Communication Networks

Spring 2017

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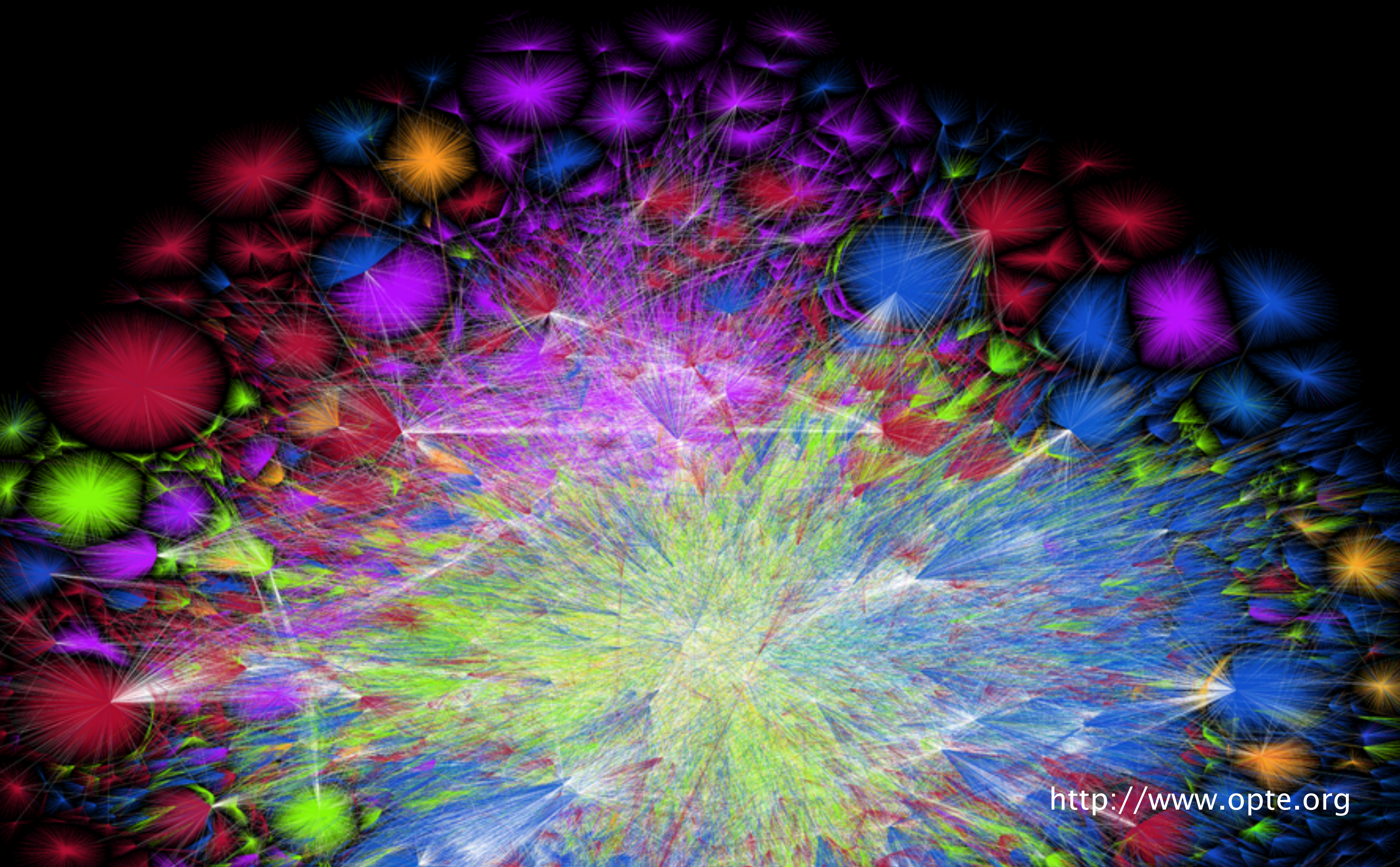
April, 10 2017

Material inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

Internet routing



Internet routing

from here to there, and back

1 **Intra-domain routing**

- Link-state protocols
- Distance-vector protocols

2 **Inter-domain routing**

- Path-vector protocols

Internet routing

from here to there, and back

1 **Intra-domain routing**

Link-state protocols

Distance-vector protocols

Inter-domain routing

Path-vector protocols

In Link-State routing, routers build a precise map of the network by flooding local views to everyone

Each router keeps track of its incident links and cost

as well as whether it is up or down

Each router broadcast its own links state

to give every router a complete view of the graph

Routers run Dijkstra on the corresponding graph

to compute their shortest-paths and forwarding tables

During network changes,
the link-state database of each node might differ

control-plane consistency

all nodes have the same link-state database

necessary

forwarding validity

the global forwarding state directs packet to its destination

Inconsistencies lead to transient disruptions in the form of blackholes or forwarding loops

Avoiding transient loops during the convergence of link-state routing protocols

Pierre Francois and Olivier Bonaventure
Université catholique de Louvain

Abstract—**When using link-state protocols such as OSPF or IS-IS, forwarding loops can occur transiently when the routers adapt their forwarding tables as a response to a topological change. In this paper[1], we present a mechanism that lets the network converge to its optimal forwarding state without risking any transient loops and the related packet loss. The mechanism is based on an ordering of the updates of the forwarding tables of the routers. Our solution can be used in the case of a planned change in the state of a set of links and in the case of unpredictable changes when combined with a local protection scheme. The supported topology changes are link transitions from up to down, down to up, and updates of link metrics. Finally, we show by simulations that sub-second loop free convergence is possible on a large Tier-1 ISP network.**

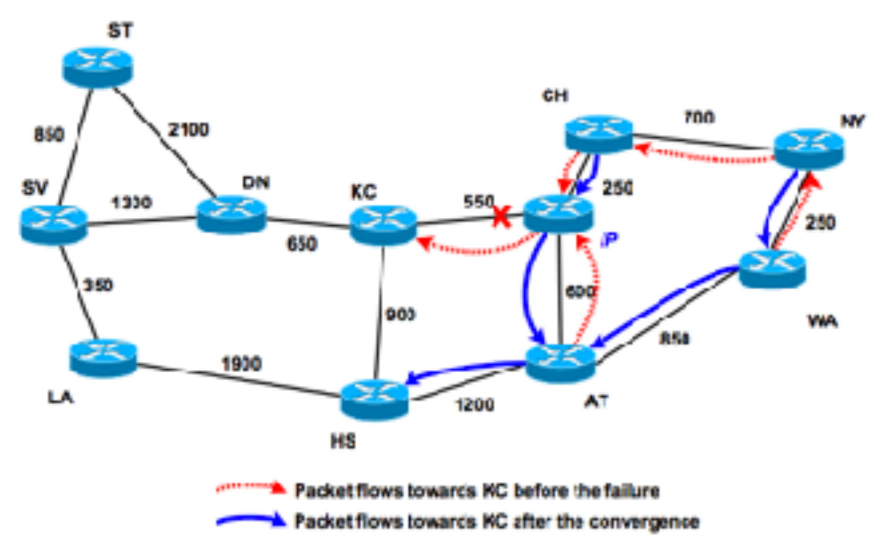


Fig. 1: Internet2 topology with IGP costs

I. Introduction

The link-state intradomain routing protocols that are used in IP networks [2], [3] were designed when IP networks were research networks carrying best-effort packets. The same protocols are now used in large commercial ISPs with strin-
...ements (SLA). Furthermore, for most
...s, fast convergence in case of failures
is a key problem that must be solved [4], [5]. Today, customers are requiring 99.99% reliability or better and providers try to

net2/Abilene backbone[2]. Figure 1 shows the IGP topology of this network. Assume that the link between IP and KC fails but was protected by an MPLS tunnel between IP and KC via AT and HS. When AT receives a packet with destination DN, it forwards it to IP, which forwards it back to AT, but inside the protection tunnel, so that KC will decapsulate the packet, and forward it to its destination, DN.

This suboptimal routing should not last long, and thus after a

see http://bit.ly/2olXtnF

Distance-vector protocols are based on Bellman-Ford algorithm

Let $d_x(y)$ be the cost of the least-cost path known by x to reach y

Each node bundles these distances into one message (called a vector)

until convergence

that it repeatedly sends to all its neighbors

Each node updates its distances based on neighbors' vectors:

$d_x(y) = \min\{\ c(x,v) + d_v(y)\ \}$ over all neighbors v

Unlike Link-State protocols,

Distance-Vector protocols converge slowly

Internet routing

from here to there, and back

Intra-domain routing

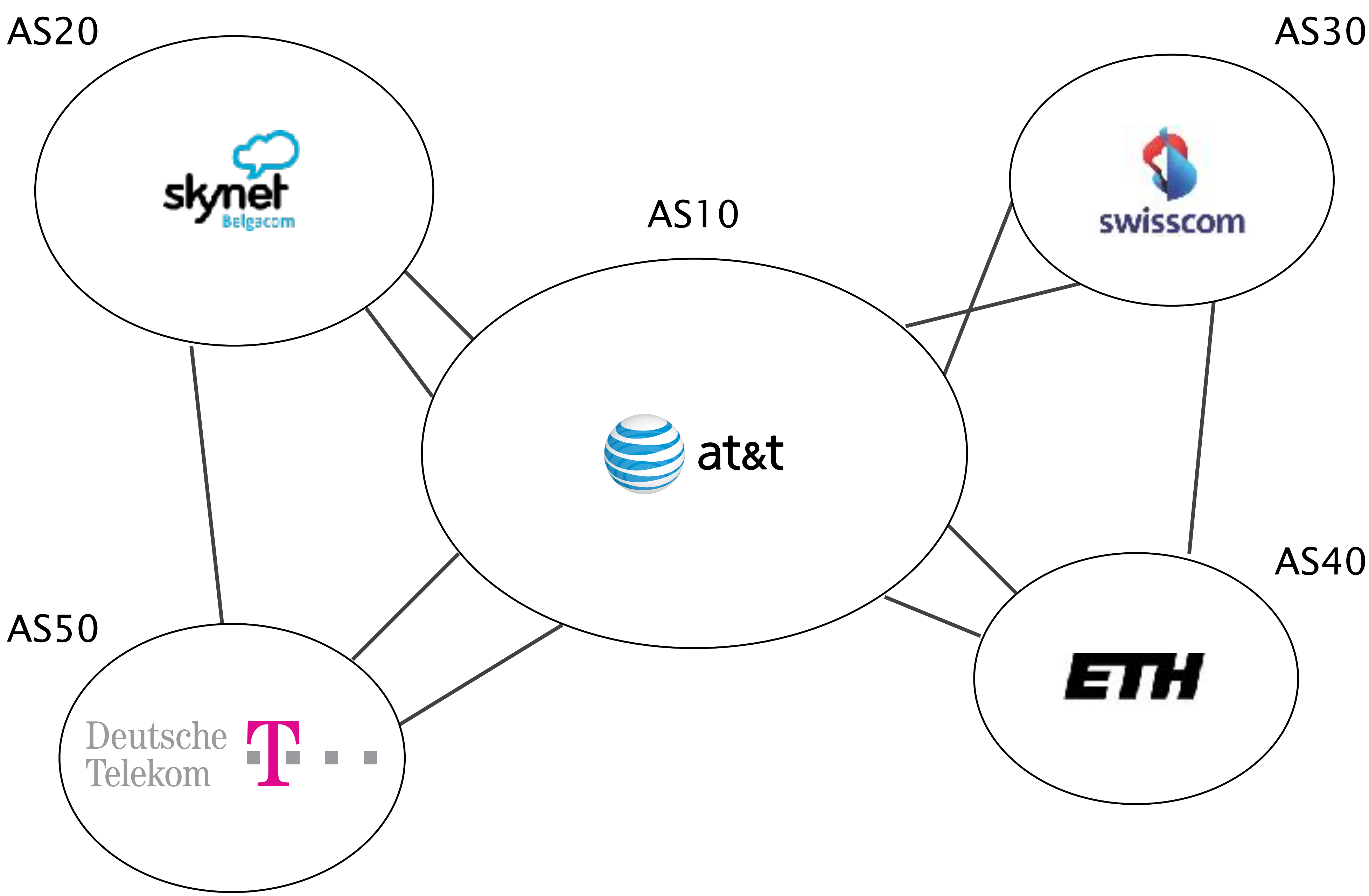
Link-state protocols

Distance-vector protocols

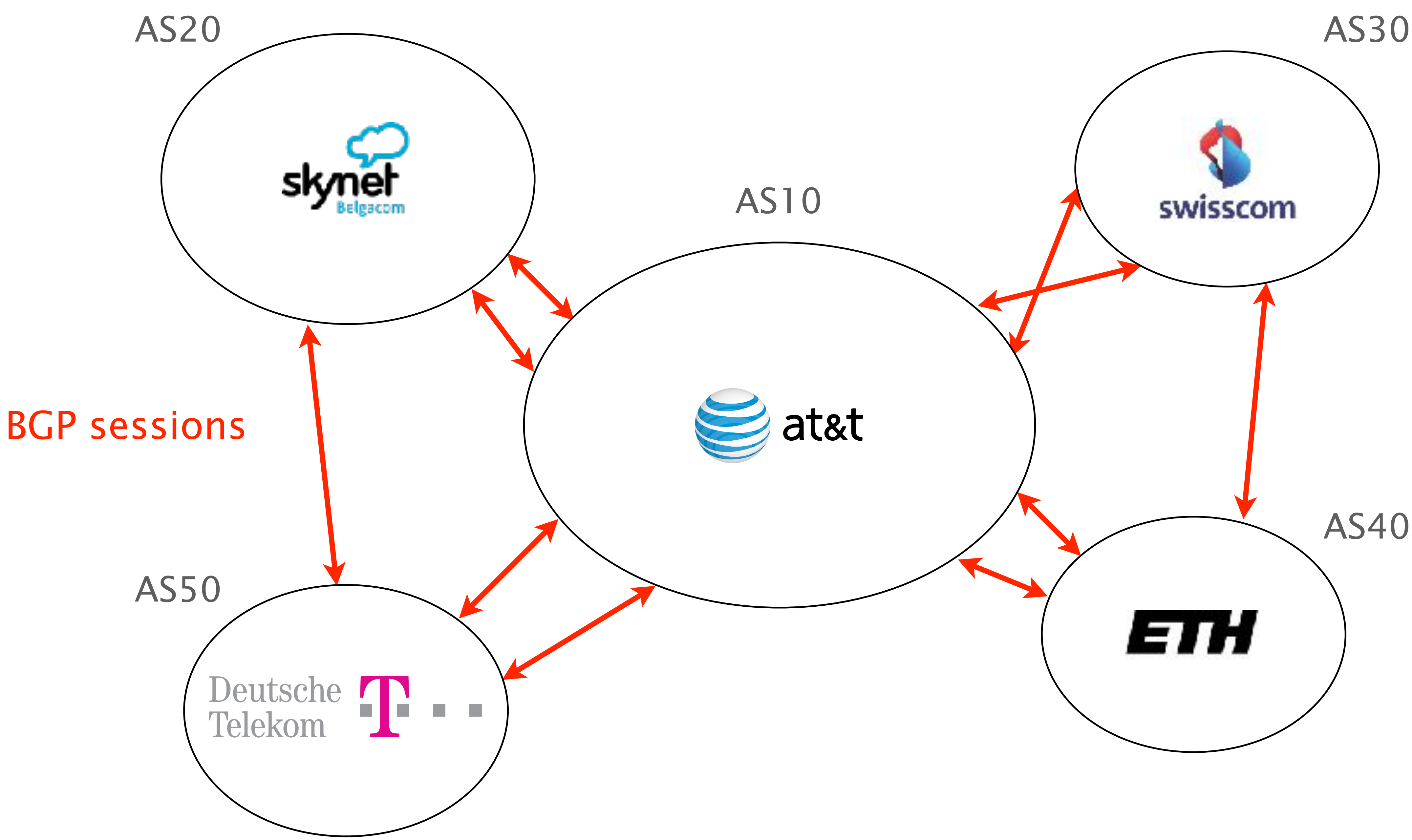
2 Inter-domain routing

Path-vector protocols

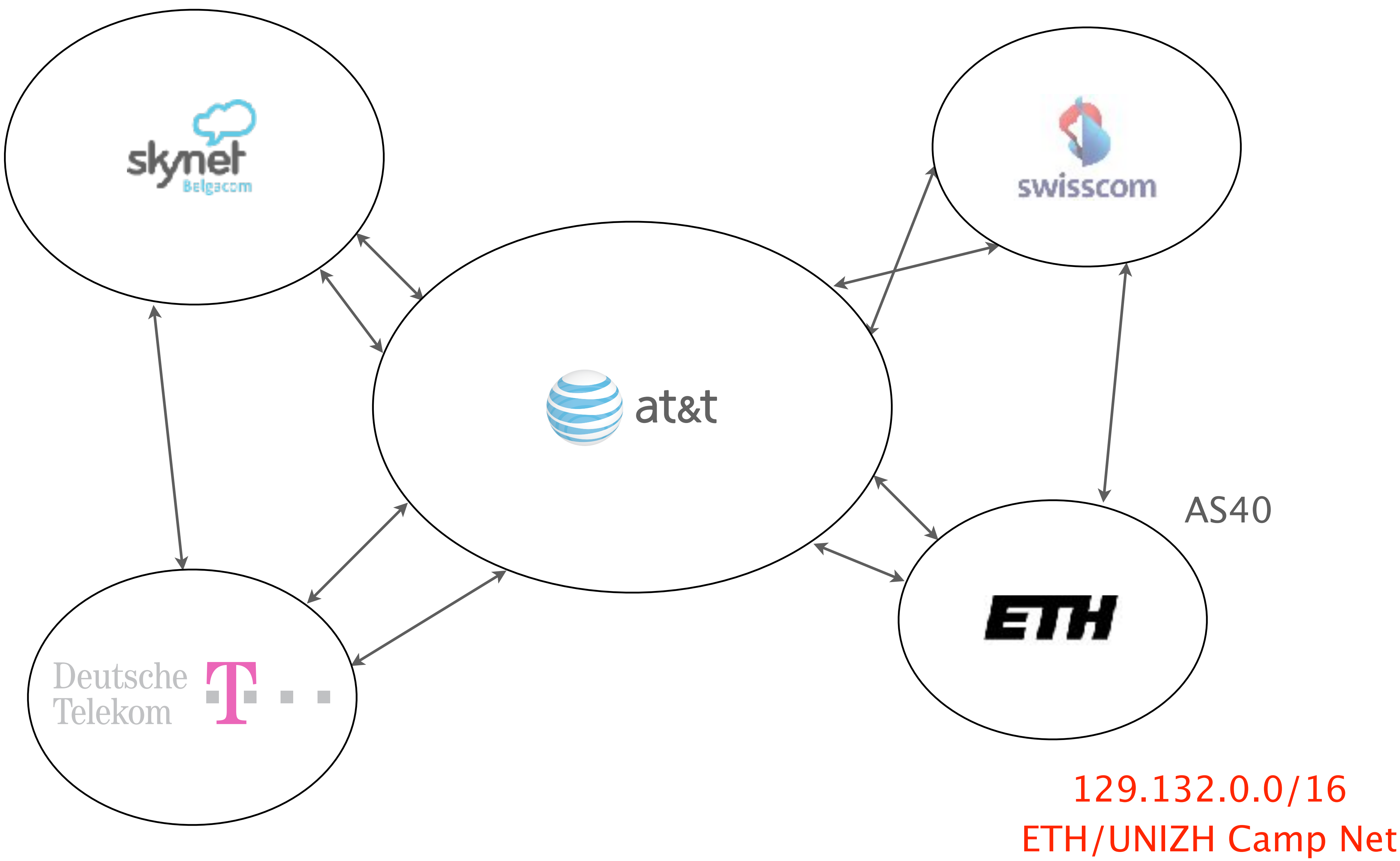
The Internet is a network of networks, referred to as Autonomous Systems (AS)



BGP is the routing protocol "glueing" the Internet together



Using BGP, ASes exchange information about the IP prefixes they can reach, directly or indirectly



BGP needs to solve three key challenges: scalability, privacy and policy enforcement

There is a huge # of networks and prefixes

600k prefixes, >50,000 networks, millions (!) of routers

Networks don't want to divulge internal topologies

or their business relationships

Networks needs to control where to send and receive traffic

without an Internet-wide notion of a link cost metric

Link-State routing does not solve these challenges

Floods topology information

high processing overhead

Requires each node to compute the entire path

high processing overhead

Minimizes some notion of total distance

works only if the policy is shared and uniform

Distance-Vector routing is on the right track

pros

Hide details of the network topology

nodes determine only “next-hop” for each destination

Distance-Vector routing is on the right track,
but not really there yet…

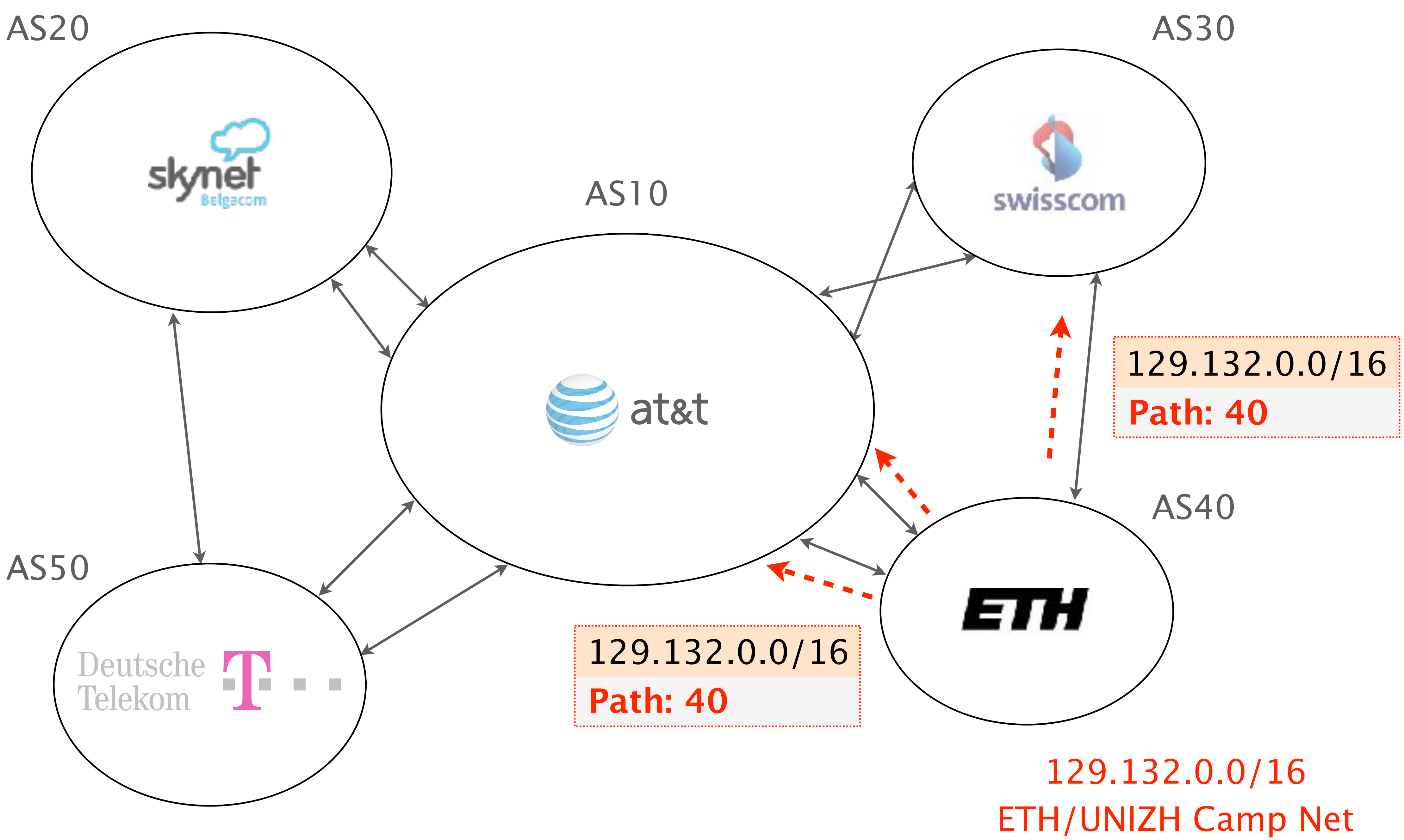
pros	Hide details of the network topology
	nodes determine only "next-hop" for each destination
cons	It still minimizes some common distance
	impossible to achieve in an inter domain setting
	It converges slowly
	counting-to-infinity problem

BGP relies on path-vector routing to support flexible routing policies and avoid count-to-infinity

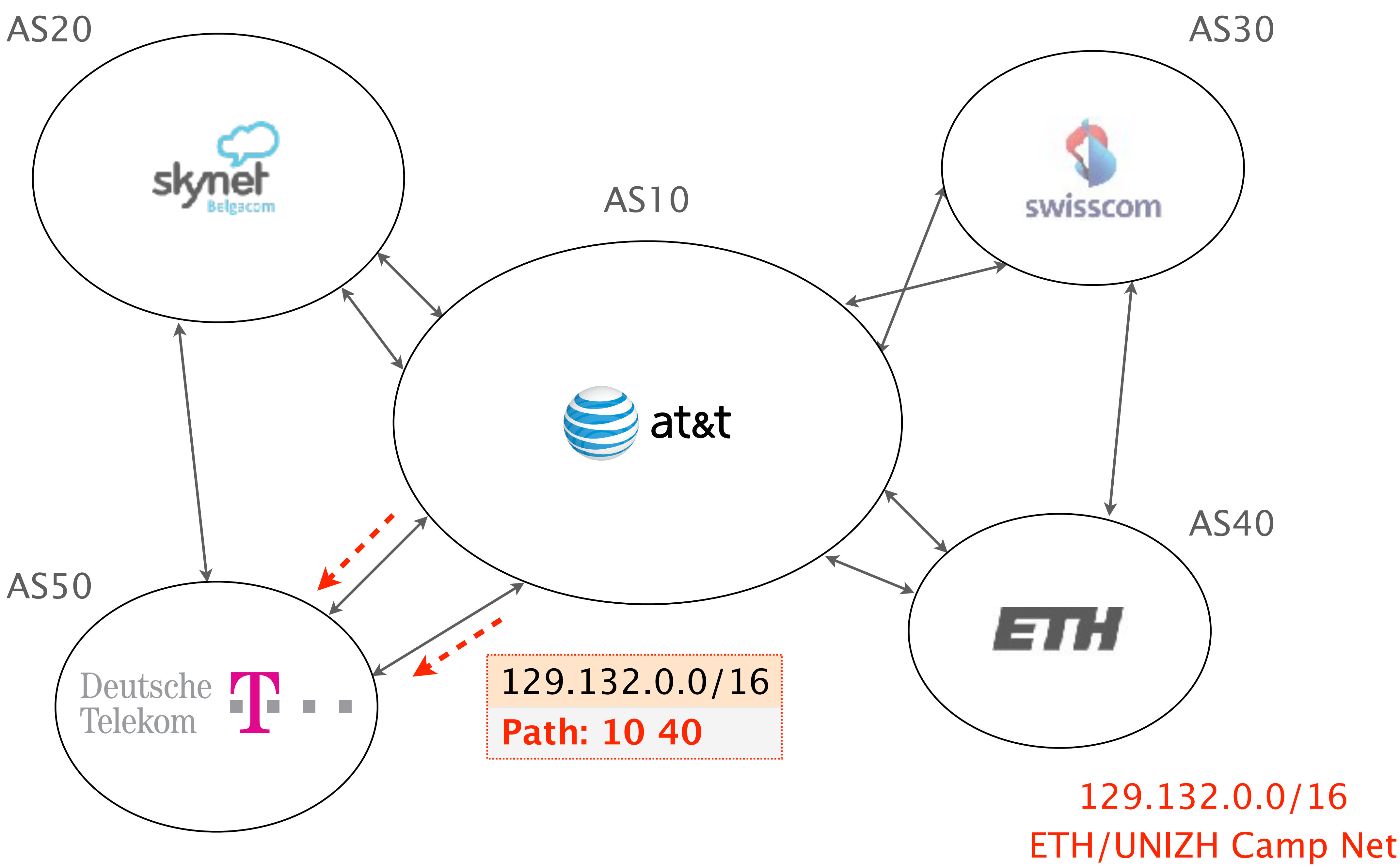
key idea

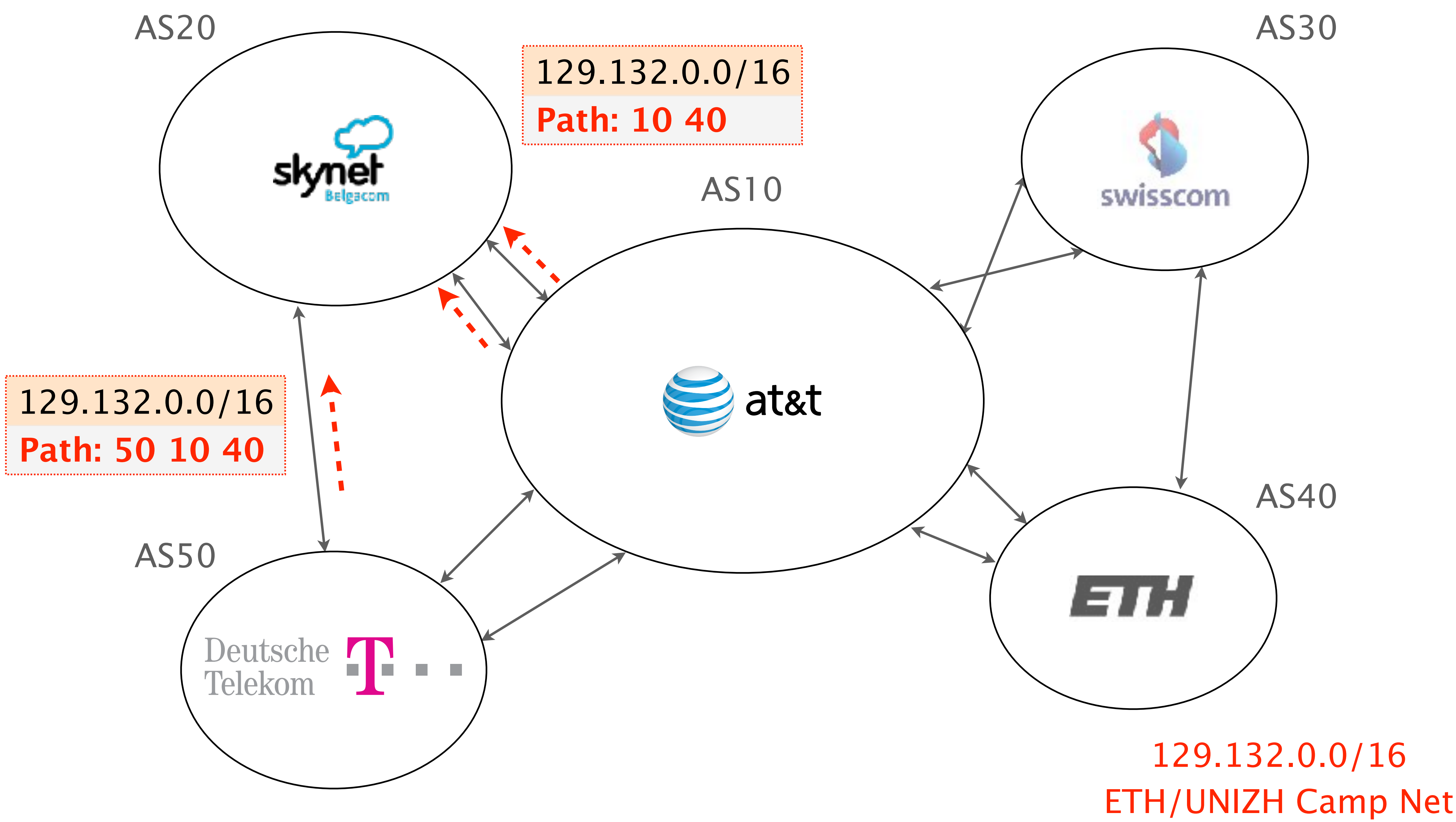
advertise the entire path instead of distances

BGP announcements carry complete path information instead of distances



Each AS appends itself to the path when it propagates announcements



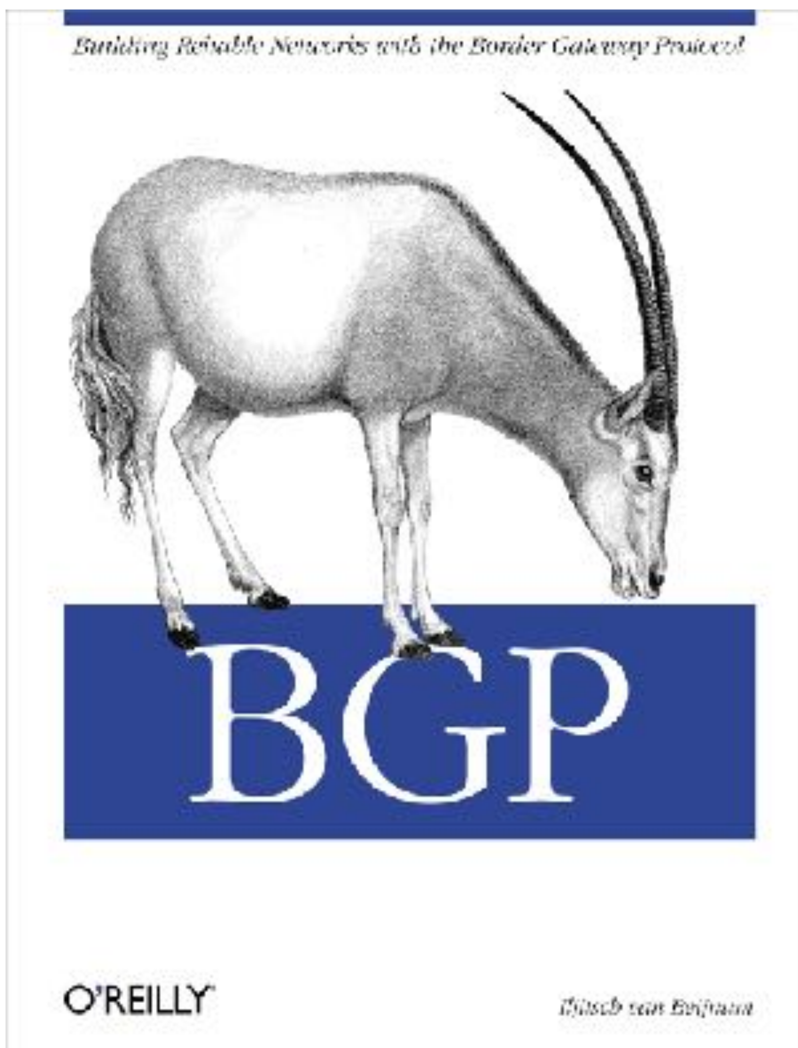

AS20
129.132.0.0/16
Path: 10 40
AS30
AS10
129.132.0.0/16
Path: 50 10 40
AS40
AS50
129.132.0.0/16
ETH/UNIZH Camp Net

This week on

Communication Networks

Border Gateway Protocol

policies and more



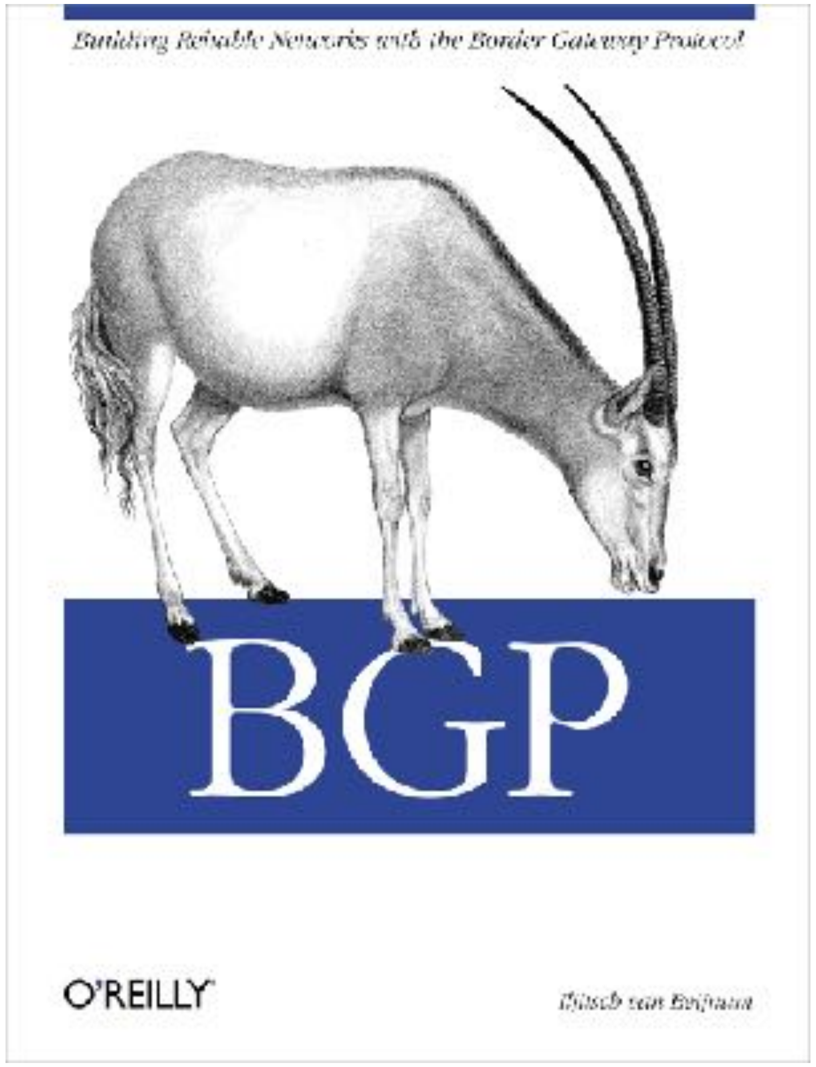
1 **BGP Policies**
Follow the Money

2 **Protocol**
How does it work?

