Communication Networks

Spring 2021

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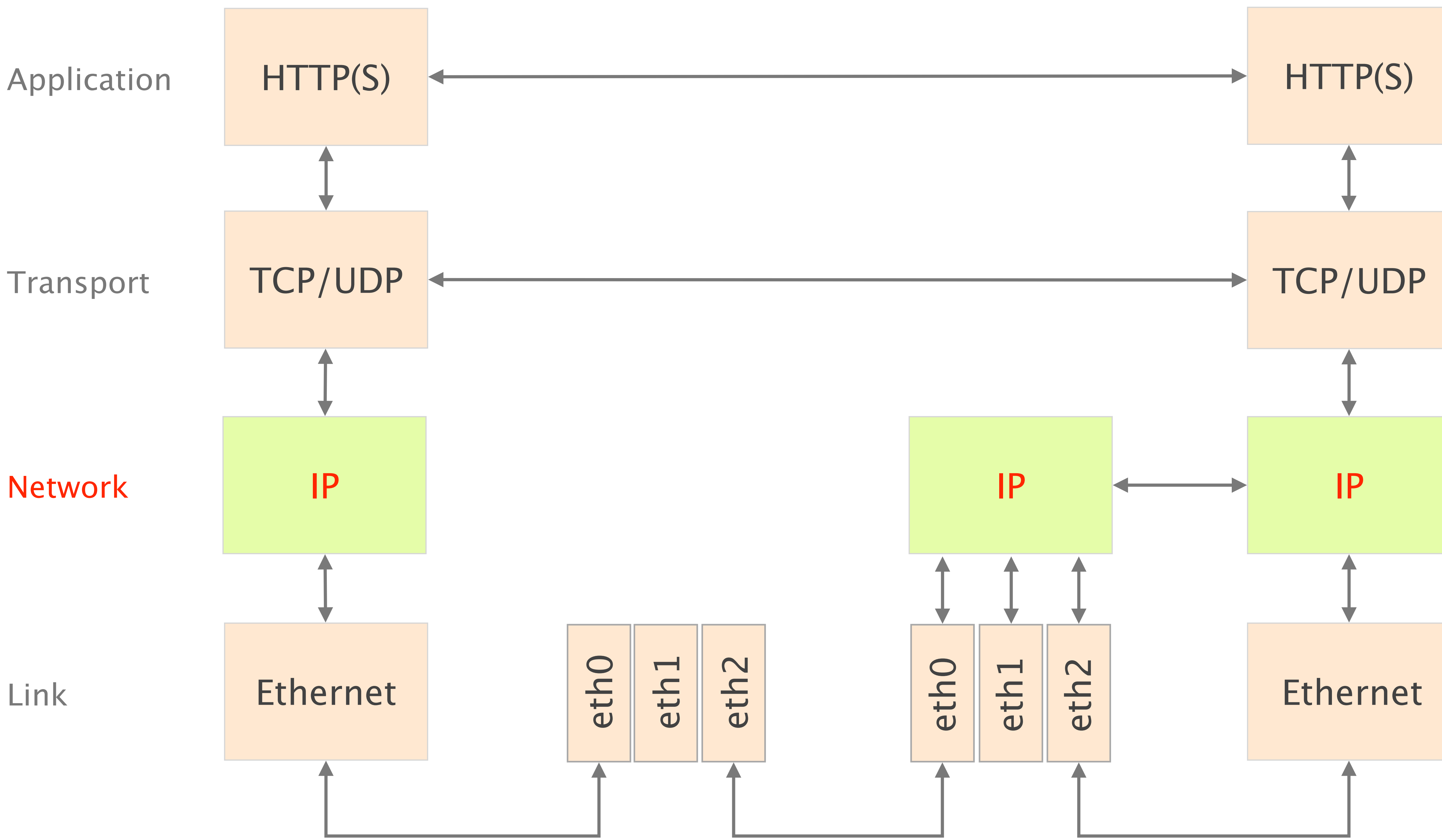
April 12 2021

