Programming networks

Not your standard API

Laurent Vanbever

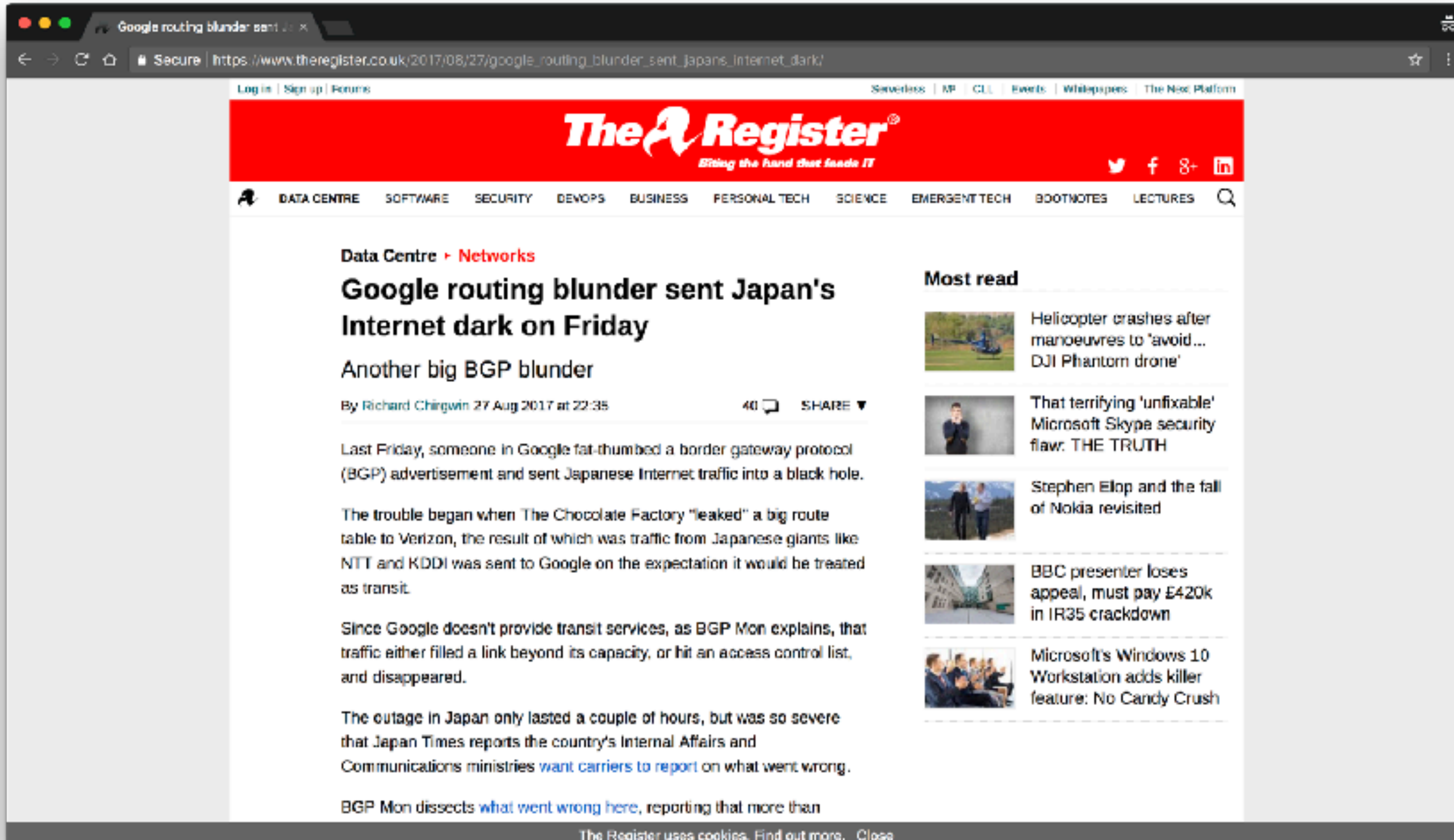
nsg.ee.ethz.ch

NII Shonan Meeting

Mon Feb 26 2018

a couple of hours

a couple of hours??



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Data Centre ▸ Networks

Google routing blunder sent Japan's Internet dark on Friday

Another big BGP blunder

By Richard Chirgwin 27 Aug 2017 at 22:35

40 SHARE ▼

Last Friday, someone in Google fat-thumbed a border gateway protocol (BGP) advertisement and sent Japanese Internet traffic into a black hole.

The trouble began when The Chocolate Factory "leaked" a big route table to Verizon, the result of which was traffic from Japanese giants like NTT and KDDI was sent to Google on the expectation it would be treated as transit.

Since Google doesn't provide transit services, as BGP Mon explains, that traffic either filled a link beyond its capacity, or hit an access control list, and disappeared.

The outage in Japan only lasted a couple of hours, but was so severe that Japan Times reports the country's Internal Affairs and Communications ministries want carriers to report on what went wrong.

BGP Mon dissects what went wrong here, reporting that more than

Most read

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https://www.theregister.co.uk/2017/08/27/google_routing_blunder_sent_japans_internet_dark/

In August 2017

Someone in Google fat-thumbed a
Border Gateway Protocol (BGP) advertisement
and sent Japanese Internet traffic into a black hole.

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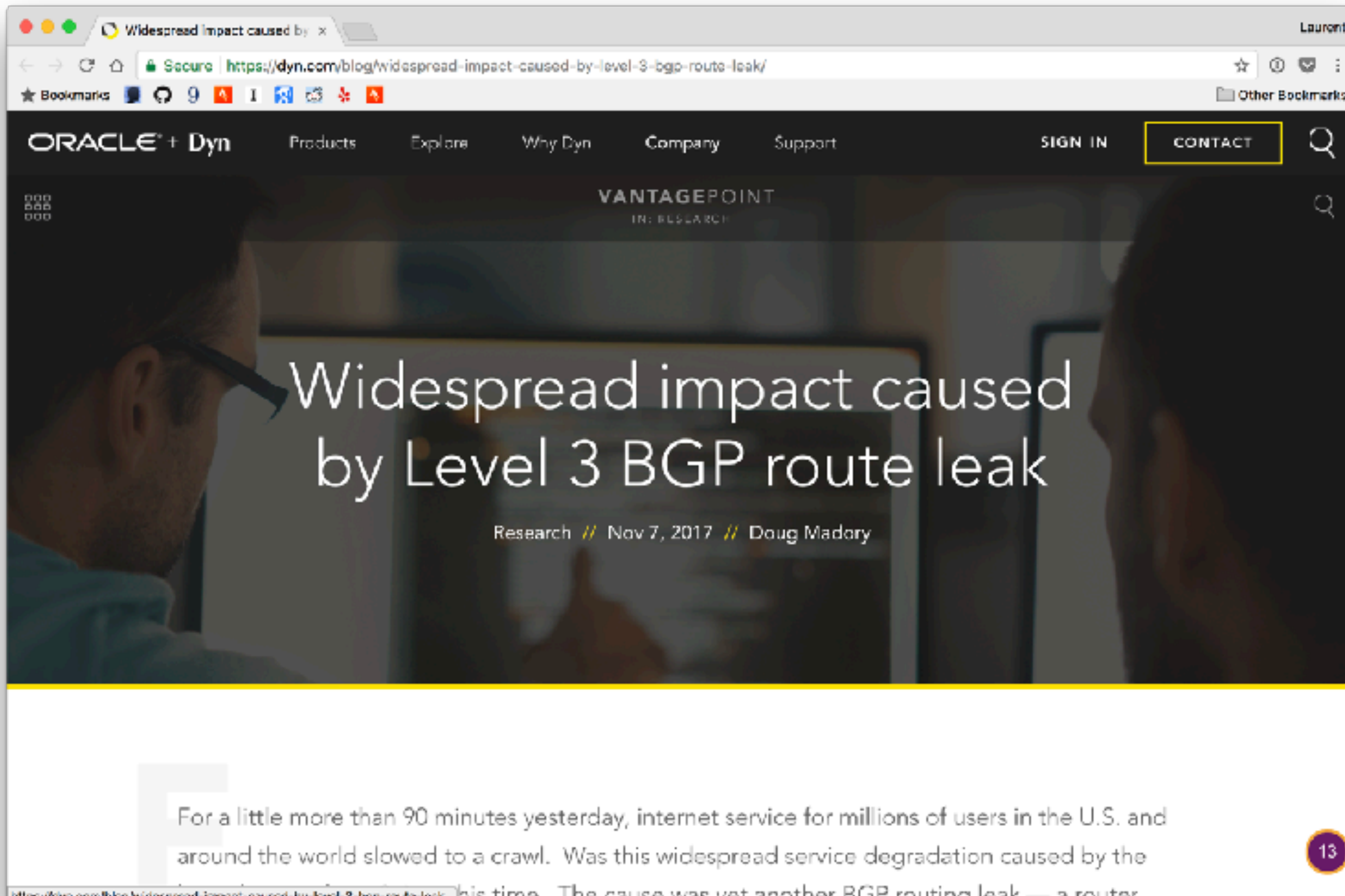
it would be treated as transit.

The outage in Japan only lasted a couple of hours
but was so severe that […] the country's
Internal Affairs and Communications ministries
want carriers to report on what went wrong.

Another example,
this time from November 2017



https://dyn.com/blog/widespread-impact-caused-by-level-3-bgp-route-leak/

For a little more than 90 minutes [...],

Internet service for millions of users in the U.S. and around the world slowed to a crawl.

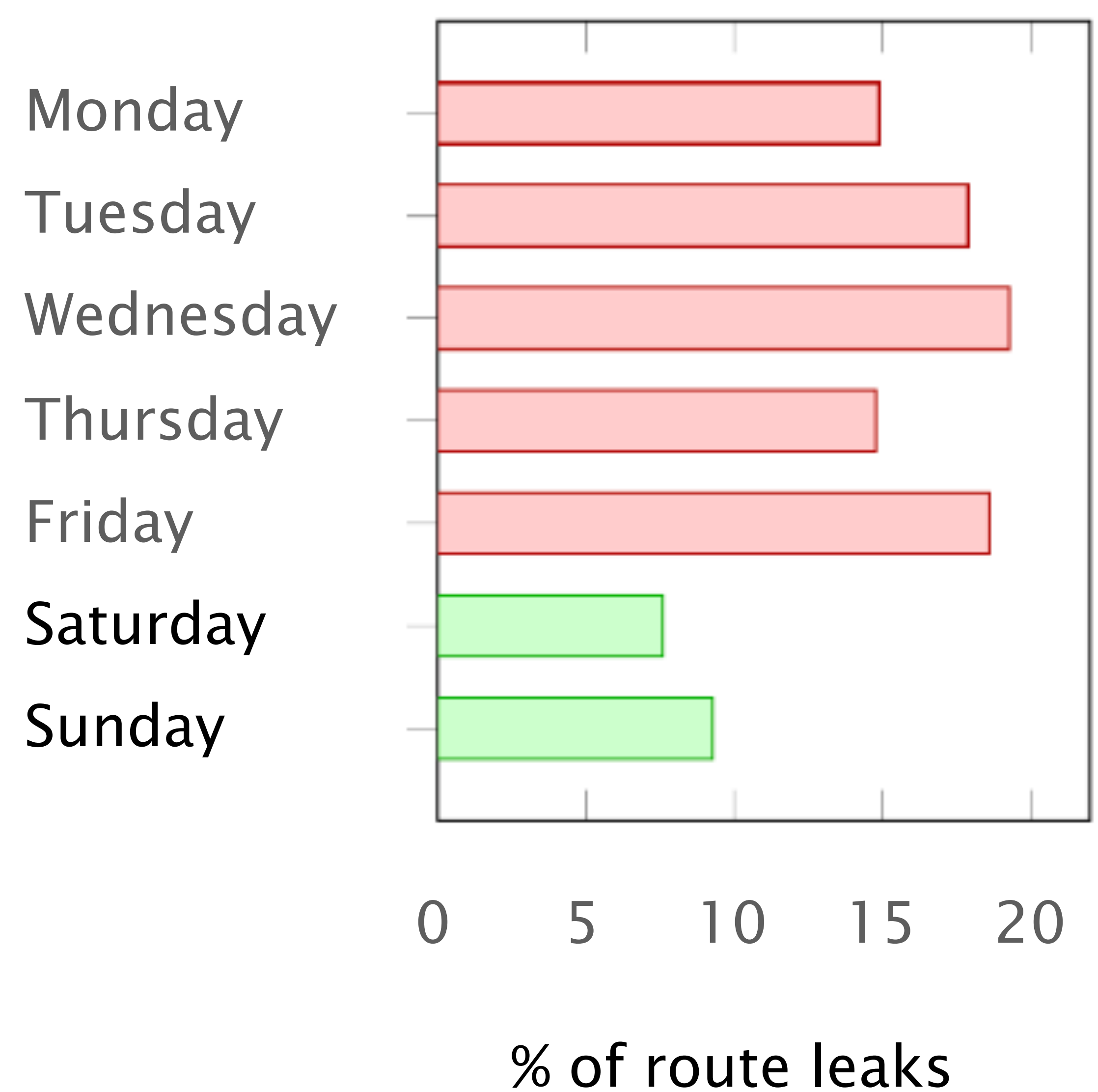
The cause was yet another BGP routing leak, a router misconfiguration directing Internet traffic from its intended path to somewhere else.

“Human factors are responsible

for 50% to 80% of network outages”

Juniper Networks, *What’s Behind Network Downtime?*, 2008

Ironically, this means that the Internet works better during the week-ends…



source: Job Snijders (NTT)

It’s not only about people breaking the Internet…

People destroy their own infrastructure too!

Traders work on the floor of the New York Stock Exchange (NYSE) in July 2015. (Photo by Spencer Platt/Getty Images)

DOWNTIME

UPDATED: "Configuration Issue" Halts Trading on NYSE

The article has been updated with the time trading resumed.

A second update identified the cause of the outage as a "configuration issue."

A third update added information about a software update that created the configuration issue.

NYSE network operators identified the culprit of the 3.5 hour outage, blaming the incident on a "network configuration issue"

Forbes / Personal Finance

JUL 8, 2015 @ 03:36 PM 11,261 VIEWS

United Airlines Blames Router for Grounded Flights

Alexandra Talty, CONTRIBUTOR
I cover personal finance and travel.
FOLLOW ON FORBES (110)
Opinions expressed by Forbes Contributors are their own.

FULL BIO

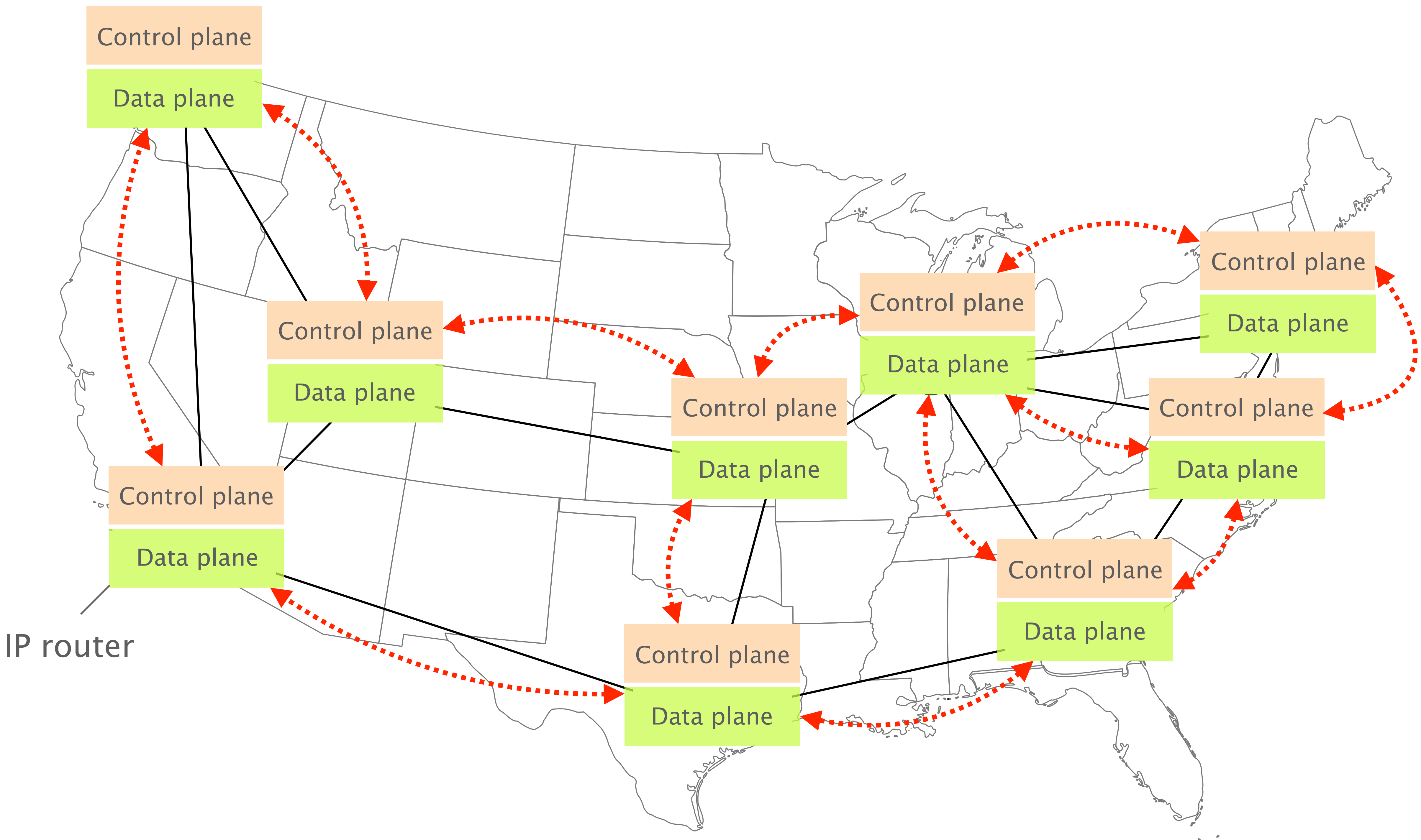
After a computer problem caused nearly two hours of grounded flights for United Airlines this morning and ongoing delays throughout the day, the airline announced the culprit: a faulty router.