3 **Problems**
security, performance, …

Border Gateway Protocol

policies and more



1 **BGP Policies**

Follow the Money

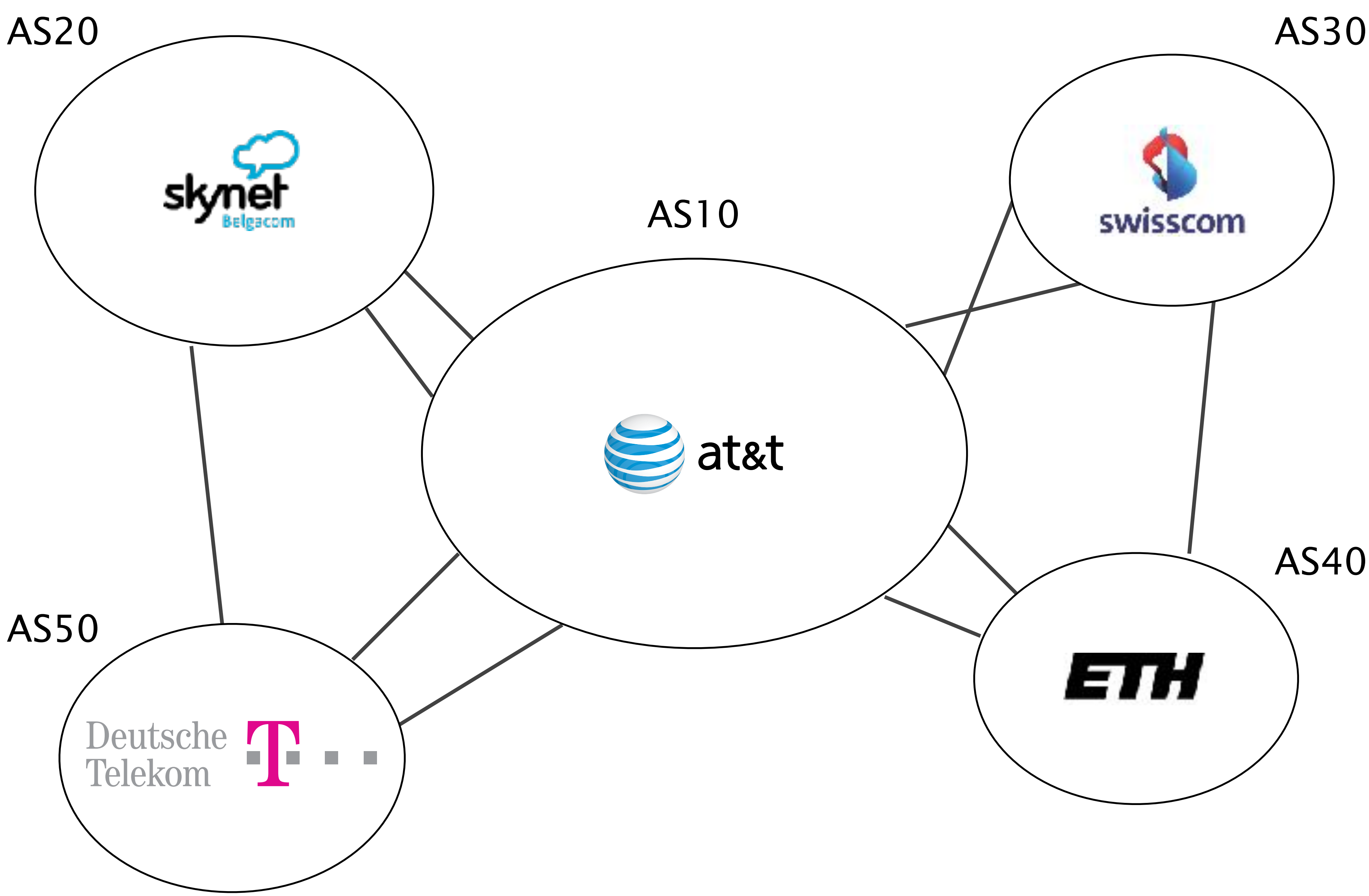
Protocol

How does it work?

Problems

security, performance, …

The Internet topology is shaped according to business relationships



Intuition

2 ASes connect only if they have a business relationship

BGP is a "follow the money" protocol

There are 2 main business relationships today:

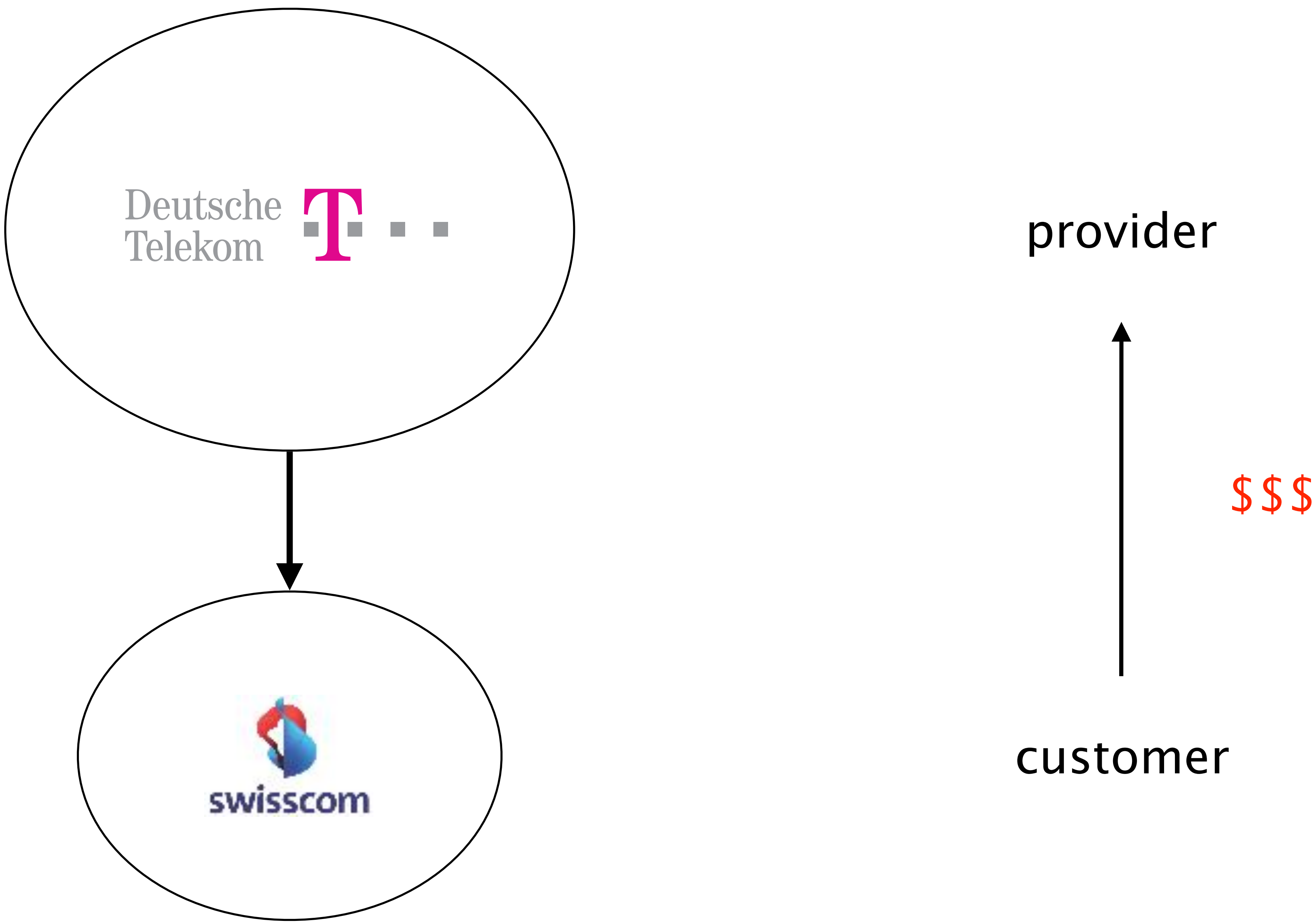
- customer/provider
- peer/peer

many less important ones (siblings, backups,…)

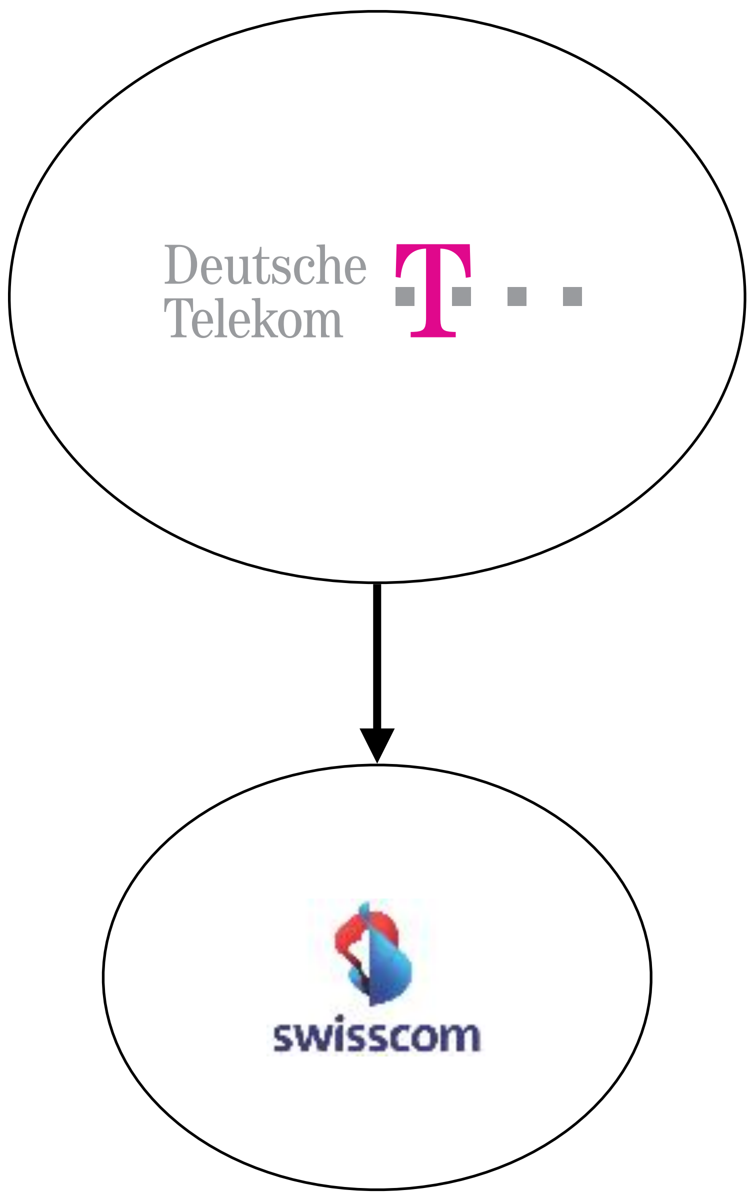
There are 2 main business relationships today:

- customer/provider
- peer/peer

Customers pay providers
to get Internet connectivity



The amount paid is based on peak usage, usually according to the 95th percentile rule



Every 5 minutes, DT

records the # of bytes sent/received

At the end of the month, DT

- sorts all values in decreasing order
- removes the top 5% values
- bills wrt highest remaining value

Most ISPs discounts traffic unit price when pre-committing to certain volume

commit		unit price ($)	Minimum monthly bill ($/month)
10	Mbps	12	120
100	Mbps	5	500
1	Gbps	3.50	3,500
10	Gbps	1.20	12,000
100	Gbps	0.70	70,000

Examples taken from The 2014 Internet Peering Playbook

Internet Transit Prices have been continuously declining during the last 20 years

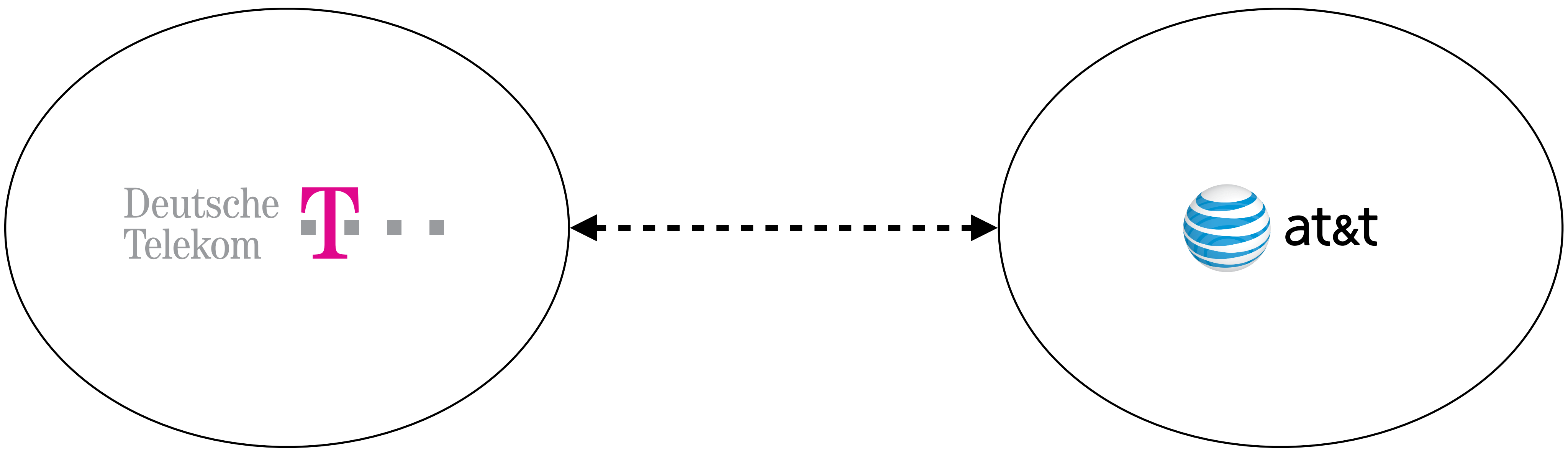
Internet Transit Pricing (1998-2015)			
Source: http://DrPeering.net			
Year	**Internet Transit Price**		**% decline**
1998	$1,200.00	per Mbps	
1999	$800.00	per Mbps	33%
2000	$675.00	per Mbps	16%
2001	$400.00	per Mbps	41%
2002	$200.00	per Mbps	50%
2003	$120.00	per Mbps	40%
2004	$90.00	per Mbps	25%
2005	$75.00	per Mbps	17%
2006	$50.00	per Mbps	33%
2007	$25.00	per Mbps	50%
2008	$12.00	per Mbps	52%
2009	$9.00	per Mbps	25%
2010	$5.00	per Mbps	44%
2011	$3.25	per Mbps	35%
2012	$2.34	per Mbps	28%
2013	$1.57	per Mbps	33%
2014	$0.94	per Mbps	40%
2015	$0.63	per Mbps	33%

The reason? Internet commoditization & competition

There are 2 main business relationships today:

- customer/provider
- peer/peer

Peers don't pay each other for connectivity,
they do it *out of common interest*

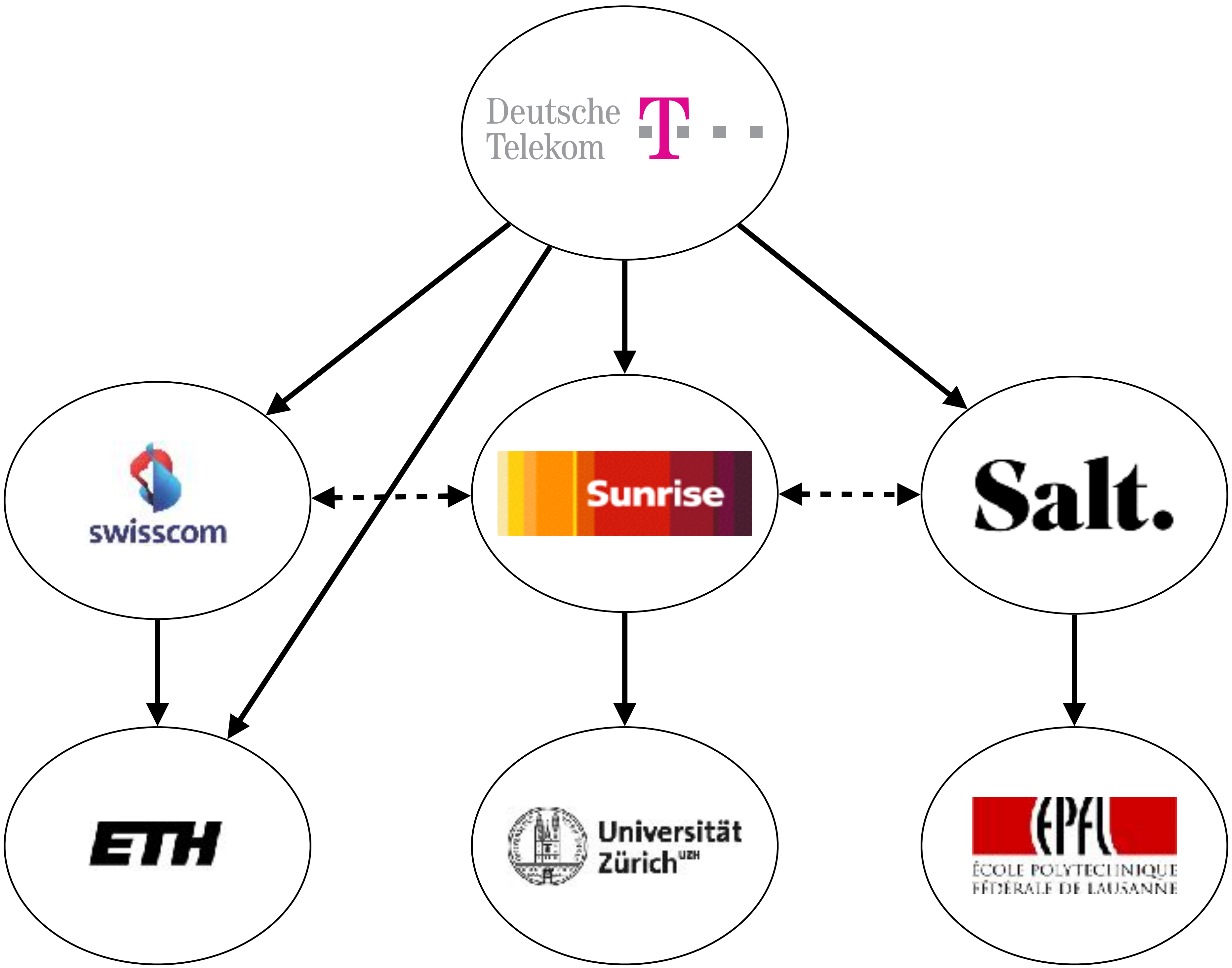


peer peer

DT and ATT exchange *tons* of traffic.
they save money by directly connecting to each other

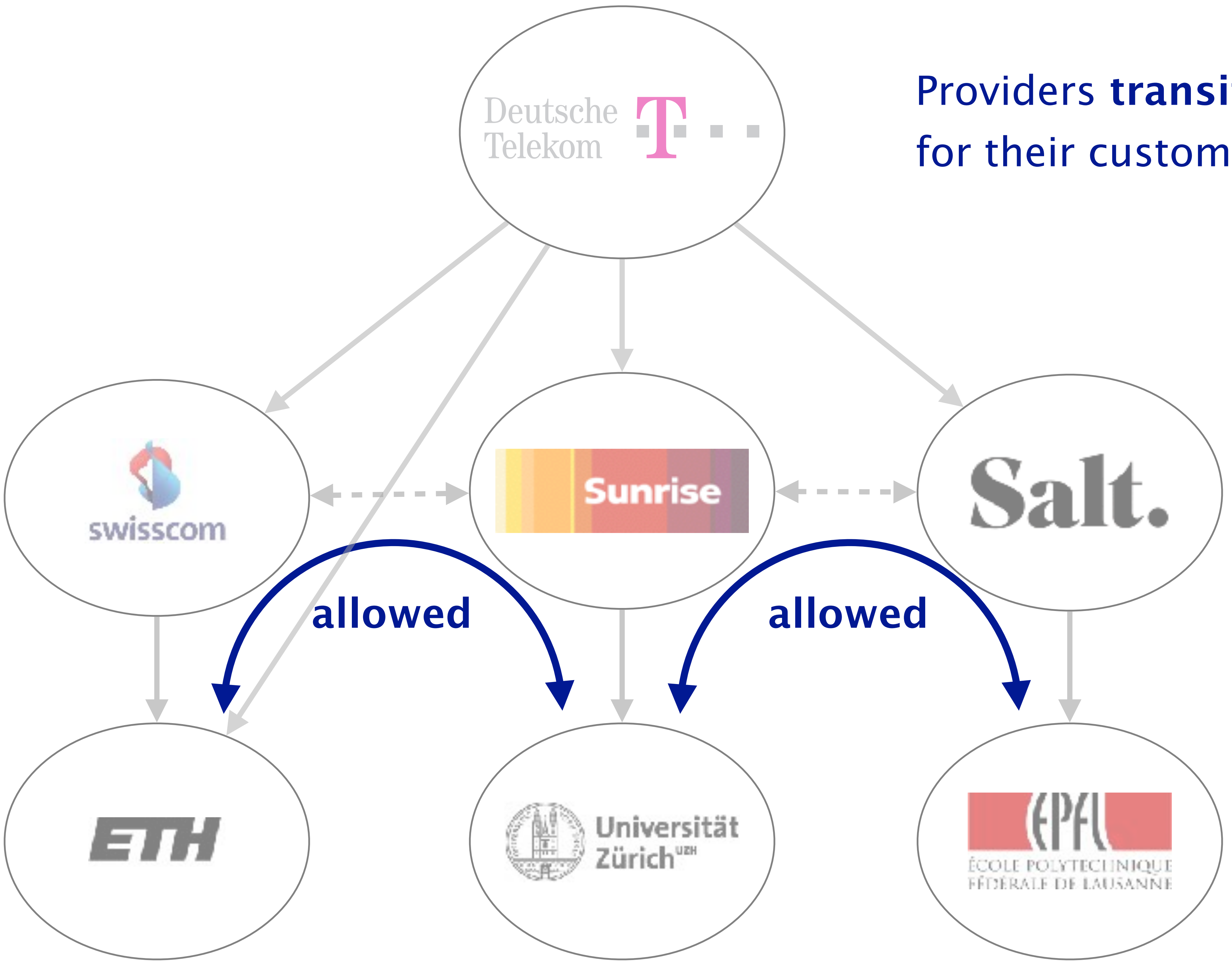
To understand Internet routing,

follow the money

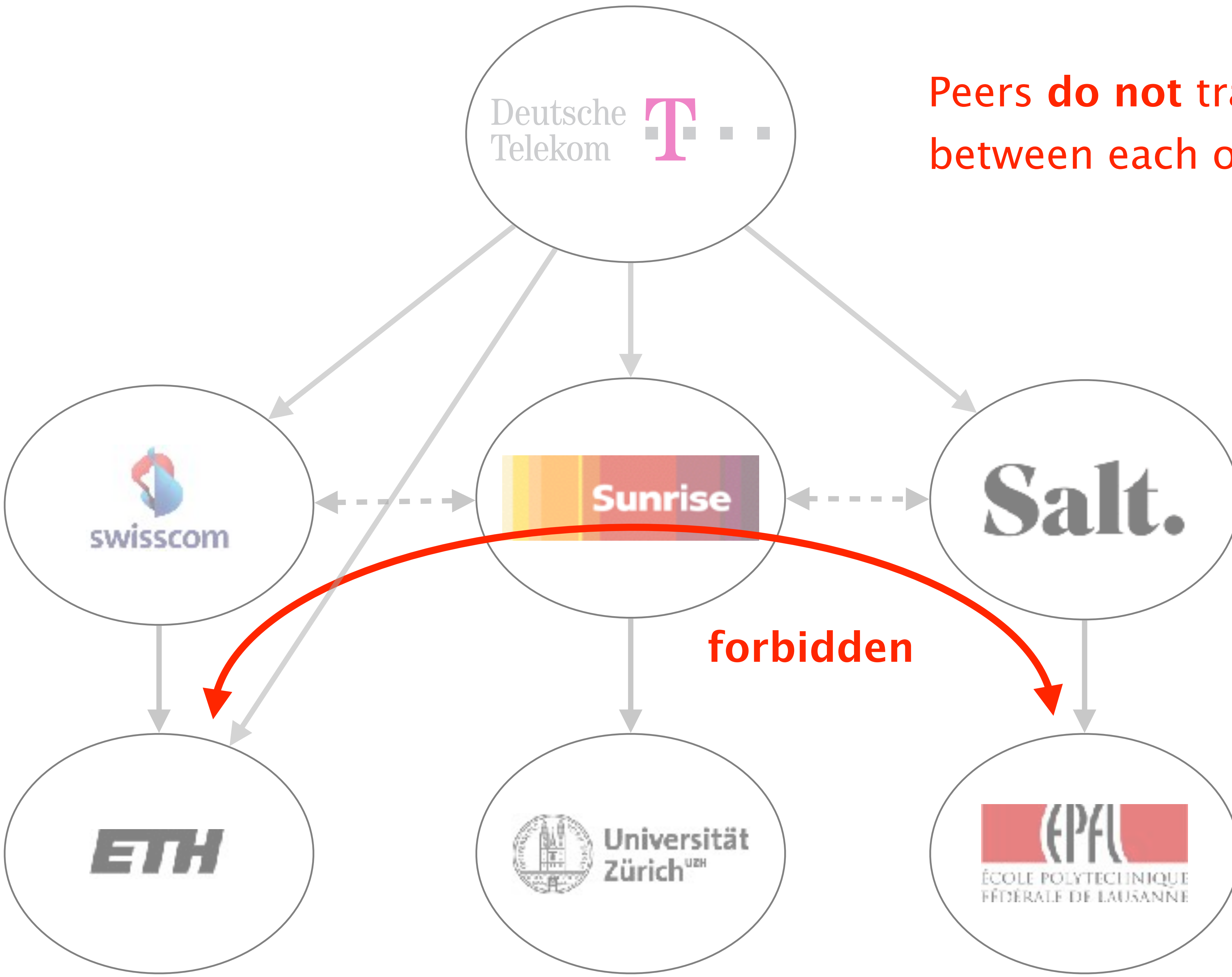


Deutsche Telekom
swisscom
Sunrise
Salt.
ETH
Universität Zürich UZH
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

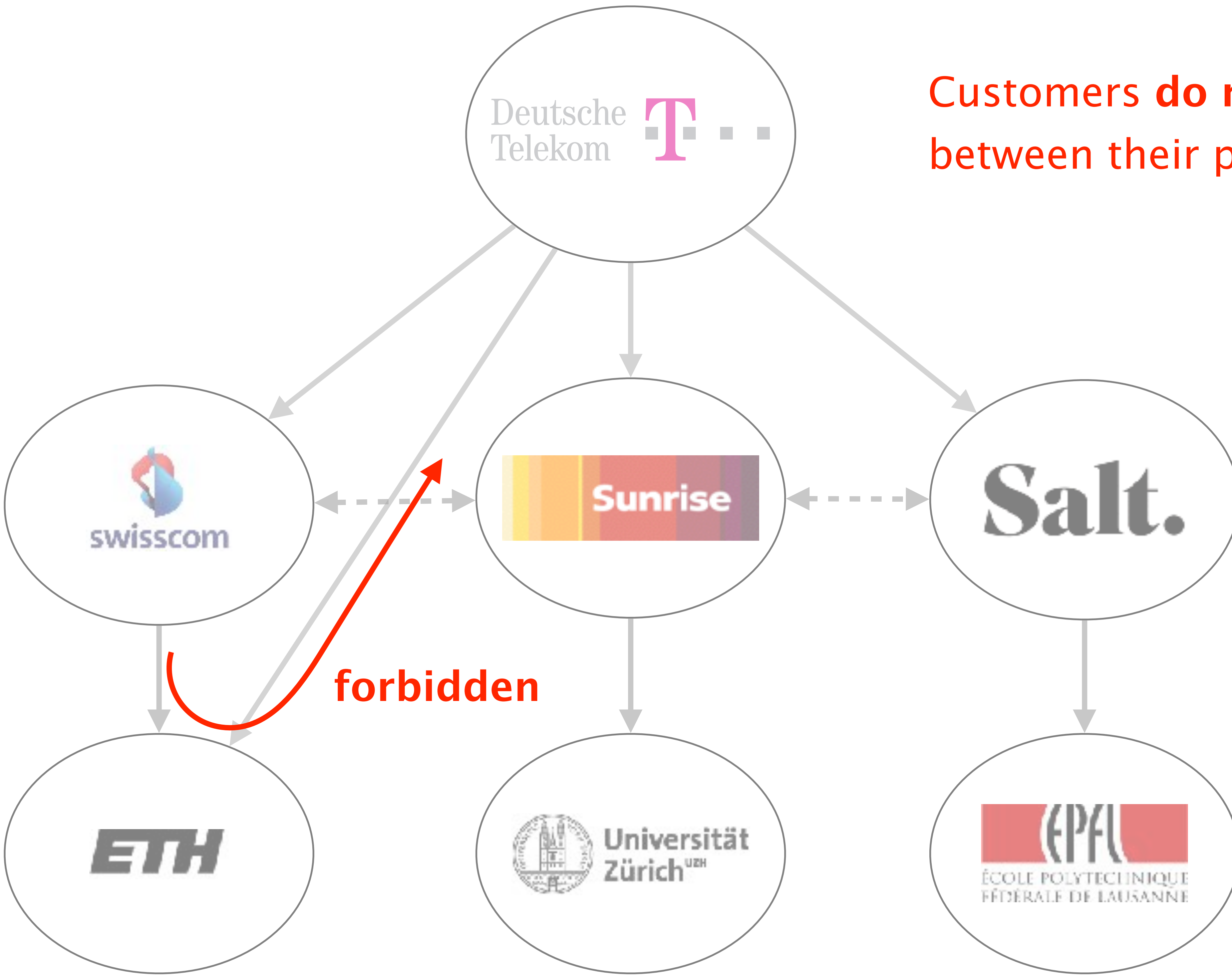
Providers **transit** traffic for their customers



Peers **do not** transit traffic between each other



Customers **do not** transit traffic between their providers



These policies are defined by constraining which BGP routes are *selected* and *exported*

Selection

which path to use?

Export

which path to advertise?

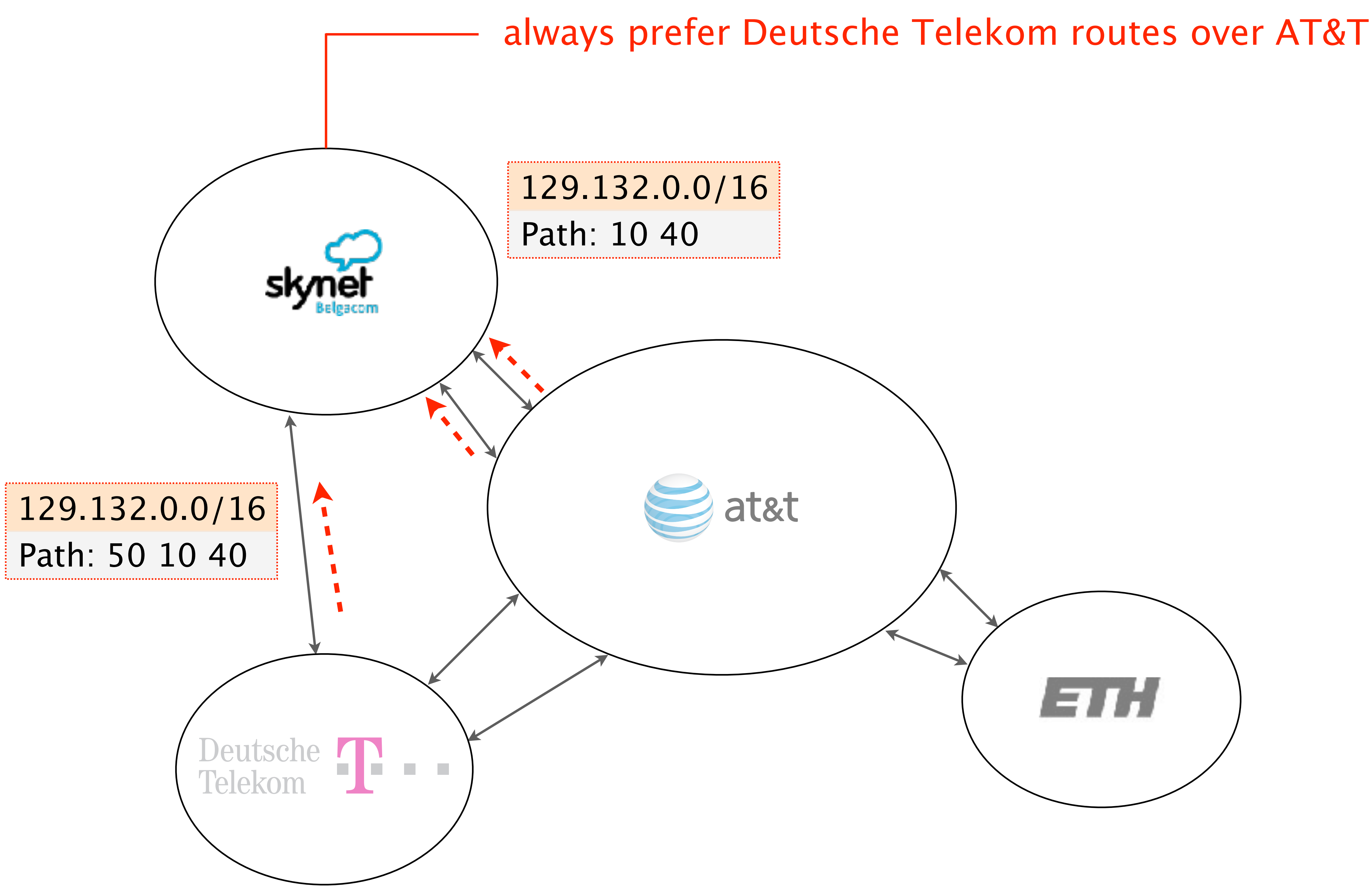
Selection

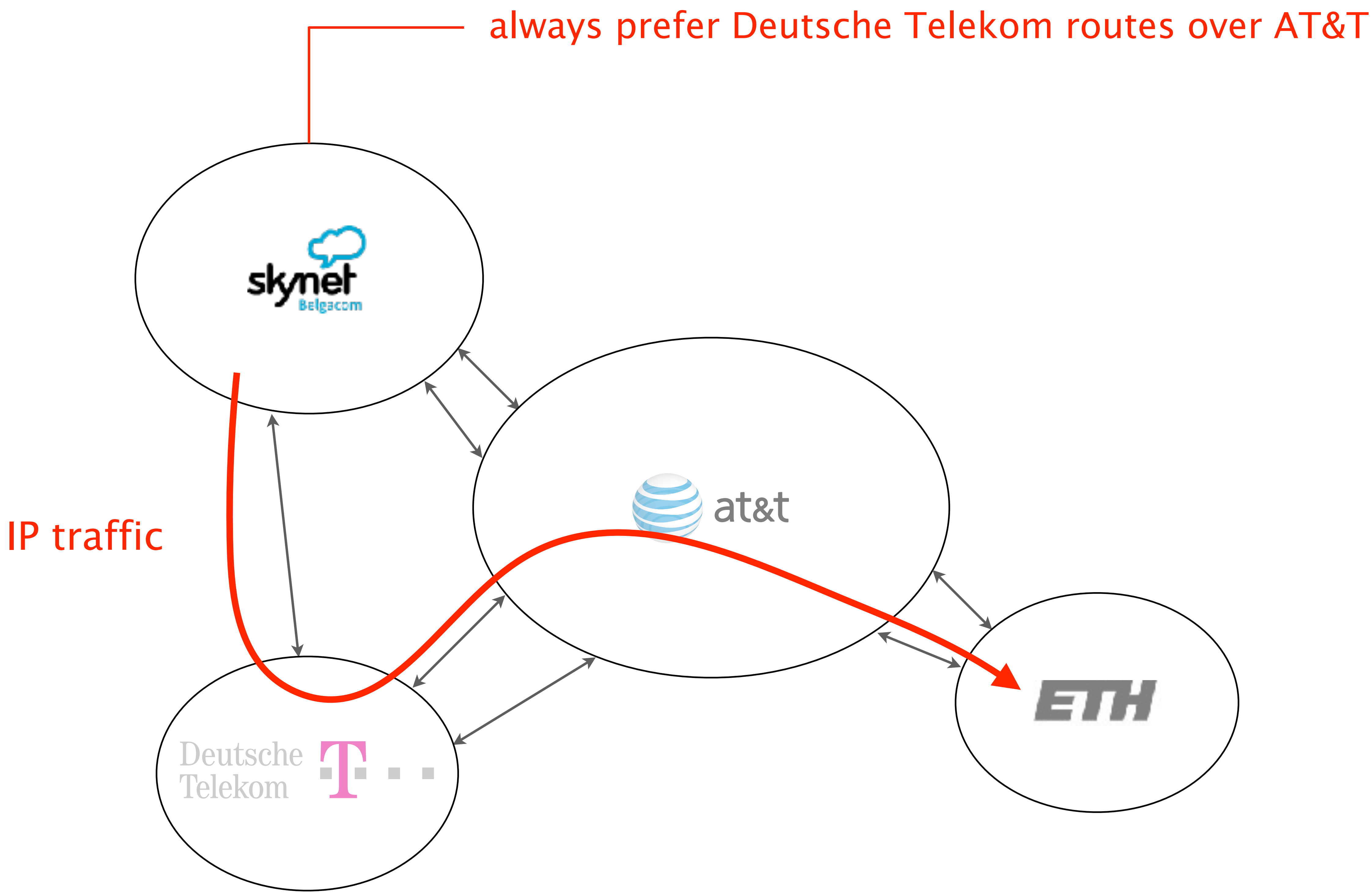
Export

which path to use?

which path to advertise?

control outbound traffic


always prefer Deutsche Telekom routes over AT&T
129.132.0.0/16
Path: 10 40
129.132.0.0/16
Path: 50 10 40
skynet
Belgacom
at&t
Deutsche
Telekom
T
ETH


always prefer Deutsche Telekom routes over AT&T
IP traffic
skynet
Belgacom
at&t
Deutsche
Telekom
ETH