Materials inspired from Scott Shenker & Jennifer Rexford

Where we are in the lecture

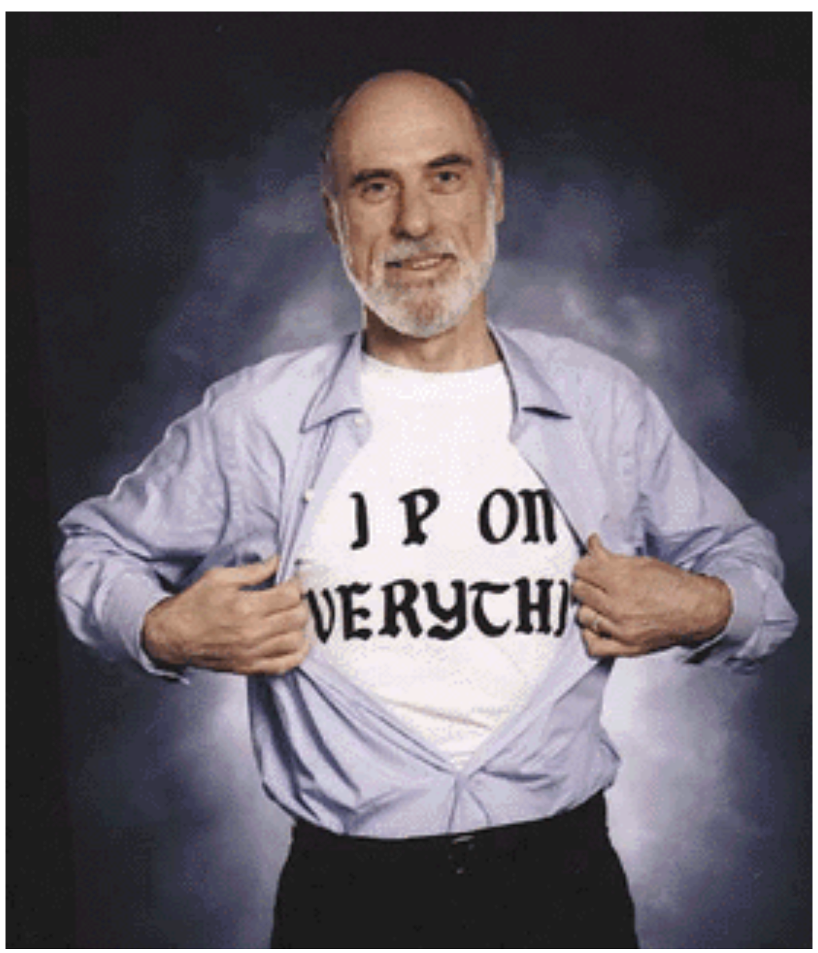
Starting with the really "juicy" bits!



Last week on

Communication Networks

Internet Protocol and Forwarding



source: Boardwatch Magazine

1 **IP addresses**

use, structure, allocation

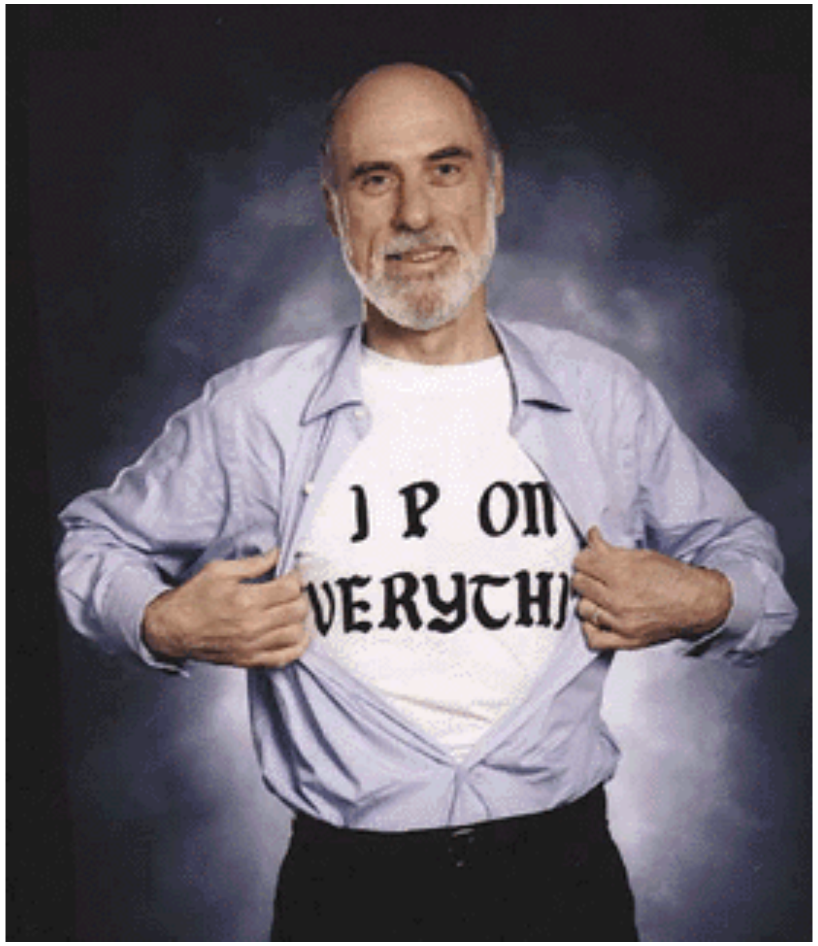
2 **IP forwarding**

longest prefix match rule

3 **IP header**

IPv4 and IPv6, wire format

Internet Protocol and Forwarding



1 **IP addresses**

use, structure, allocation

IP forwarding

longest prefix match rule

IP header

IPv4 and IPv6, wire format

IP addresses are unique 32/128-bits number associated to a network interface (on a host, a router, ...)