Spokeswoman Jennifer Dohm said that the router problem caused "degraded network connectivity," which affected various applications.

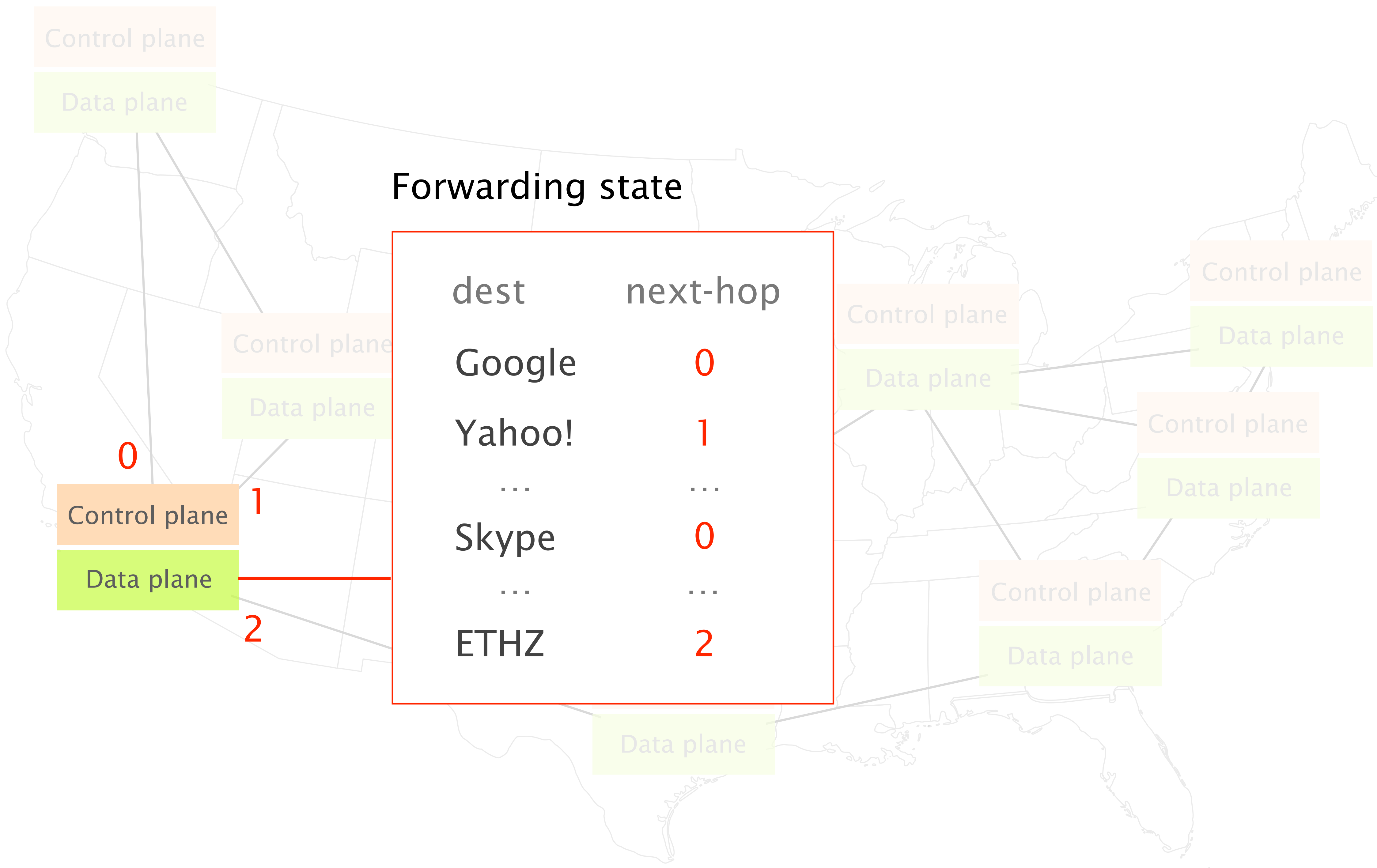
A computer glitch in the airline's reservations system caused the Federal Aviation Administration to impose a groundstop at 8:26 a.m. E.T. Planes that were in the air continued to operate, but all planes on the ground were held. There were reports of agents writing tickets by hand. The ground stop was lifted around 9:47 a.m. ET.

http://bit.ly/2sBJ2jf

Think of the network as a **distributed system** running multiple **distributed algorithms**



These algorithms produce the **forwarding state** which **drives IP traffic** to its destination



Operators adapt their network forwarding behavior
by configuring each network device individually

Configuring each element is often **done manually,** using arcane **low-level, vendor-specific** "languages"

Cisco IOS

```
!
ip multicast-routing
!
interface Loopback0
 ip address 120.1.7.7 255.255.255.255
 ip ospf 1 area 0
!
!
interface Ethernet0/0
 no ip address
!
interface Ethernet0/0.17
 encapsulation dot1Q 17
 ip address 125.1.17.7 255.255.255.0
 ip pim bsr-border
 ip pim sparse-mode
!
!
router ospf 1
 router-id 120.1.7.7
 redistribute bgp 700 subnets
!
router bgp 700
 neighbor 125.1.17.1 remote-as 100
 !
 address-family ipv4
  redistribute ospf 1 match internal external 1 external 2
  neighbor 125.1.17.1 activate
 !
 address-family ipv4 multicast
  network 125.1.79.0 mask 255.255.255.0
  redistribute ospf 1 match internal external 1 external 2
```

Juniper JunOS

```
interfaces {
   so-0/0/0 {
        unit 0 {
            family inet {
                address 10.12.1.2/24;
            }
            family mpls;
        }
    }
   ge-0/1/0 {
        vlan-tagging;
        unit 0 {
            vlan-id 100;
            family inet {
                address 10.108.1.1/24;
            }
            family mpls;
        }
        unit 1 {
            vlan-id 200;
            family inet {
                address 10.208.1.1/24;
            }
        }
    }
…
}
protocols {
    mpls {
        interface all;
    }
    bgp {
```

A single mistyped line is enough to bring down the entire network

Cisco IOS

```
!
ip multicast-routing
!
interface Loopback0
 ip address 120.1.7.7 255.255.255.255
 ip ospf 1 area 0
!
!
interface Ethernet0/0
 no ip address
!
interface Ethernet0/0.17
 encapsulation dot1Q 17
 ip address 125.1.17.7 255.255.255.0
 ip pim bsr-border
 ip pim sparse-mode
!
!
router ospf 1
 router-id 120.1.7.7
 redistribute bgp 700 subnets
!
router bgp 700
 neighbor 125.1.17.1 remote-as 100
 !
 address-family ipv4
  redistribute ospf 1 match internal external 1 external 2
  neighbor 125.1.17.1 activate
 !
 address-family ipv4 multicast
  network 125.1.79.0 mask 255.255.255.0
  redistribute ospf 1 match internal external 1 external 2
```

Anything else than 700 creates blackholes

Juniper JunOS

```
interfaces {
   so-0/0/0 {
        unit 0 {
            family inet {
                address 10.12.1.2/24;
            }
            family mpls;
        }
    }
   ge-0/1/0 {
        vlan-tagging;
        unit 0 {
            vlan-id 100;
            family inet {
                address 10.108.1.1/24;
            }
            family mpls;
        }
        unit 1 {
            vlan-id 200;
            family inet {
                address 10.208.1.1/24;
            }
        }
    }
…
}
protocols {
    mpls {
        interface all;
    }
    bgp {
```

My research goal? **Automate!**

Remove the need to rely on humans

Develop a complete & sound network controller which can automatically enforce high-level requirements

Develop a complete & sound network controller which can automatically enforce high-level requirements

Twist

Control networks running distributed protocols

where the computation of the forwarding state is distributed

Develop a complete & sound network controller which can automatically enforce high-level requirements

Twist

Control networks running distributed protocols

where the computation of the forwarding state is distributed

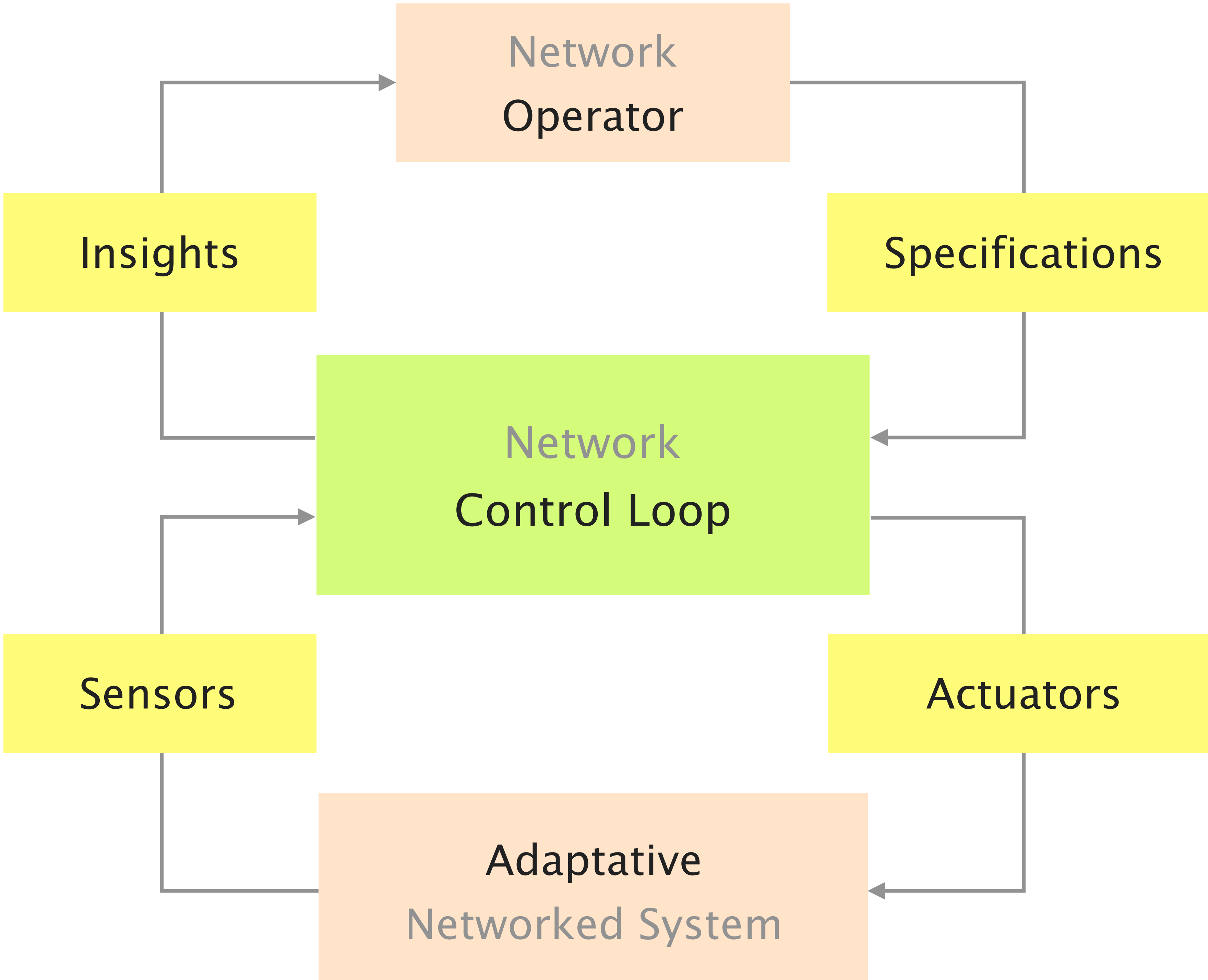
Why?

Designing central, scalable *and* robust control is hard

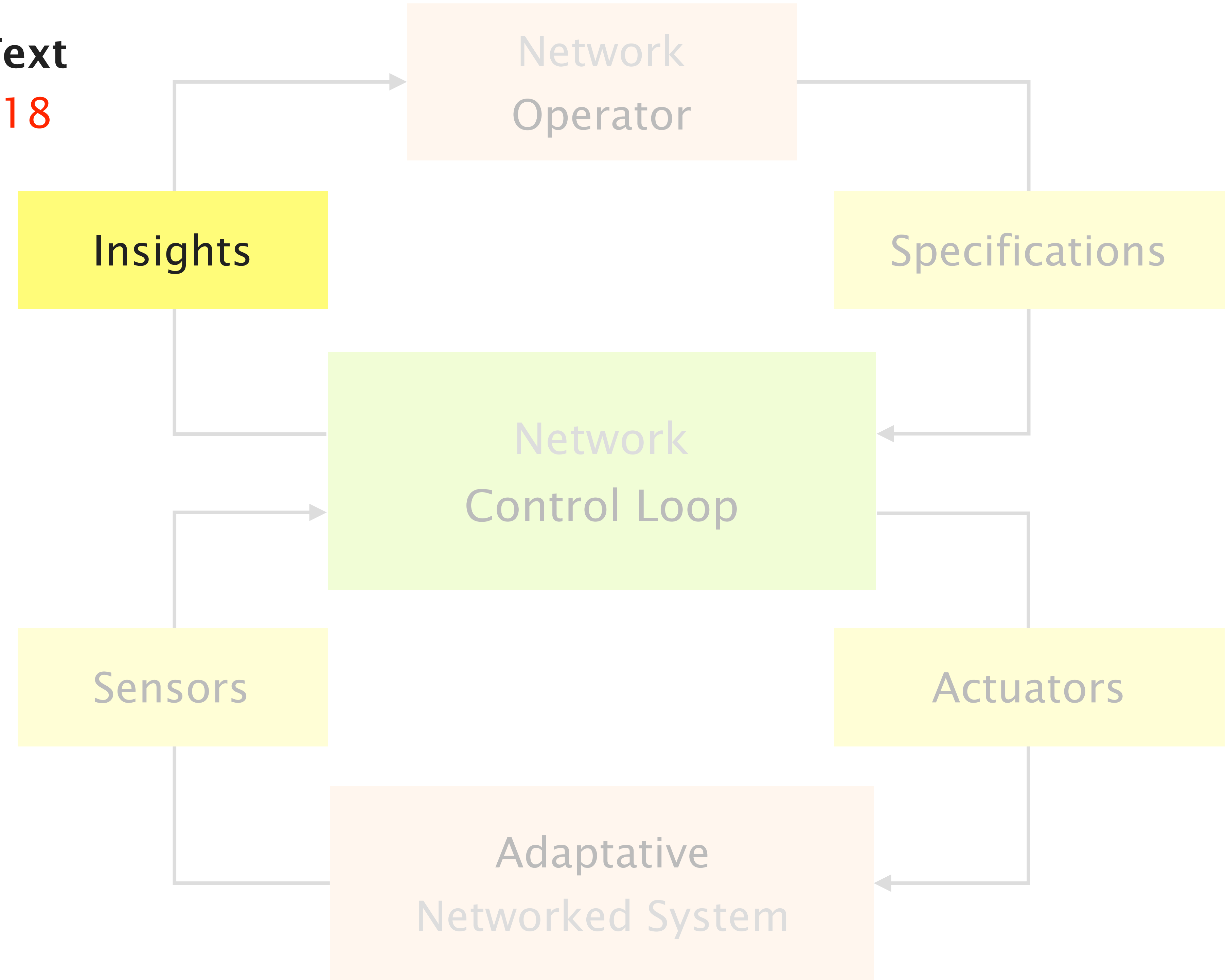
must ensure always-on connectivity to the controller

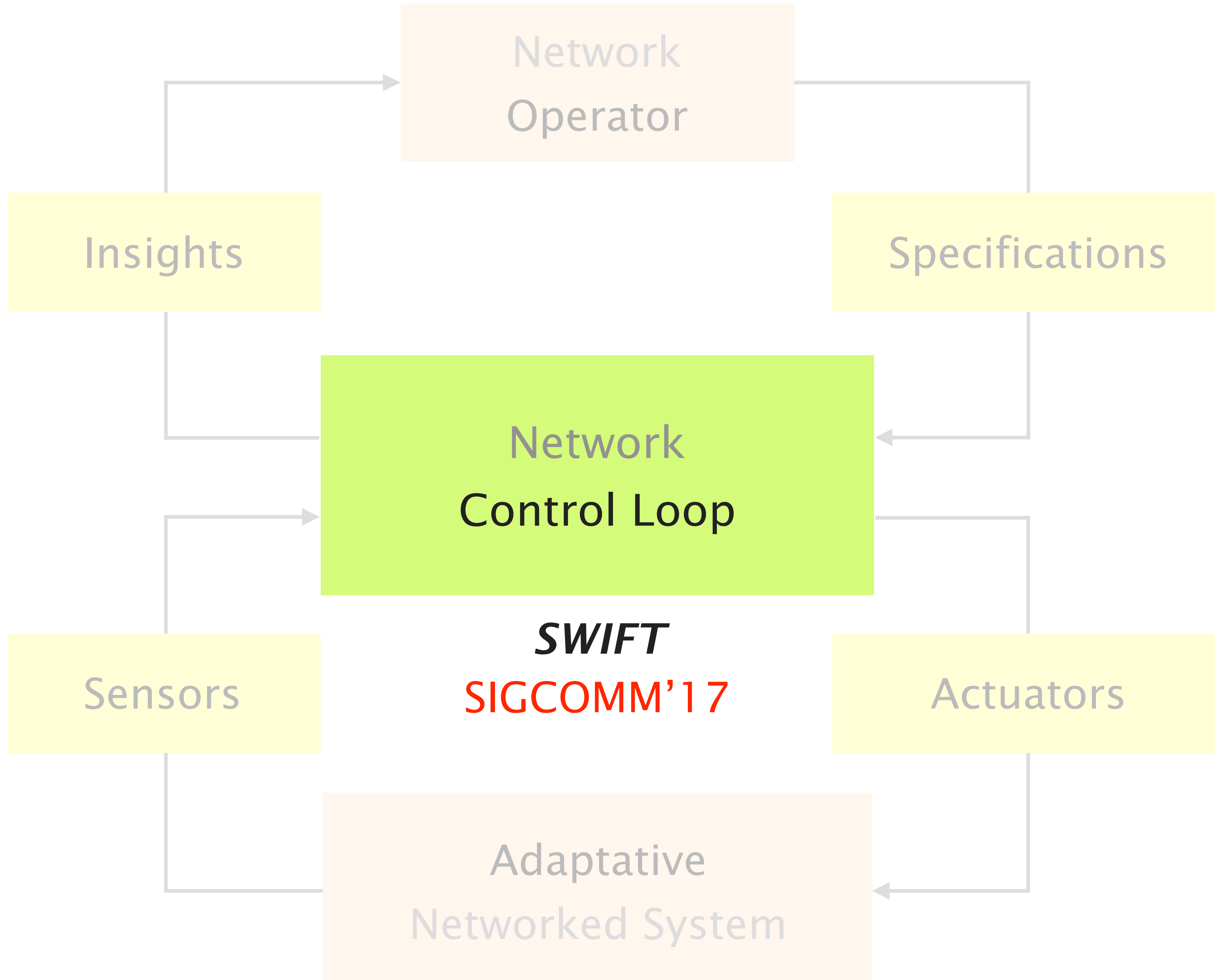
Distributed protocols are still ruling over networks