Business relationships conditions

route selection

For a destination p, prefer routes coming from

- customers over
- peers over
- providers

route type

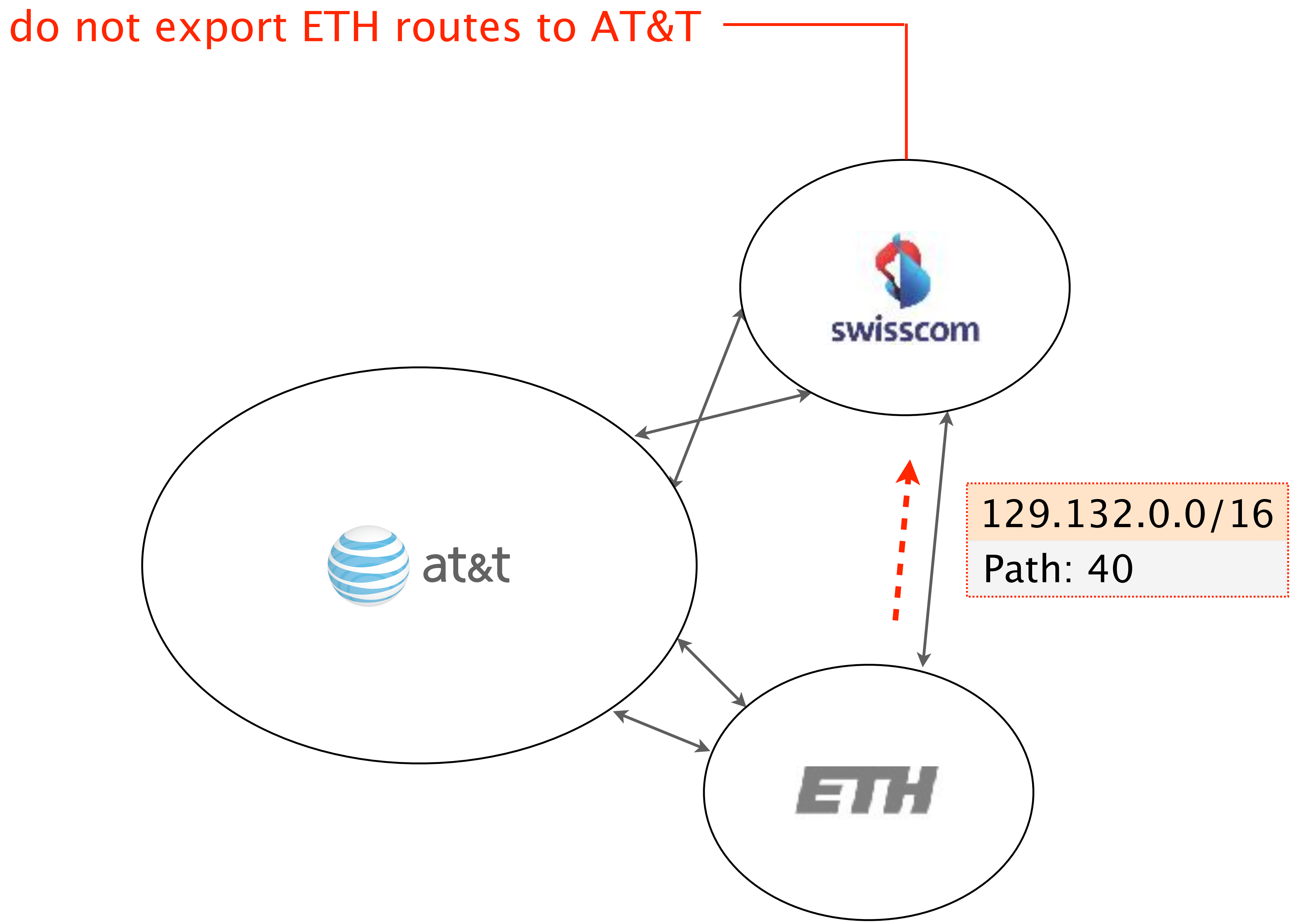
Selection

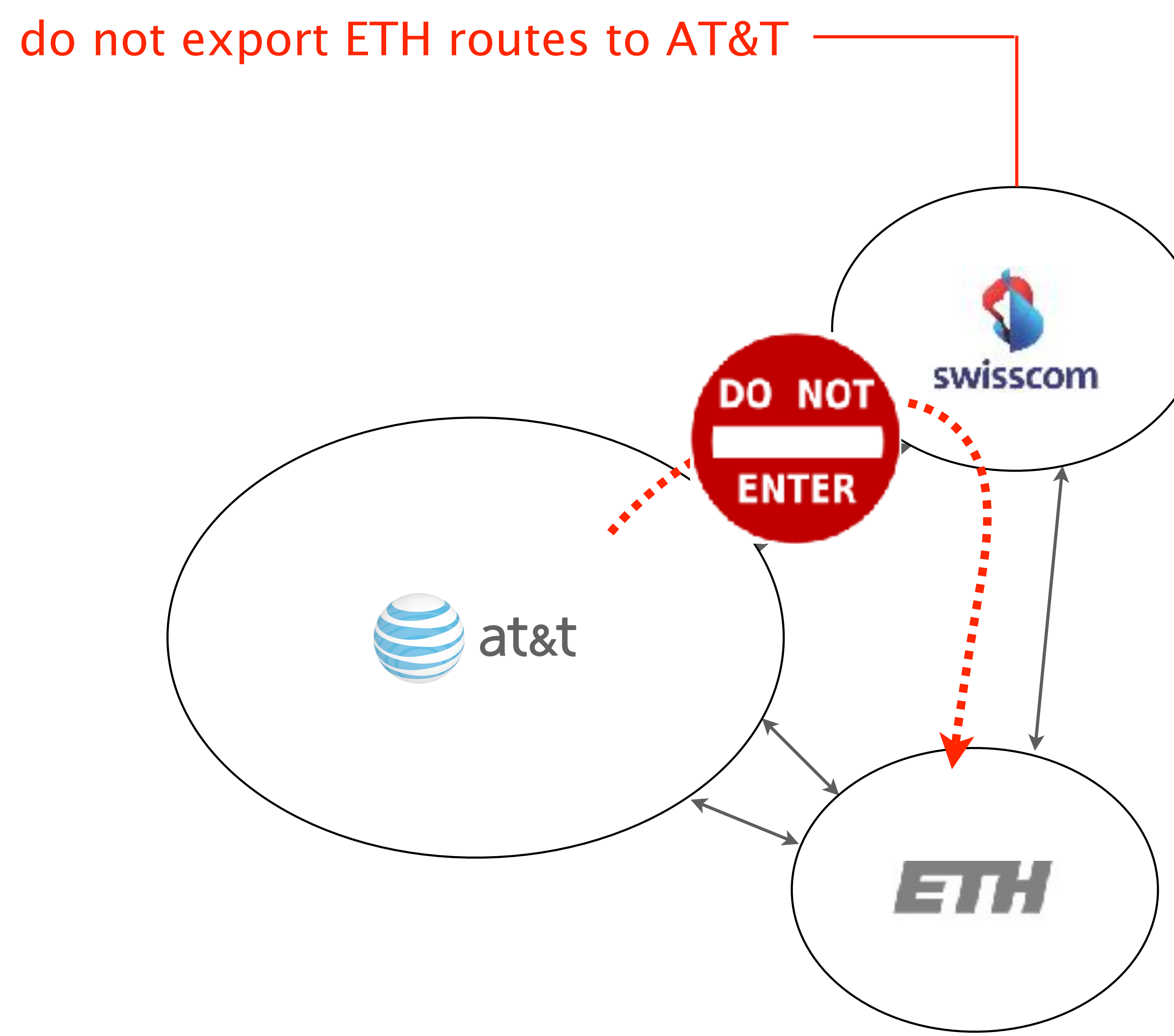
which path to use?

Export

which path to advertise?

control inbound traffic


do not export ETH routes to AT&T
129.132.0.0/16
Path: 40


do not export ETH routes to AT&T
swisscom
DO NOT
ENTER
at&t
ETH

Business relationships conditions

route exportation

		send to		
		customer	peer	provider
	customer			
from	peer			
	provider			

Routes coming from customers are propagated to everyone else

		send to		
		customer	peer	provider
from	customer	✓	✓	✓
	peer			
	provider			

Routes coming from peers and providers are only propagated to customers

		send to		
		customer	peer	provider
	customer	✓	✓	✓
from	peer	✓	-	-
	provider	✓	-	-

Selection

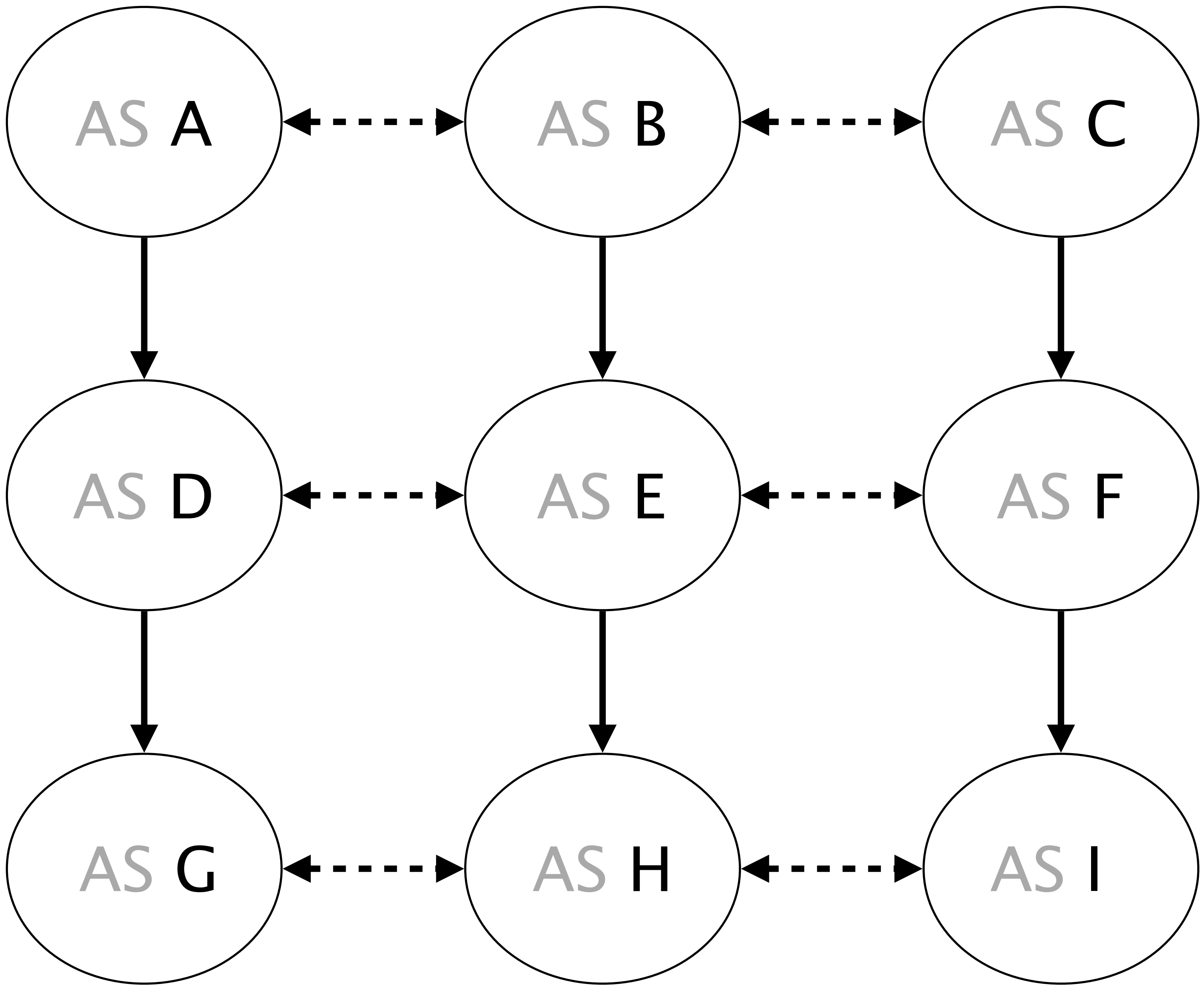
which path to use?

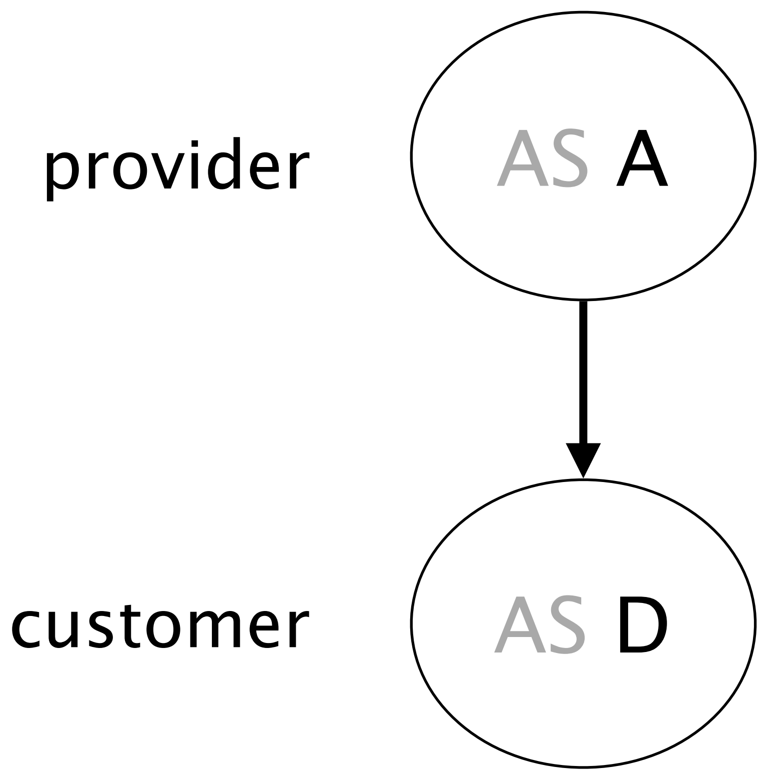
control outbound traffic

Export

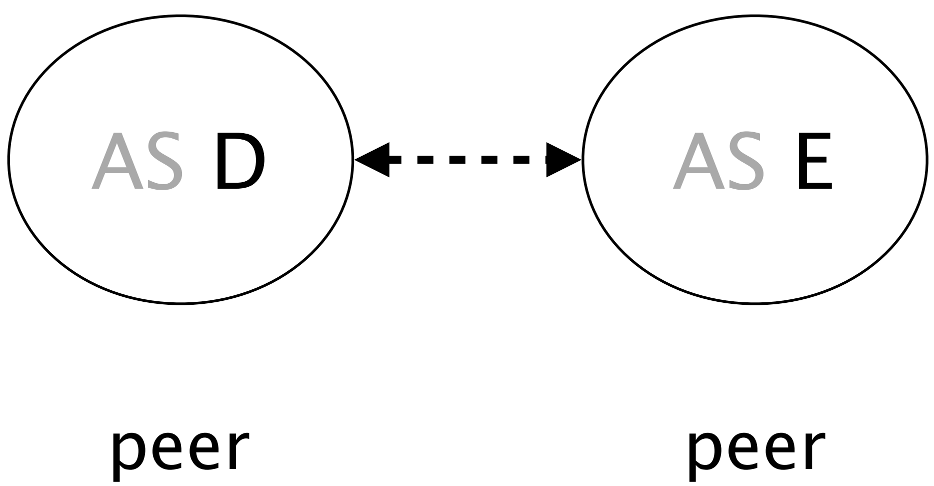
which path to advertise?

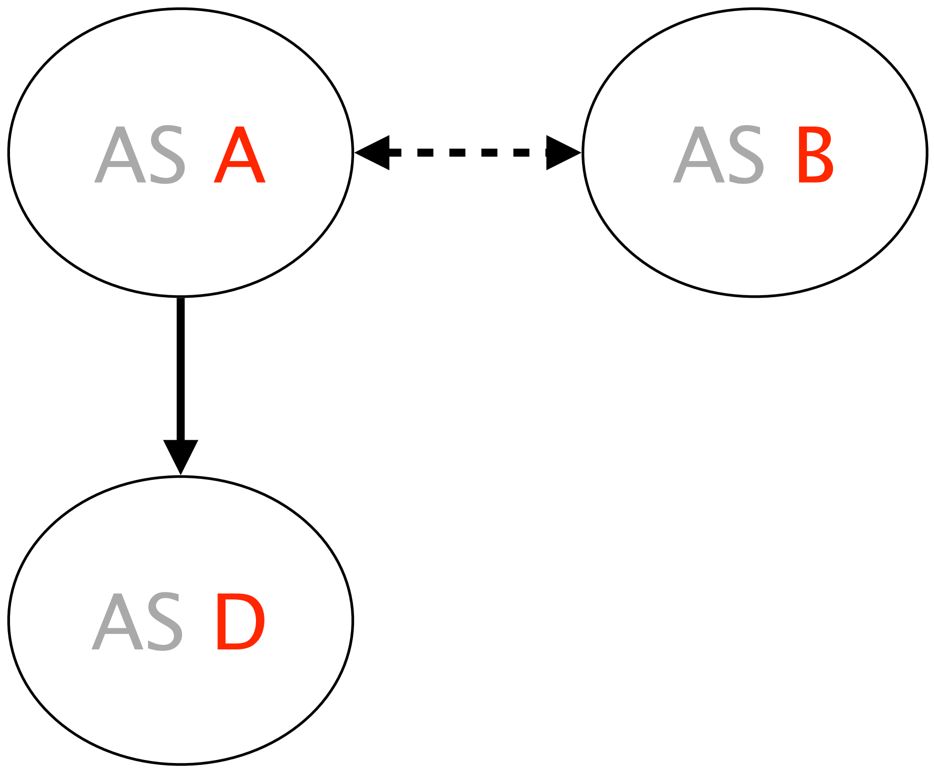
control inbound traffic


AS A
AS B
AS C
AS D
AS E
AS F
AS G
AS H
AS I

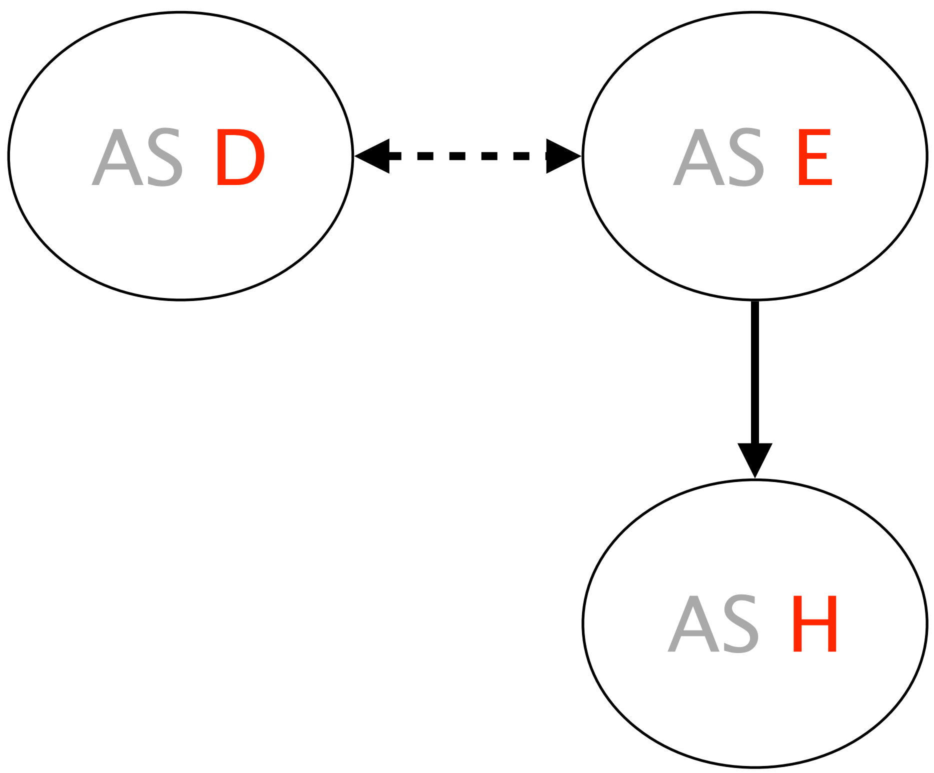


provider
AS A
customer
AS D

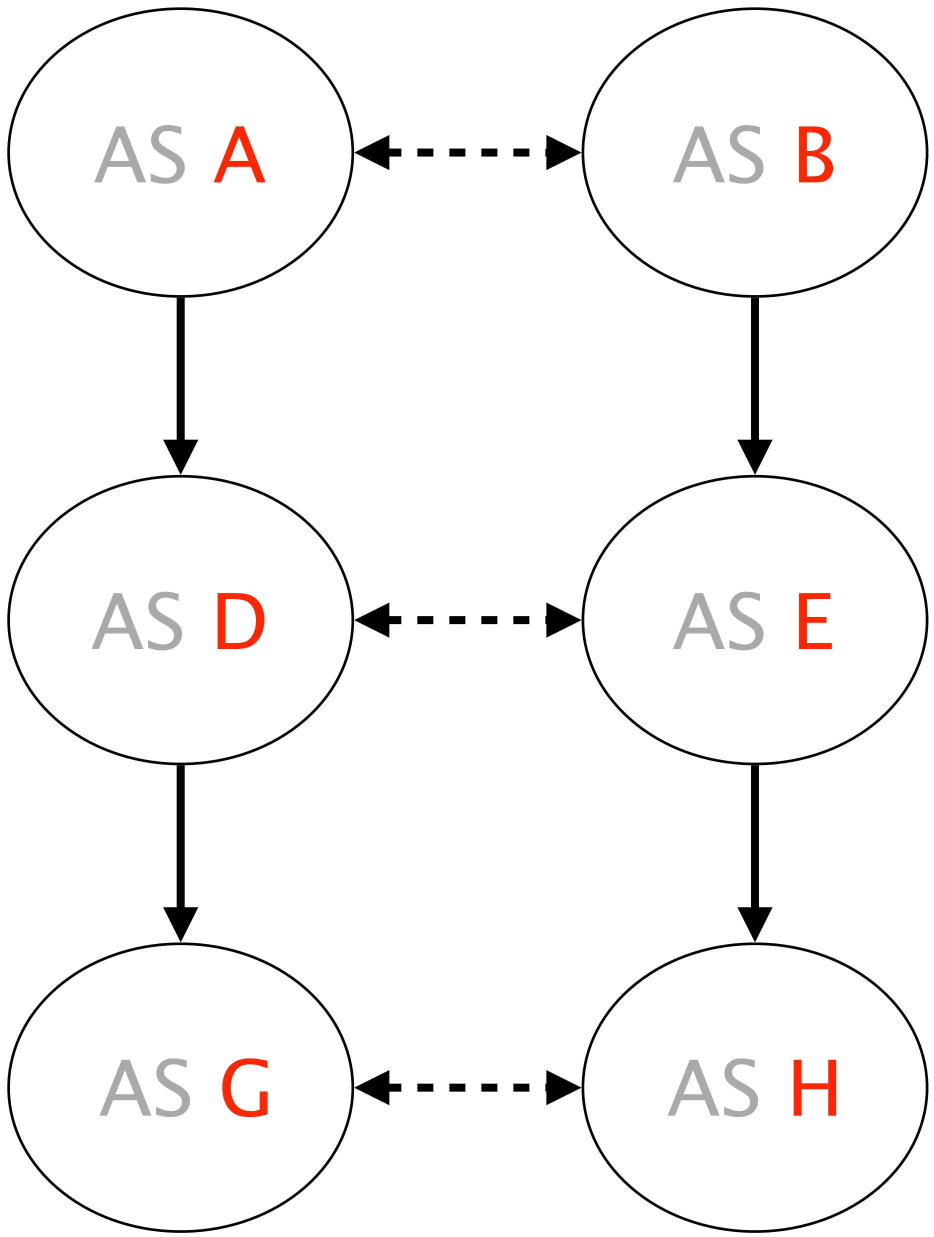

AS D
AS E
peer
peer



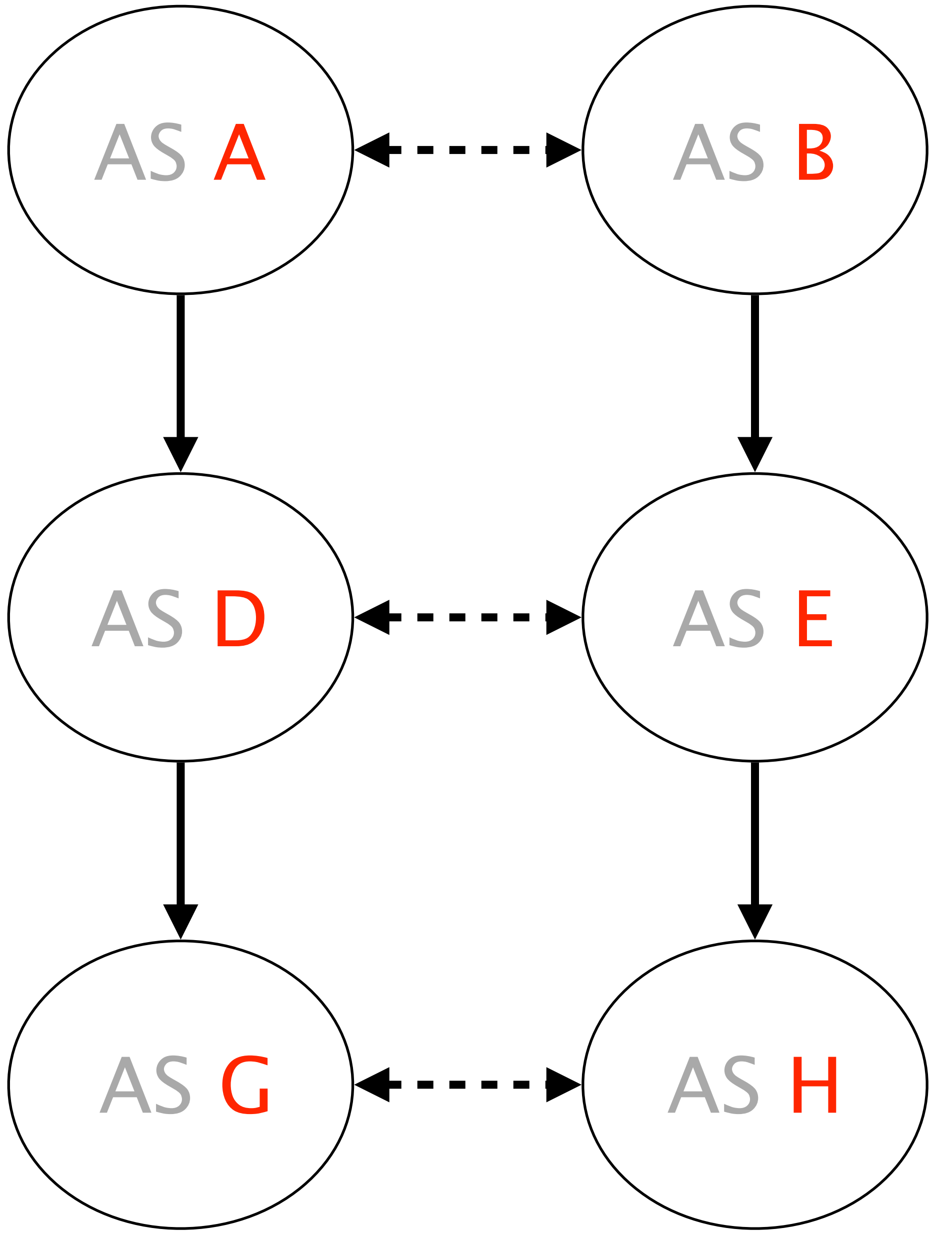
Is (B, A, D) a valid path? Yes/No



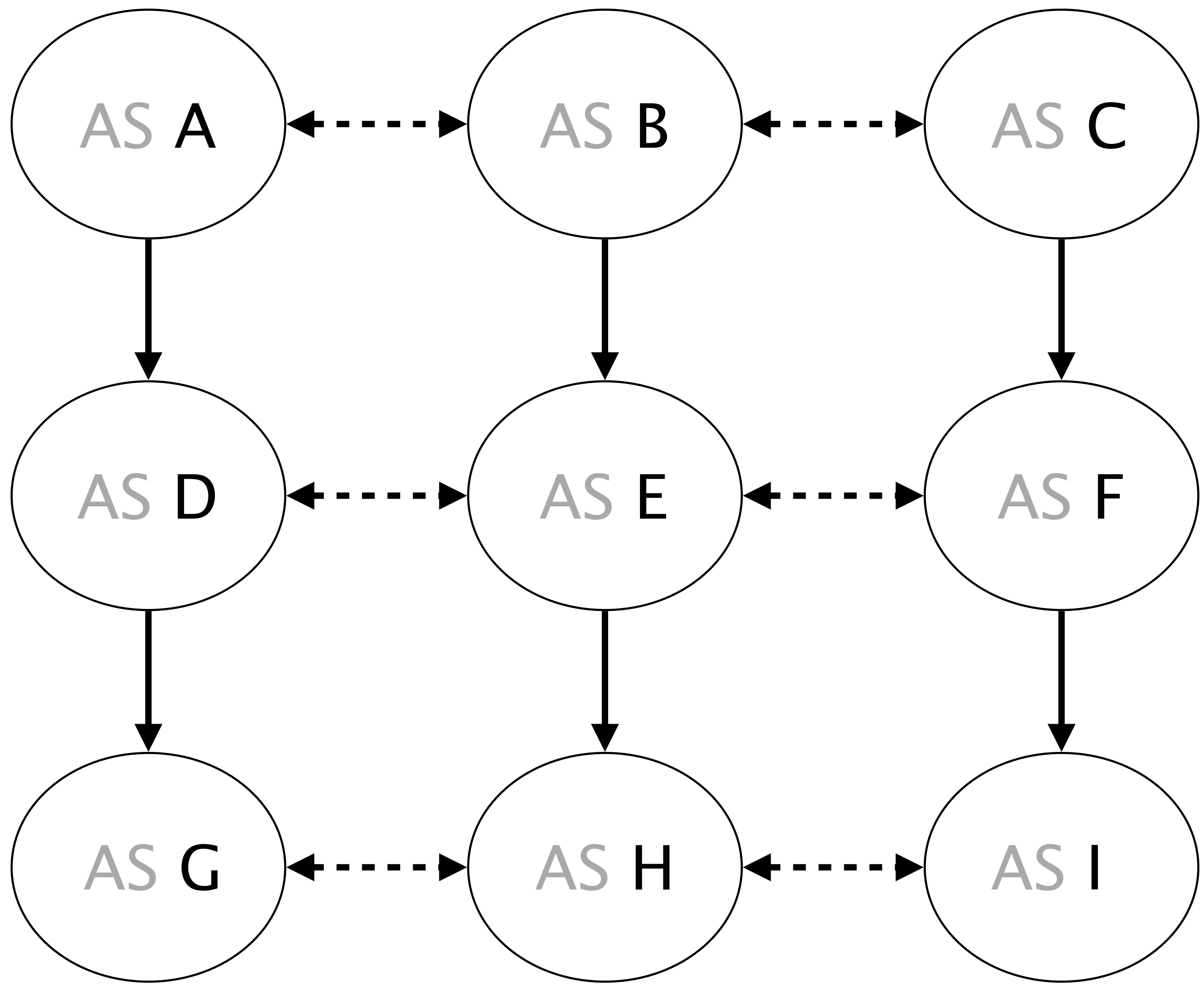
Is (H, E, D) a valid path?   Yes/No



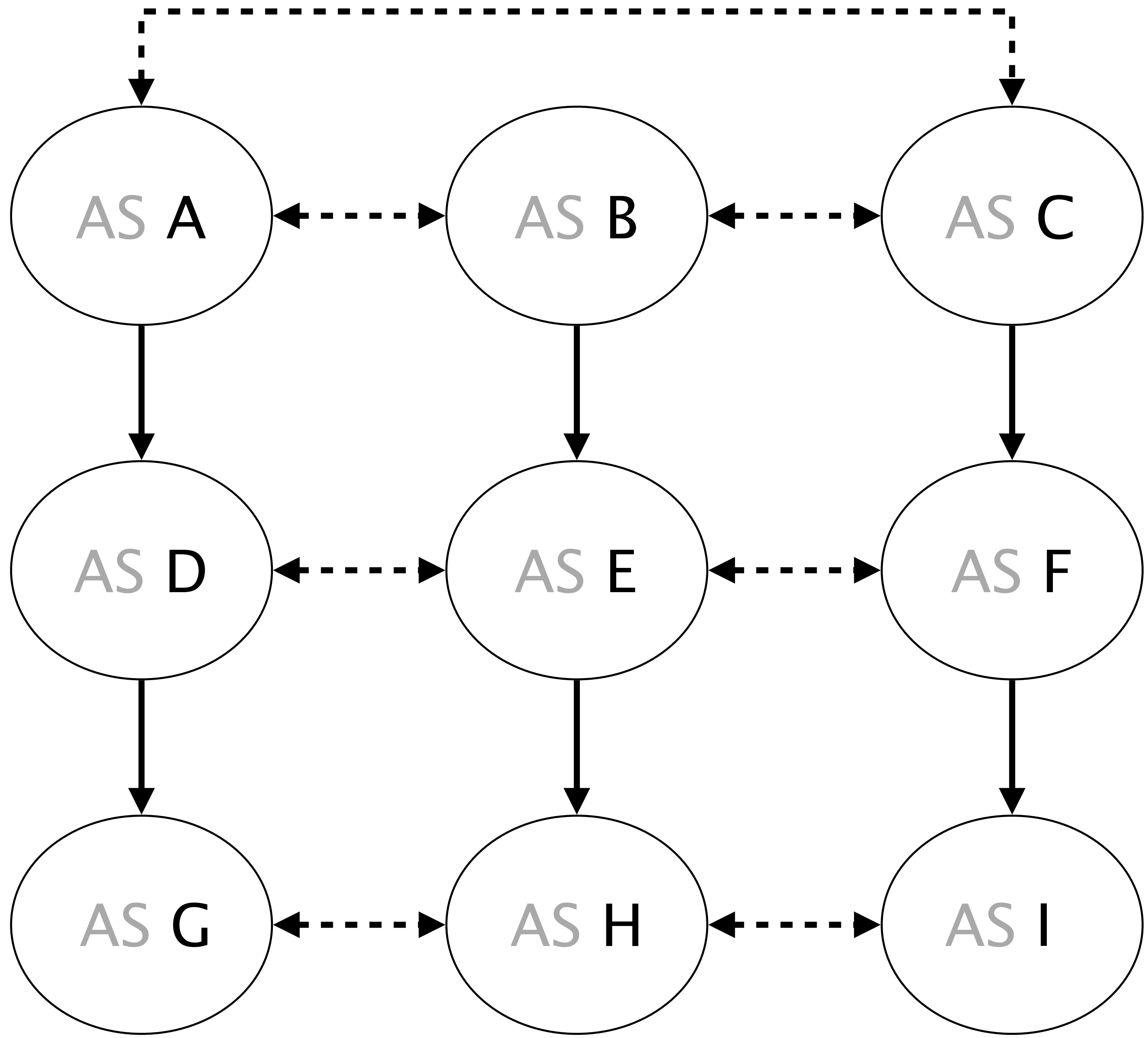
Is (G,D,A,B,E,H) a valid path? Yes/No



Will (G,D,A,B,E,H) actually see packets? Yes/No



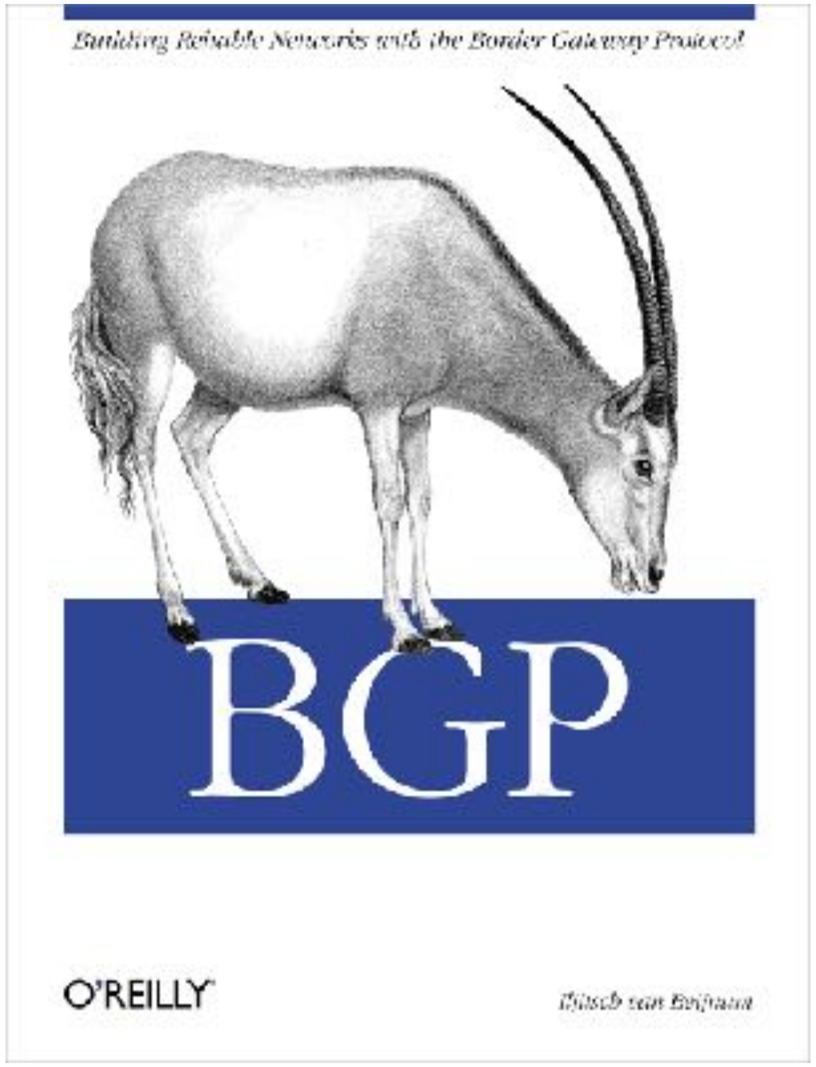
What's a valid path between G and I?



What’s a valid path between G and I?

