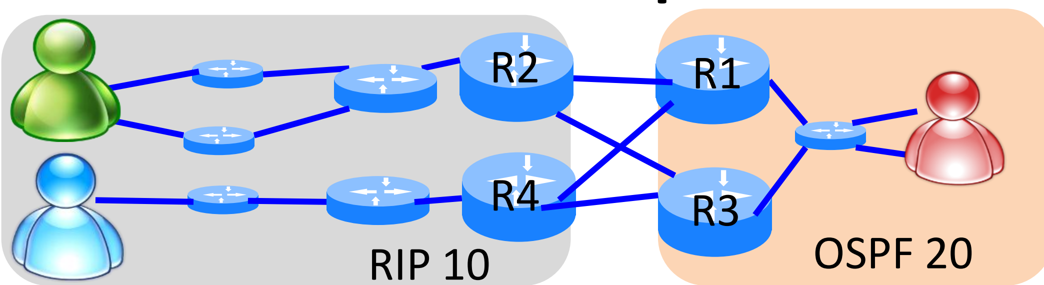
Static and Default Routes with Multiple Border Routers



- We assume the resiliency input will specify both # of border routers for each instance, and the # of "edges" between each pair of border routers.

<u>R1</u>
1. **ip route *s1-ip R2-ip***
2. **ip route *s2-ip R2-ip***
3. ip route *s1-ip R4-ip*
4. ip route *s2-ip Rr4-ip*

Static and Default Routes with Multiple Border Routers

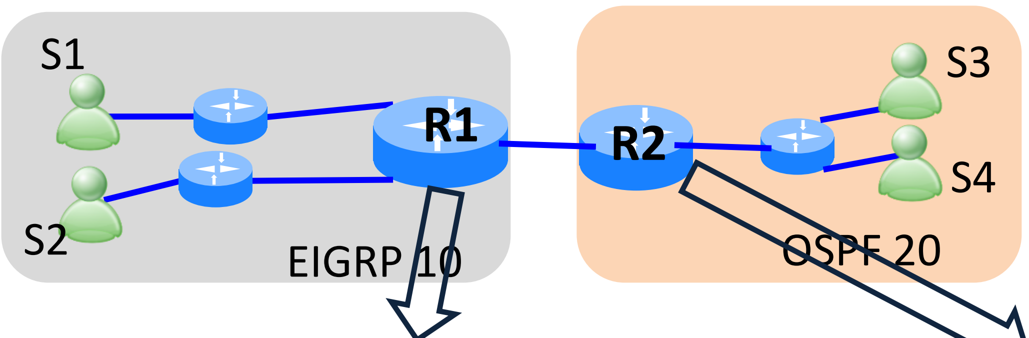


$$C_{sr}(i,j) = |W_{ij}| * (K_{sr} + K_{obj}) + K'_{rr}$$

$$C_{dr}(i,j) = K_{dr} + K_{obj} + K'_{rr}$$

- We assume the input will specify both # of border routers for each instance, and the # of “edges” between each pair of border routers, as the resiliency requirement.
- When no failure, default behavior is load sharing among all “edges”.
- Router/link failure may not be detected -> still forward to failed link/router -> packet drop
- solution: object tracking (Cisco Proprietary)
  - configured on each border router; one for each “edge”
  - tracks the live-ness of other routers/links, by periodically ping other routers
  - Configuration is similar to configure static route (need to specify IP of the router to ping, and local interface to send the ping)

BGP



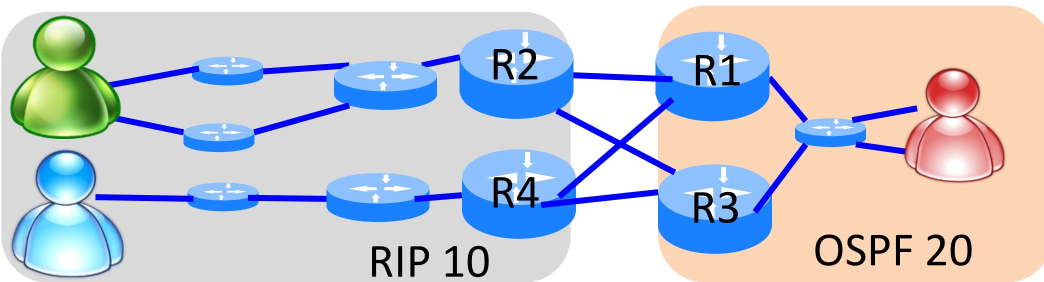
- Total complexity = Peering + RR + route filter (if needed)

R1
1. router bgp 10
2. *redistribute eigrp10*
3. *neighbor R1-IP remote-as 20*
4. *neighbor R1-IP prefix-list TO-OSPF out*
5. *!*
6. *router eigrp 10*
7. *redistribute bgp 10*
8. *!*
9. *ip prefix-list TO-OSPF seq 5 permit s4*
10. *!*

R2
1. router bgp 20
2. *redistribute ospf 20*
3. *neighbor R2-IP remote-as 10*
4. *!*
5. *router ospf 20*
6. *redistribute bgp 20*
7. *!*

Also modeled static routes and default routes – details in thesis.