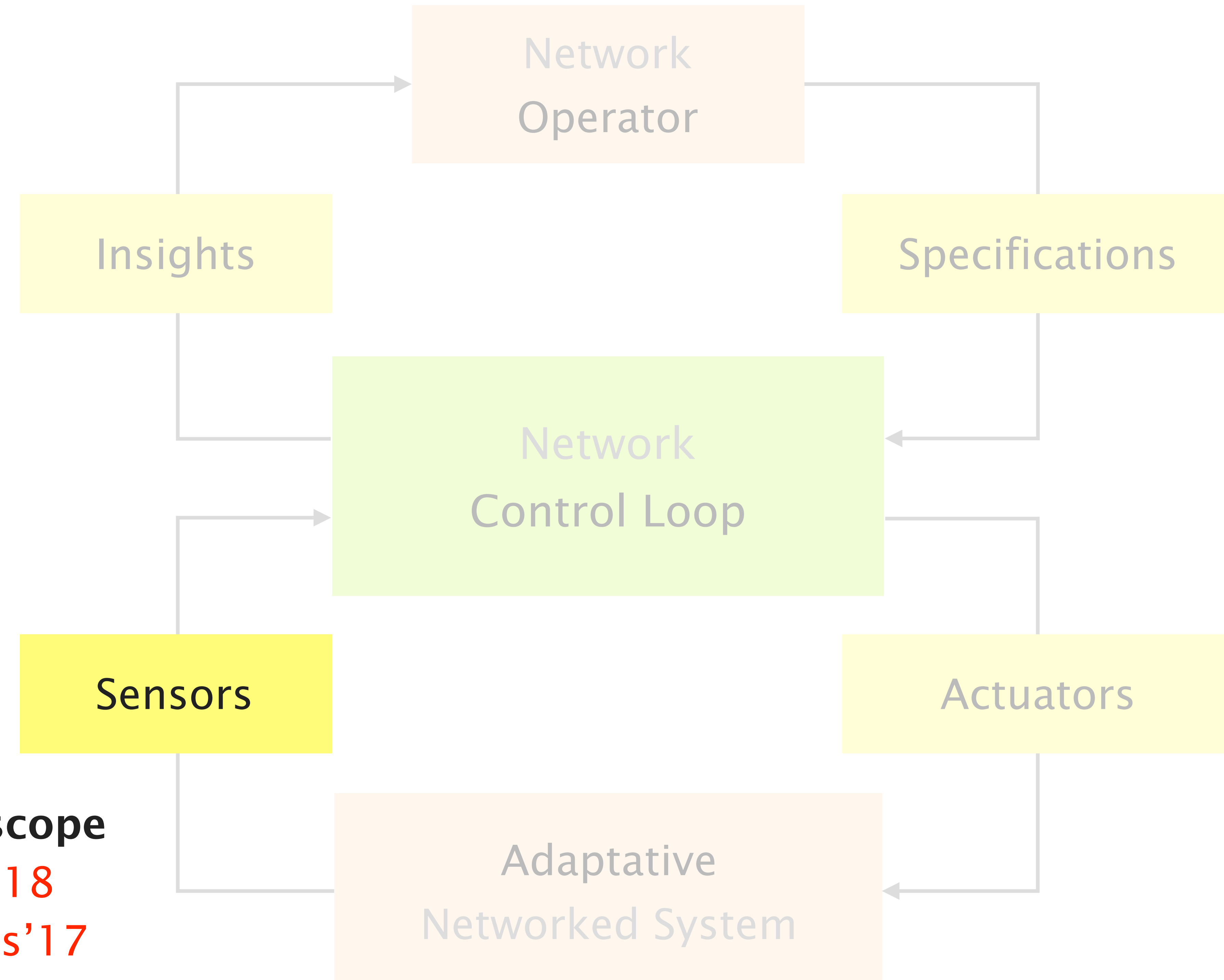
the vast majority of the networks rely on OSPF, BGP, MPLS, …


Network
Operator
Insights
Specifications
Network
Control Loop
Sensors
Actuators
Adaptative
Networked System

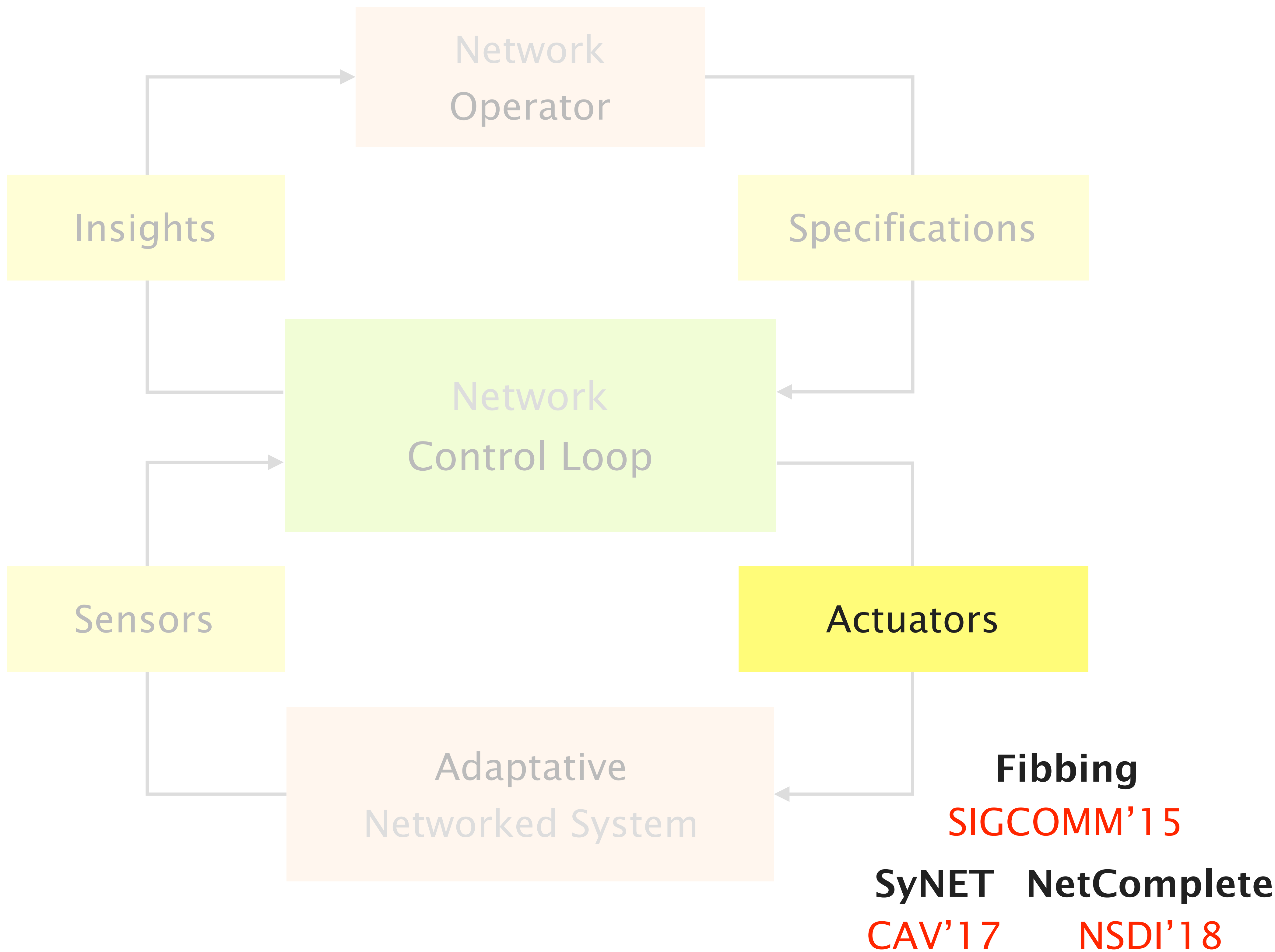
Net2Text
NSDI'18




Network
Operator
Insights
Specifications
Network
Control Loop
SWIFT
SIGCOMM'17
Sensors
Actuators
Adaptative
Networked System



Stroboscope
NSDI'18
HotNets'17


Network
Operator
Insights
Specifications
Network
Control Loop
Sensors
Actuators
Adaptative
Networked System
Fibbing
SIGCOMM'15
SyNET
CAV'17
NetComplete
NSDI'18

How can we control the network-wide forwarding state produced by distributed protocols?

How can we control the network-wide forwarding state produced by distributed protocols?

What are our knobs?

The network-wide forwarding state depends on three parameters

Network-wide
Forwarding state

Topology	+	Network-wide	+	Network	→	Network-wide
(fixed)		Configuration		Environment		Forwarding state

Topology (fixed) + Network-wide Configuration + Network Environment → Network-wide Forwarding state

links & nodes status
routing announcements

Out of these three parameters,

two can be controlled

Topology (fixed) + Network-wide Configuration + Network Environment → Network-wide Forwarding state

~~links & nodes status~~

routing announcements

Given a forwarding state we want to program,
we therefore have two ways to provision it

Given a network-wide forwarding state
to provision, one can synthesize

way 1	the routing messages shown to the routers
way 2	the configurations run by the routers

Given a network-wide forwarding state

output to provision, one can synthesize

inputs the routing messages shown to the routers

functions the configurations run by the routers

Network control & programmability

through synthesis

Topology (fixed) + Network-wide Configuration + Network Environment → Network-wide Forwarding state

Part 2 — Network-wide Configuration

Part 1 — Network Environment

Network control & programmability

through synthesis

Topology
(fixed)

+

Network-wide
Configuration

+

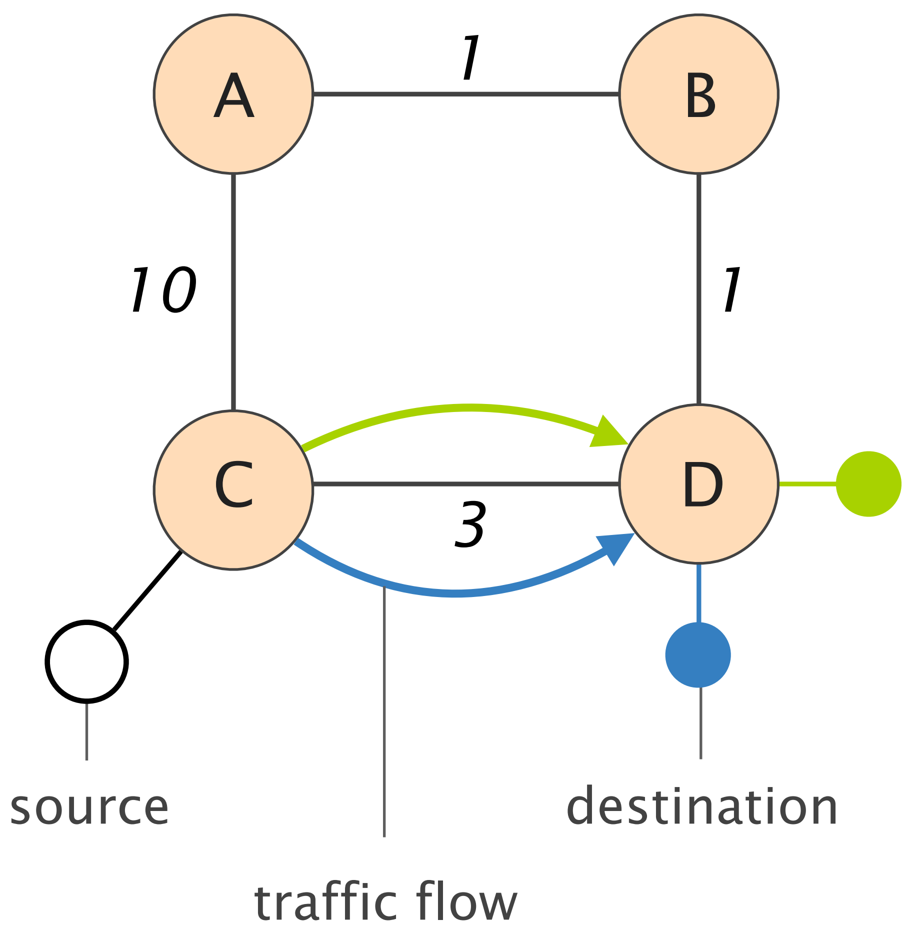
Network
Environment

→

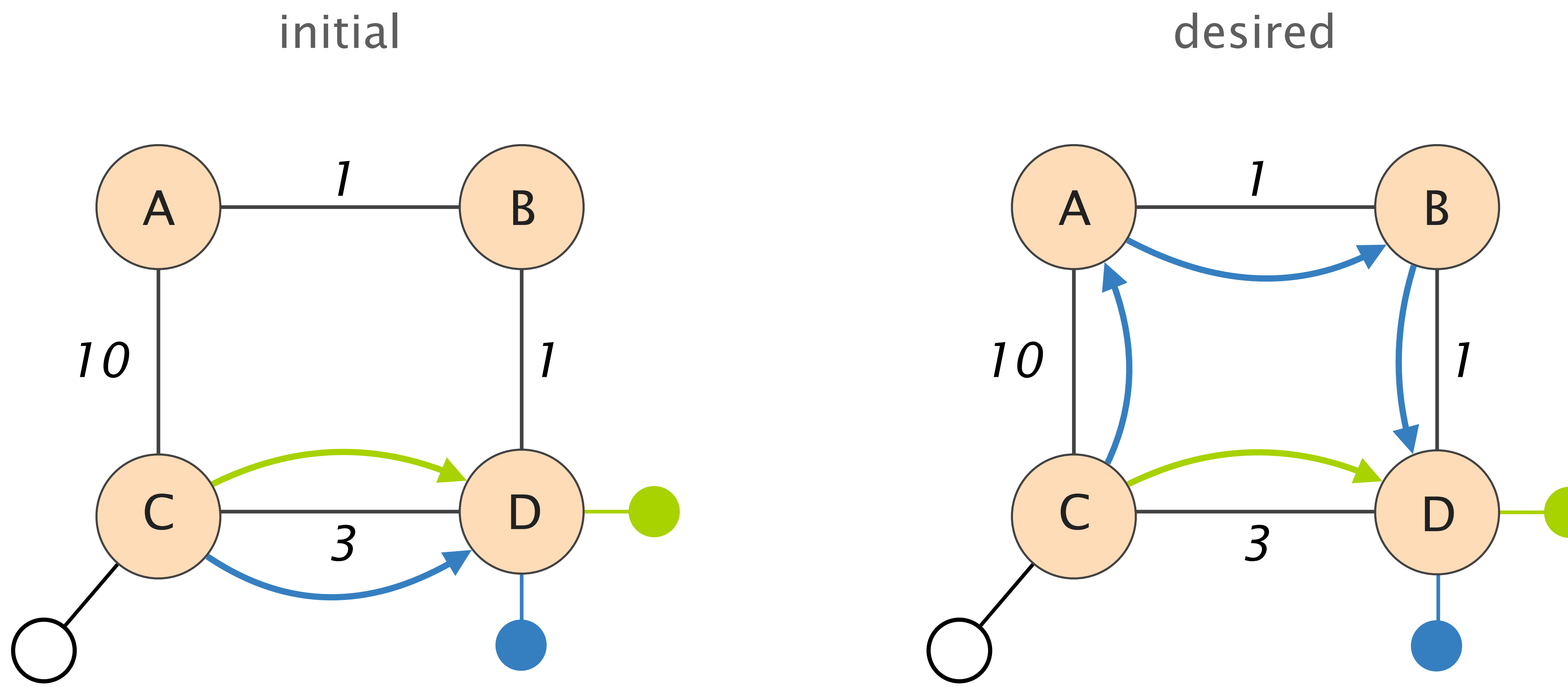
Network-wide
Forwarding state

Part 1

Consider this network where a source sends traffic to 2 destinations

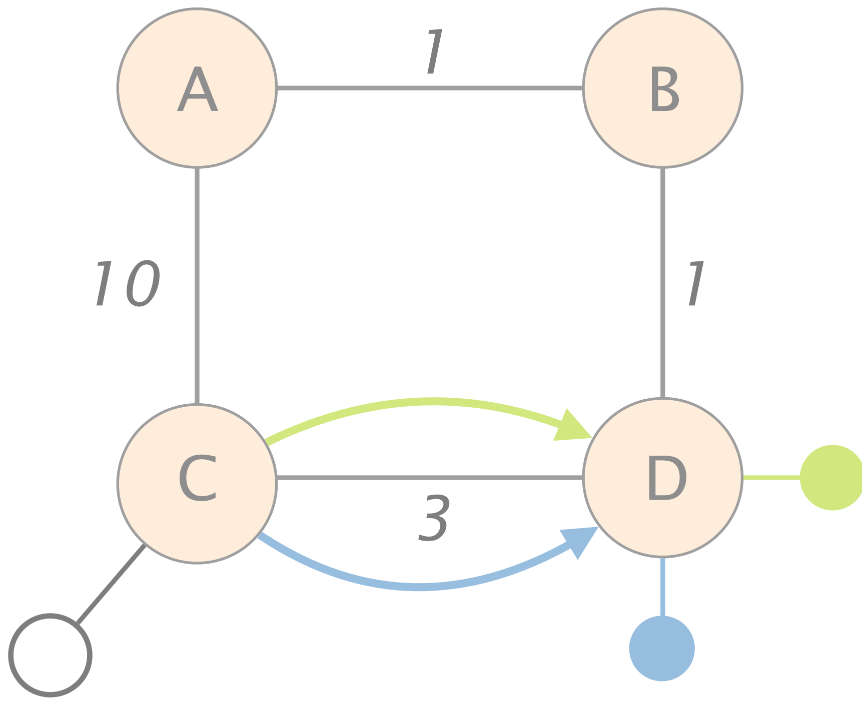


As congestion appears, the operator wants to shift away one flow from (C,D)