Border Gateway Protocol

policies and more



BGP Policies

Follow the Money

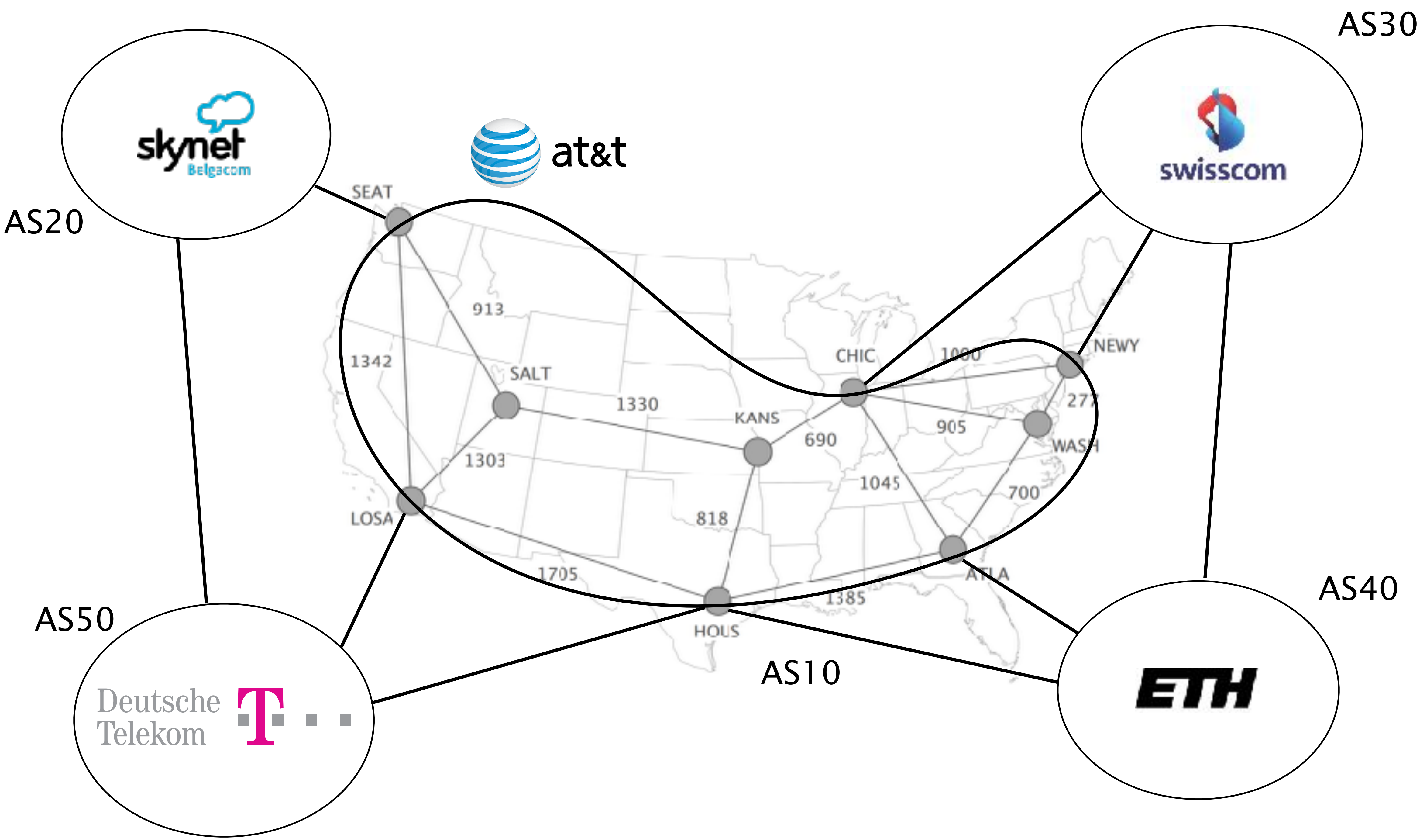
2 Protocol

How does it work?

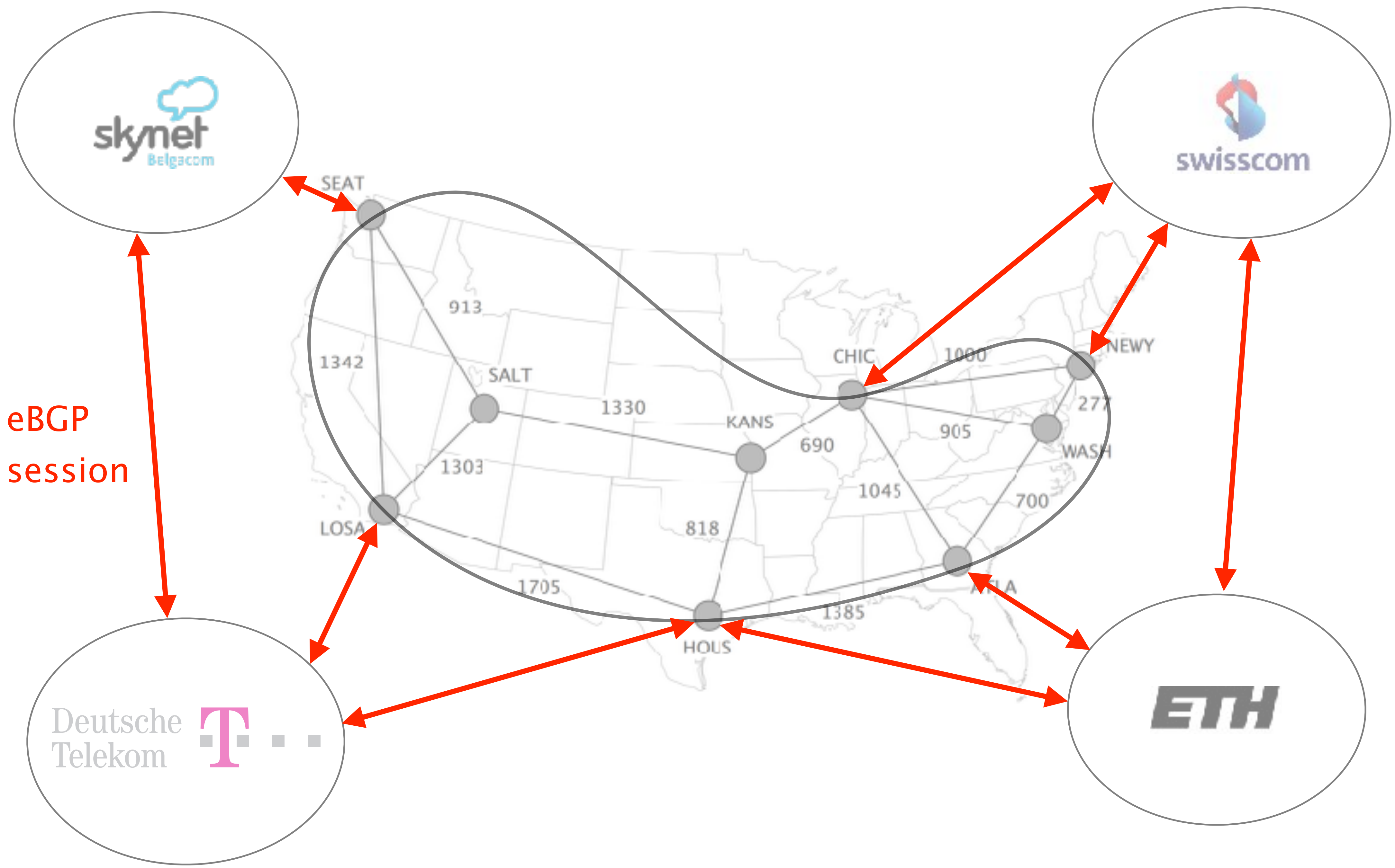
Problems

security, performance, …

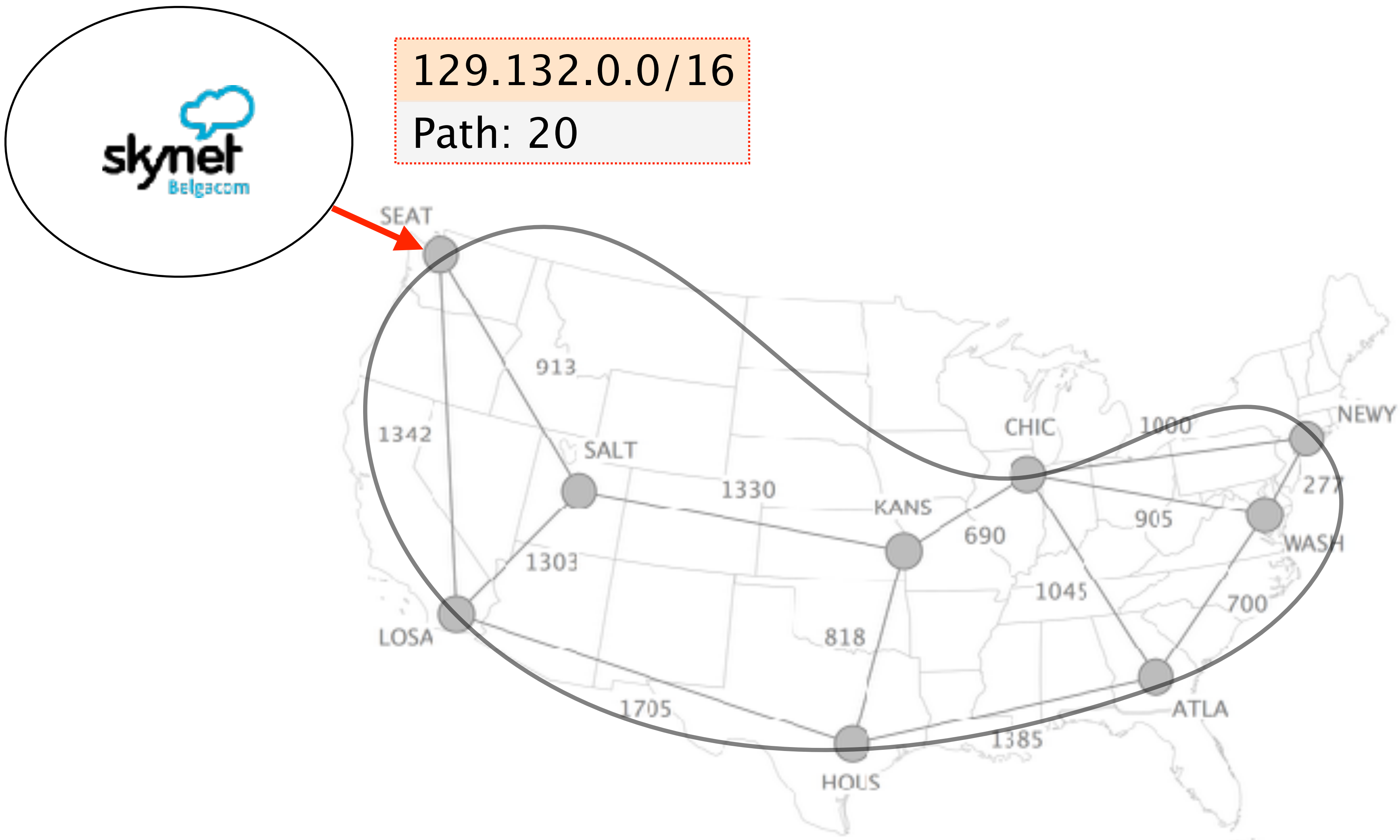
BGP sessions come in two flavors



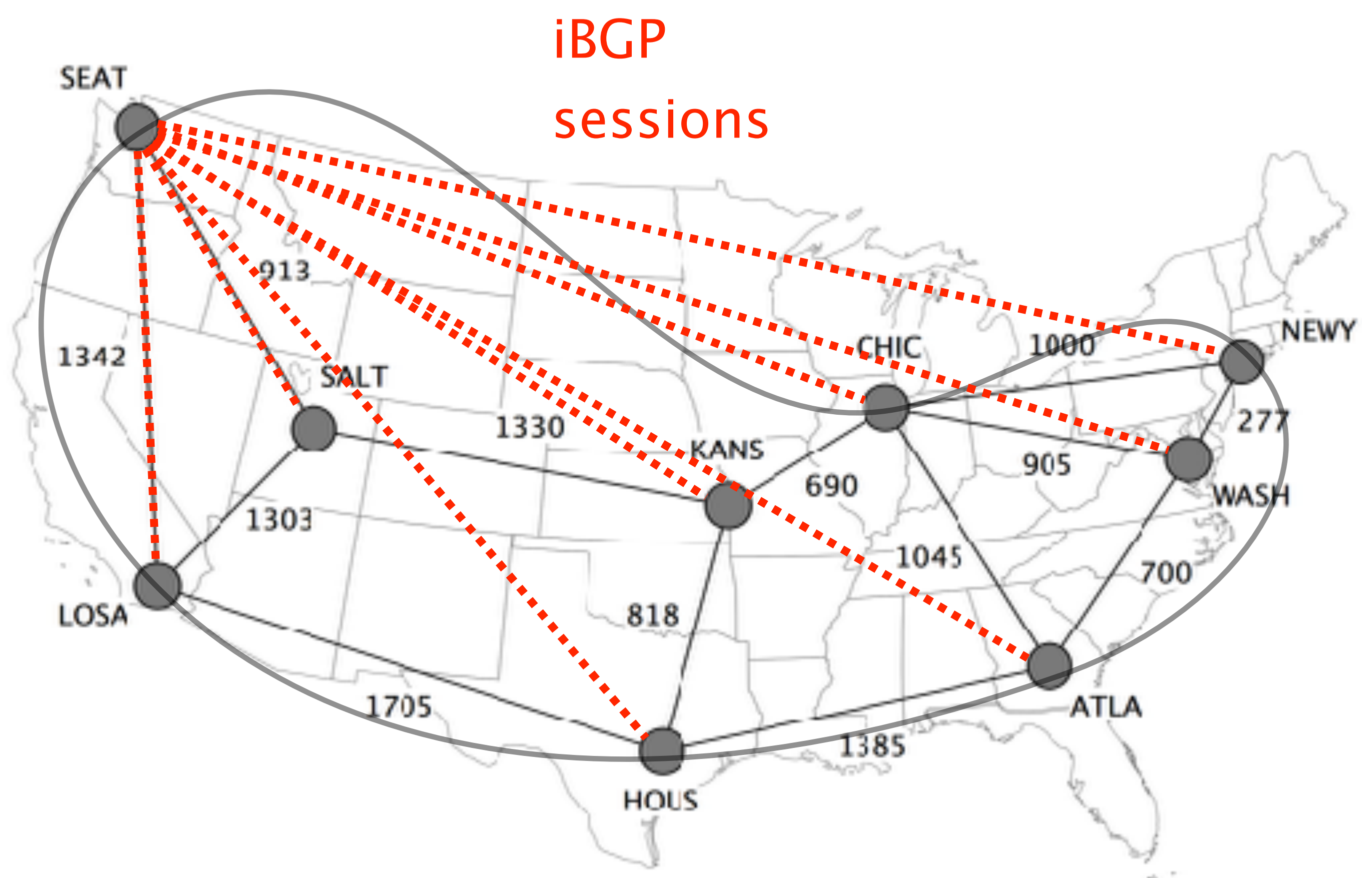
external BGP (eBGP) sessions connect border routers in different ASes



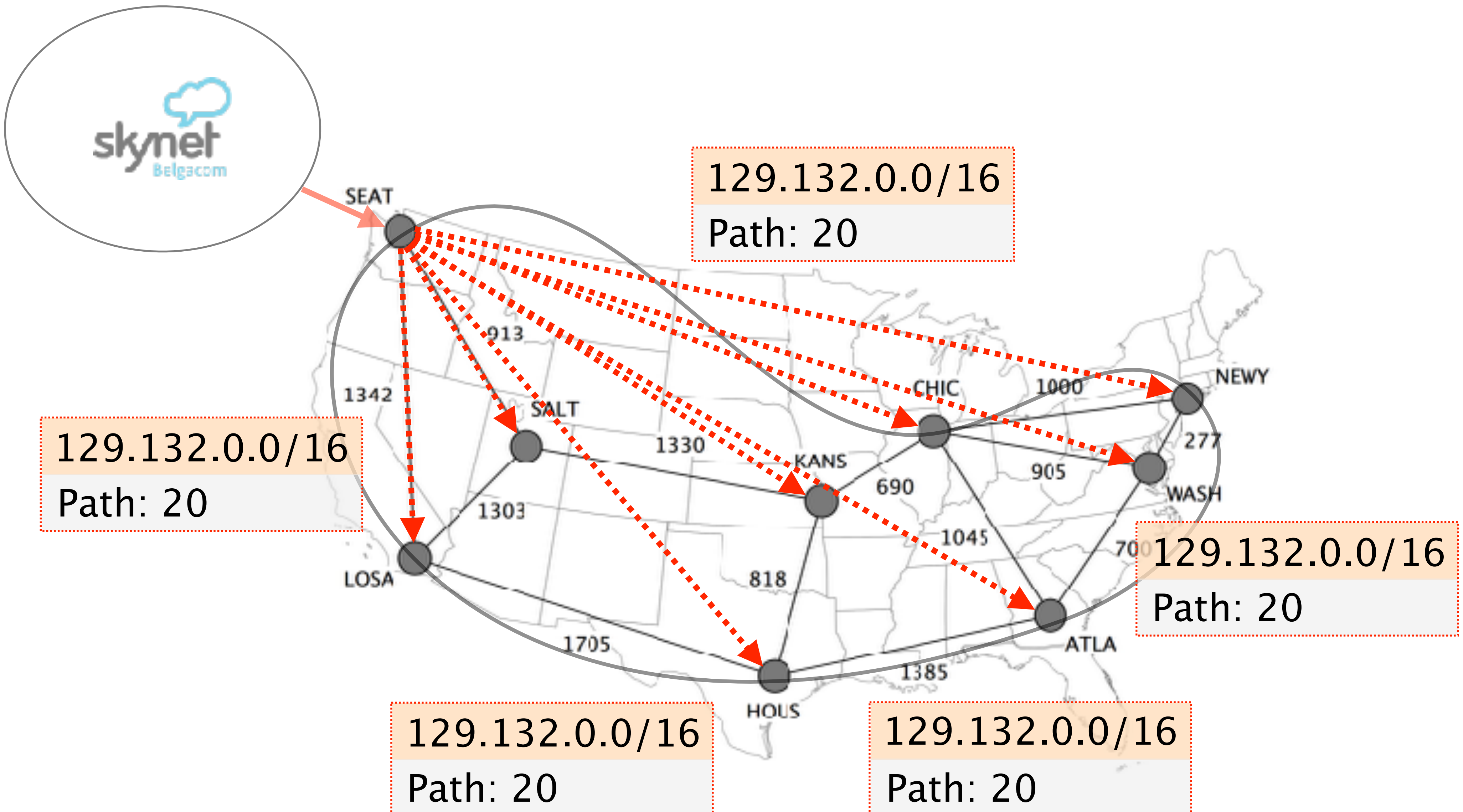
eBGP sessions are used to learn routes to external destinations

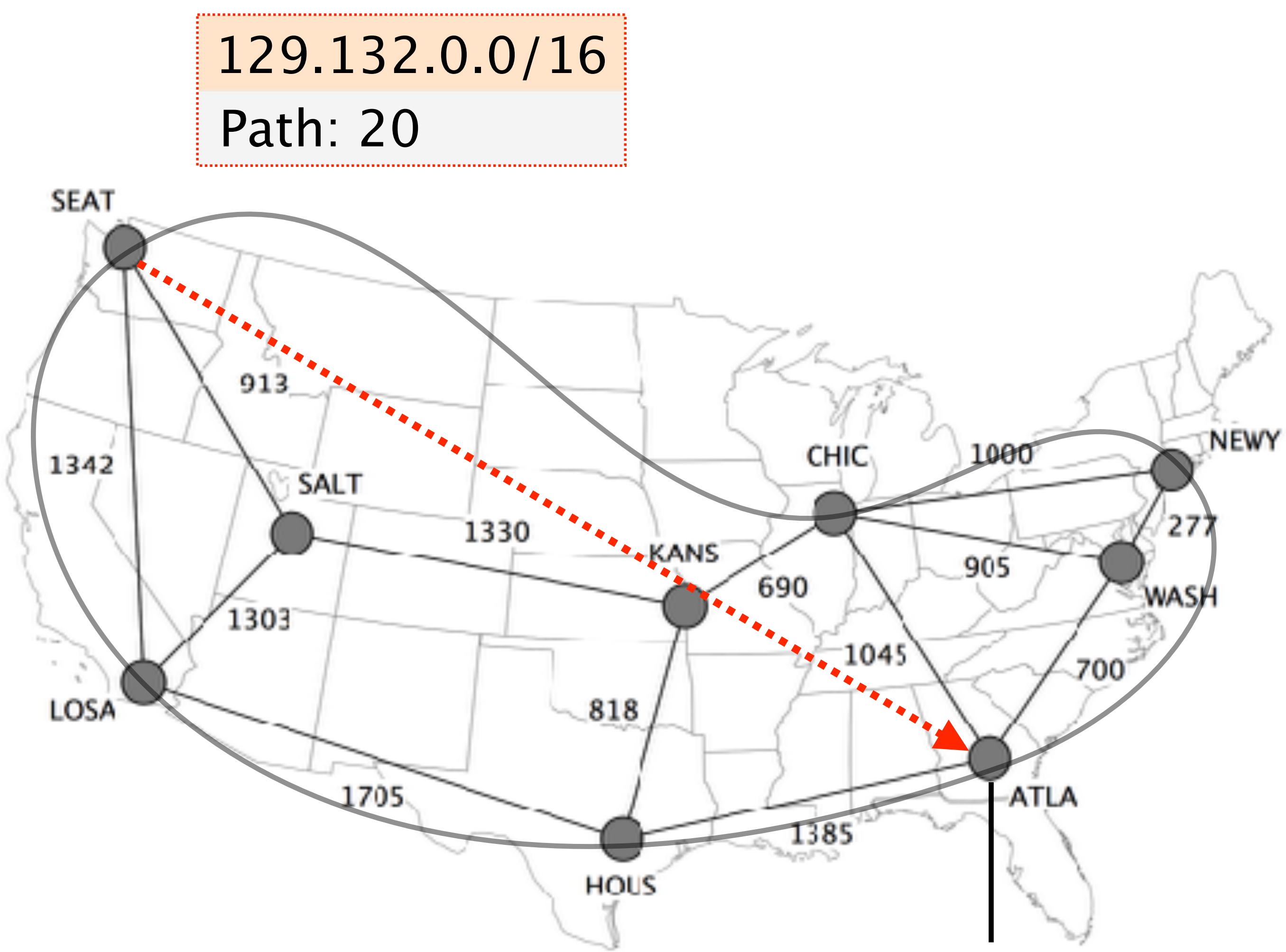


internal BGP (iBGP) sessions connect the routers in the same AS



iBGP sessions are used to disseminate externally-learned routes internally

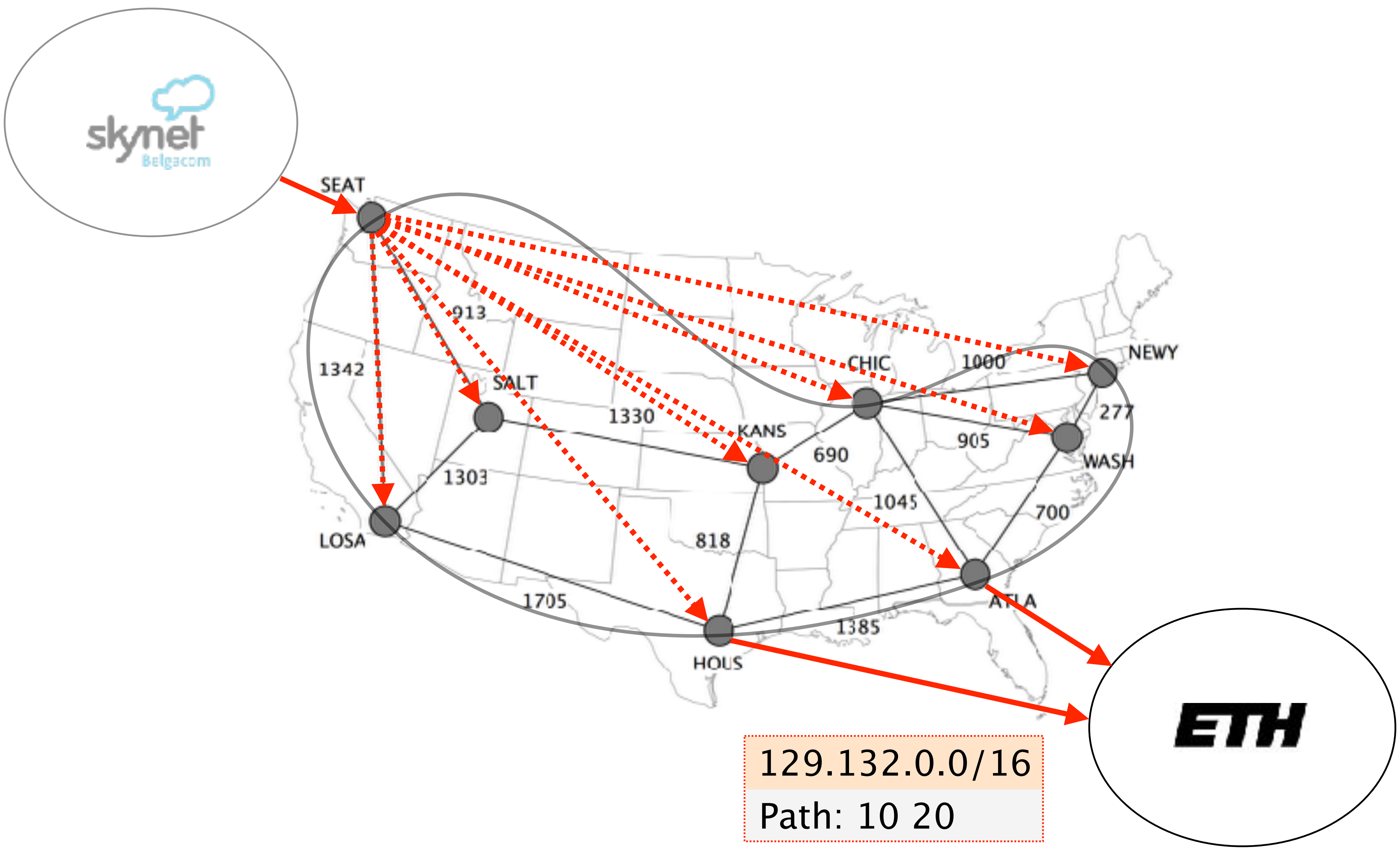




I can reach “129.132/16” via SEAT,
internal NH is CHIC

learned via IGP (*e.g.*, OSPF)

Routes disseminated internally are then announced externally again, using eBGP sessions



On the wire, BGP is a rather simple protocol composed of four basic messages

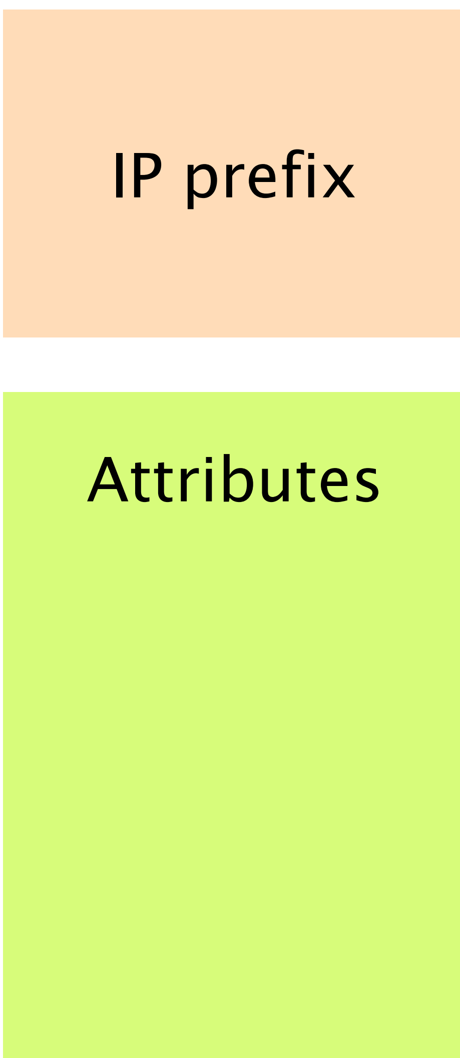
type	used to…
OPEN	establish TCP-based BGP sessions
NOTIFICATION	report unusual conditions
UPDATE	inform neighbor of a new best route a change in the best route the removal of the best route
KEEPALIVE	inform neighbor that the connection is alive

UPDATE inform neighbor of a new best route

a change in the best route

the removal of the best route

BGP UPDATEs carry an IP prefix together with a set of attributes



BGP UPDATEs carry an IP prefix together with a set of attributes

IP prefix

Attributes

Describe route properties

used in route selection/exportation decisions

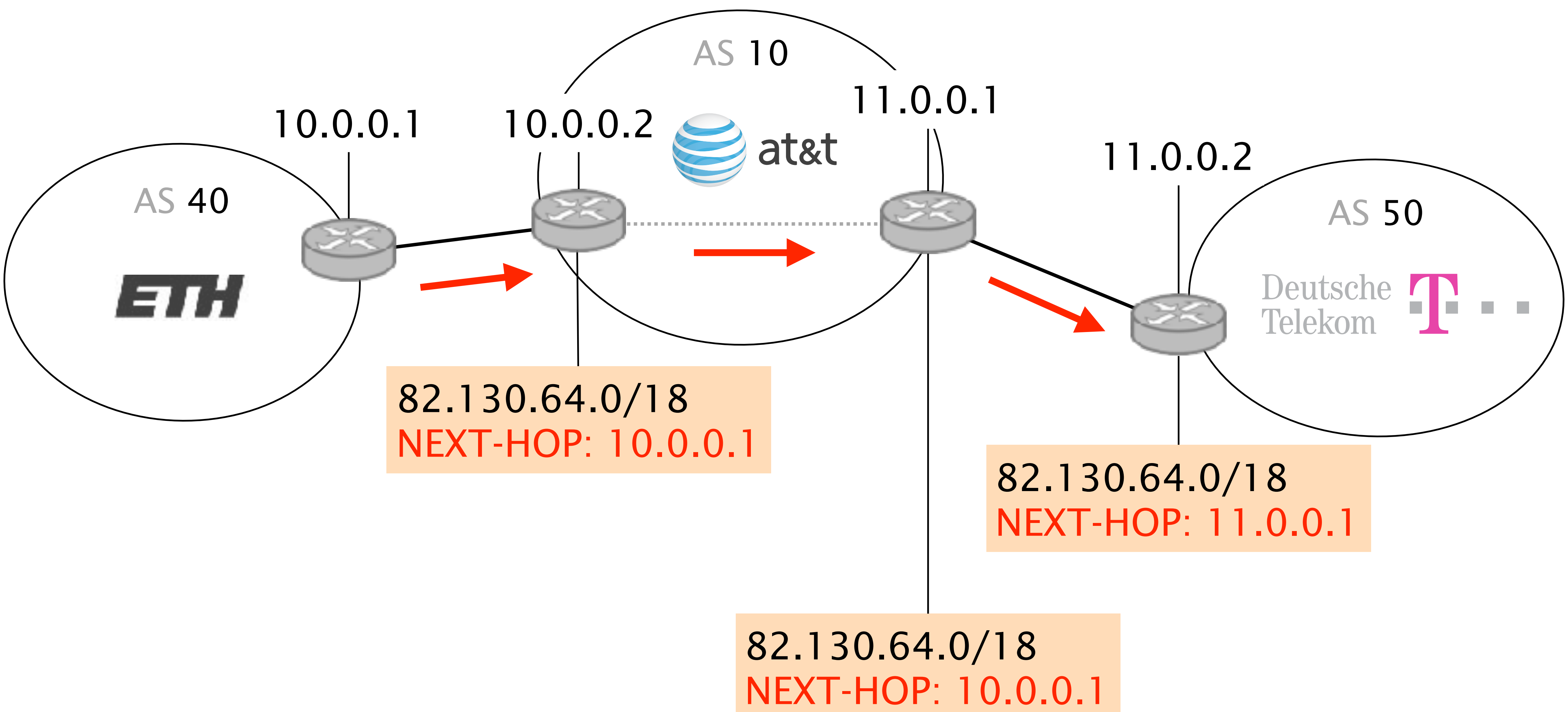
are either local (*only* seen on iBGP)

or global (seen on iBGP *and* eBGP)

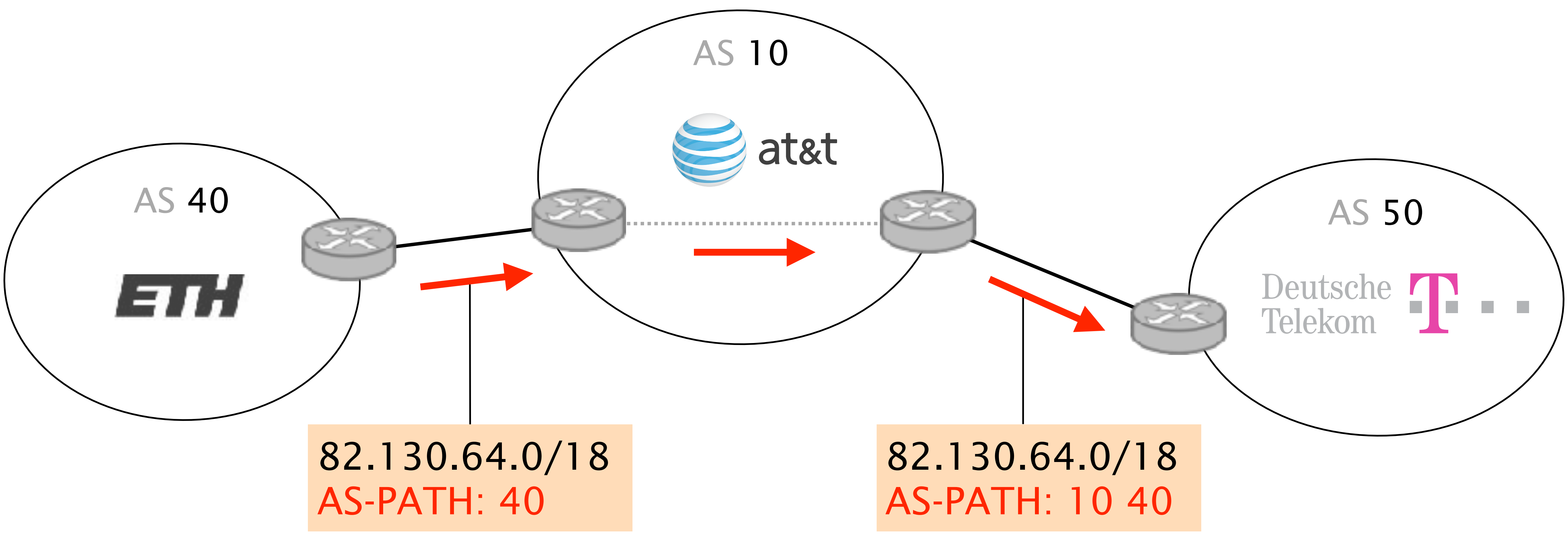
Attributes	Usage
NEXT-HOP	egress point identification
AS-PATH	loop avoidance outbound traffic control inbound traffic control
LOCAL-PREF	outbound traffic control
MED	inbound traffic control

The NEXT-HOP is a global attribute which indicates where to send the traffic next

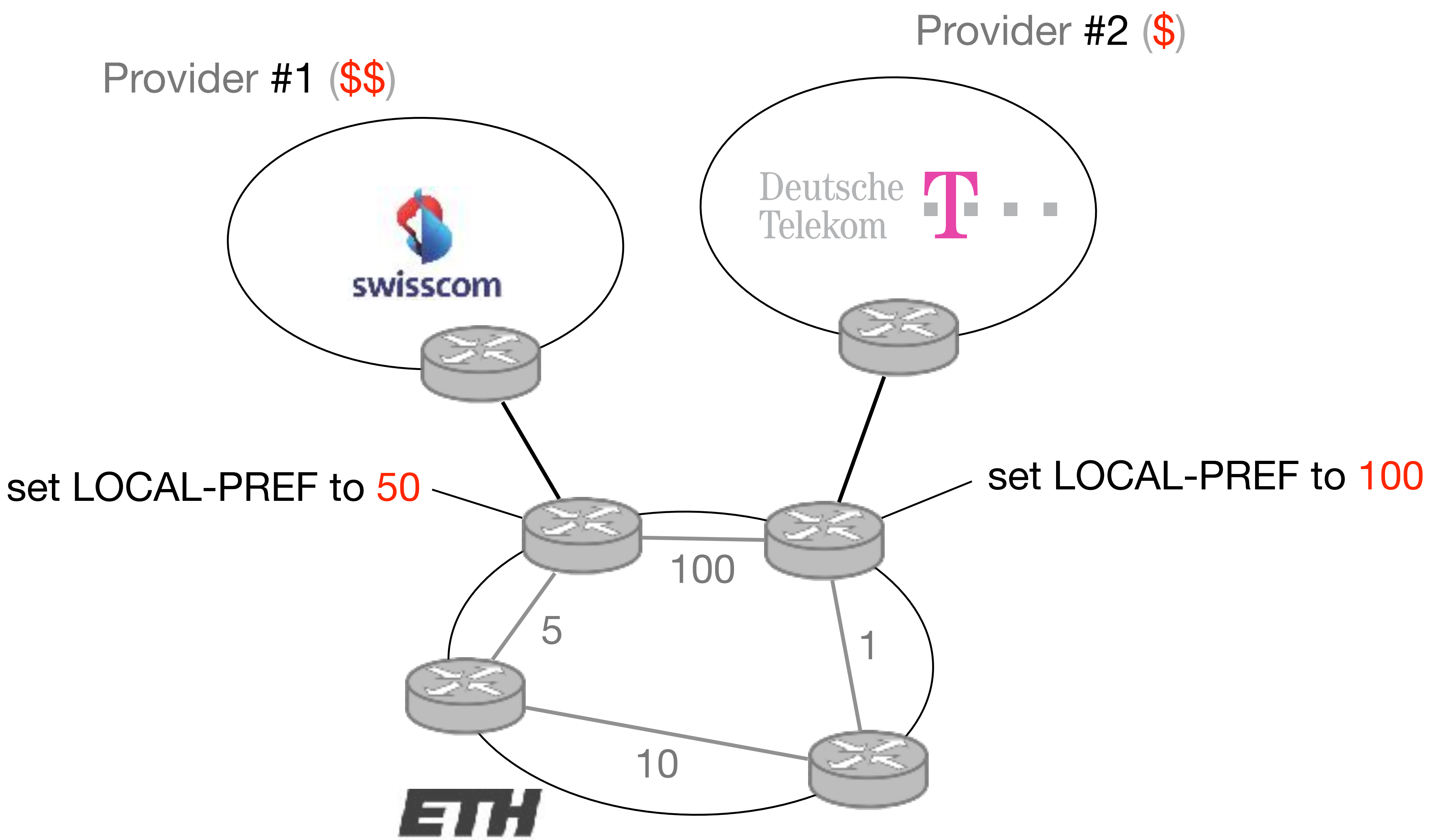
The NEXT-HOP is set when the route enters an AS,
it does not change within the AS