BGP with Multiple Border Routers



$$C^{M}{}_{bgp}(i,j) = \left(\left(\underline{\left(|W_{ij}| + K_f\right) * g(ij)} + \underline{K_{bgp}}\right) * N_{ij} + \underline{K''{}_{rr}} * M_{ij}\right)$$

Nij: # of "edges"
Mij: # of border routers

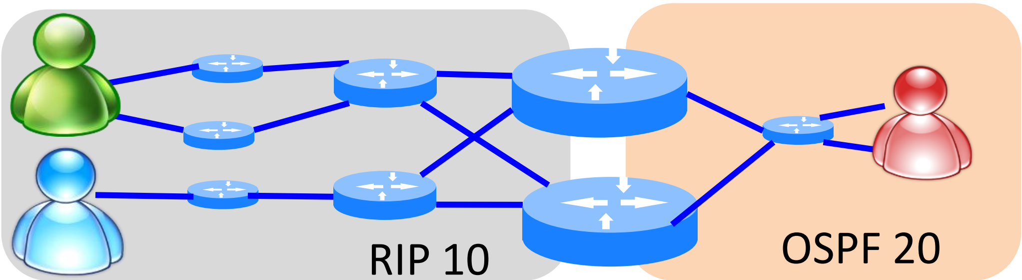
<u>R2</u>

1. router bgp 10
2. *redistribute rip 10*
3. *neighbor R1-IP remote-as 20*
4. *neighbor R3-IP remote-as 20*
5. *neighbor R1-IP prefix-list TO-RED out*
6. *neighbor R3-IP prefix-list TO-RED out*
7. *!*
8. *router rip 10*
9. *redistribute bgp 10*
10. *!*
11. *ip prefix-list TO-RED seq 5 permit s1*
12. *ip prefix-list TO-RED seq 10 permit s2*

<u>R1</u>

1. router bgp 20
2. *redistribute ospf 20*
3. *neighbor R2-IP remote-as 10*
4. *neighbor R4-IP remote-as 10*
5. *!*
6. *router ospf 20*
7. *redistribute bgp 20*
8. *!*

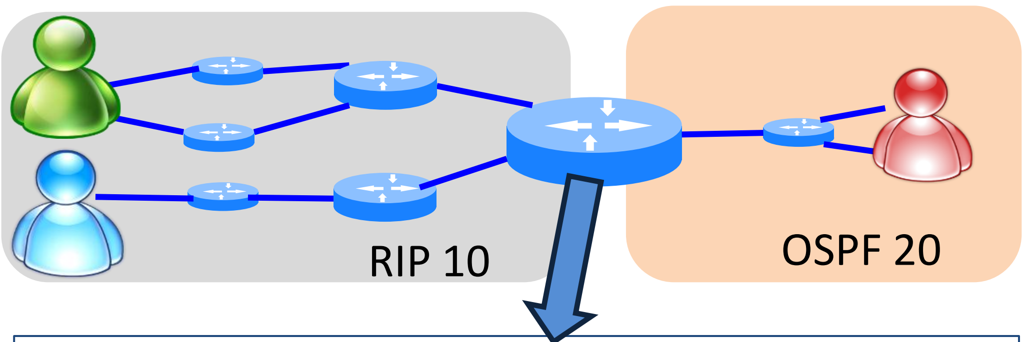
Route Redistribution with Multiple Border Routers



- Route feedback could occur when multiple routers performing mutual redistribution
  - May cause forwarding loop
  - Depending on the selection logic on the routers
  - Determining whether forwarding loop will happen is NP-hard. [*Understanding Route Redistribution, F. Le, G. Xie and H. Zhang, ICNP 2007*]

- We assume that route filters will always be used in this case

Route Redistribution



$$C_{rr}(i,j) = \underbrace{(|W_{ij}| + K_f) * g(ij)}_{\text{route filter}} + \underbrace{K_{rr}}_{\text{RR}}$$

```
1.   router rip 10
2.       redistribute ospf 20
3.   !
4.   router ospf 20
5.       redistribute rip 10 route-map RIP2OSPF
6.   !
7.   route-map RIP2OSPF permit 10
8.       match ip address 1
9.   !
10. access-list 1 permit s1
11. access-list 1 permit s2
12. !
```

Wij: the set of routes that instance i should advertise to instance j

Kf: A constant denoting the complexity of configuring the route filter itself

g(ij): An indicator function

Krr: A constant denoting the complexity of configuring RR itself.

Advantages of Our Approach

- Can guide the design process
  - Requires only high-level design specifications
  - Does not require access to configuration files
  - immune to misconfigurations
- Enables “what-if” analysis
- Sheds light on factors contribute to complexity → Helps operators identify the best design
- Ensures correctness of design
  - Complexity makes sense only when design is correct.