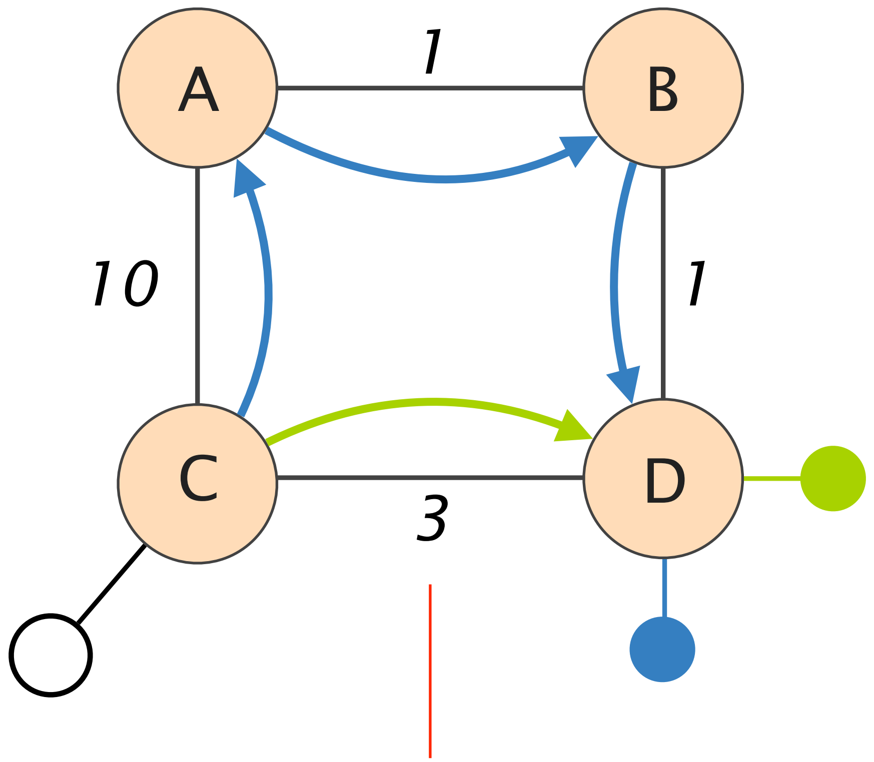


Moving only one flow is impossible though as both destinations are connected to D

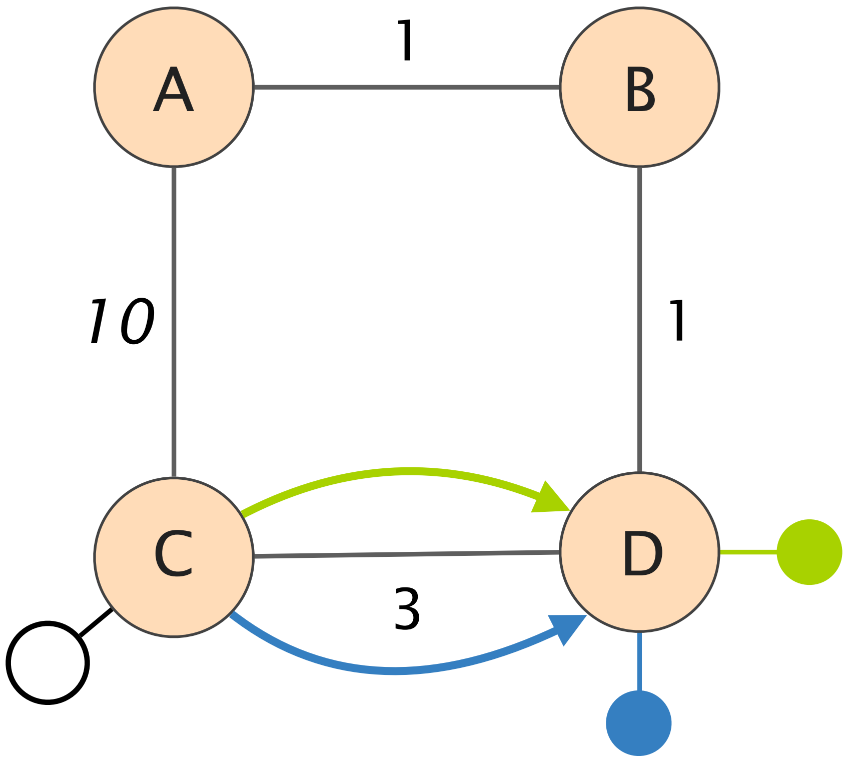
initial



desired

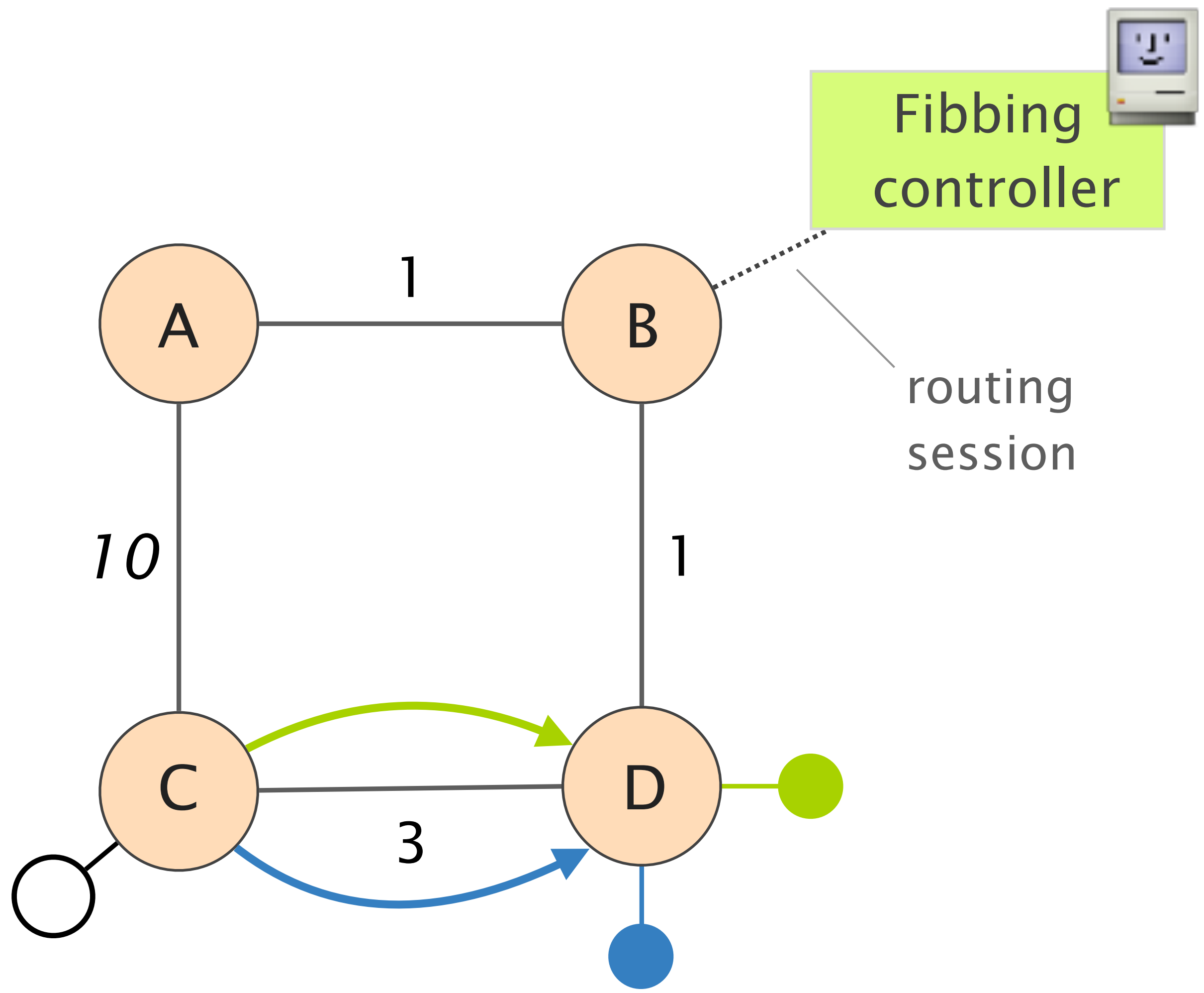


impossible to achieve by reweighing the links

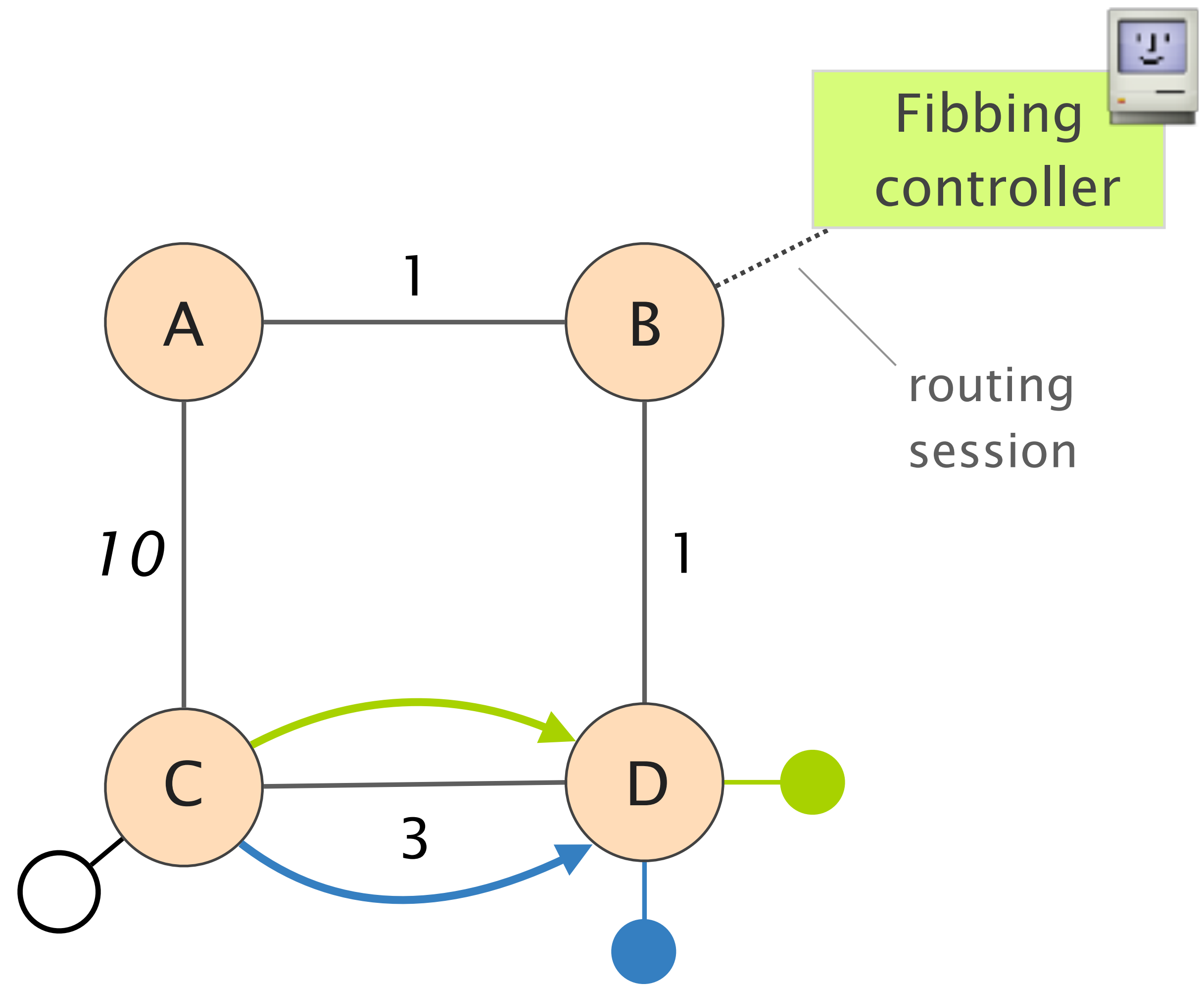


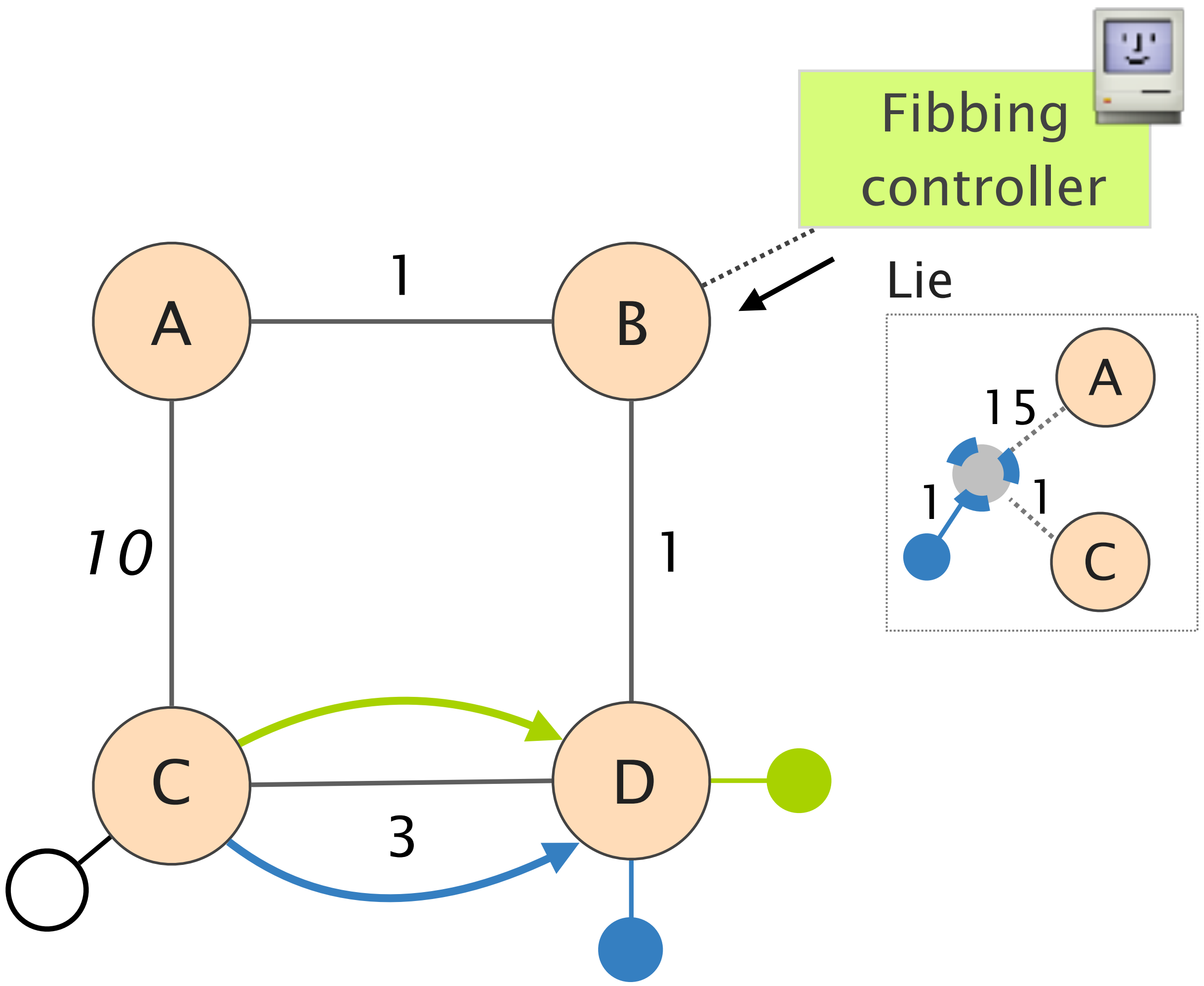
A
B
C
D
1
10
1
3

Let's lie to the routers



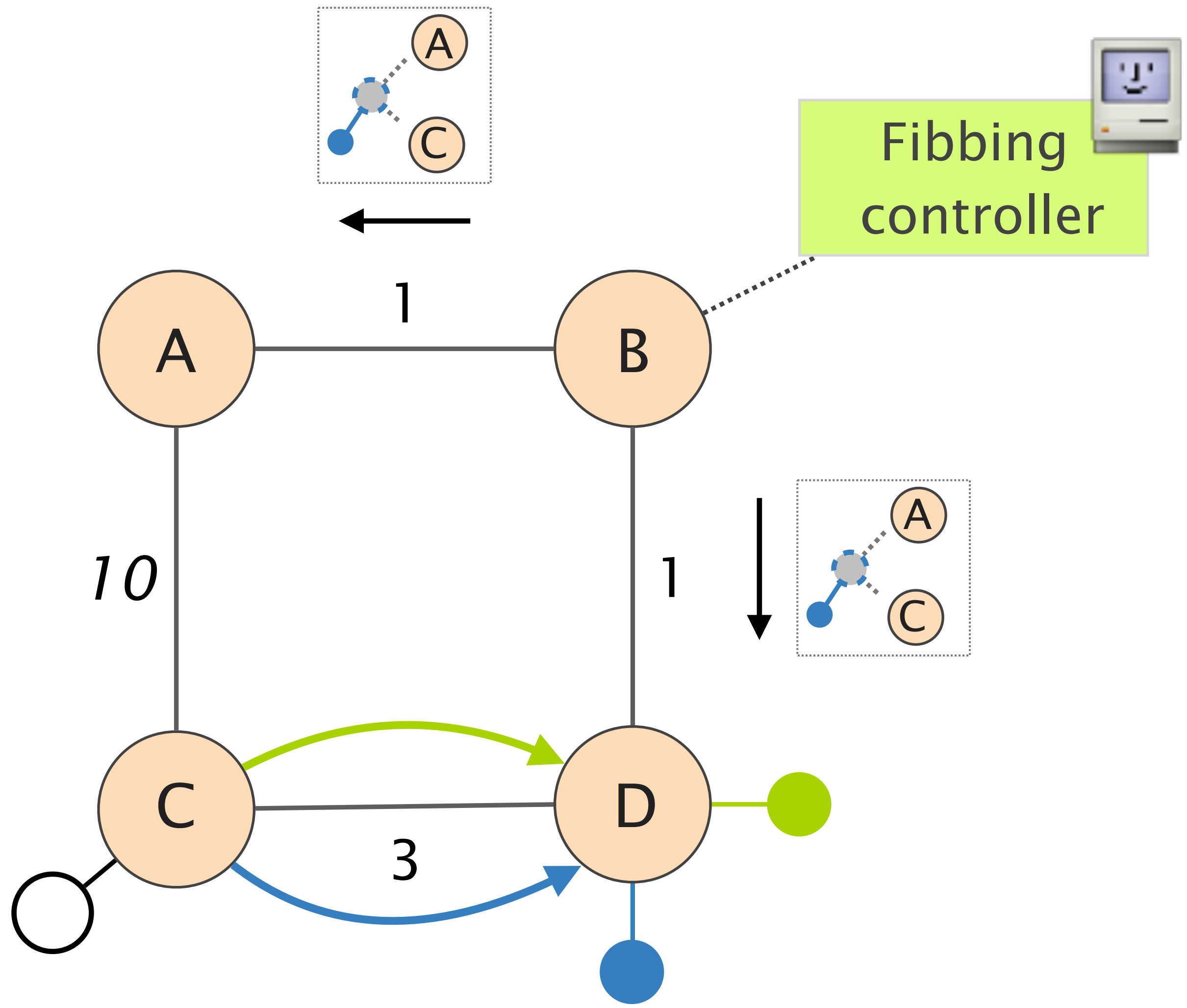
Let's **lie** to the routers, by **injecting fake nodes, links and destinations**