The AS-PATH is a global attribute that lists all the ASes a route has traversed (in reverse order)


AS 40
ETH
AS 10
at&t
AS 50
Deutsche
Telekom
82.130.64.0/18
AS-PATH: 40
82.130.64.0/18
AS-PATH: 10 40

The LOCAL-PREF is a *local* attribute set at the border, it represents how “preferred” a route is

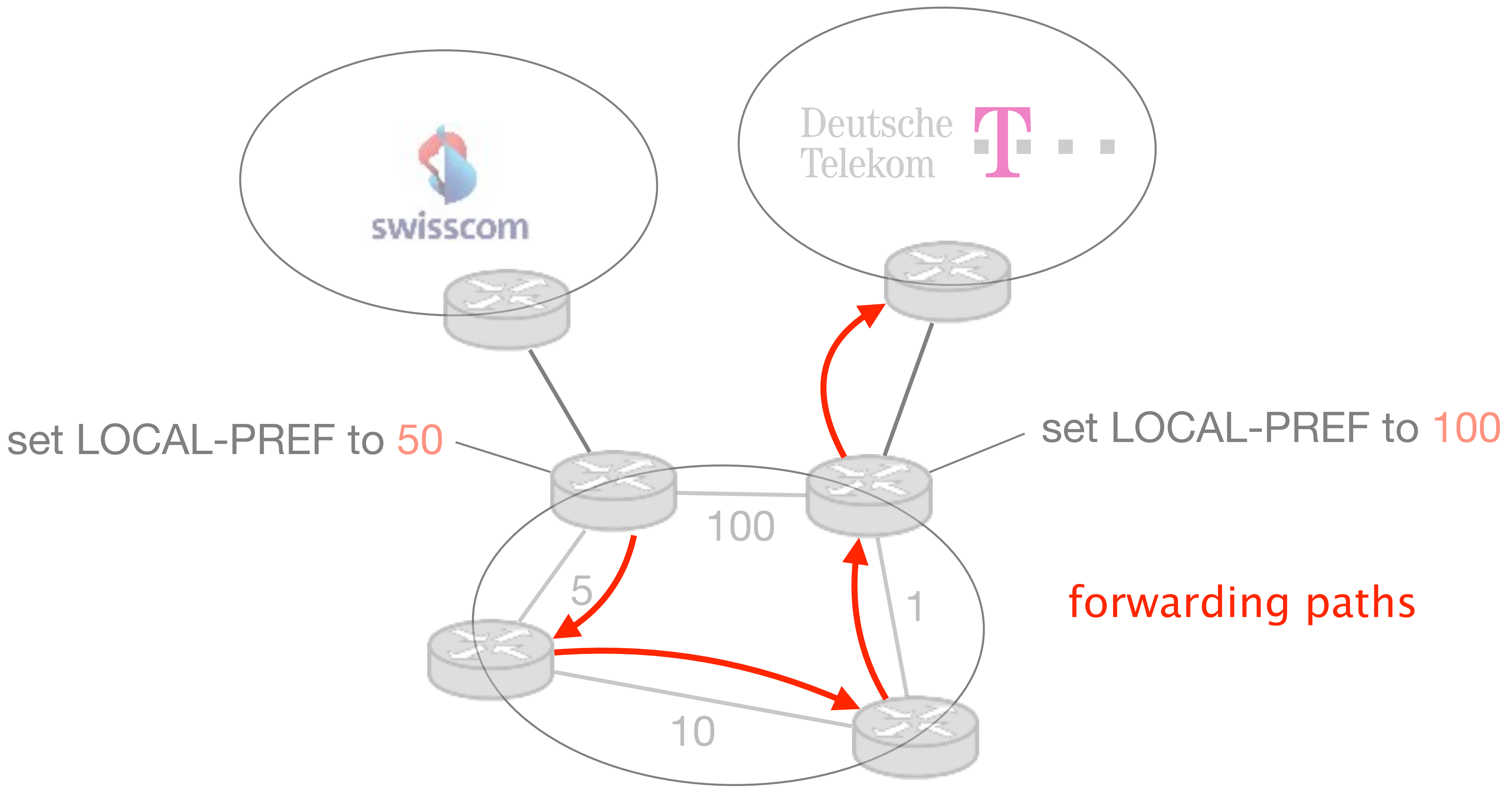


Provider #1 ($$)
Provider #2 ($)
swisscom
Deutsche Telekom
T
set LOCAL-PREF to 50
set LOCAL-PREF to 100
100
5
1
10
ETH

By setting a higher LOCAL-PREF,

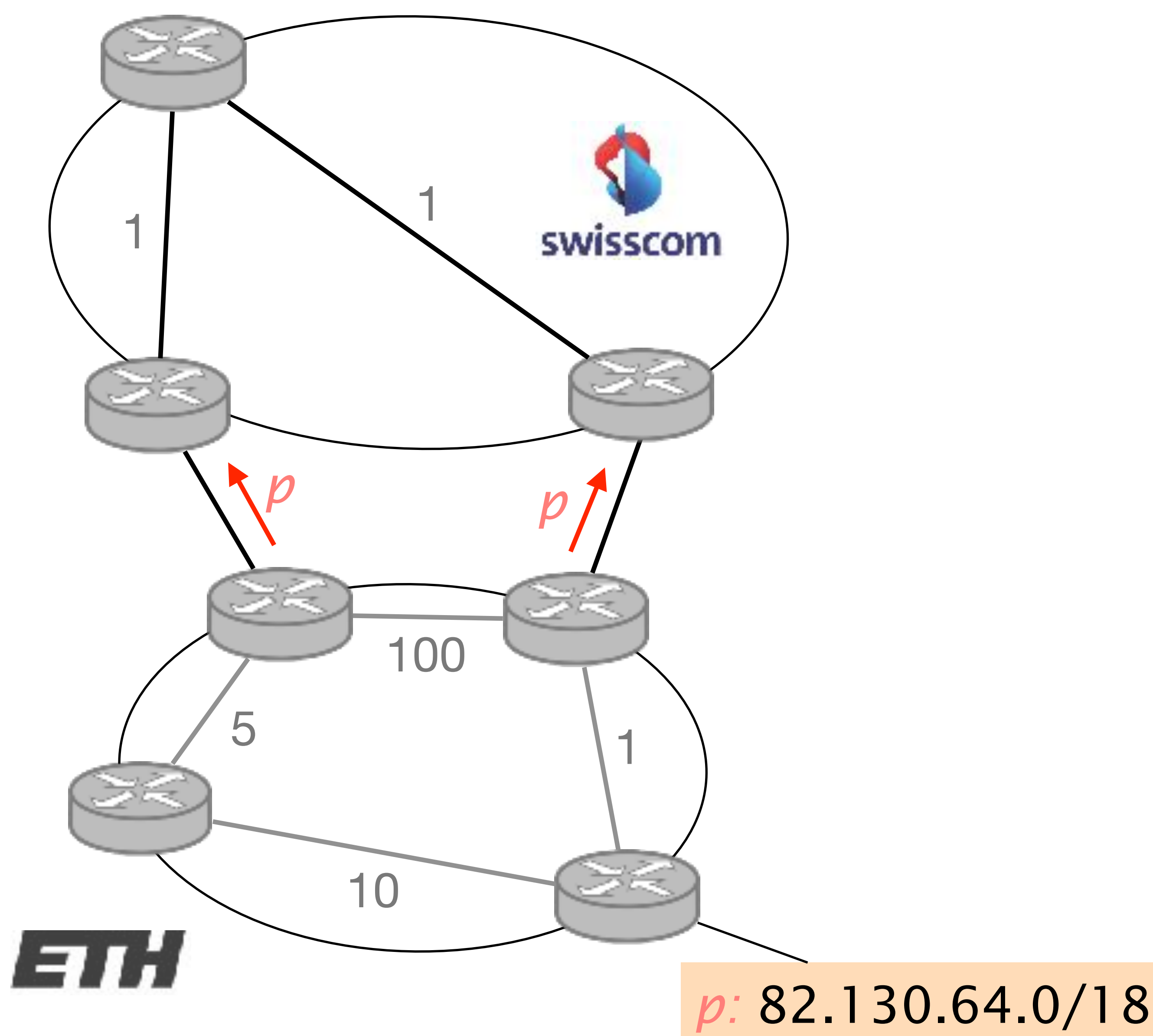
all routers end up using DT to reach any external prefixes,

even if they are closer (IGP-wise) to the Swisscom egress



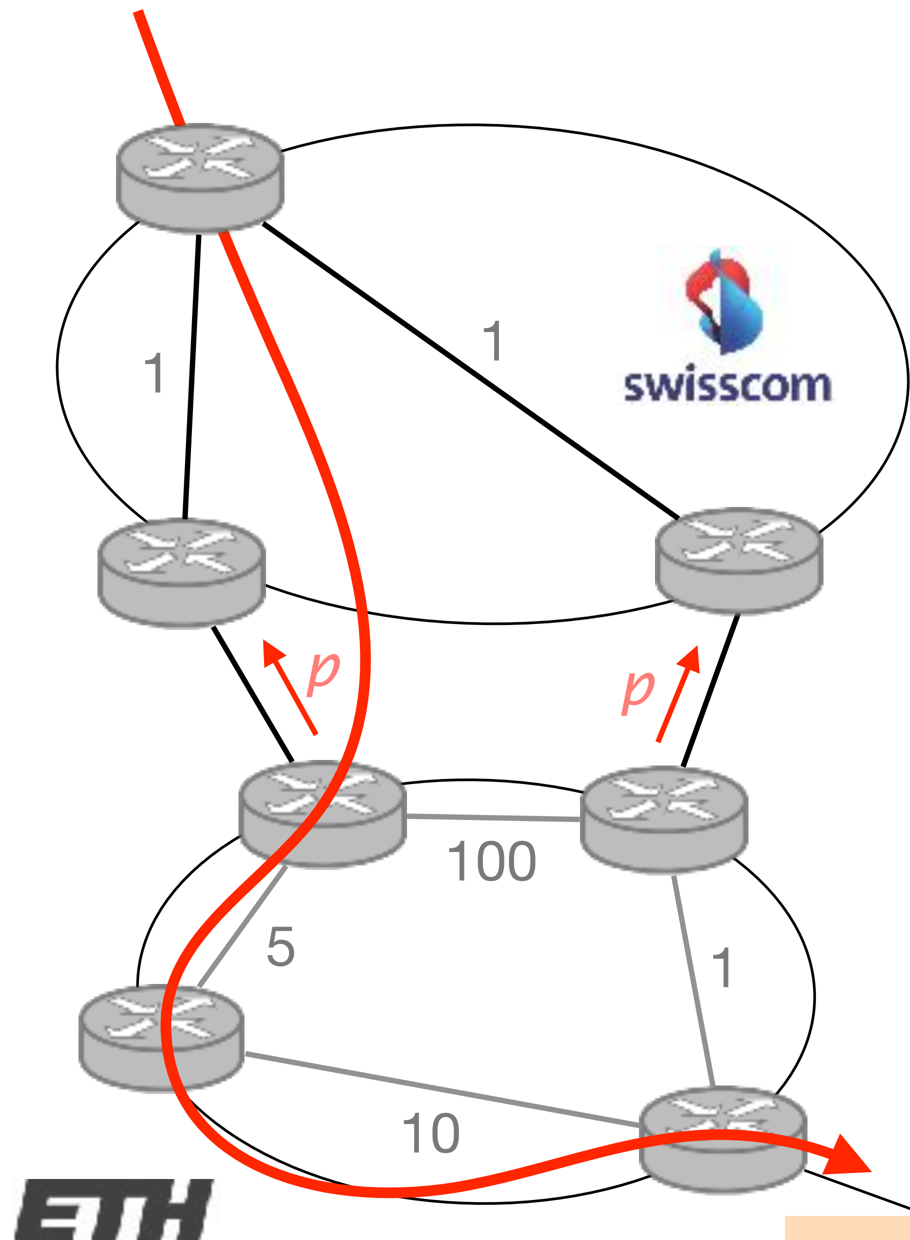
The MED is a *global* attribute which encodes
the relative “proximity” of a prefix wrt to the announcer

Swisscom receives two routes to reach *p*



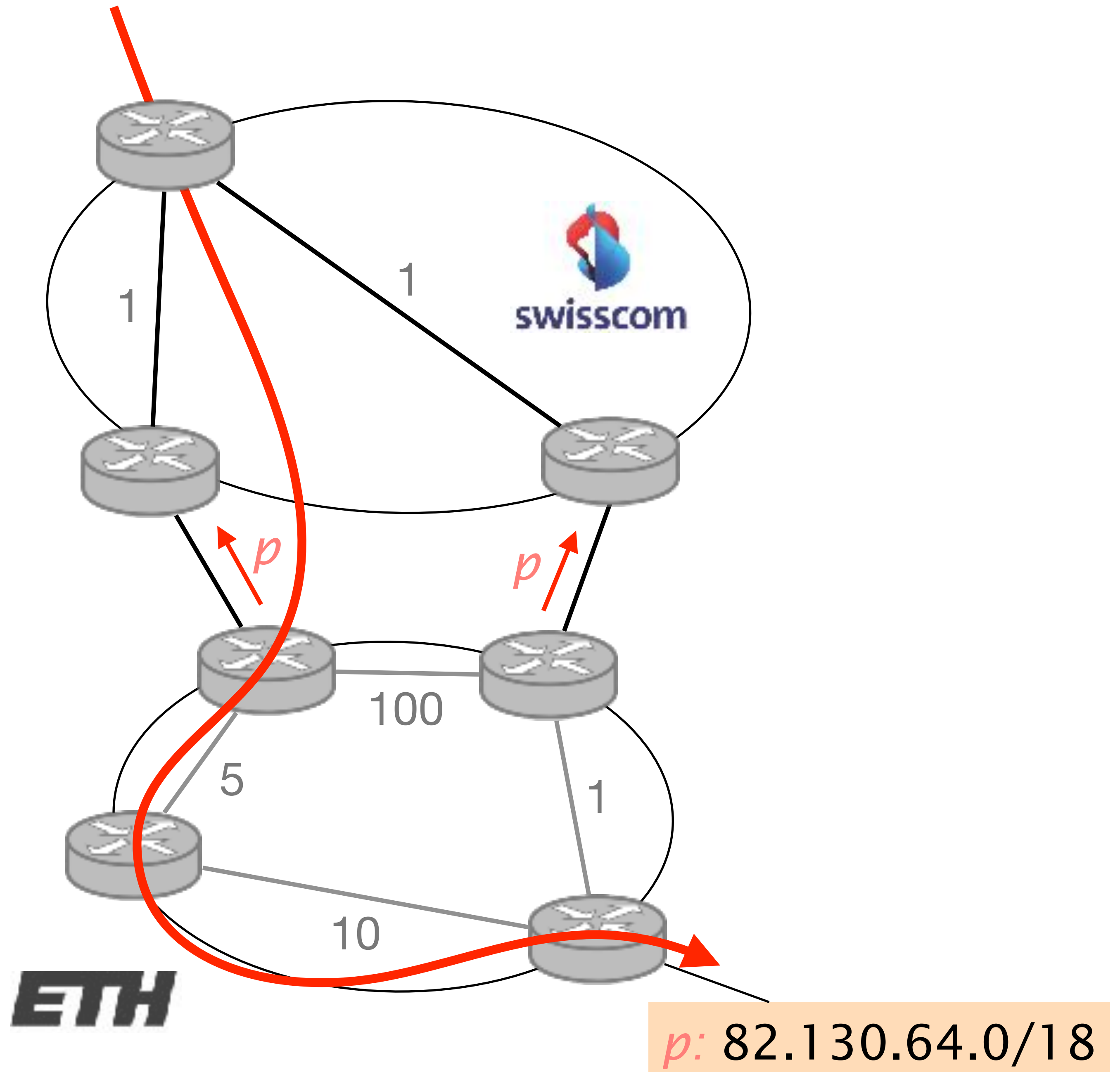
Swisscom receives two routes to reach *p*

and chooses (arbitrarily) its left router as egress



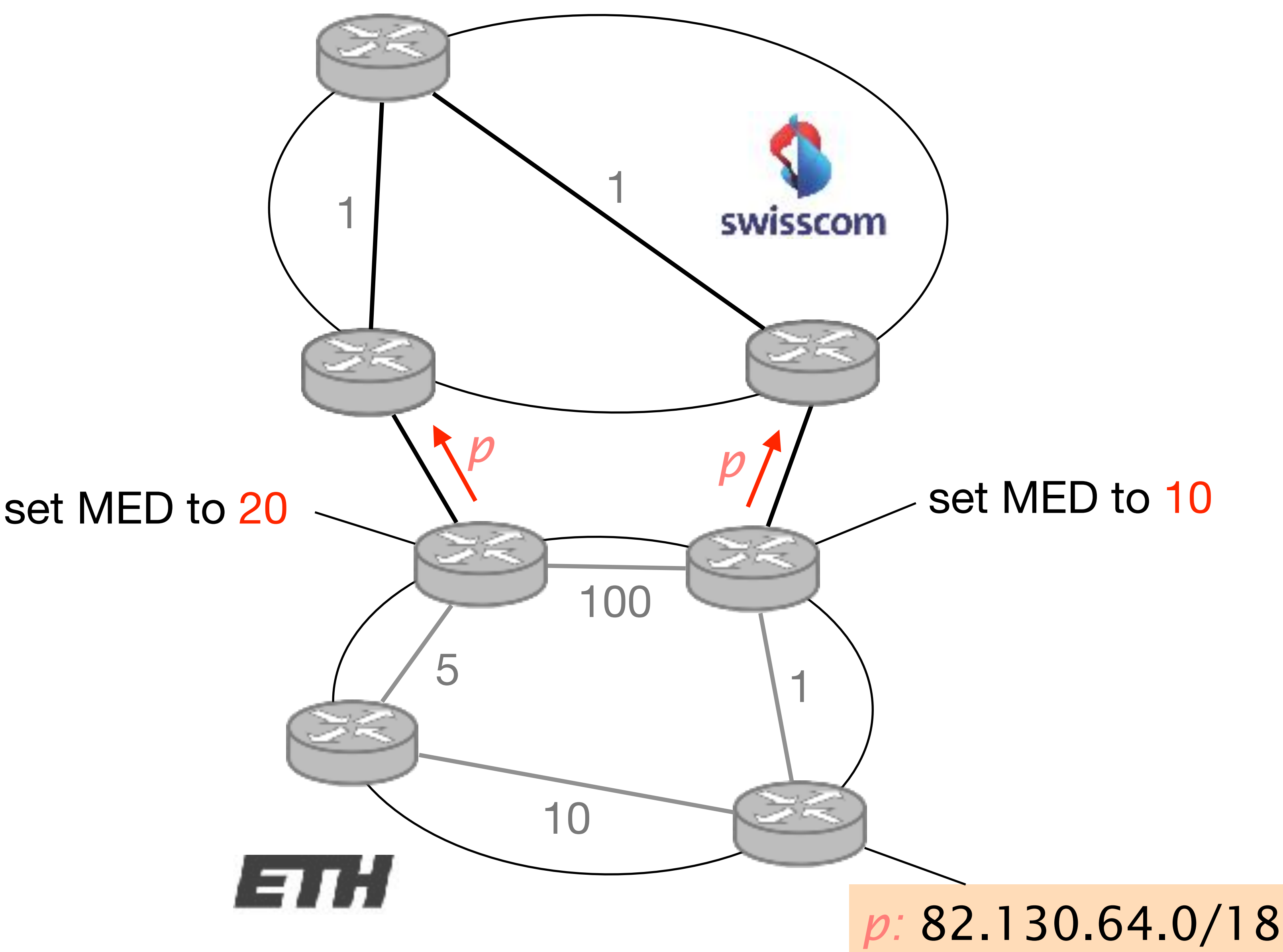
p: 82.130.64.0/18

Yet, ETH would prefer to receive traffic for *p*
on its right border router which is closer to the actual destination

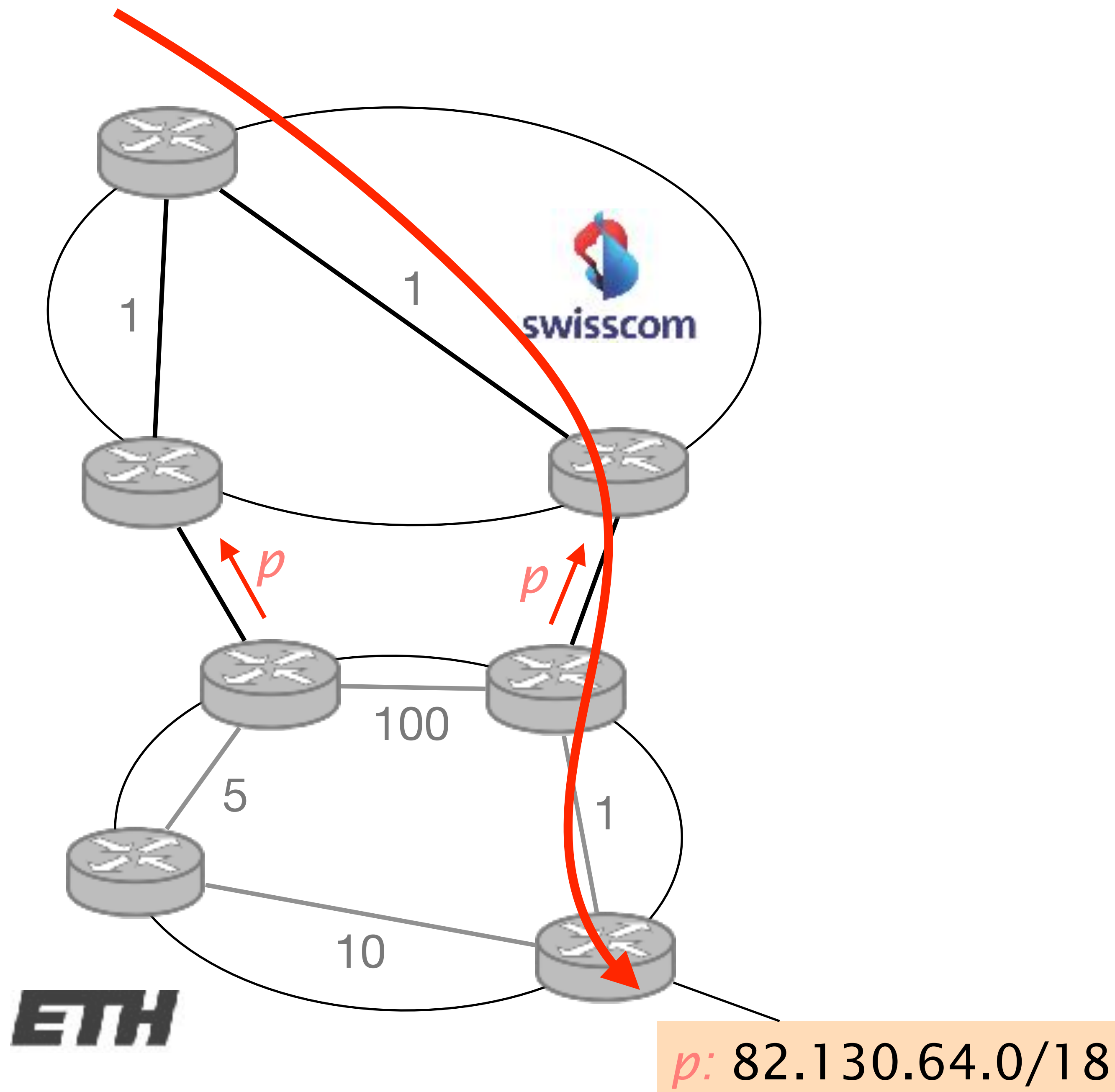


ETH can communicate that preferences to Swisscom

by setting a higher MED on *p* when announced from the left



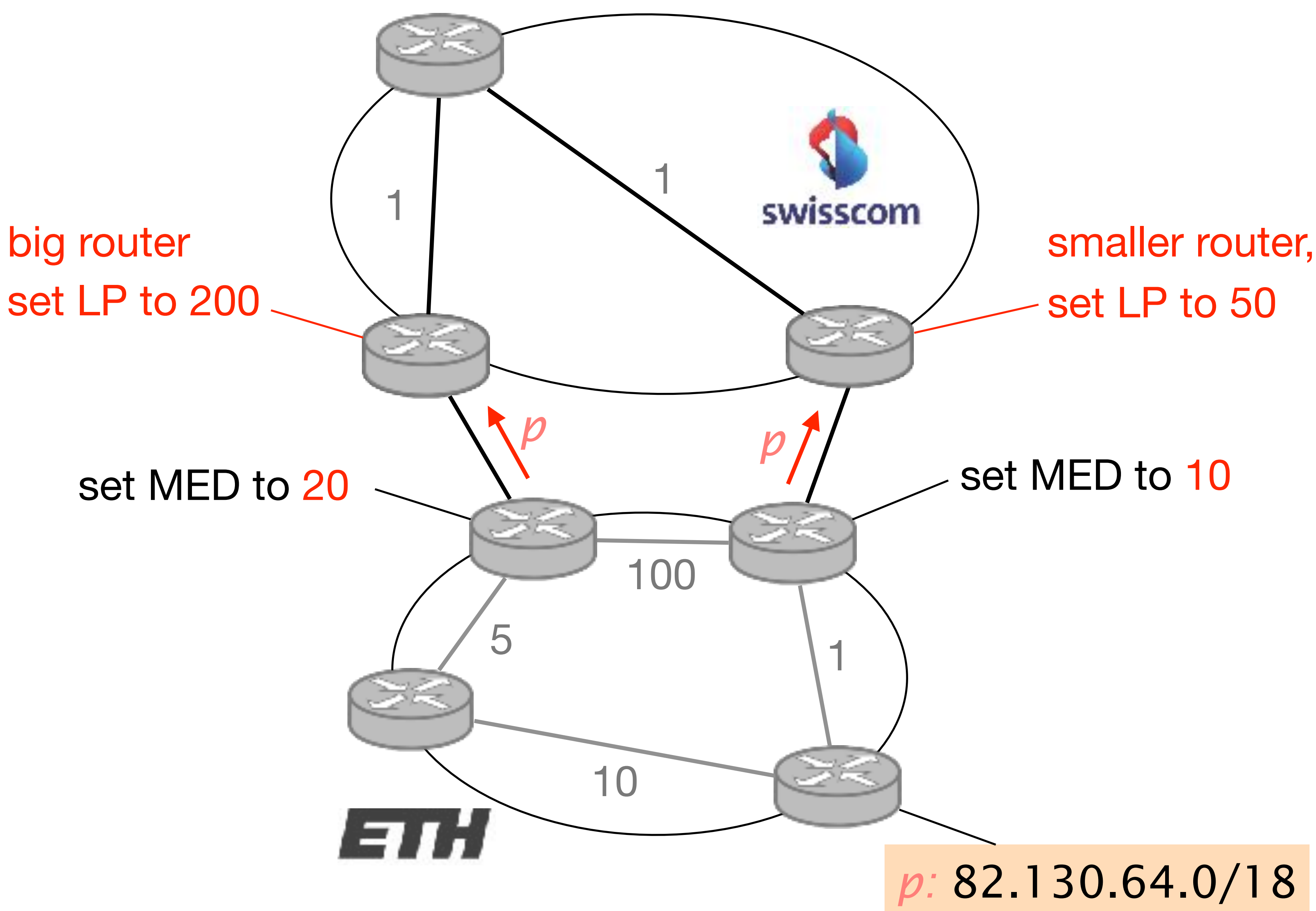
Swisscom receives two routes to reach *p*
and, *given it does not cost it anything more*,
chooses its right router as egress



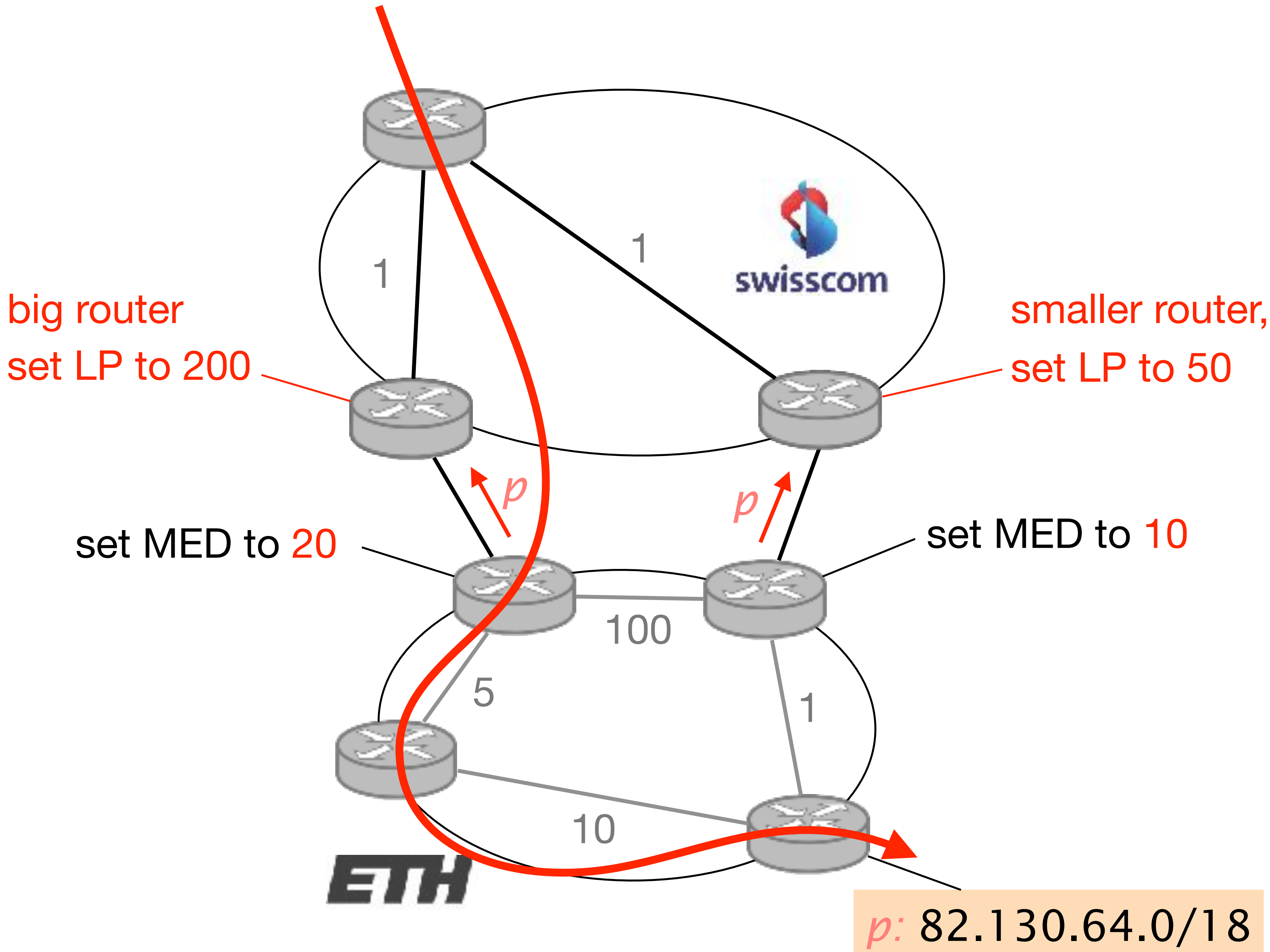
Swisscom receives two routes to reach p and, *given it does not cost it anything more*, chooses its right router as egress

But what if it does?

Consider that Swisscom always prefer to send traffic via its left egress point (bigger router, less costly)



In this case, Swisscom will not care about the MED value and still push the traffic via its left router



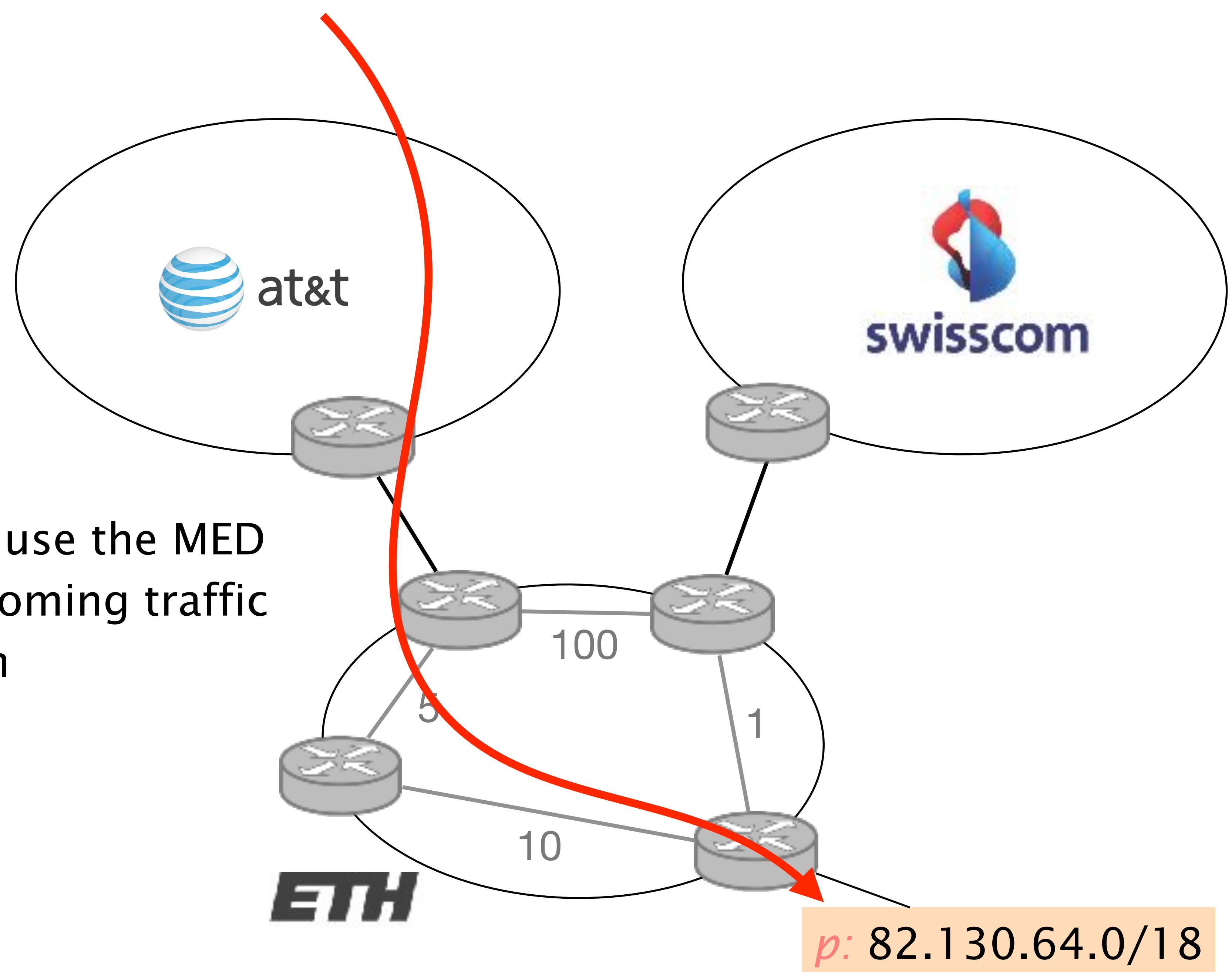
Lesson

The network which is sending the traffic always has the final word when it comes to deciding where to forward

Corollary

The network which is receiving the traffic can just influence remote decision, not control them

With the MED, an AS can influence its inbound traffic between multiple connection towards the same AS



ETH cannot use the MED to move incoming traffic to Swisscom

BGP UPDATEs carry an IP prefix together with a set of attributes

IP prefix

Attributes

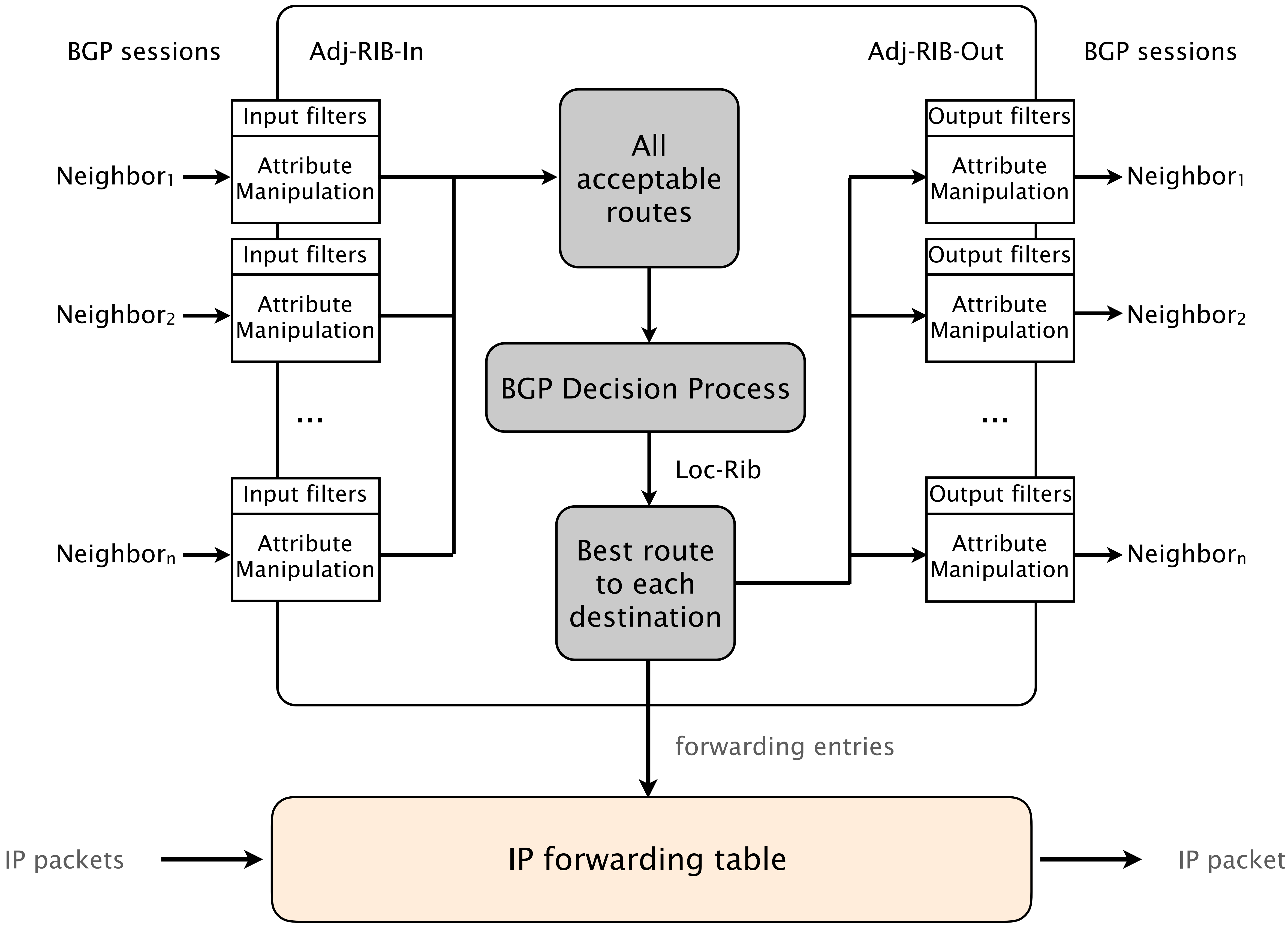
Describe route properties

used in route selection/exportation decisions

are either local (*only* seen on iBGP)

or global (seen on iBGP *and* eBGP)