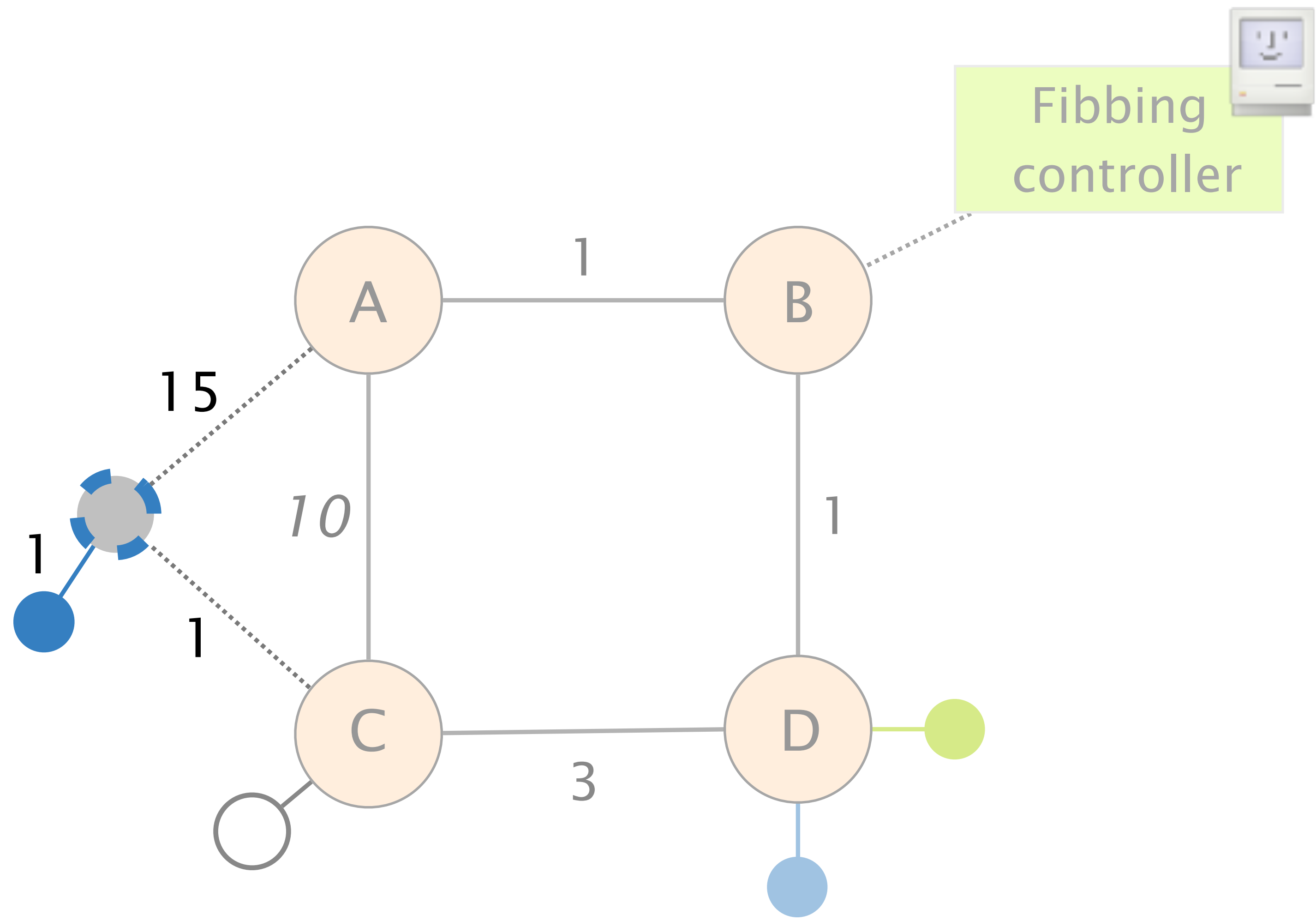


Fibbing controller
Lie
A
B
C
D
1
10
1
3
15
1
1
A
C

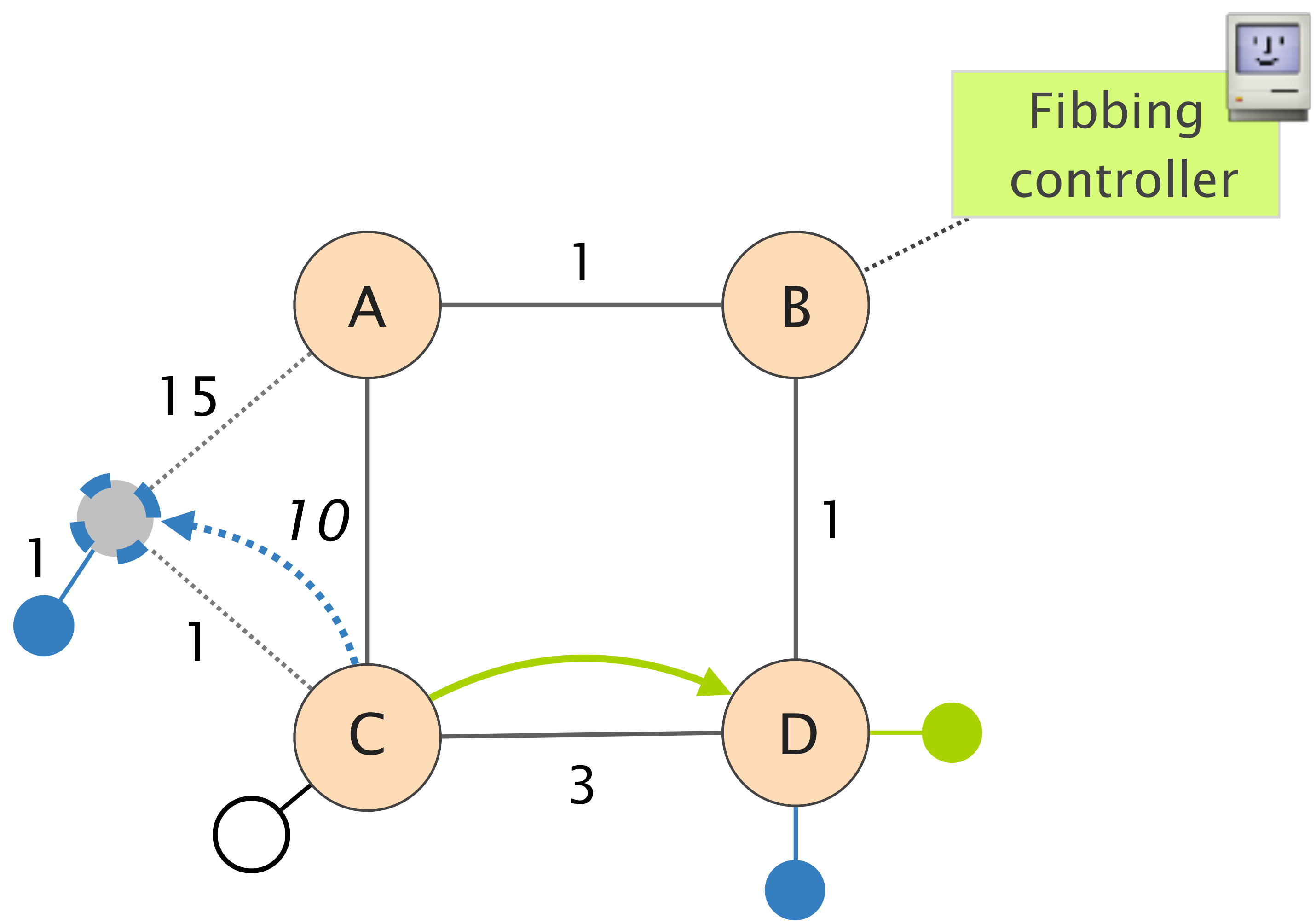
Lies are propagated network-wide by the routing protocol



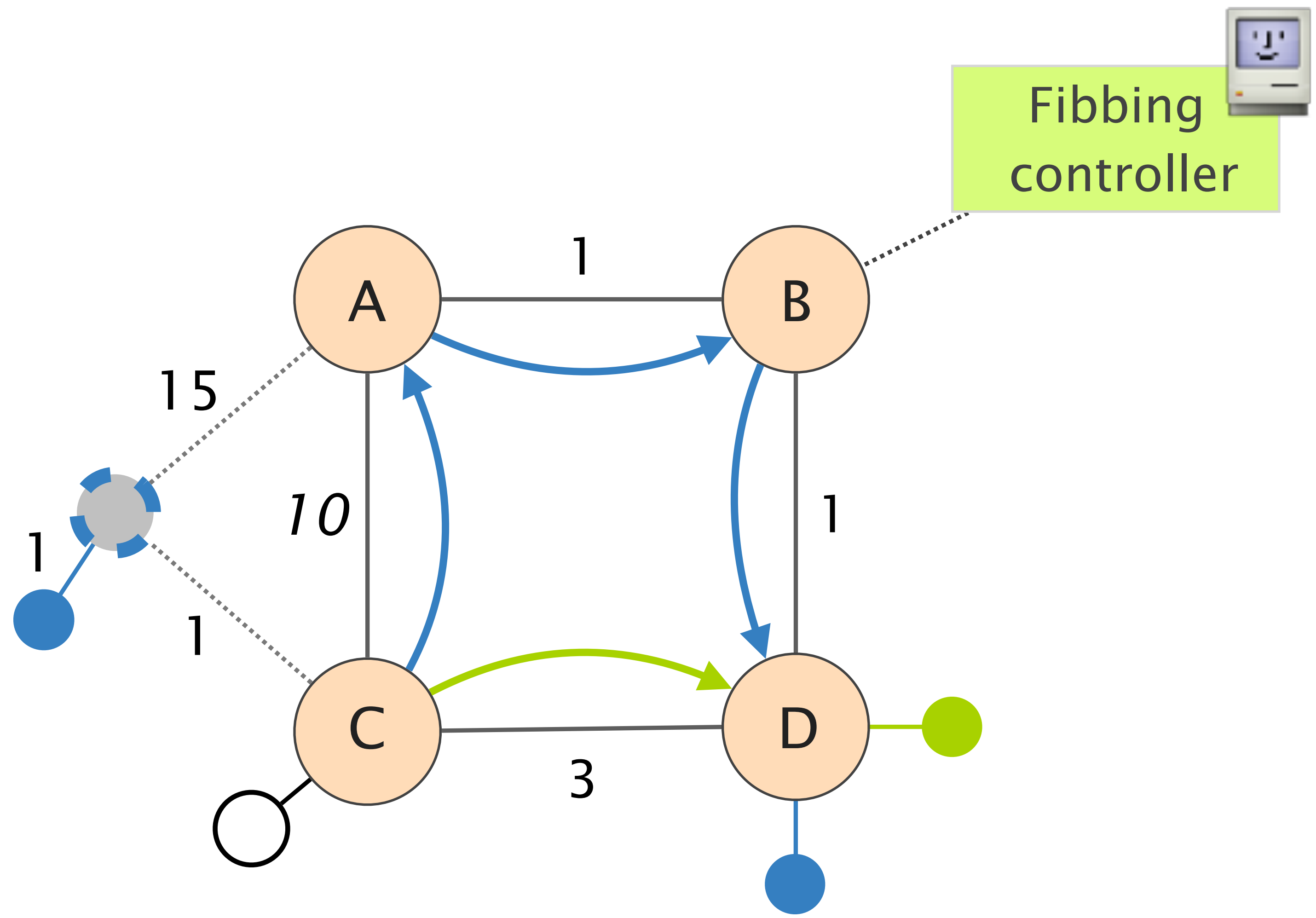
All routers compute their shortest-paths on the augmented topology



C prefers the virtual node (cost 2)
to reach the blue destination…



As the virtual node does not really exist, actual traffic is **physically sent to A**



Synthesizing routing messages is powerful

Theorem

Fibbing can program any set of non-contradictory paths

Theorem

Fibbing can program
any set of non-contradictory paths

Theorem

Fibbing can program

any set of non-contradictory paths

any path is loop-free

(*e.g.*, [s1, a, b, a, d] is not possible)

paths are consistent

(*e.g.* [s1, a, b, d] and
[s2, b, a, d] are inconsistent)