Each BGP router processes UPDATEs according to a precise pipeline


BGP sessions
Adj-RIB-In
Adj-RIB-Out
BGP sessions
Input filters
Attribute Manipulation
Neighbor1
Input filters
Attribute Manipulation
Neighbor2
...
Input filters
Attribute Manipulation
Neighborn
All acceptable routes
BGP Decision Process
Loc-Rib
Best route to each destination
Output filters
Attribute Manipulation
Neighbor1
Output filters
Attribute Manipulation
Neighbor2
...
Output filters
Attribute Manipulation
Neighborn
forwarding entries
IP packets
IP forwarding table
IP packets

Given the set of all acceptable routes for each prefix, the BGP Decision process elects a single route

BGP is often referred to as a single path protocol

Prefer routes…

with higher LOCAL-PREF

with shorter AS-PATH length

with lower MED

learned via eBGP instead of iBGP

with lower IGP metric to the next-hop

with smaller egress IP address (tie-break) learned via eBGP instead of iBGP

with lower IGP metric to the next-hop

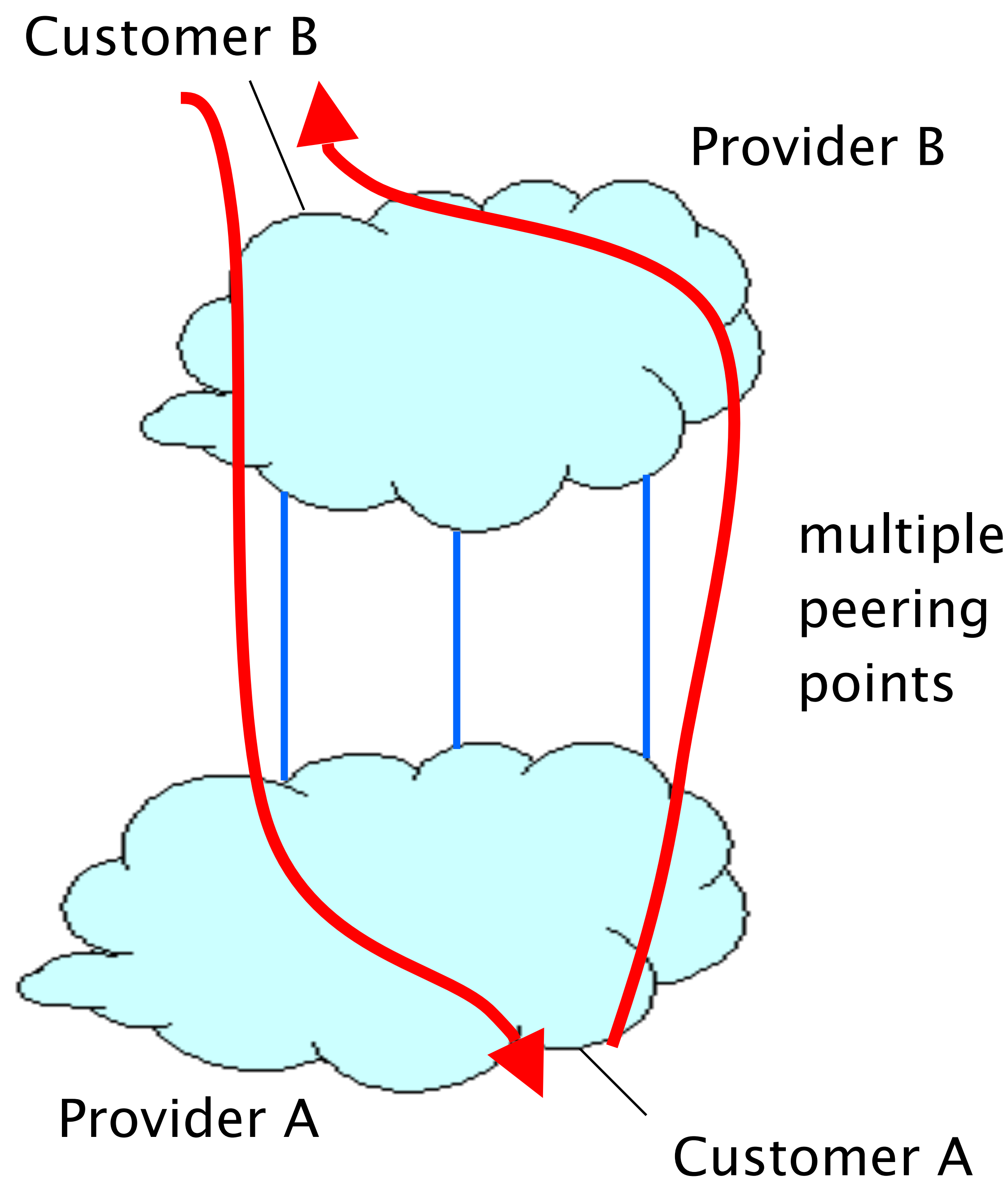
These two steps aim at directing traffic
as quickly as possible out of the AS (early exit routing)

ASes are selfish

They dump traffic
as soon as possible
to someone else

This leads to asymmetric routing

Traffic does not flow on
the same path
in both directions



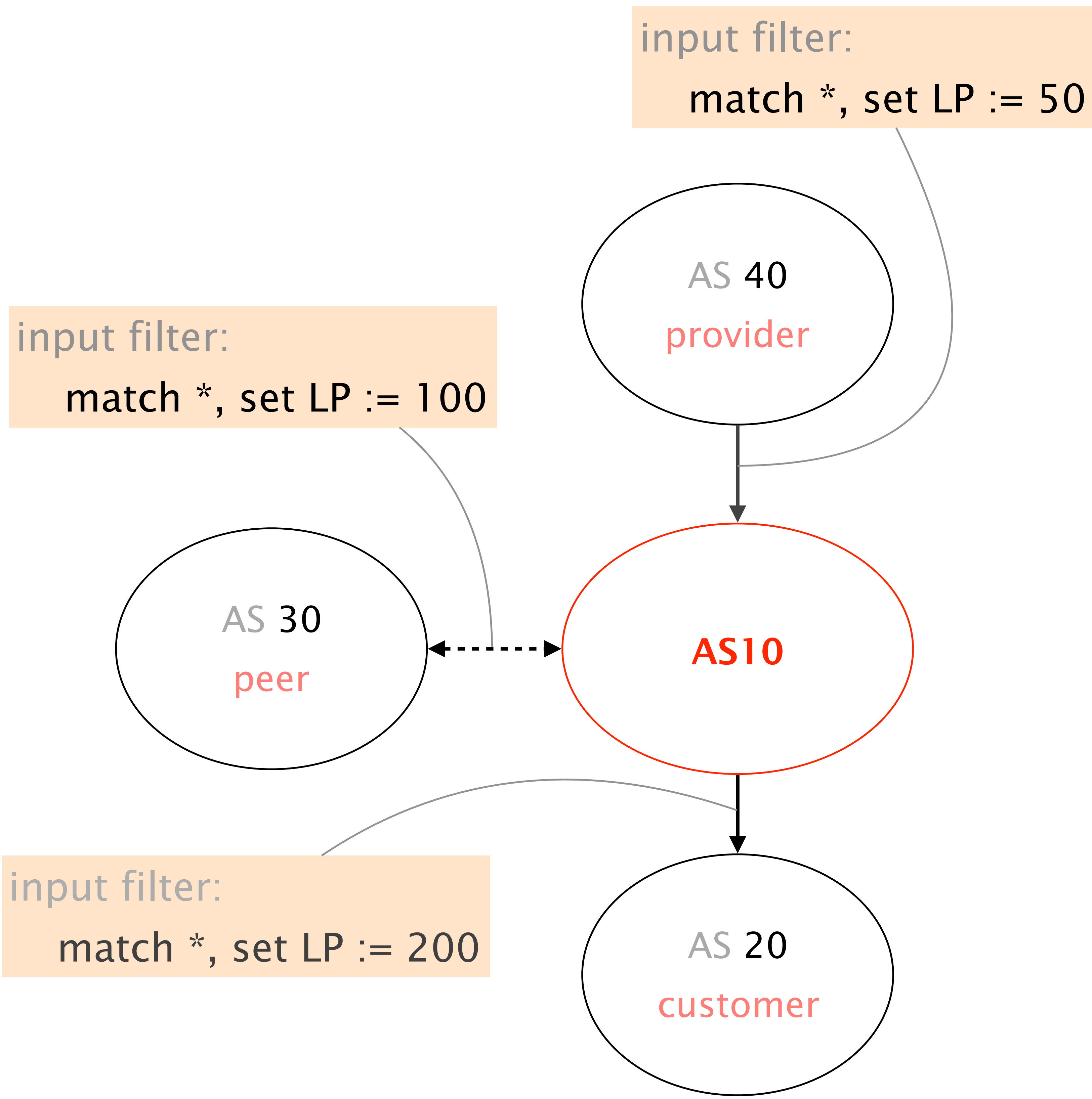
Let’s look at how operators implement customer/provider and peer policies in practice

To implement their selection policy, operators define input filters which manipulates the LOCAL-PREF

For a destination *p*, prefer routes coming from

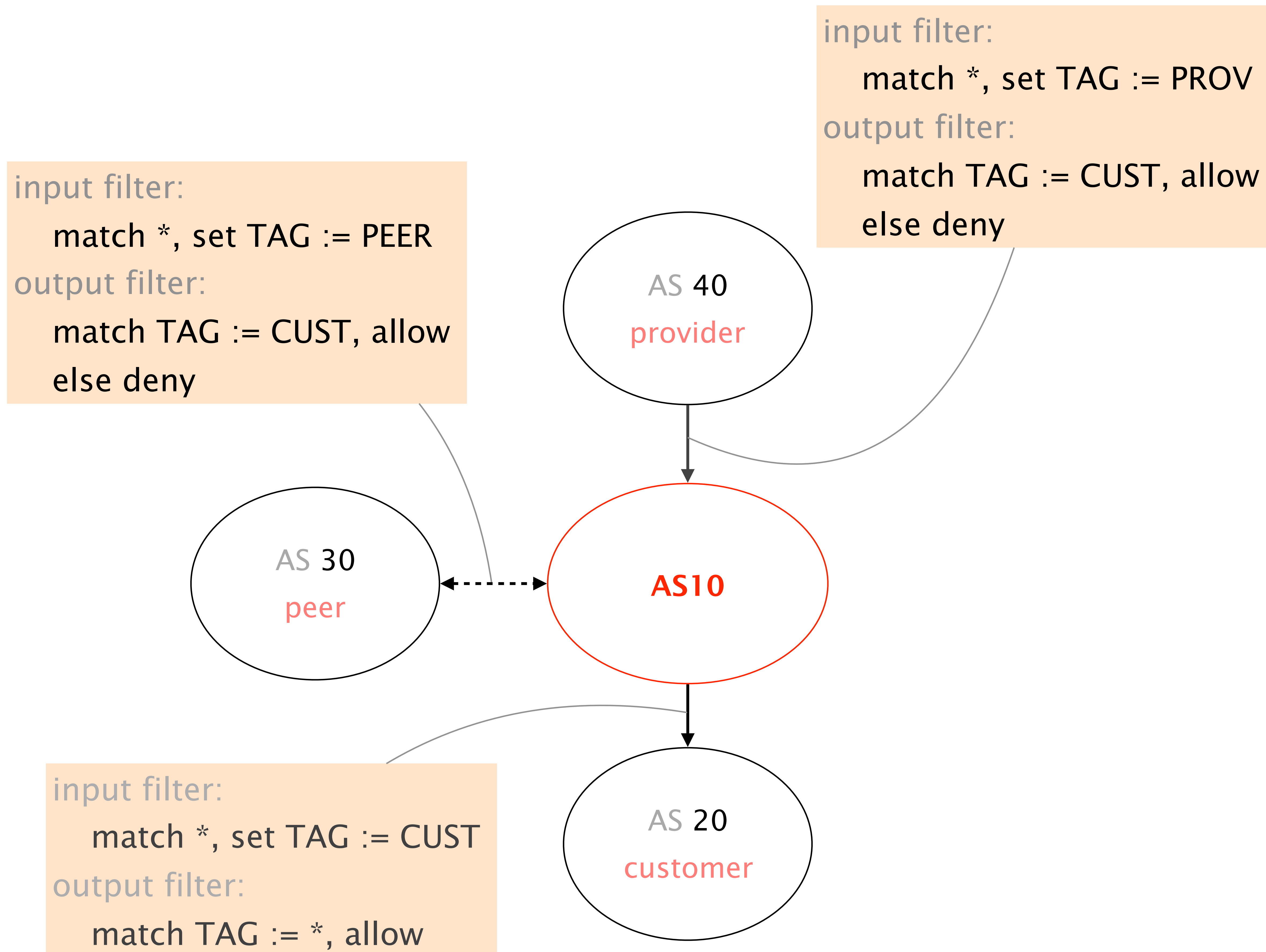
- customers over
- peers over
- providers

route type


input filter:
match *, set LP := 50
AS 40
provider
input filter:
match *, set LP := 100
AS 30
peer
AS10
input filter:
match *, set LP := 200
AS 20
customer

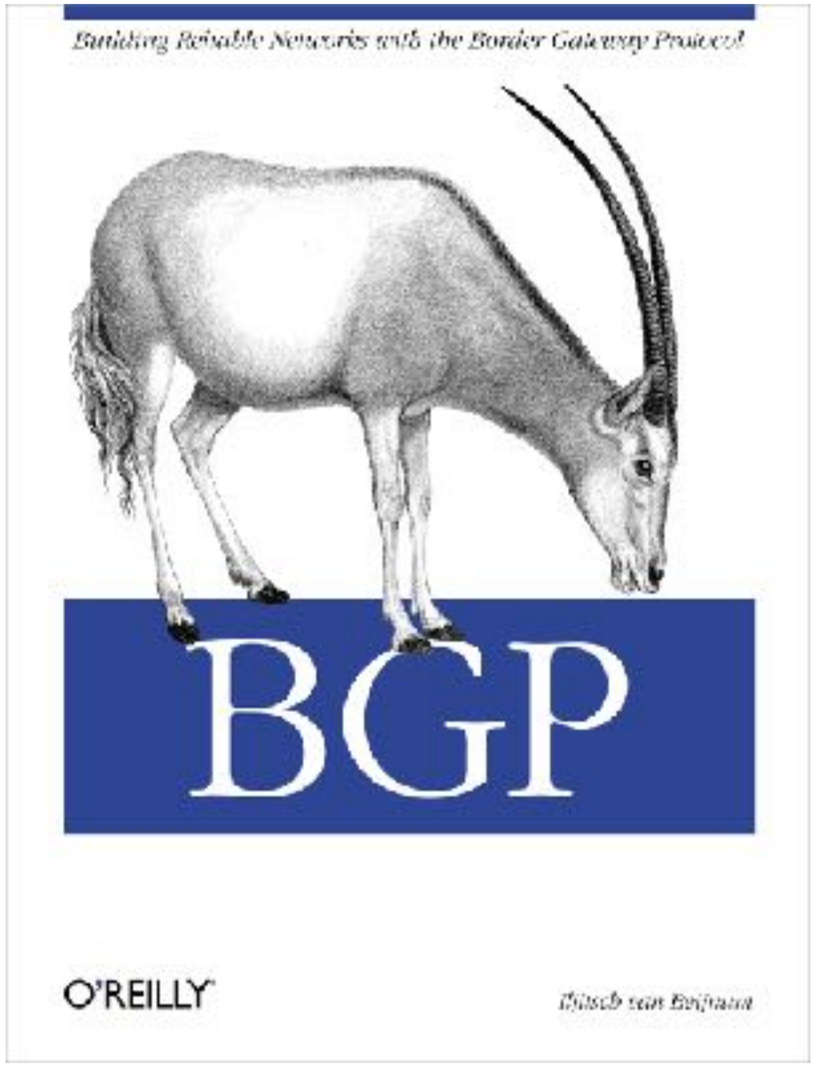
To implement their exportation rules, operators use a mix of import and export filters

		send to		
		customer	peer	provider
	customer	✓	✓	✓
from	peer	✓	-	-
	provider	✓	-	-


input filter:
match *, set TAG := PROV
output filter:
match TAG := CUST, allow
else deny
input filter:
match *, set TAG := PEER
output filter:
match TAG := CUST, allow
else deny
AS 40
provider
AS 30
peer
AS10
input filter:
match *, set TAG := CUST
output filter:
match TAG := *, allow
AS 20
customer

Border Gateway Protocol

policies and more



BGP Policies

Follow the Money

Protocol

How does it work?

3 Problems

security, performance, …

BGP suffers from many rampant problems

Problems	Reachability
	Security
	Convergence
	Performance
	Anomalies
	Relevance

Problems

Reachability

Security

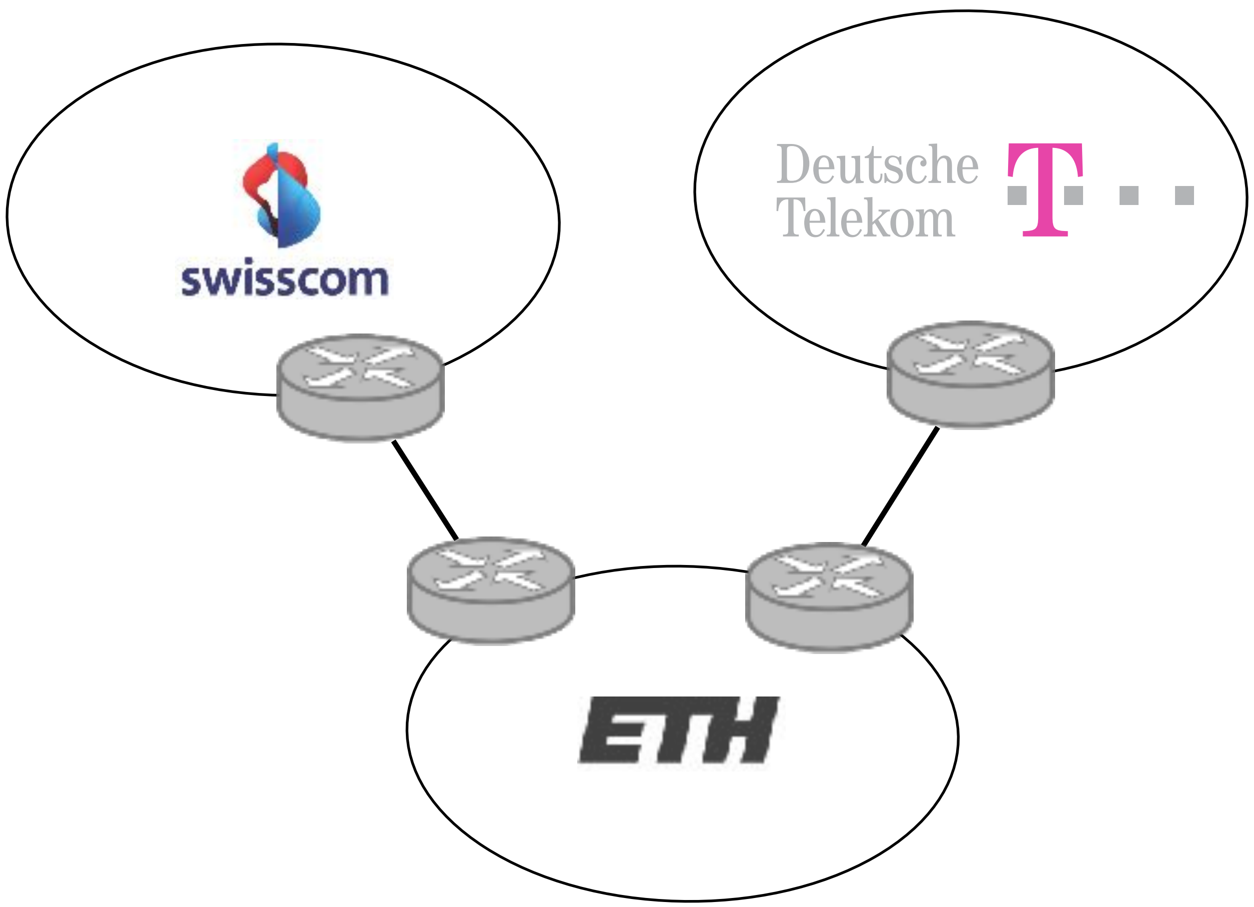
Convergence

Performance

Anomalies

Relevance

Unlike normal routing, policy routing does not guarantee reachability even if the graph is connected



Because of policies,

Swisscom cannot reach DT

even if the graph is connected

Problems

Reachability

Security

Convergence

Performance

Anomalies

Relevance

Many security considerations are simply absent from BGP specifications

ASes can advertise any prefixes

even if they don't own them!

ASes can arbitrarily modify route content

e.g., change the content of the AS-PATH

ASes can forward traffic along different paths

than the advertised one

We’ll do a deep dive into BGP security next week

Problems

Reachability

Security

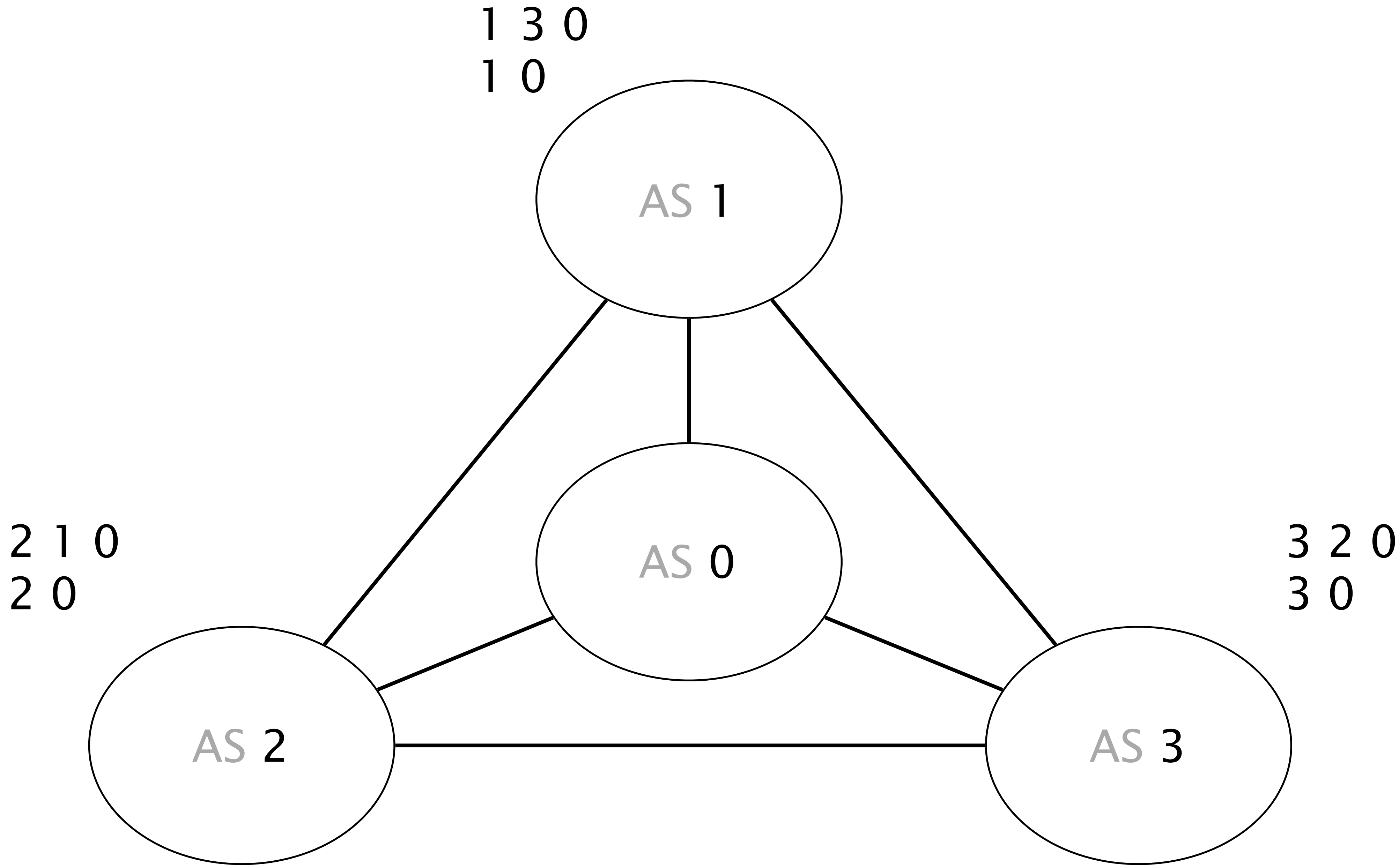
Convergence

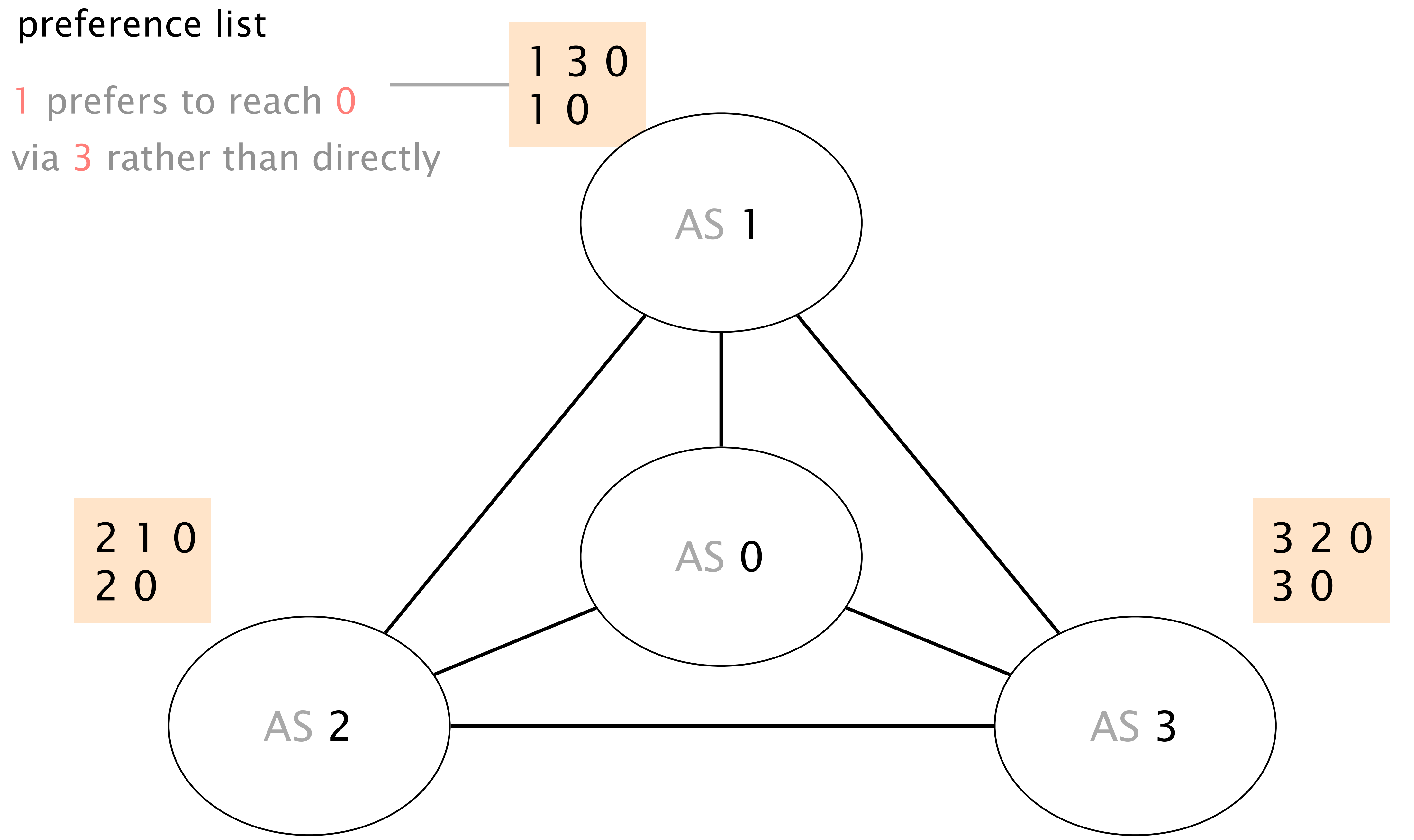
Performance

Anomalies

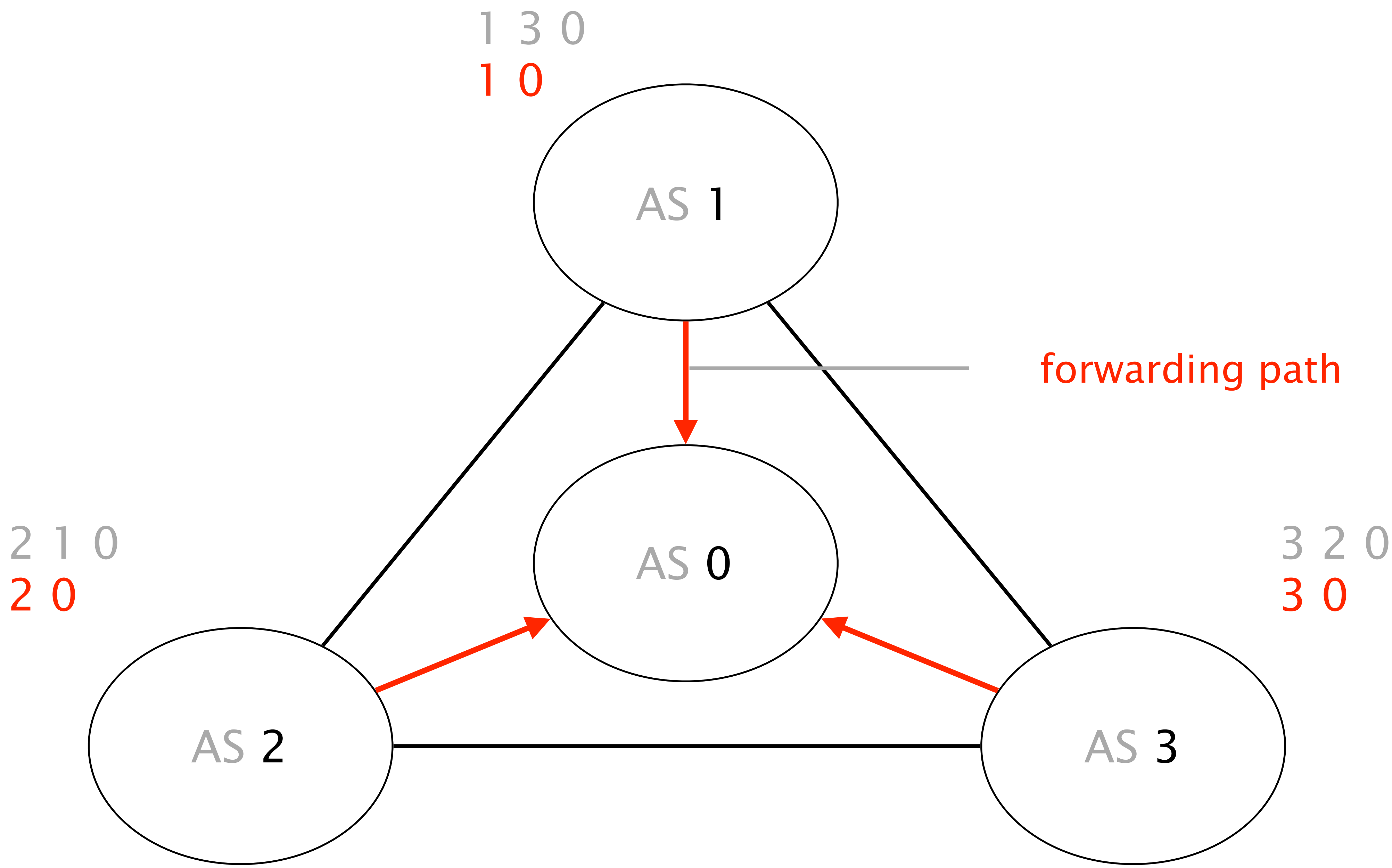
Relevance

With arbitrary policies,
BGP may fail to converge

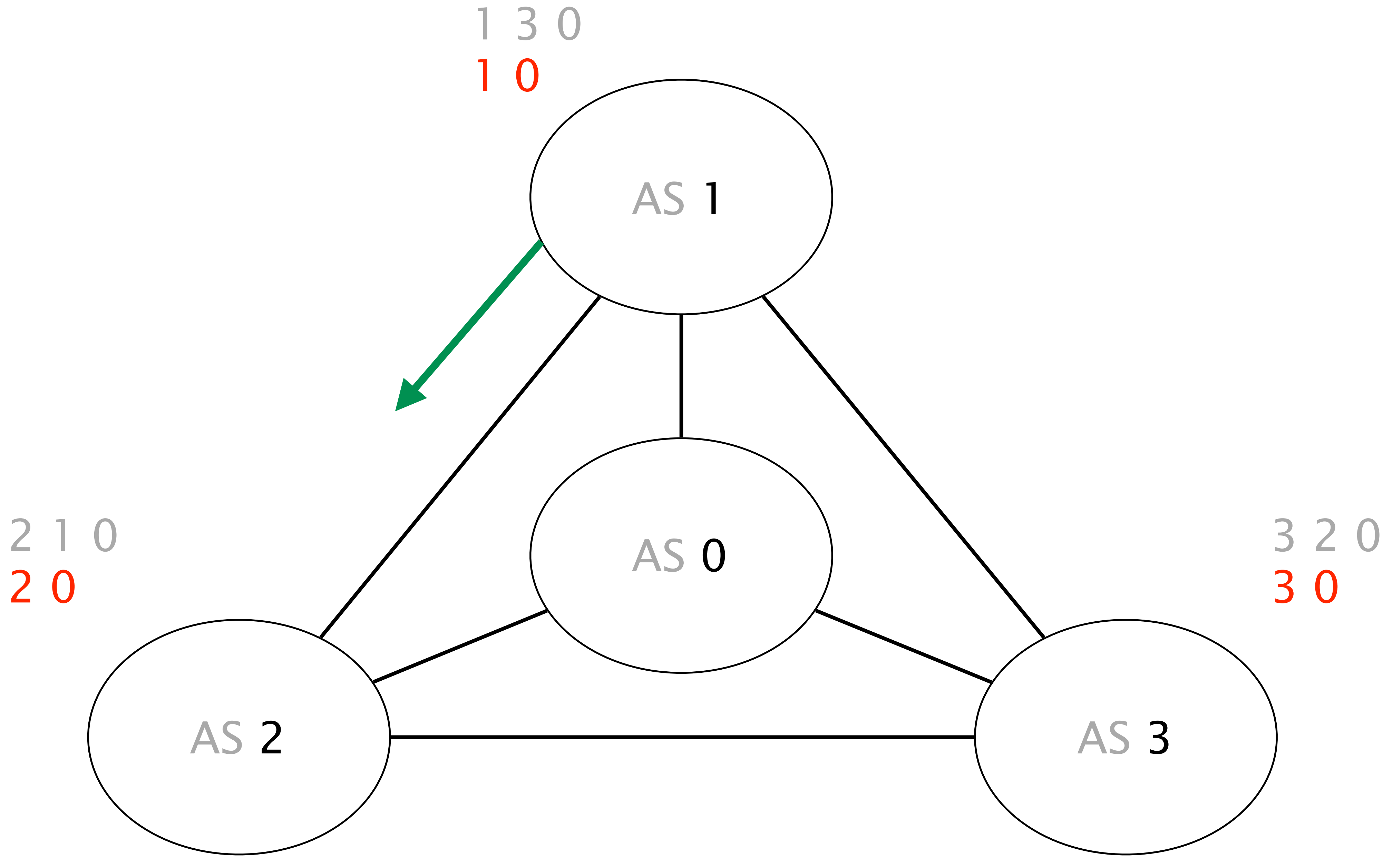

1 3 0
1 0
AS 1
2 1 0
2 0
AS 0
3 2 0
3 0
AS 2
AS 3


preference list
1 prefers to reach 0
via 3 rather than directly
1 3 0
1 0
2 1 0
2 0
3 2 0
3 0
AS 1
AS 0
AS 2
AS 3