Synthesizing routing messages is fast and works in practice

We developed efficient algorithms

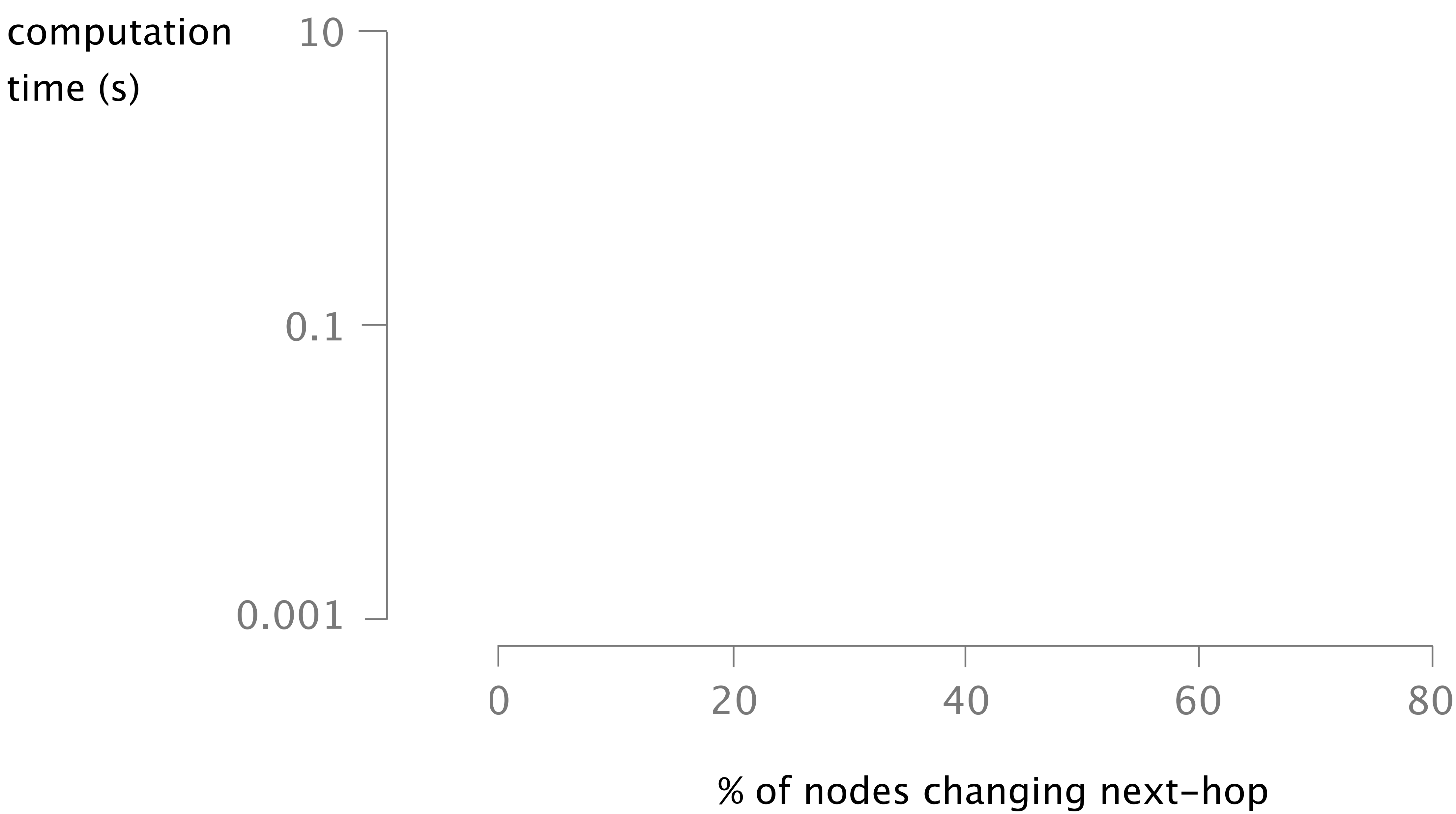
polynomial in the # of requirements

Compute and minimize topologies in ms

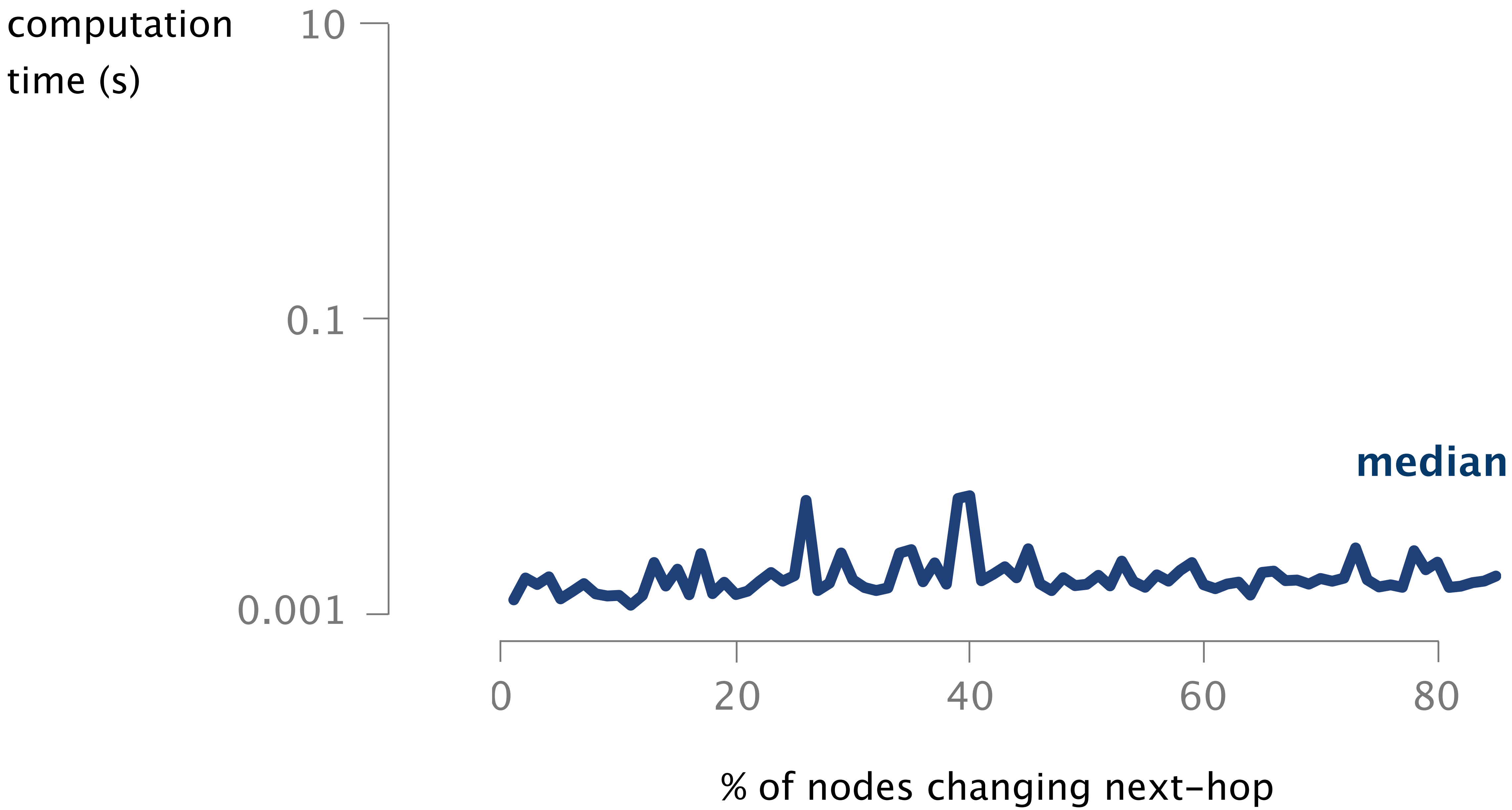
independently of the size of the network

We tested them against real routers

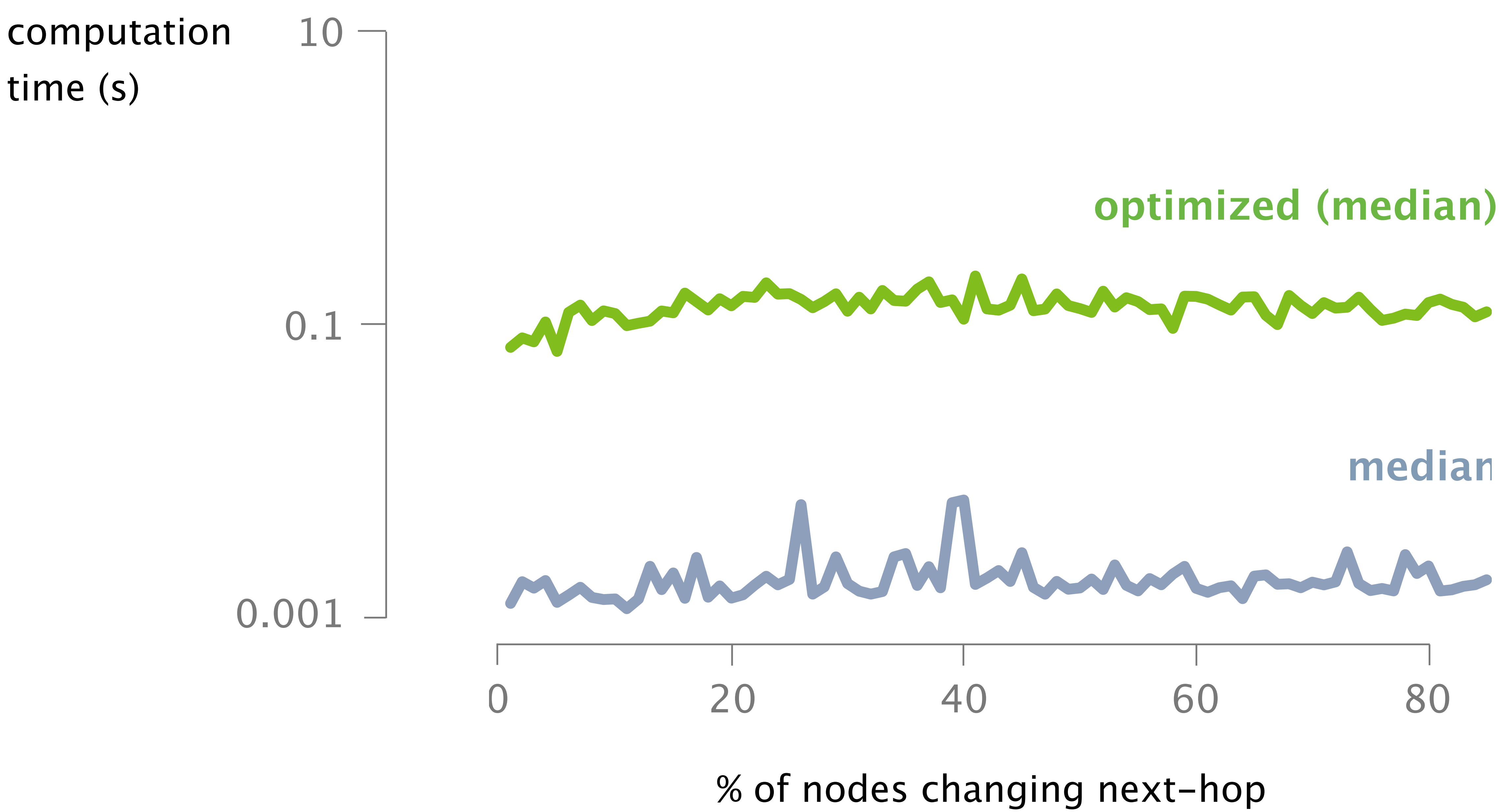
works on both Cisco and Juniper


computation
time (s)
10
0.1
0.001
0
20
40
60
80
% of nodes changing next-hop

Fibbing computes routing messages to inject in ~1ms



Fibbing minimizes the # of routing messages to inject in ~100ms



Fibbing is fully implemented
and works with real routers

Existing routers can easily sustain
Fibbing-induced load, even with huge topologies

# fake nodes	router memory (MB)	
1000	0.7	
5 000	6.8	
10 000	14.5	
50 000	76.0	
100 000	153	DRAM is cheap

Because it is entirely distributed, programming forwarding entries is fast

# fake nodes	installation time (s)	
1000	0.9	
5 000	4.5	
10 000	8.9	
50 000	44.7	
100 000	89.50	894.50 µs/entry

Fibbing is limited though, among others by the configurations running on the routers

Works with a single protocol family

Dijkstra-based shortest-path routing

Can lead to loads of messages

if the configuration is not adapted

Suffers from reliability issues

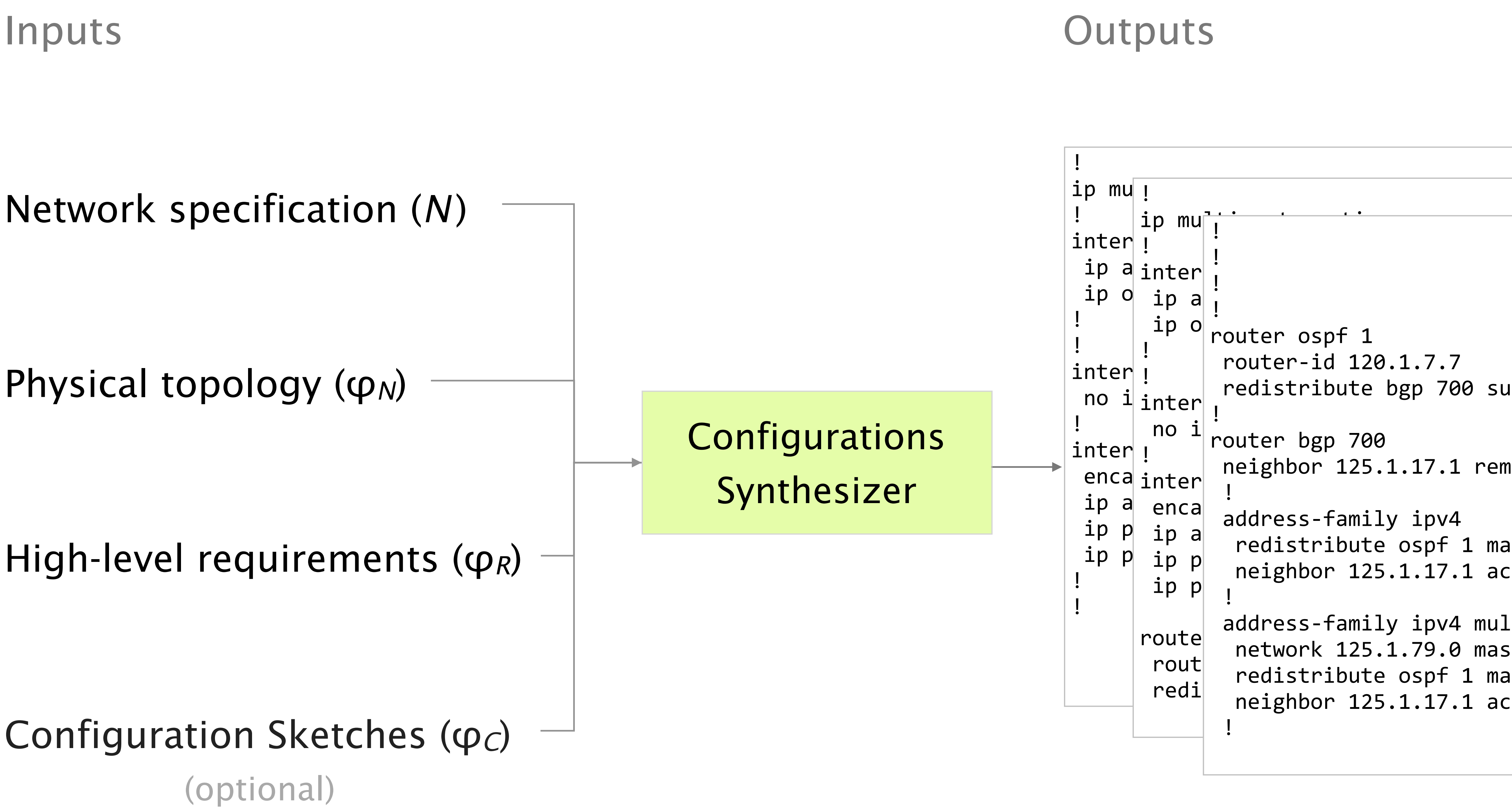
need to remove the lies upon failures

Network control & programmability

through synthesis

Topology (fixed)	+	Network-wide Configuration	+	Network Environment	→	Network-wide Forwarding state

Part 2


Inputs
Outputs
Network specification (N)
Physical topology (φN)
High-level requirements (φR)
Configuration Sketches (φC)
(optional)
Configurations Synthesizer
router ospf 1
router-id 120.1.7.7
router bgp 700
address-family ipv4

Inputs

Network specification (N)

Physical topology (φ_N)

High-level requirements (φ_R)

Configuration Sketches (φ_C)

Inputs

Network specification (N)

A model of how the routers
compute their forwarding state
as a function of their configuration

Physical topology (φ_N)

High-level requirements (φ_R)

Configuration Sketches (φ_C)

Inputs

Network specification (N)

Physical topology (φ_N)

High-level requirements (φ_R)

Configuration Sketches (φ_C)

An encoding of the physical topology

Inputs

Network specification (*N*)

Physical topology (φ_N)

High-level requirements (φ_R)

Configuration Sketches (φ_C)

A set of constraints over the forwarding state produced by the synthesized configurations

Inputs

Network specification (N)

Physical topology (φ_N)

High-level requirements (φ_R)

Configuration Sketches (φ_C)
(optional)

A set of constraints on the content of the synthesized configurations problem

Given $N, \varphi_{N,} \varphi_{R,} \varphi_C$

Generate a network-wide configuration C s.t. the $\varphi_{N,} \varphi_{R,}$ and φ_C constraints are satisfied for the given network specification N

problem	Given N, φ_N, φ_R, φ_C
	Generate a network-wide configuration C s.t. the φ_N, φ_R, and φ_C constraints are satisfied for the given network specification N
challenge	**this is undecidable** (in general)

problem Given N, φ_N, φ_R, φ_C

Generate a network-wide configuration C s.t. the φ_N, φ_R, and φ_C constraints are satisfied for the given network specification N

challenge this is undecidable (in general)

insights domain-specific heuristics

Network Configuration synthesis: a booming field!

Out of high-level requirements, synthesize

Genesis [POPL'17]

static routes

doesn't support distributed routing protocols

Propane [SIGCOMM'16]

PropaneAT [PLDI'17]