Initially, all ASes only know the direct route to 0

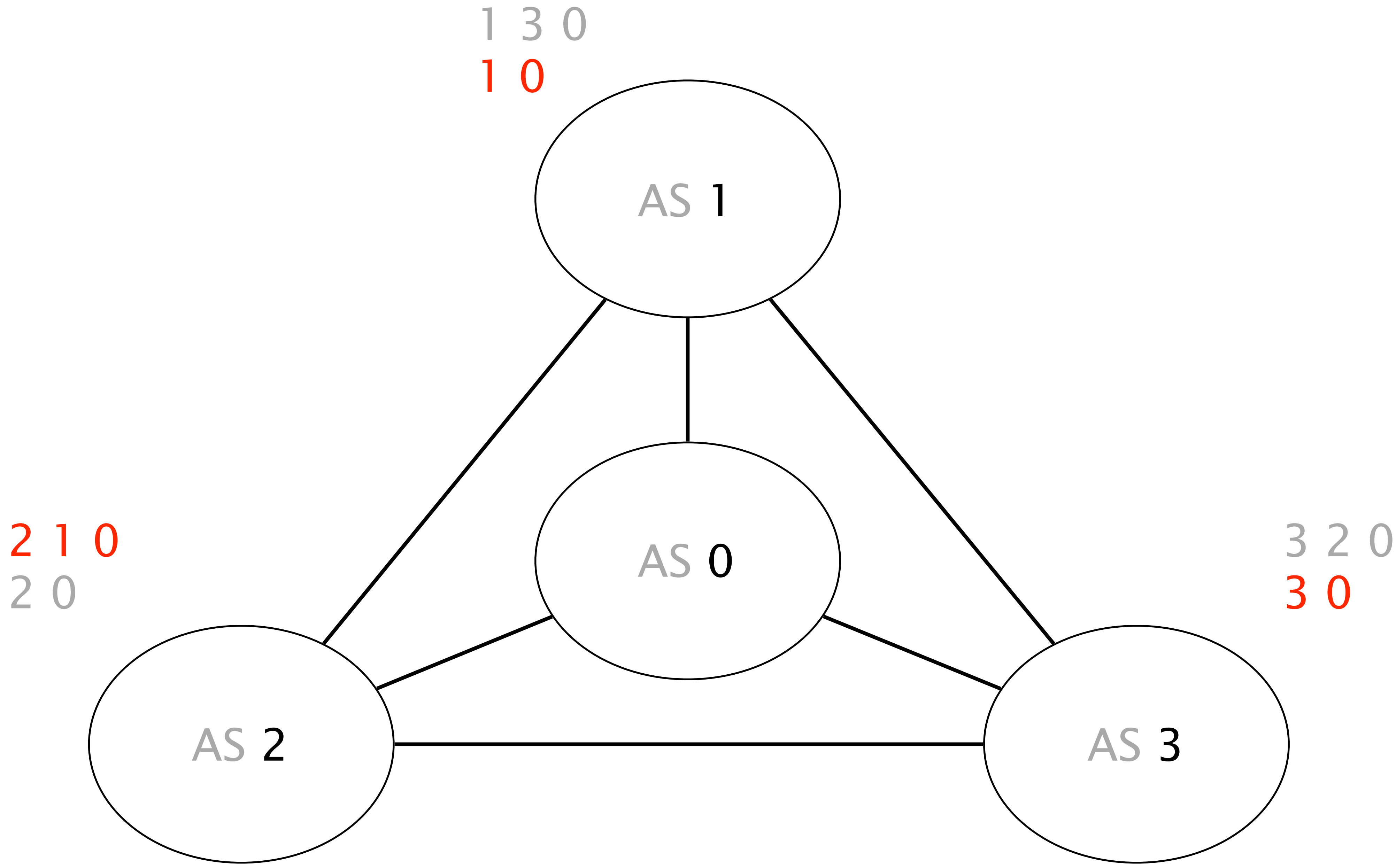


AS 1 advertises its path to AS 2

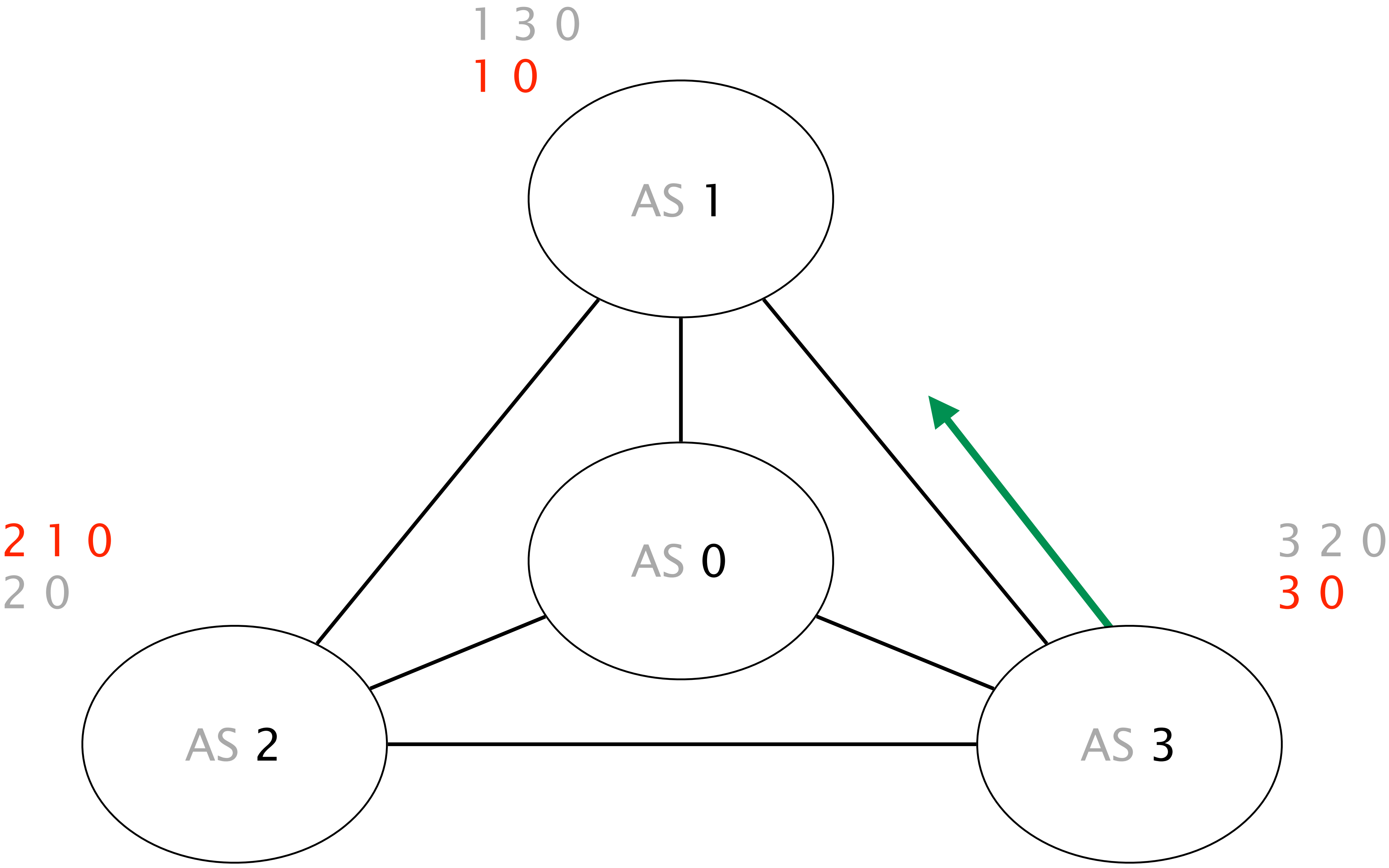


Upon reception,

AS 2 switches to 2 1 0 (preferred)

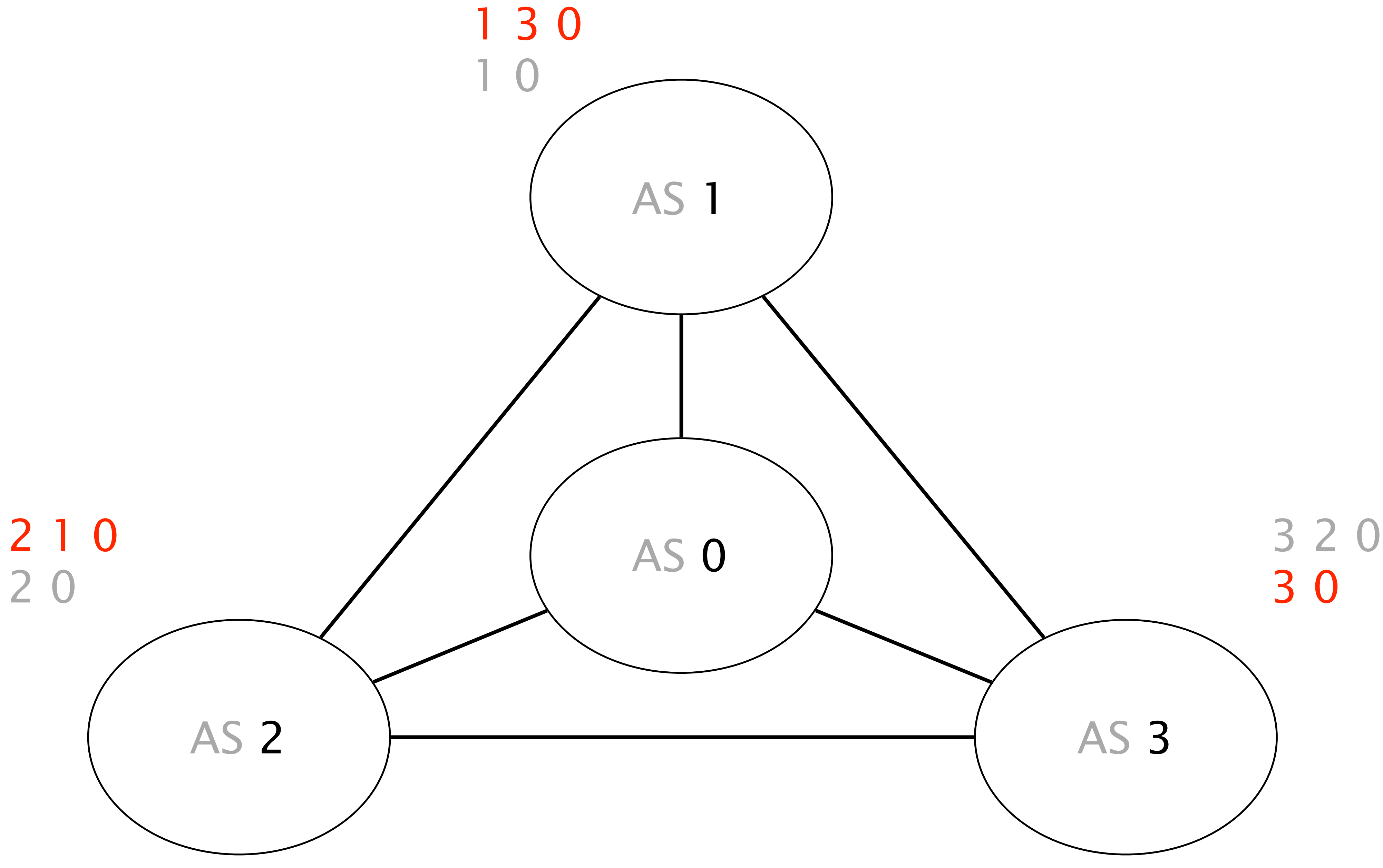


AS 3 advertises its path to AS 1

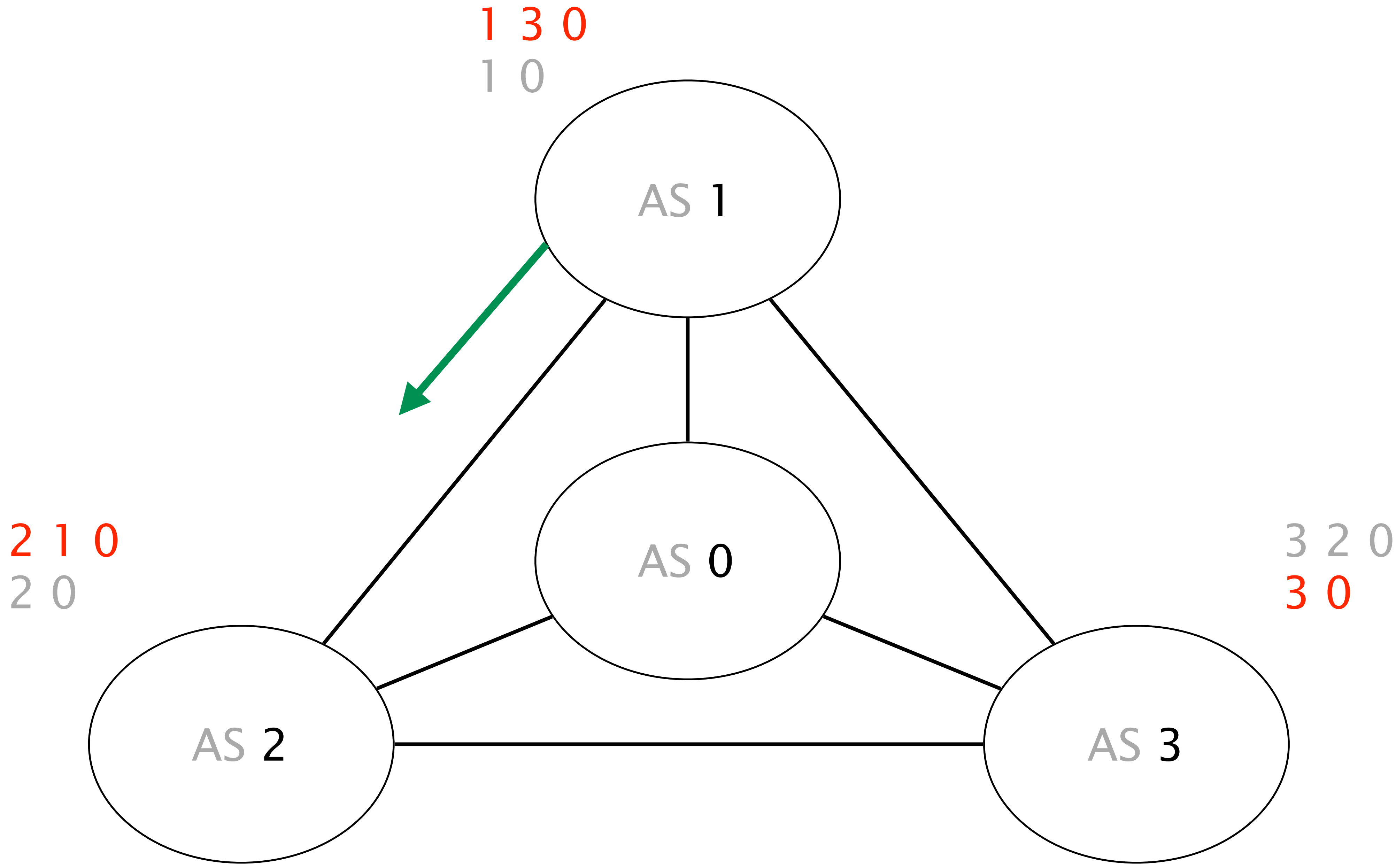


Upon reception,

AS 1 switches to 1 3 0 (preferred)

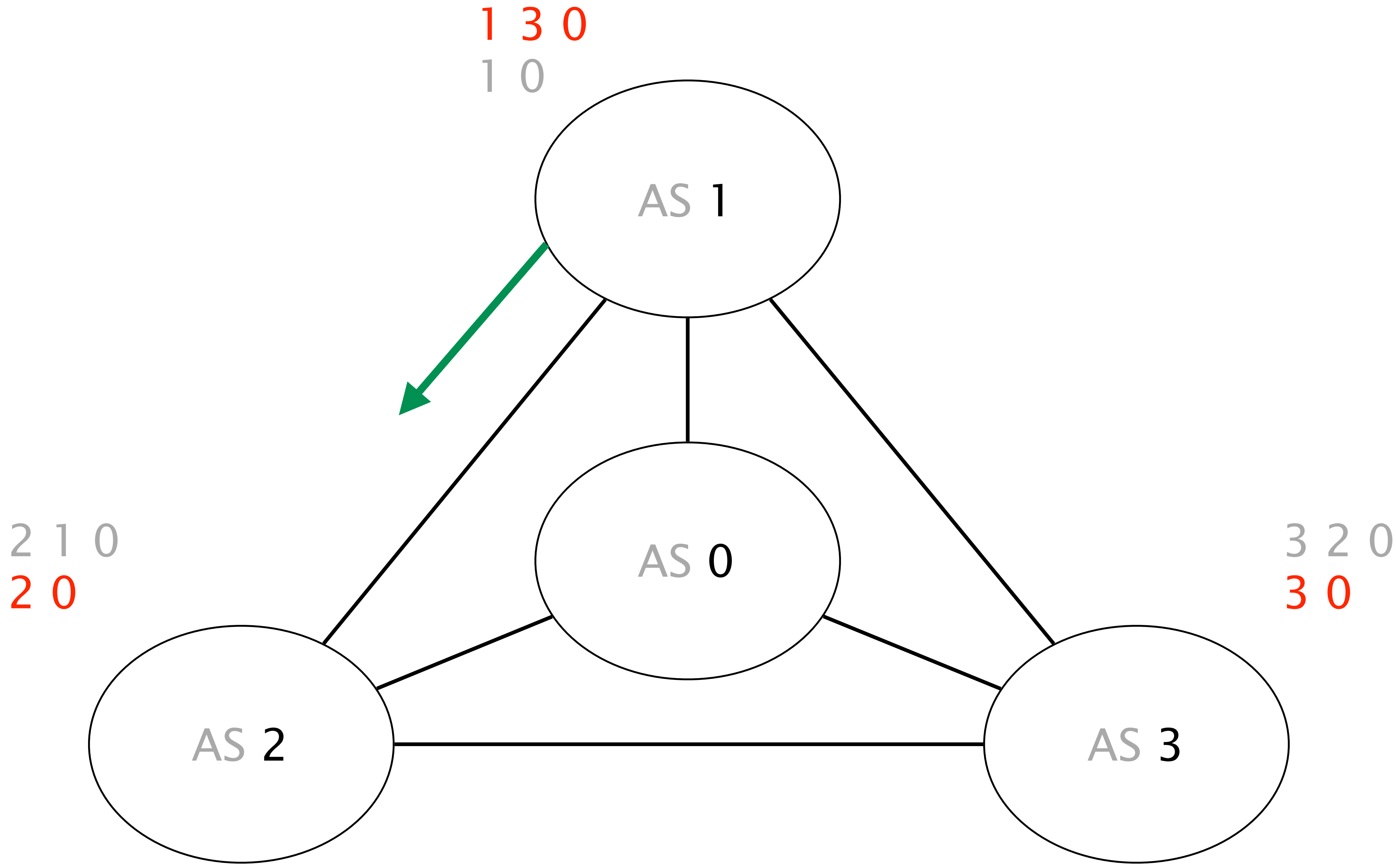


AS 1 advertises its new path 1 3 0 to AS 2

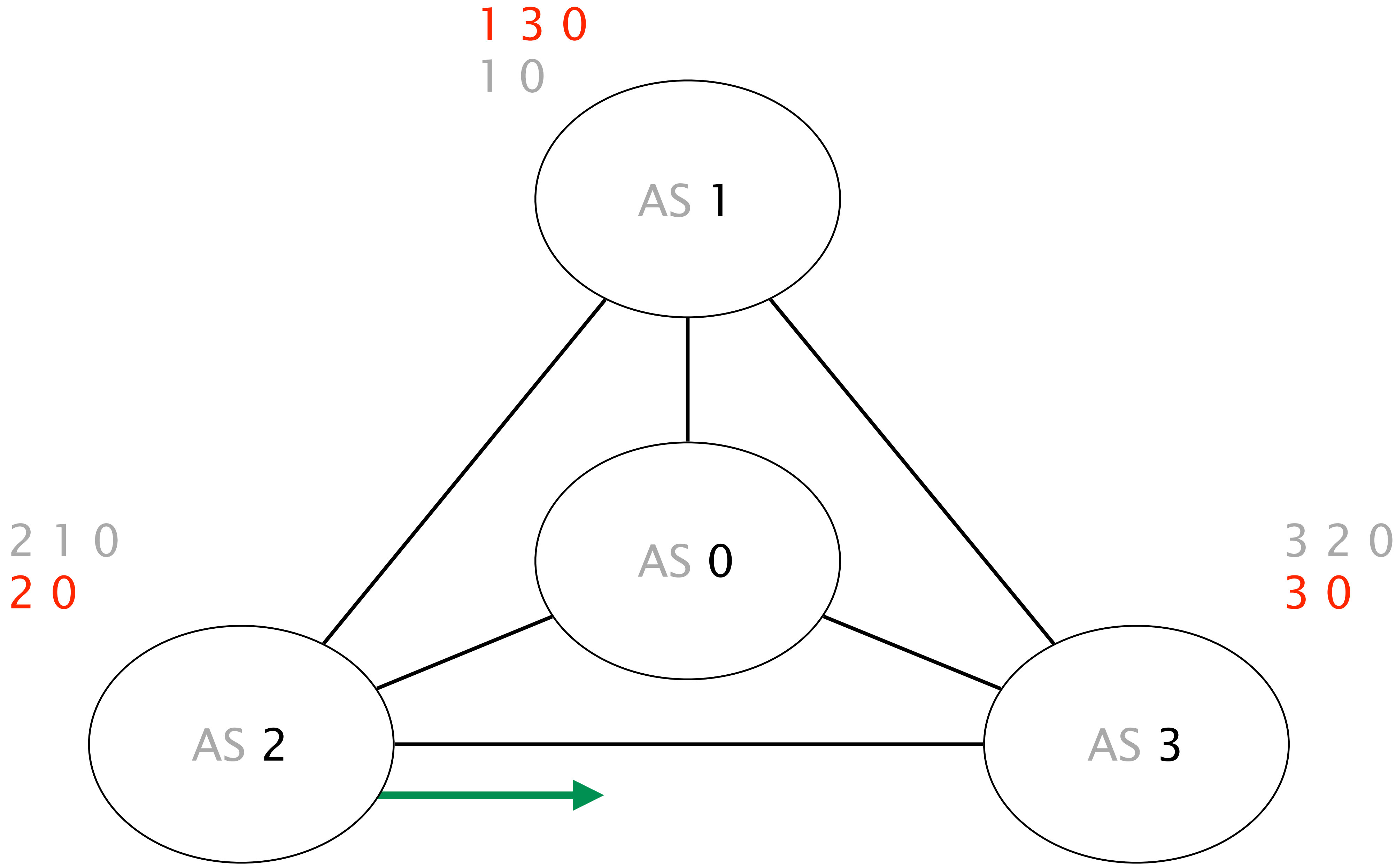


Upon reception,

AS 2 reverts back to its initial path 2 0

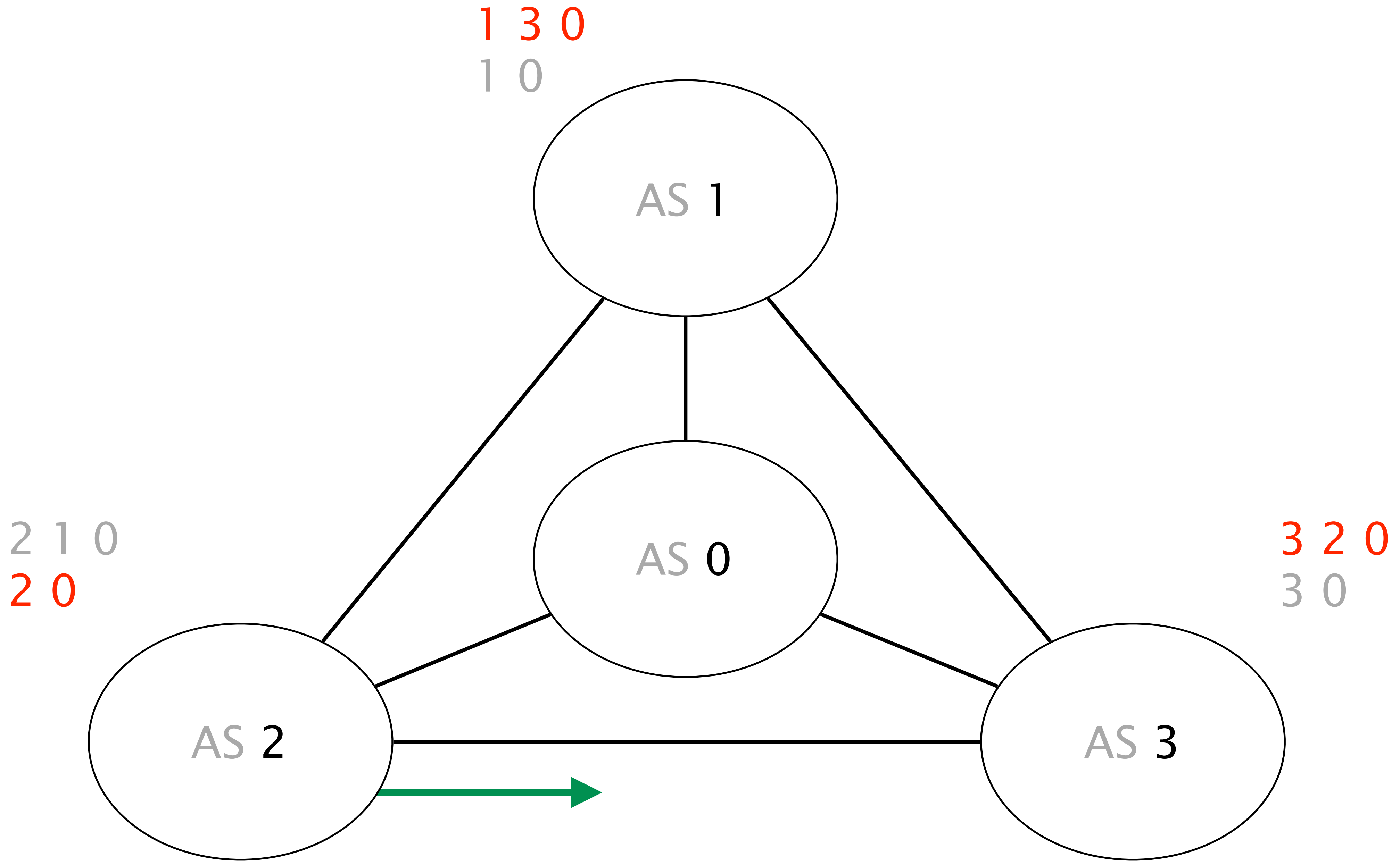


AS 2 advertises its path 2 0 to AS 3

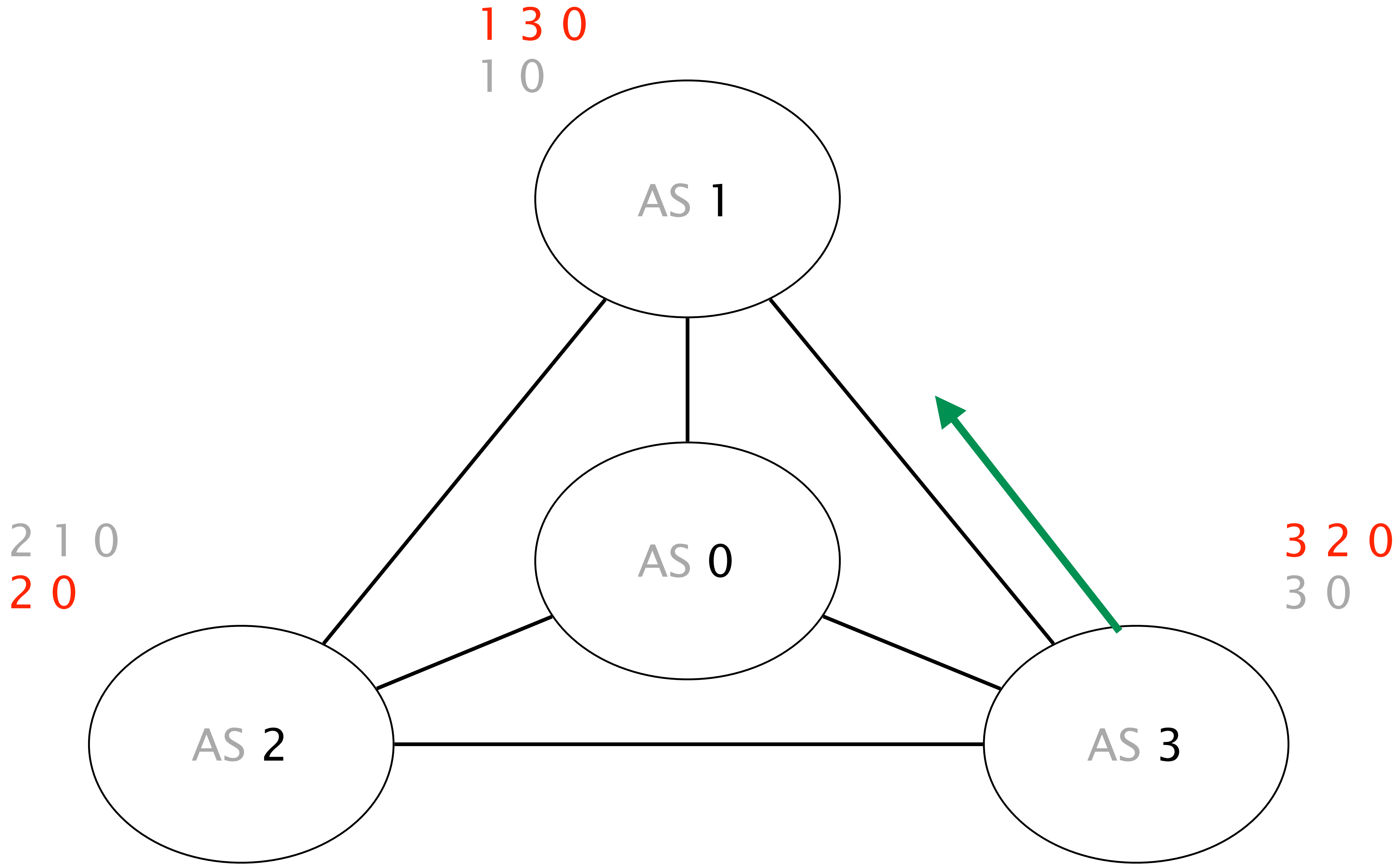


Upon reception,

AS 3 switches to 3 2 0 (preferred)

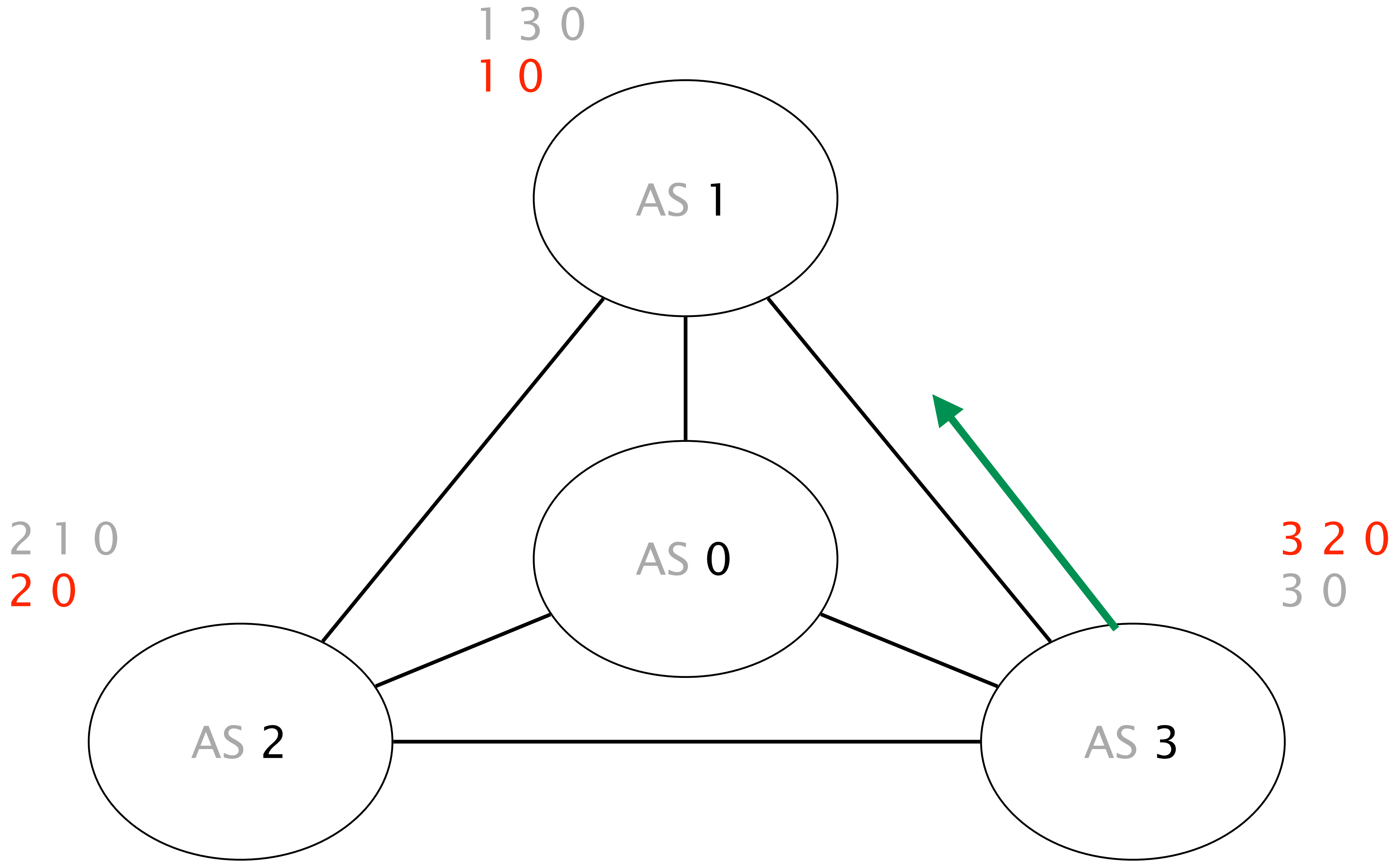


AS 3 advertises its new path 3 2 0 to AS 1

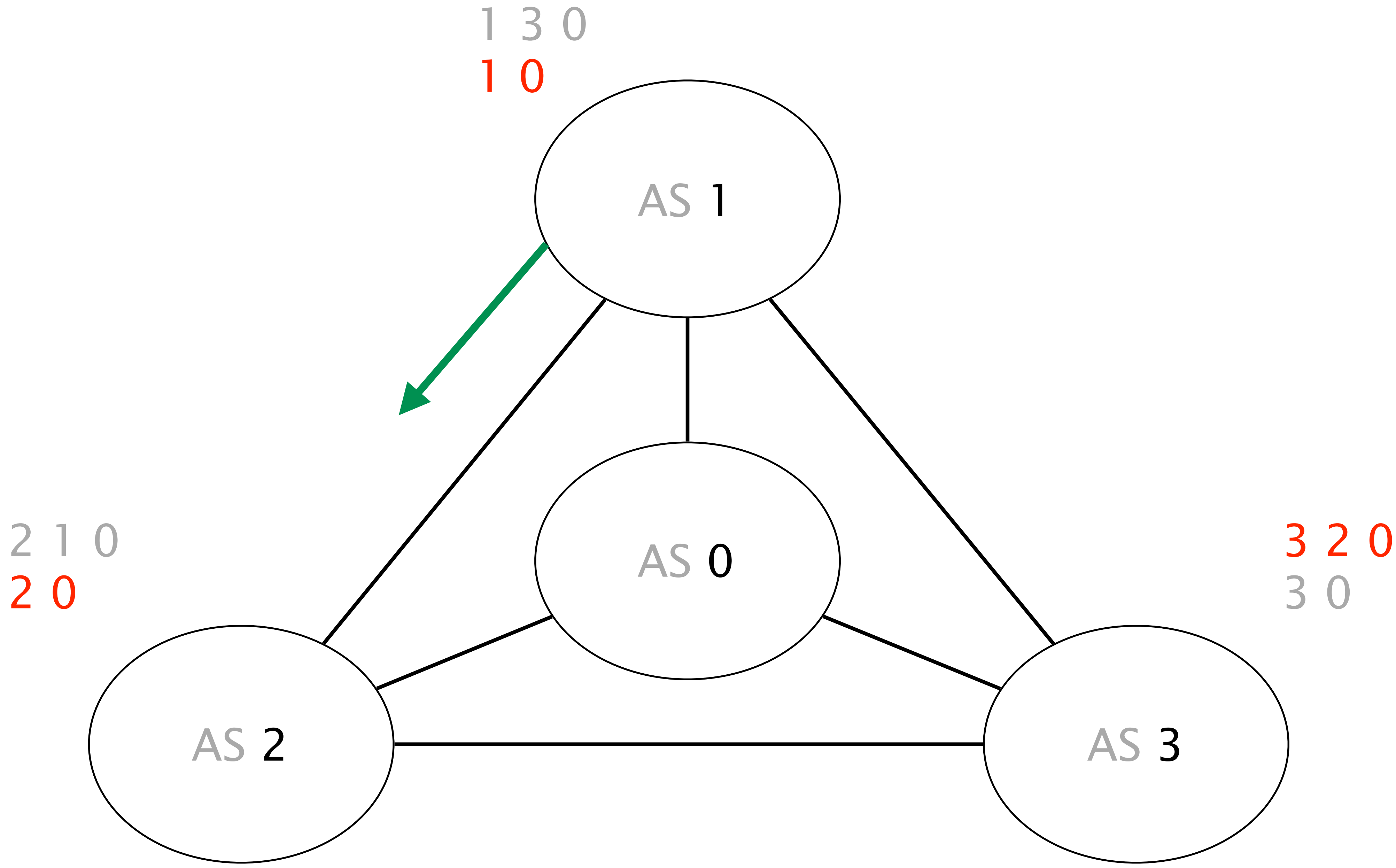


Upon reception,

AS 1 reverts back to 1 0 (initial path)