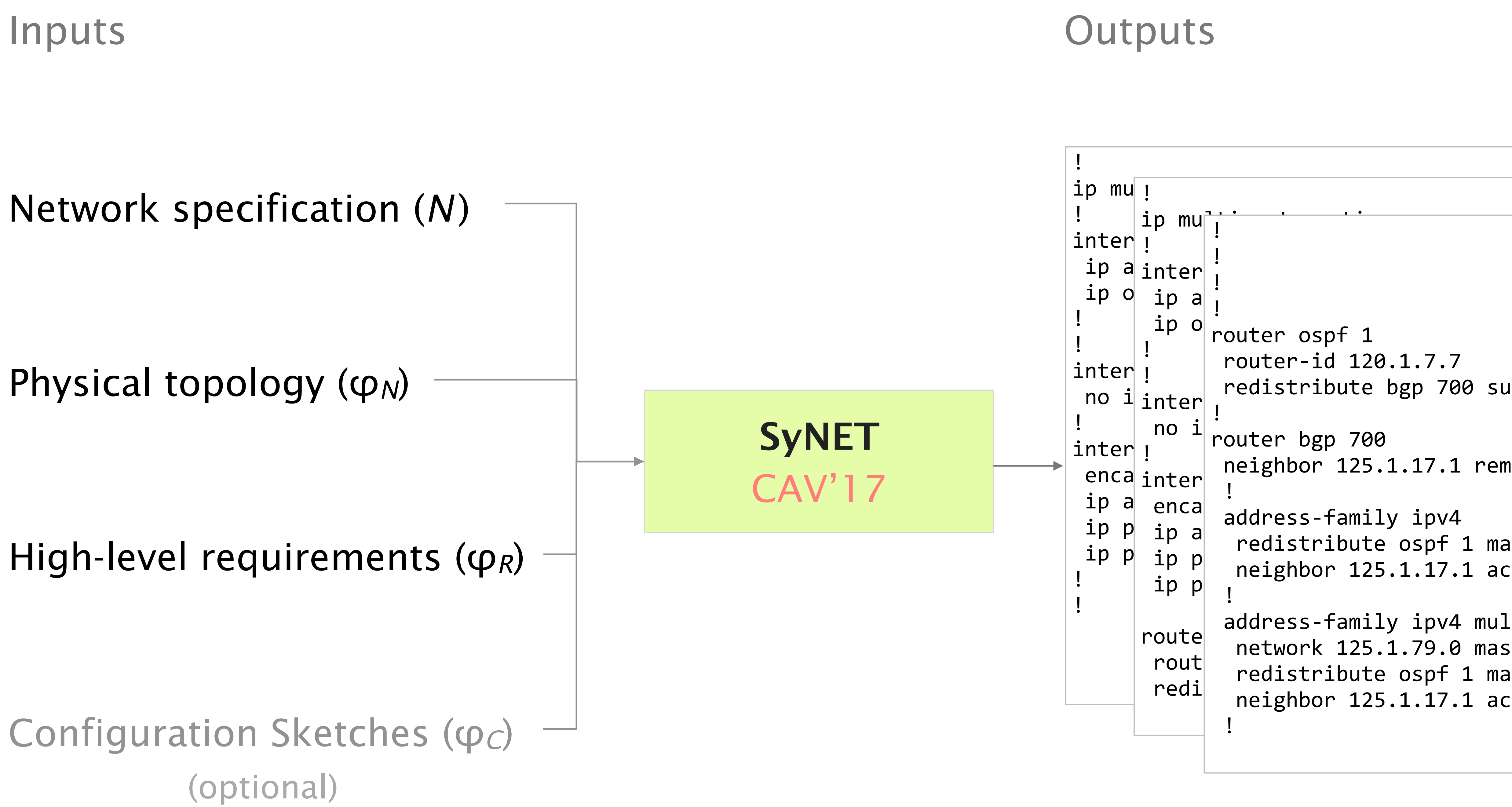
BGP configurations

doesn't support other protocols

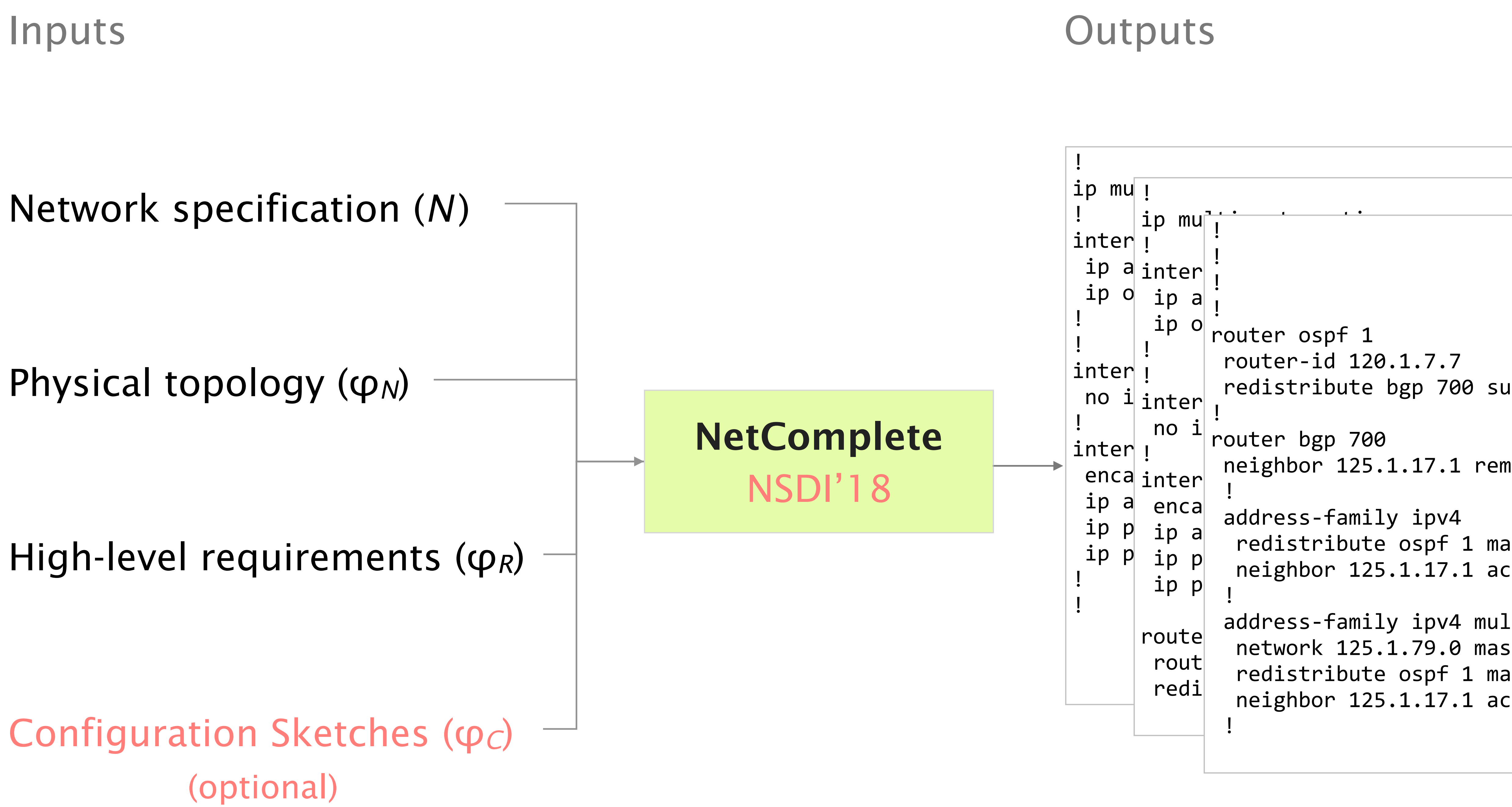
CPR [SOSP'17]

Minimal configuration repairs

partial support for BGP policies



Inputs
Outputs
Network specification (N)
Physical topology (φN)
High-level requirements (φR)
Configuration Sketches (φC)
(optional)
SyNET
CAV'17
router ospf 1
router-id 120.1.7.7
redistribute bgp 700 su
router bgp 700
neighbor 125.1.17.1 rem
address-family ipv4
redistribute ospf 1 ma
neighbor 125.1.17.1 ac
address-family ipv4 mul
network 125.1.79.0 mas
redistribute ospf 1 ma
neighbor 125.1.17.1 ac



Inputs
Outputs
Network specification (N)
Physical topology (φN)
High-level requirements (φR)
Configuration Sketches (φC)
(optional)
NetComplete
NSDI'18
router ospf 1
router-id 120.1.7.7
router bgp 700
address-family ipv4

By accepting partial configurations as inputs,
NetComplete solves two problems of SyNET

Problem #1

Interpretability

Existing synthesizers can produce configurations that differ widely from existing ones

Problem #1 Interpretability	Existing synthesizers can produce configurations that differ widely from existing ones
NetComplete	Operators can control the synthesizer output

Problem #1
Interpretability

Existing synthesizers can produce configurations that differ widely from existing ones

NetComplete

Operators can control the synthesizer output

Problem #2
Scalability

Large search space doesn’t bode well with performance

Problem #1 Interpretability	Existing synthesizers can produce configurations that differ widely from existing ones
NetComplete	Operators can control the synthesizer output
Problem #2 Scalability	Large search space doesn’t bode well with performance
NetComplete	Partial configurations reduce the search space

By accepting partial configurations as inputs, NetComplete solves two problems of SyNET

How? Using a "sketching language"

A configuration sketch is a configuration containing “holes” that have to be synthesized

```
interface TenGigabitEthernet1/1/1
  ip address ? ?
  ip ospf cost 10 < ? < 100

router ospf 100
  ?
  ...

router bgp 6500
  ...
  neighbor AS200 import route-map imp-p1
  neighbor AS200 export route-map exp-p1
  ...
ip community-list C1 permit ?
ip community-list C2 permit ?
```

```
route-map imp-p1 permit 10
  set ?
  set ?
route-map exp-p1 ? 10
  match community C2
route-map exp-p2 ? 20
  match community C1
...
```

The holes can identify specific attributes such as IP addresses, link costs or BGP local preferences

```
interface TenGigabitEthernet1/1/1
  ip address ? ?
  ip ospf cost 10 < ? < 100

router ospf 100
  ?
  ...

router bgp 6500
  ...
  neighbor AS200 import route-map imp-p1
  neighbor AS200 export route-map exp-p1
  ...
ip community-list C1 permit ?
ip community-list C2 permit ?
```

```
route-map imp-p1 permit 10
  set ?
  set ?
route-map exp-p1 ? 10
  match community C2
route-map exp-p2 ? 20
  match community C1
...
```

The holes can also identify entire pieces of the configuration

```
interface TenGigabitEthernet1/1/1
  ip address ? ?
  ip ospf cost 10 < ? < 100

router ospf 100
 ?
  ...

router bgp 6500
  ...
  neighbor AS200 import route-map imp-p1
  neighbor AS200 export route-map exp-p1
  ...
ip community-list C1 permit ?
ip community-list C2 permit ?
```

```
route-map imp-p1 permit 10
  set ?
  set ?
route-map exp-p1 ? 10
  match community C2
route-map exp-p2 ? 20
  match community C1
...
```

The sketching language also allow operators to specify constraints on the concrete values

```
interface TenGigabitEthernet1/1/1
  ip address ? ?
  ip ospf cost 10 < ? < 100

router ospf 100
  ?
  ...

router bgp 6500
  ...
  neighbor AS200 import route-map imp-p1
  neighbor AS200 export route-map exp-p1
  ...
ip community-list C1 permit ?
ip community-list C2 permit ?
```

```
route-map imp-p1 permit 10
  set ?
  set ?
route-map exp-p1 ? 10
  match community C2
route-map exp-p2 ? 20
  match community C1
...
```

NetComplete "autocompletes" the holes such that the output configuration complies with the requirements

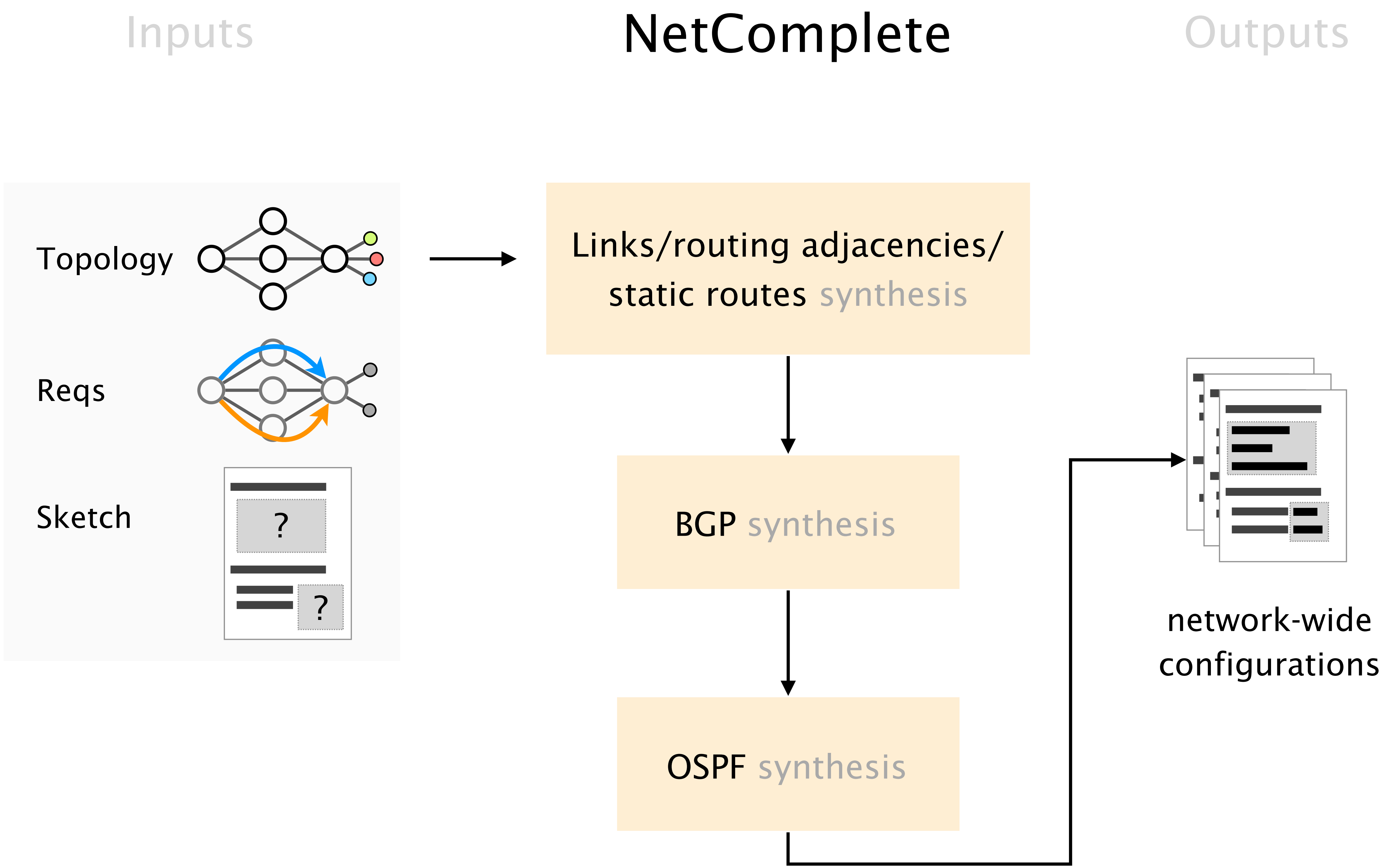
```
interface TenGigabitEthernet1/1/1
  ip address 10.0.0.1 255.255.255.254
  ip ospf cost 15

router ospf 100
  network 10.0.0.1 0.0.0.1 area 0.0.0.0
  ...

router bgp 6500
  ...
  neighbor AS200 import route-map imp-p1
  neighbor AS200 export route-map exp-p1
  ...
ip community-list C1 permit 6500:1
ip community-list C2 permit 6500:2
```

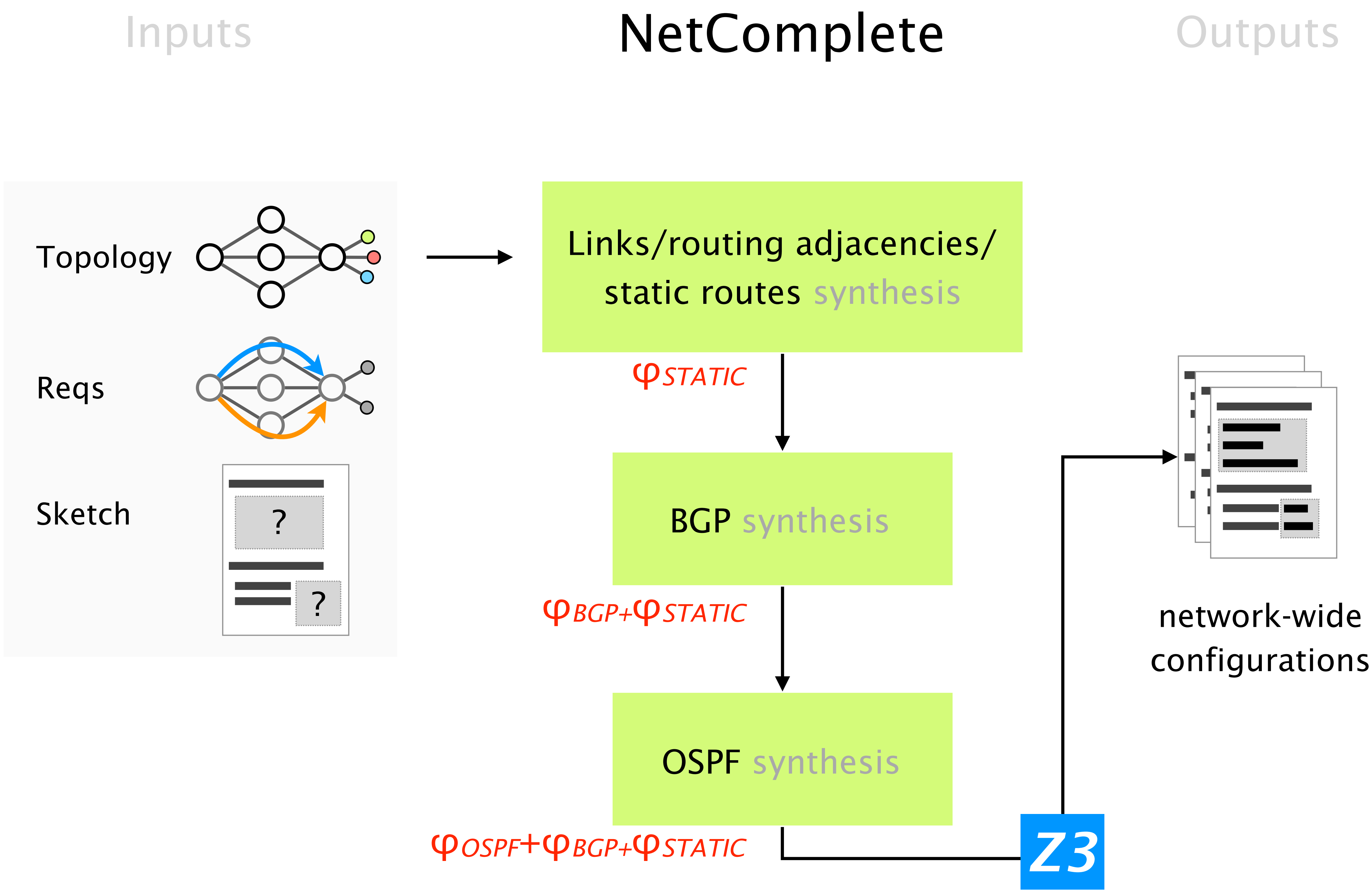
```
route-map imp-p1 permit 10
  set community 6500:1
  set local-pref 50
route-map exp-p1 permit 10
  match community C2
route-map exp-p2 deny 20
  match community C1
...
```

NetComplete

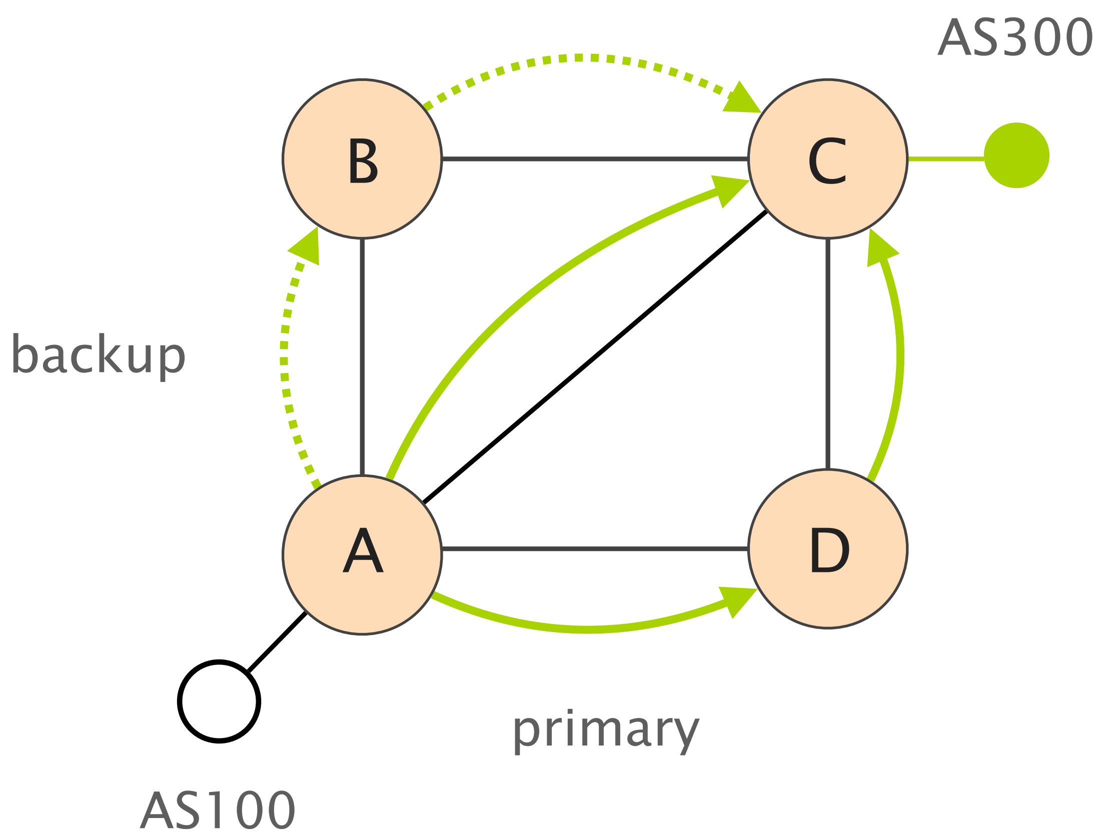


With respect to SyNET, NetComplete generates domain-specific SMT constraints for each protocol

NetComplete

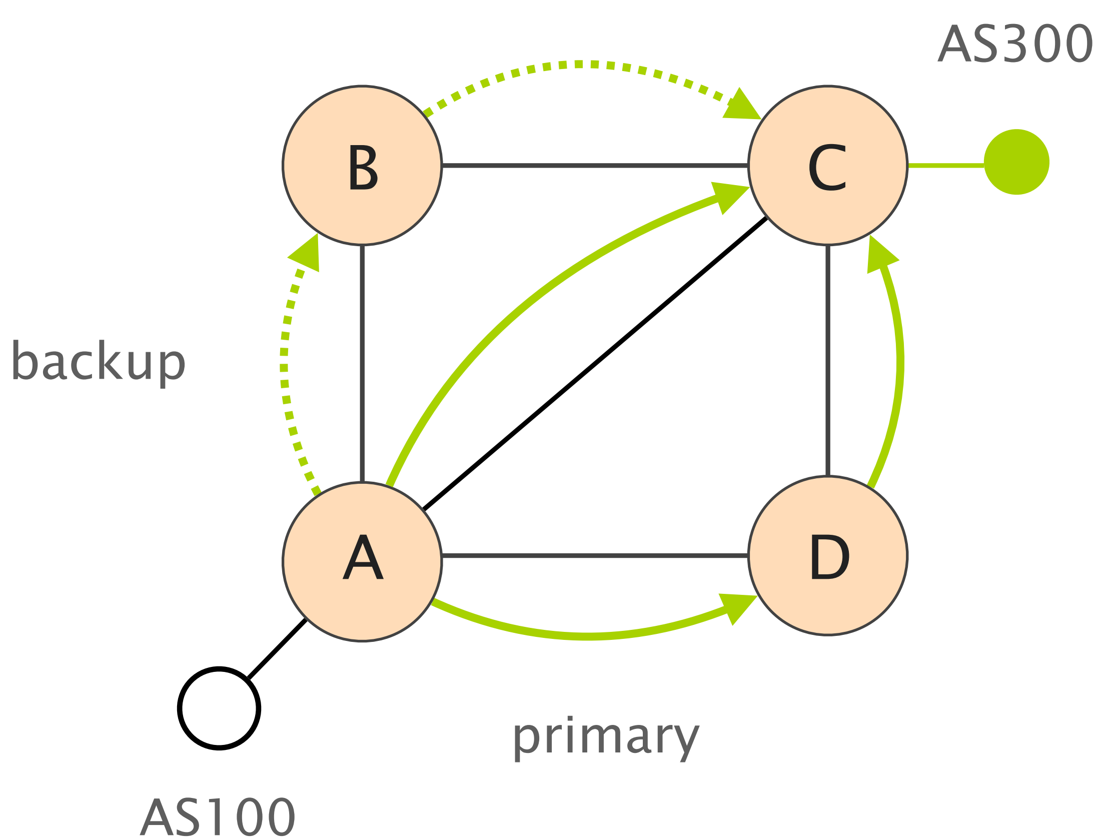


Let’s consider the OSPF box



Requirement

$$(AS100 \to A \to C \to AS300 = AS100 \to A \to D \to C \to AS300) \gg AS100 \to A \to B \to C \to AS300$$



Requirement

$$(AS100 \to A \to C \to AS300$$
$$= AS100 \to A \to D \to C \to AS300)$$
$$\gg AS100 \to A \to B \to C \to AS300$$

Naive OSPF encoding

$$Cost(A \to C) = Cost(A \to D \to C)$$
$$\wedge \left(Cost(A \to C) < Cost(A \to B \to C)\right)$$
$$\wedge \boxed{\left(\forall X \in Paths(AS100, AS300) \setminus S.\right.}$$
$$\left. Cost(A \to B \to C) < Cost(X)\right), \text{ where}$$
$$S = \{A \to C, A \to D \to C, A \to B \to C\}$$

doesn't scale to large networks!

To scale, NetComplete leverages
Counter-Example Guided Inductive Synthesis

To scale, NetComplete leverages

Counter-Example Guided Inductive Synthesis

An contemporary approach to synthesis where
a solution is iteratively learned from counter-examples

While finding weights is hard,
computing shortest-path is *easy*

Instead of considering *all* paths between X and Y

CEGIS

Part 1

Consider a random subset S of them and synthesize the weights considering S only

Instead of considering *all* paths between *X* and *Y*

Consider a random subset *S* of them and synthesize the weights considering *S* only

intuition

Fast as *S* is small compared to all paths,
but can be wrong because we don't consider all paths

Instead of considering *all* paths between X and Y

Consider a random subset S of them and synthesize the weights considering S only

CEGIS
Part 2

Check whether the weights found comply with the requirements over all paths

- If so, return
- If not, take a counter-example (a path) that violates the Req and add it to S

Repeat.

Instead of considering *all* paths between X and Y

Consider a random subset S of them and synthesize the weights considering S only

Check whether the weights found comply with the requirements over all paths

intuition

Fast too

simple shortest-path computation

The entire procedure usually converges in few iterations—making it very fast in practice

Instead of considering *all* paths between *X* and *Y*

Consider a random subset *S* of them and synthesize the weights considering *S* only

Check whether the weights found comply with the requirements over all paths

If so, return

If not, take a counter-example (a path) that violates the Req and add it to *S*

Repeat.

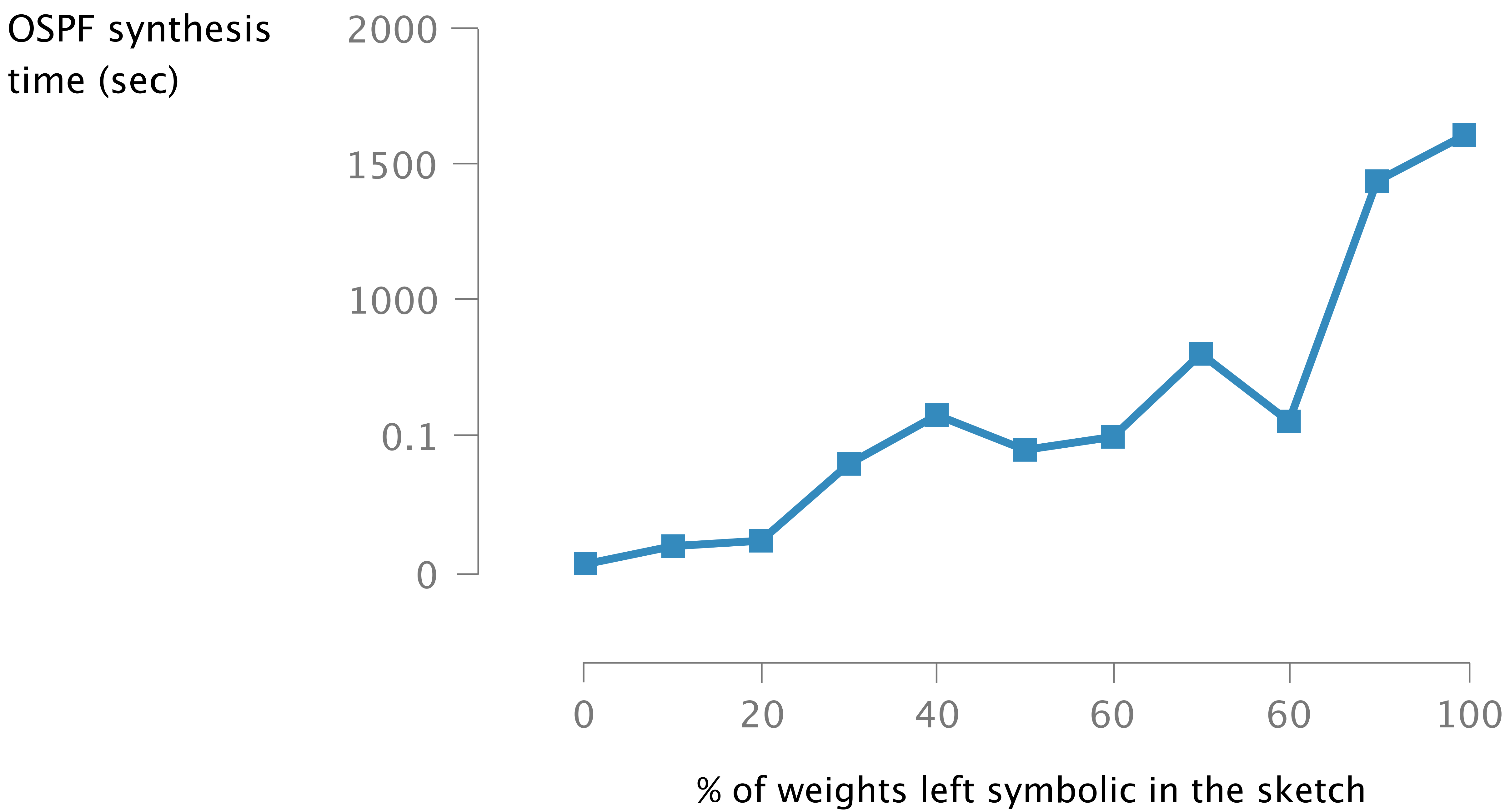
We fully implemented NetComplete and showed its practicality

Code	~10K lines of Python
	SMT-LIB v2 and Z3
Input	OSPF, BGP, static routes
	as partial and concrete configs
Output	Cisco-compatible configurations
	validated with actual Cisco routers

NetComplete can synthesize configurations for large networks in few minutes

	Network size	Reqs. type 16 in total	% of symbolic value in the sketch 50%	100%
OSPF synthesis time (sec) averaged over 5 topos	Medium 68—74 nodes	Simple	6s	6s
		ECMP	6s	6s
		Ordered	31s	43s
	Large 145—197 nodes	Simple	14s	14s
		ECMP	13s	14s
		Ordered	249s	1155s

NetComplete synthesis time increases as the sketch becomes more symbolic



NetComplete scales *much better* than SyNET

# routers	# protocols	SyNET	NetComplete
49	static	14 min	0.05s
	static, OSPF	5h 22min	2m 1s
	static, OSPF, BGP	timeout (>24h)	44m 2s
64	static	49 min	0.06s
	static, OSPF	21h 13min	2m 22s
	static, OSPF, BGP	timeout (>24h)	6h 6min

>**600x** speed-up

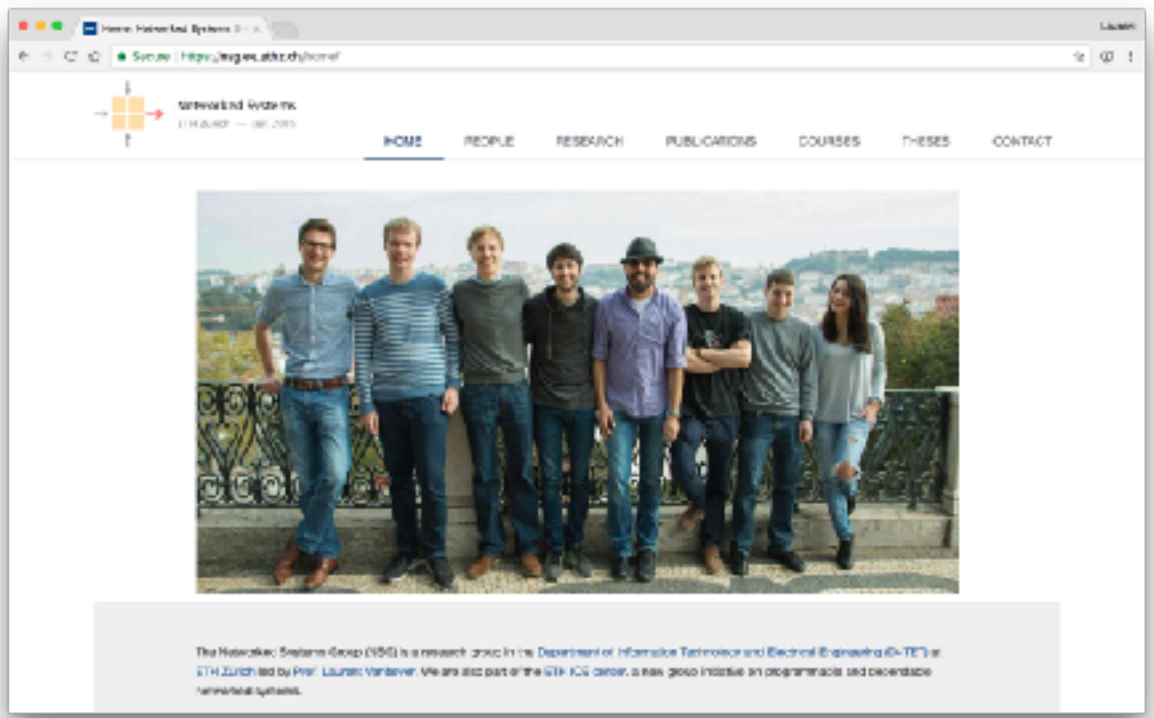
# routers	# protocols	SyNET	NetComplete
49	static	14 min	0.05s
	static, OSPF	5h 22min	2m 1s
	static, OSPF, BGP	timeout (>24h)	44m 2s
64	static	49 min	0.06s
	static, OSPF	21h 13min	2m 22s
	static, OSPF, BGP	timeout (>24h)	6h 6min

Network control & programmability

through synthesis

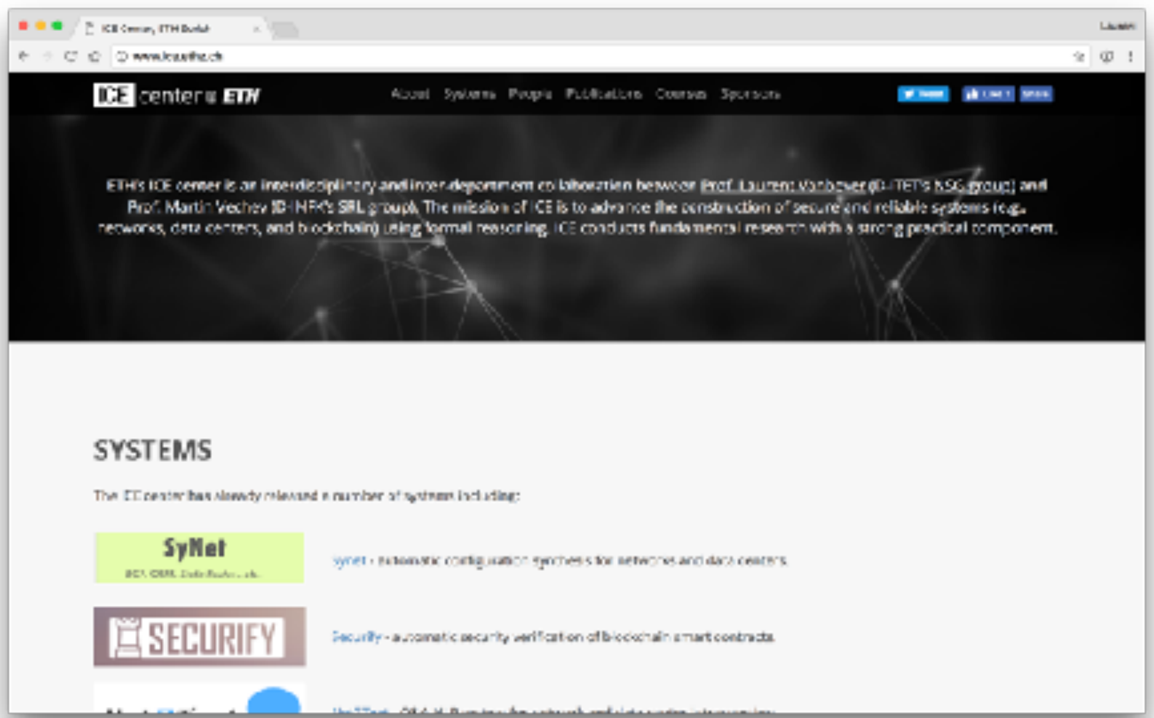
Topology (fixed)	+	Network-wide Configuration	+	Network Environment	→	Network-wide Forwarding state
		Part 2		Part 1		

If you want to have more information about our research…



Networked Systems Group

nsg.ee.ethz.ch



ICE

ice.ethz.ch

Programming networks

Not your standard API

Laurent Vanbever

nsg.ee.ethz.ch

NII Shonan Meeting

Mon Feb 26 2018