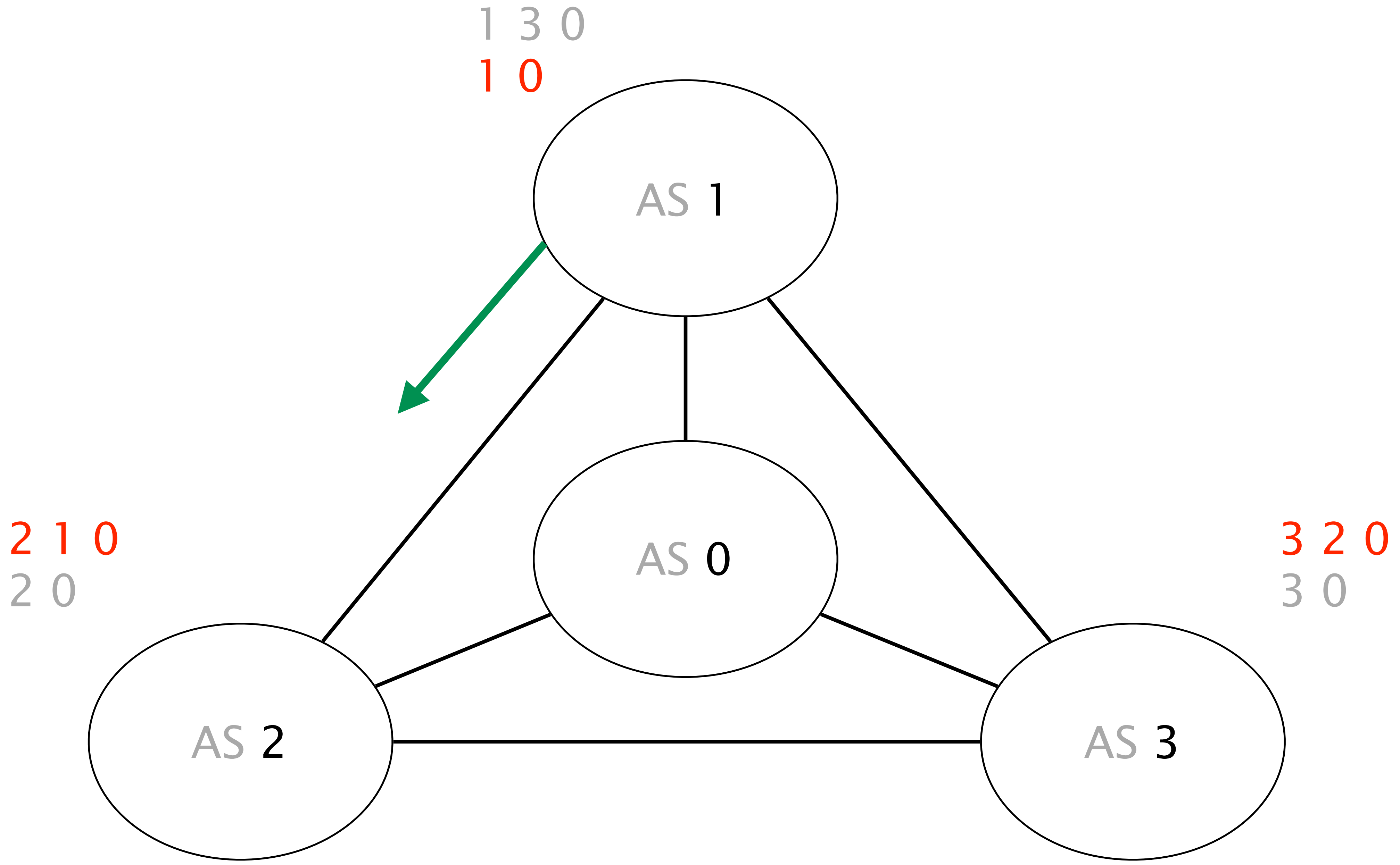


AS 1 advertises its new path 1 0 to AS 2

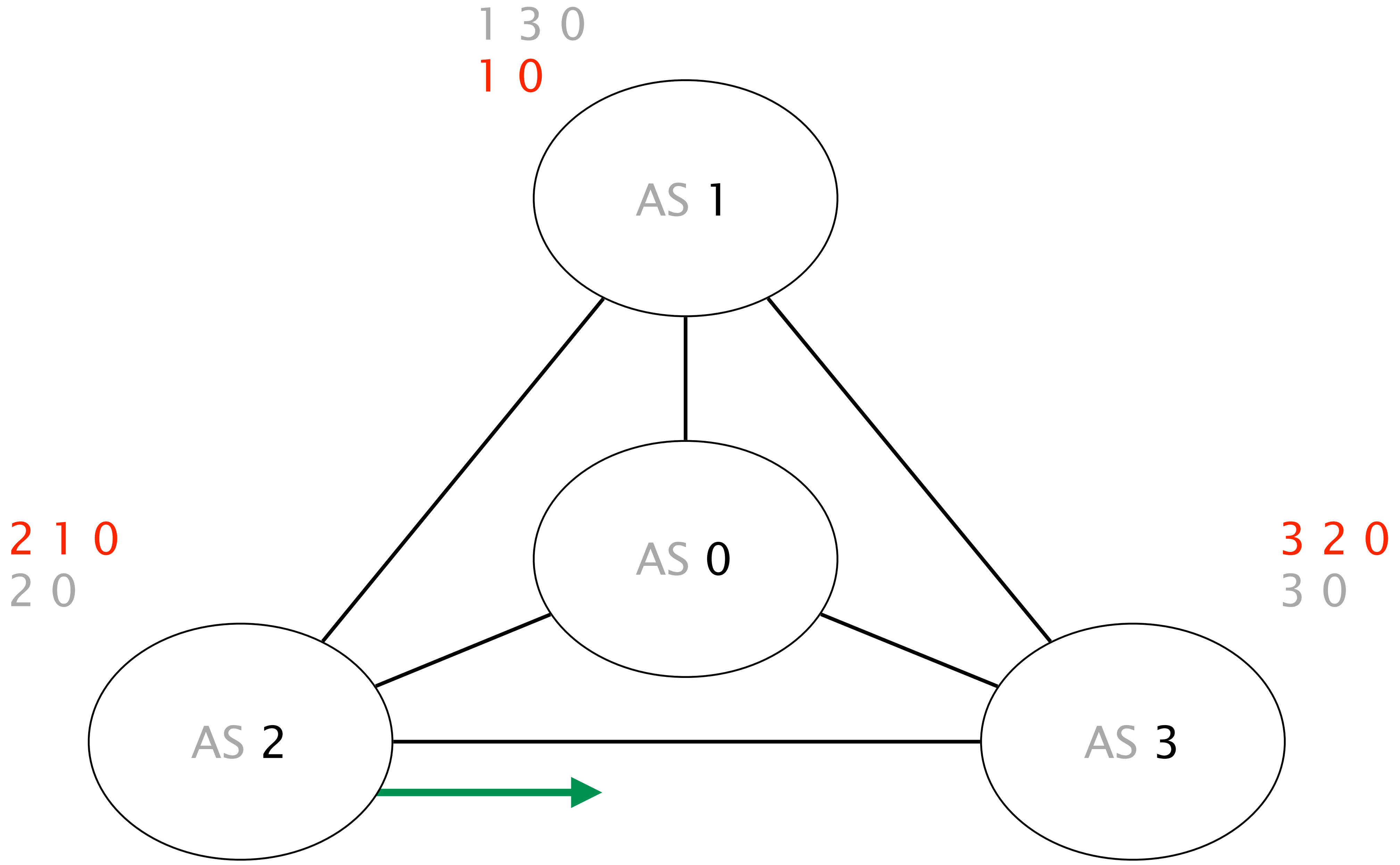


Upon reception,

AS 2 switches to 2 1 0 (preferred)

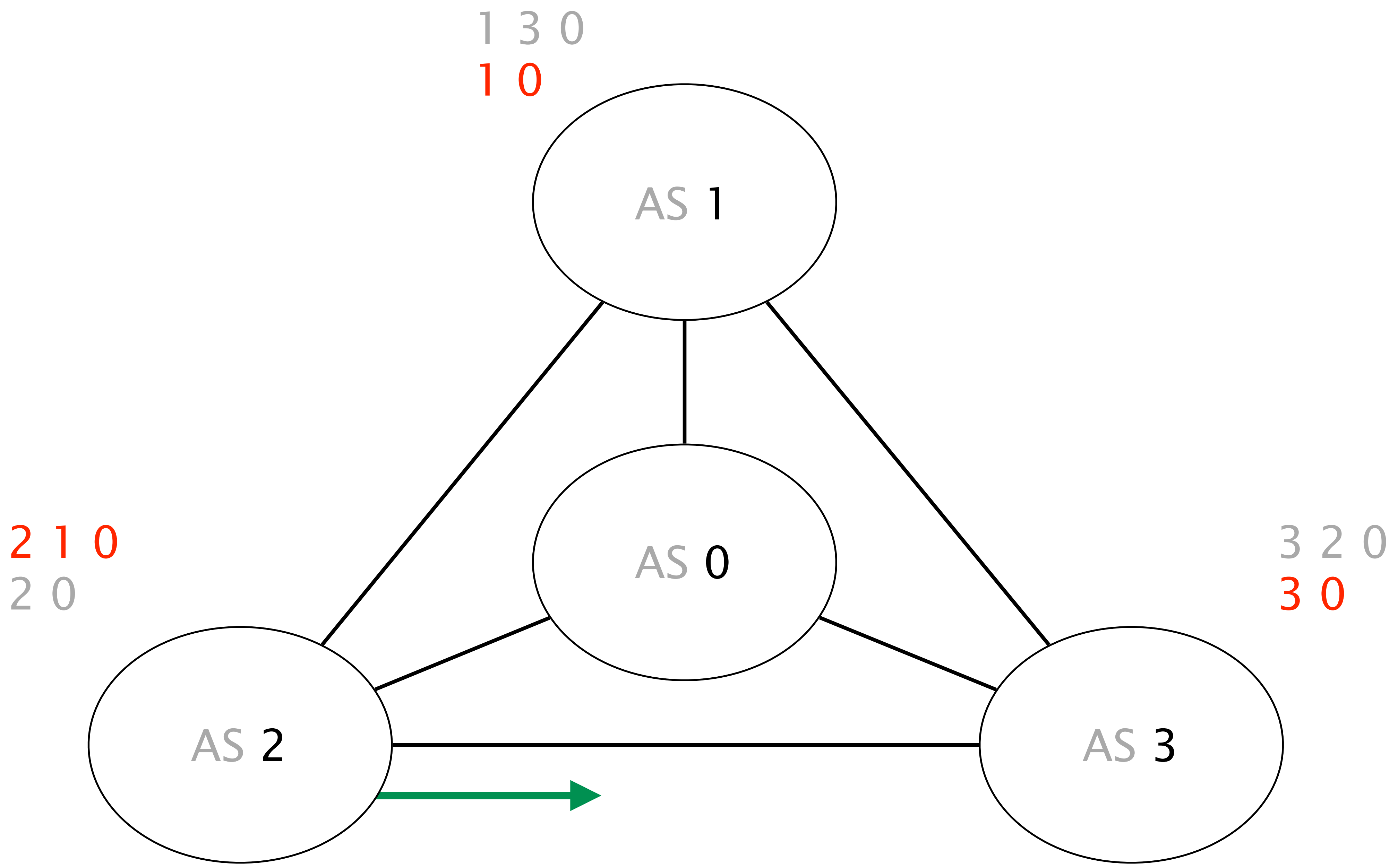


AS 2 advertises its new path 2 1 0 to AS 3

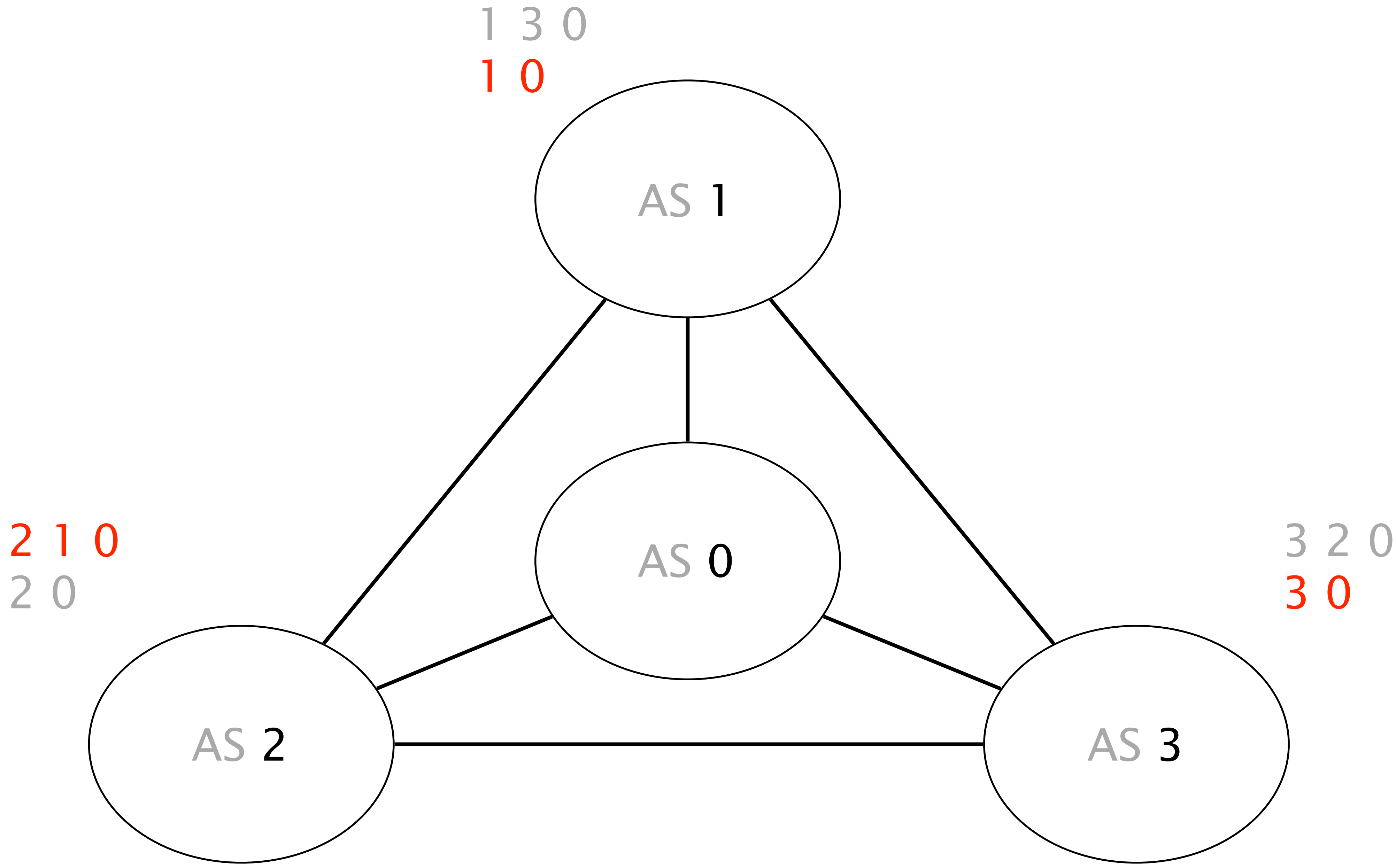


Upon reception,

AS 3 switches to its initial path 3 0



We are back where we started, from there on, the oscillation will continue forever



Policy oscillations are a direct consequence of policy autonomy

ASes are free to chose and advertise any paths they want

network stability argues against this

Guaranteeing the absence of oscillations is hard

even when you know all the policies!

Guaranteeing the absence of oscillations is hard

even when you know all the policies!

How come?

Theorem

Computationally, a BGP network is as "powerful" as

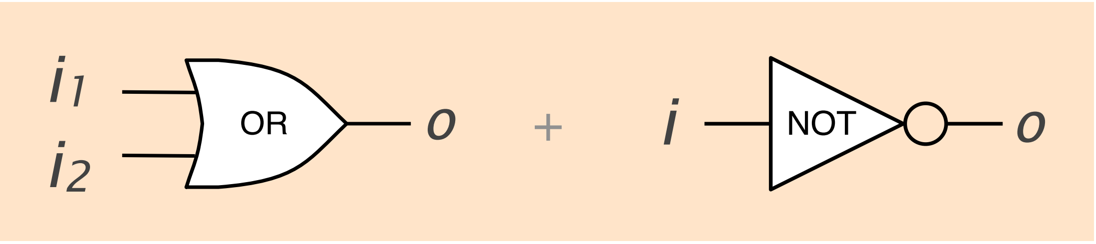
see "Using Routers to Build Logic Circuits: How Powerful is BGP?"

How do you prove such a thing?

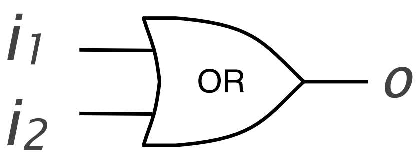
How do you prove such a thing?

Easy, you build a computer using BGP…

Logic gates



Logic gates



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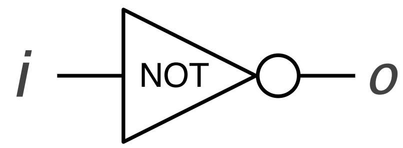

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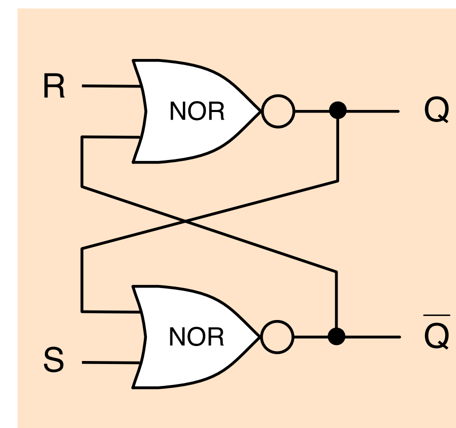
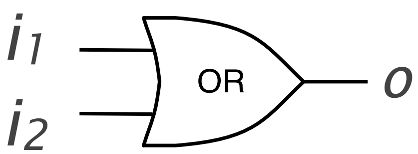
Memory



Logic gates | Memory | Clock



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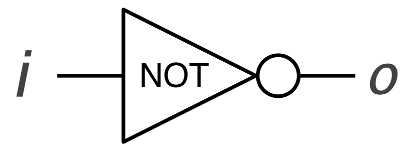

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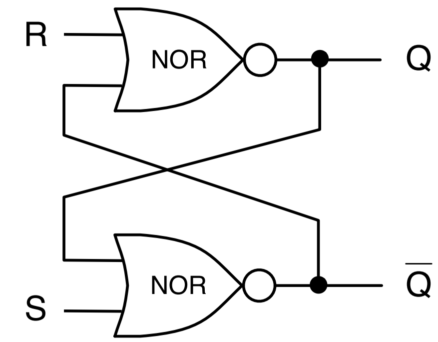

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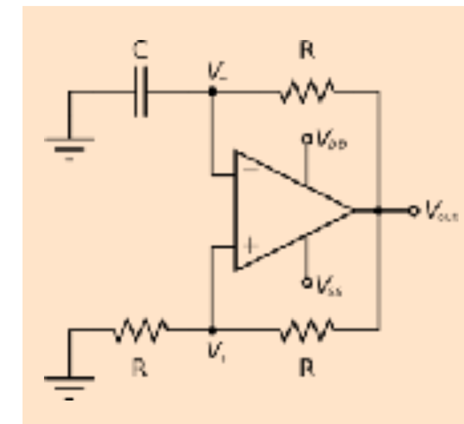
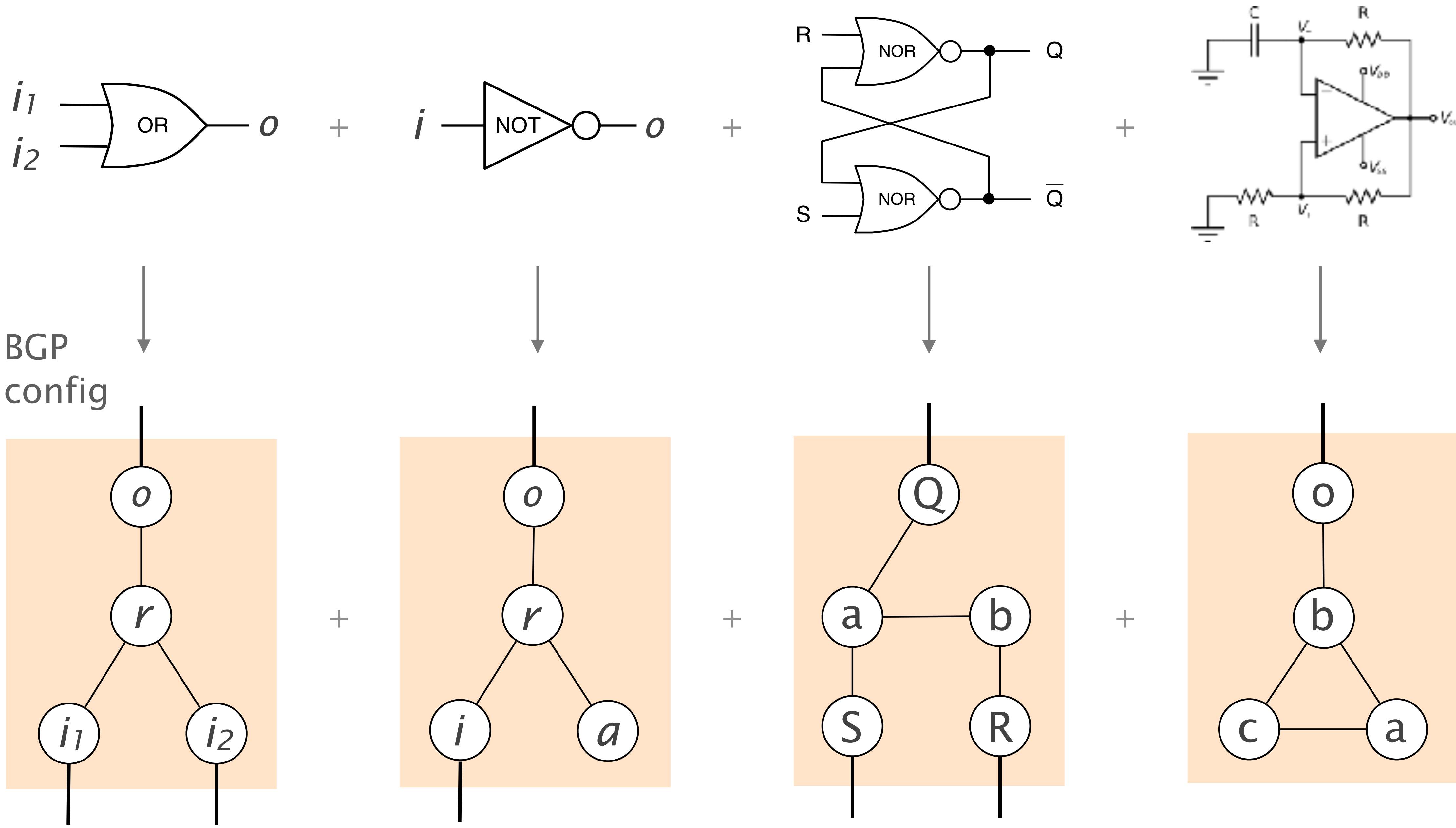
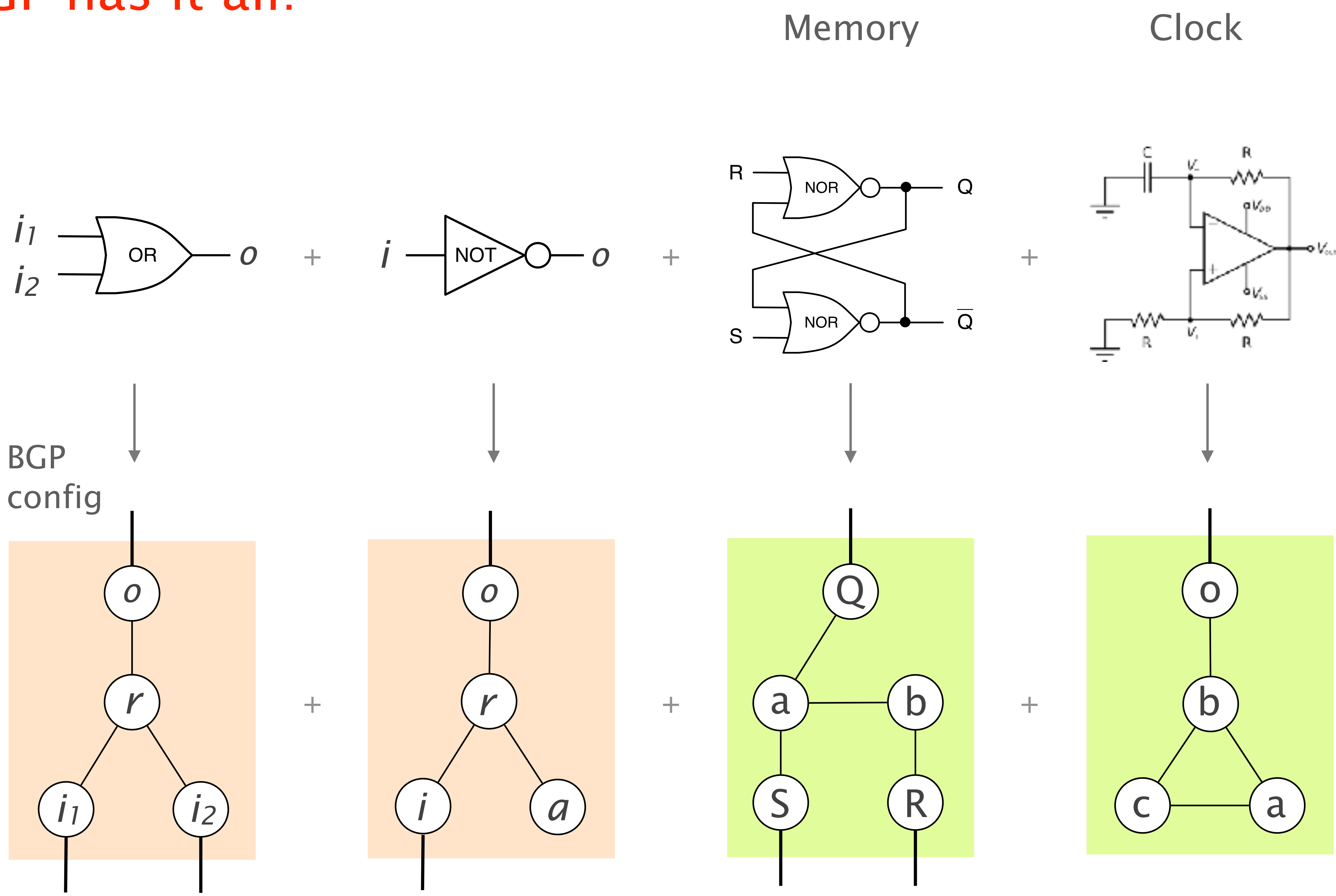


BGP has it all!



BGP has it all!

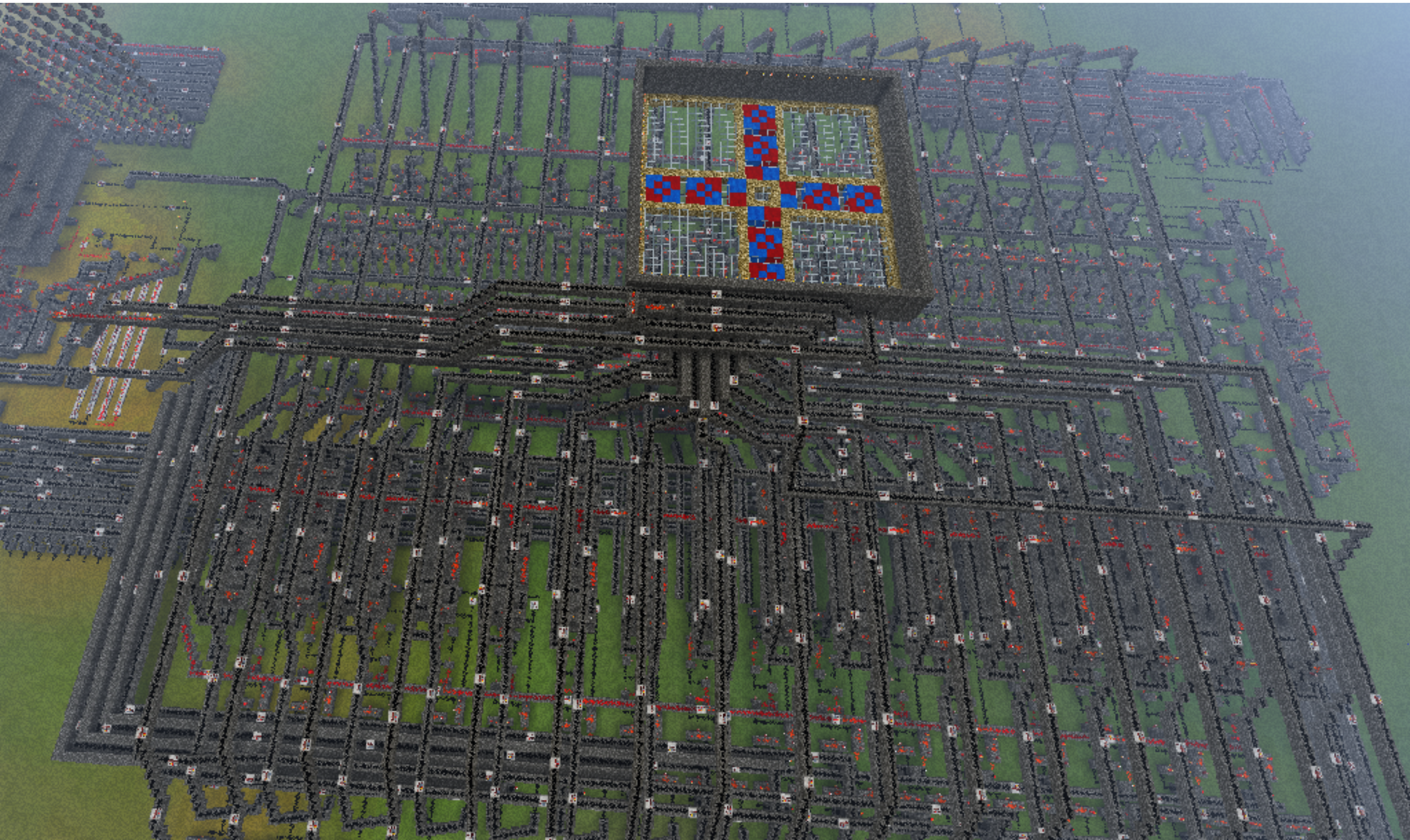


famous incorrect BGP configurations (Griffin et al.)

Instead of using Minecraft

for building a computer… use BGP!

Hack III, Minecraft's largest computer to date



Together, BGP routers form

the largest computer in the world!

Router-level view of the Internet, OPTE project

Checking BGP correctness is as hard as checking a general program

Theorem 1	Determining whether a finite BGP network converges is PSPACE-hard
Theorem 2	Determining whether an infinite BGP network converges is Turing-complete

In practice though,

BGP does not oscillate that often

known as "Gao-Rexford" rules

Theorem — If all AS policies follow the cust/peer/provider rules, BGP is guaranteed to converge

Intuition — Oscillations require "preferences cycles" which make no economical sense

Problems

Reachability

Security

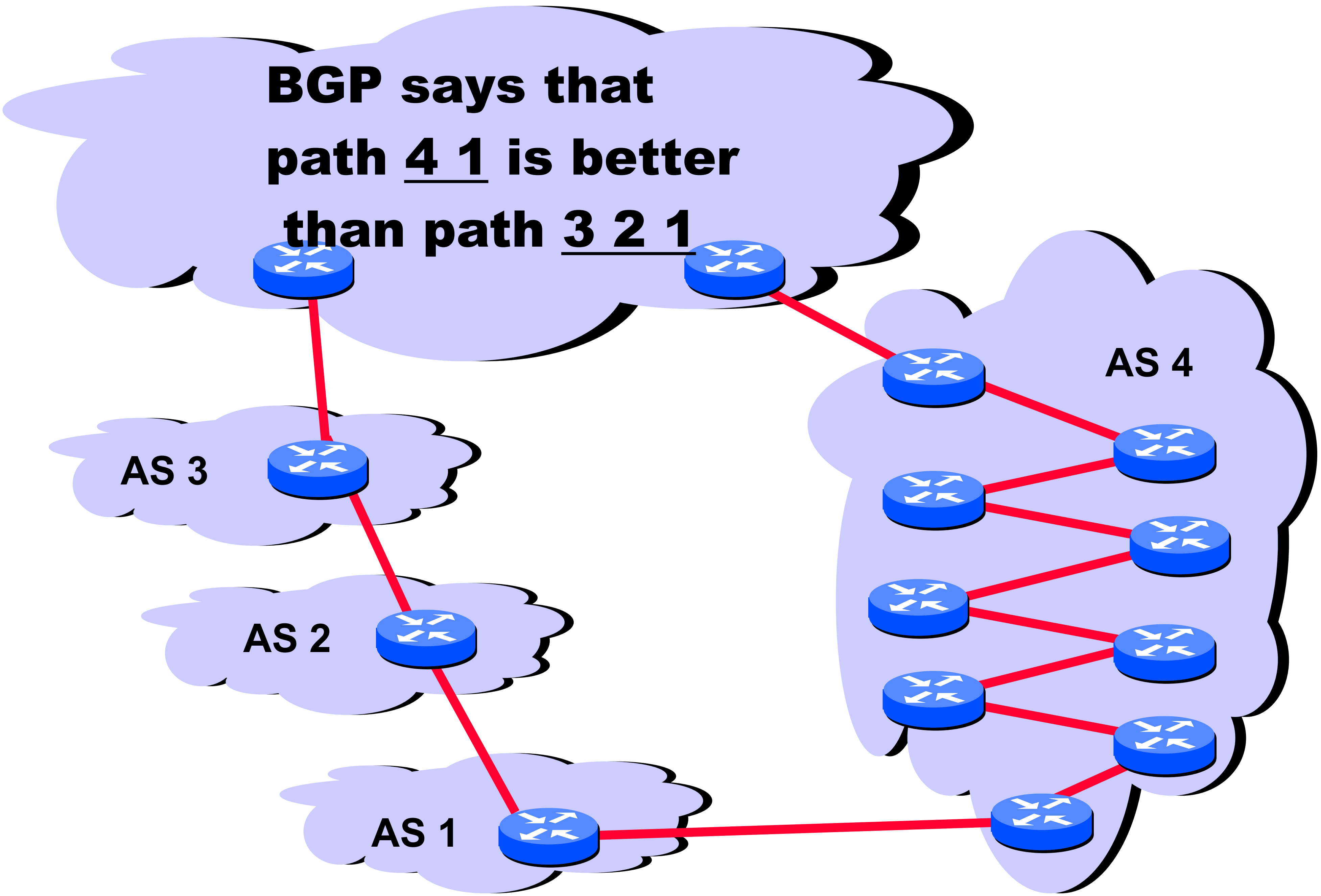
Convergence

Performance

Anomalies

Relevance

BGP path selection is mostly economical,
not based on accurate performance criteria



Problems

Reachability

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Relevance

BGP configuration is hard to get right,
you’ll understand that very soon

BGP is both “bloated” and underspecified

lots of knobs and (sometimes, conflicting) interpretations

BGP is often manually configured

humans make mistakes, often

BGP abstraction is fundamentally flawed

disjoint, router-based configuration to effect AS-wide policy

“Human factors are responsible

for 50% to 80% of network outages”

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

Problems

Reachability

Security

Convergence

Performance

Anomalies

Relevance

The world of BGP policies is rapidly changing

ISPs are now eyeballs talking to content networks

e.g., Swisscom and Netflix/Spotify/YouTube

Transit becomes less important and less profitable

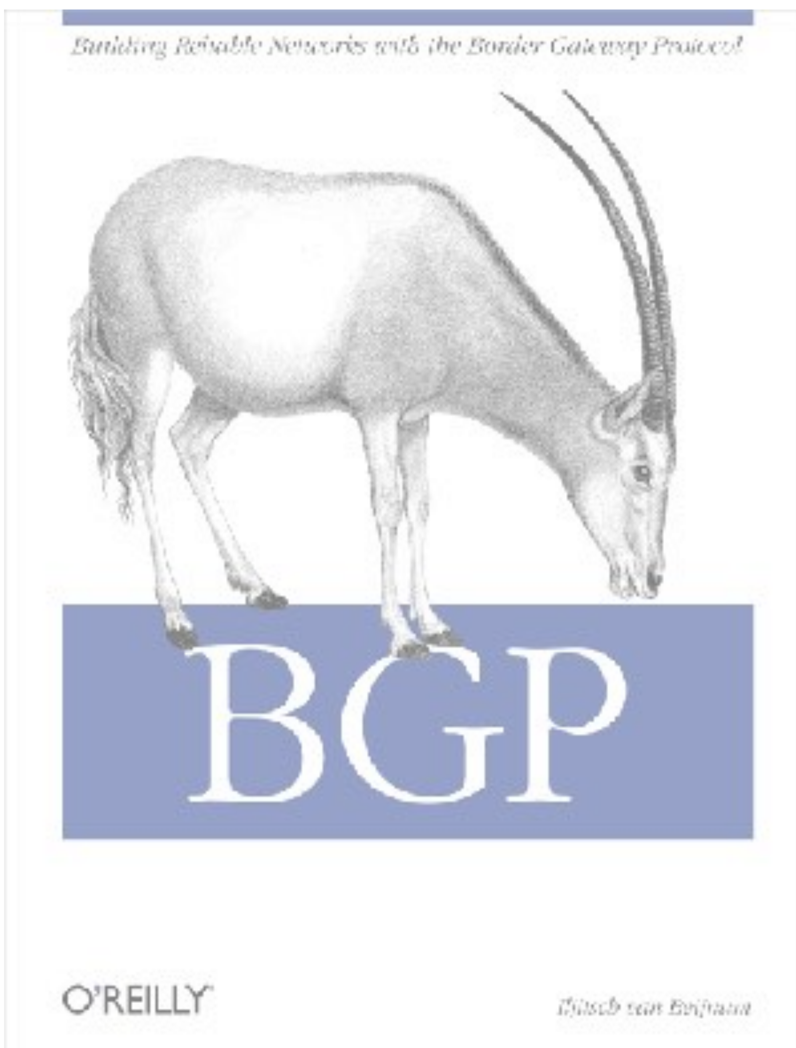
traffic move more and more to interconnection points

No systematic practices, yet

details of peering arrangements are private anyway

Border Gateway Protocol

policies and more



BGP Policies

Follow the Money

Protocol

How does it work?

Problems

security, performance, …

Internet Hackathon

April 12 @6pm in ETZ hall

2016 edition

Communication Networks

Spring 2017

Laurent Vanbever

www.vanbever.eu

ETH Zürich (D-ITET)

April,10 2017