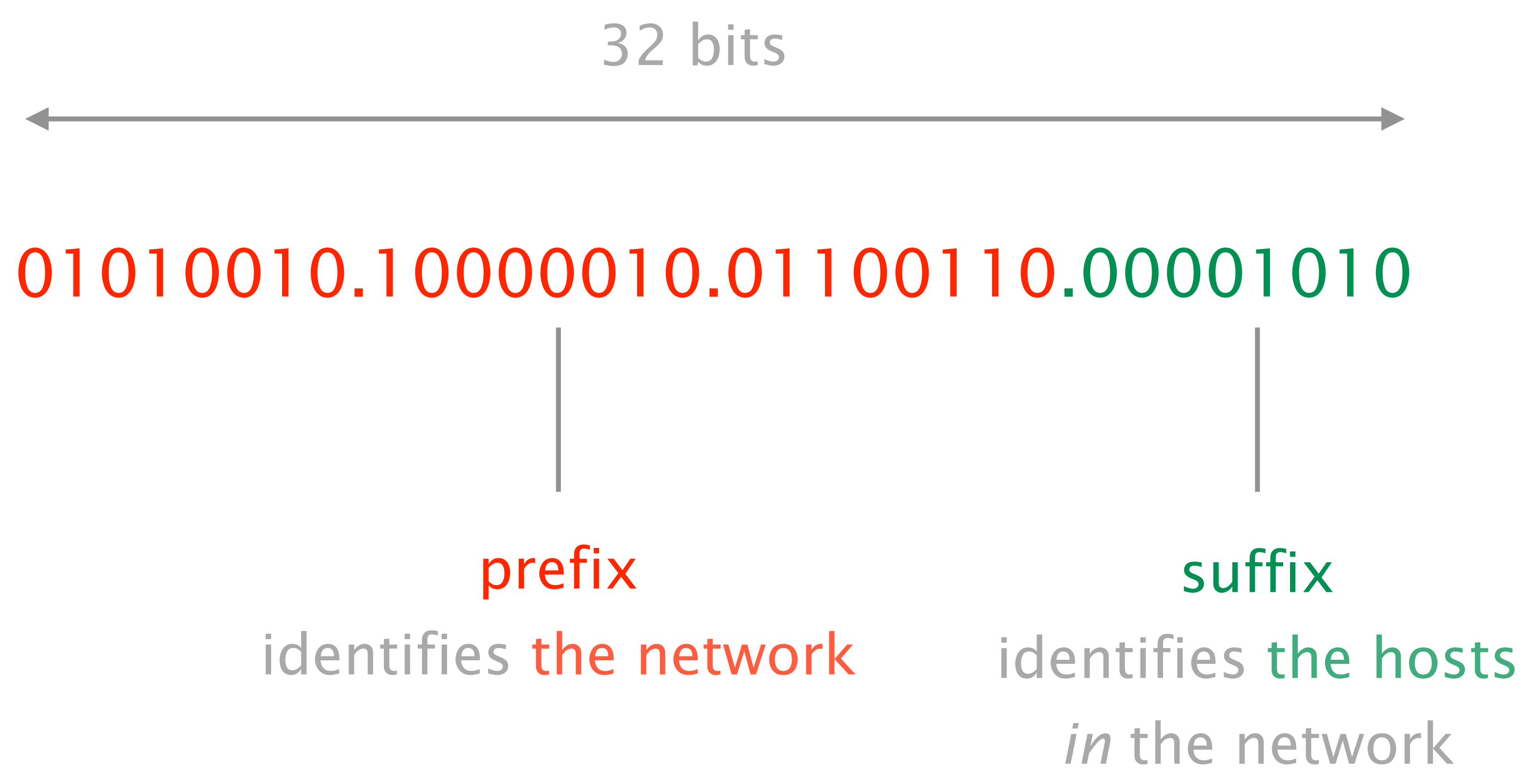
82.130.102.10

01010010 10000010 01100110 00001010

1080:0000:0000:0000:0008:0800:200c:417a

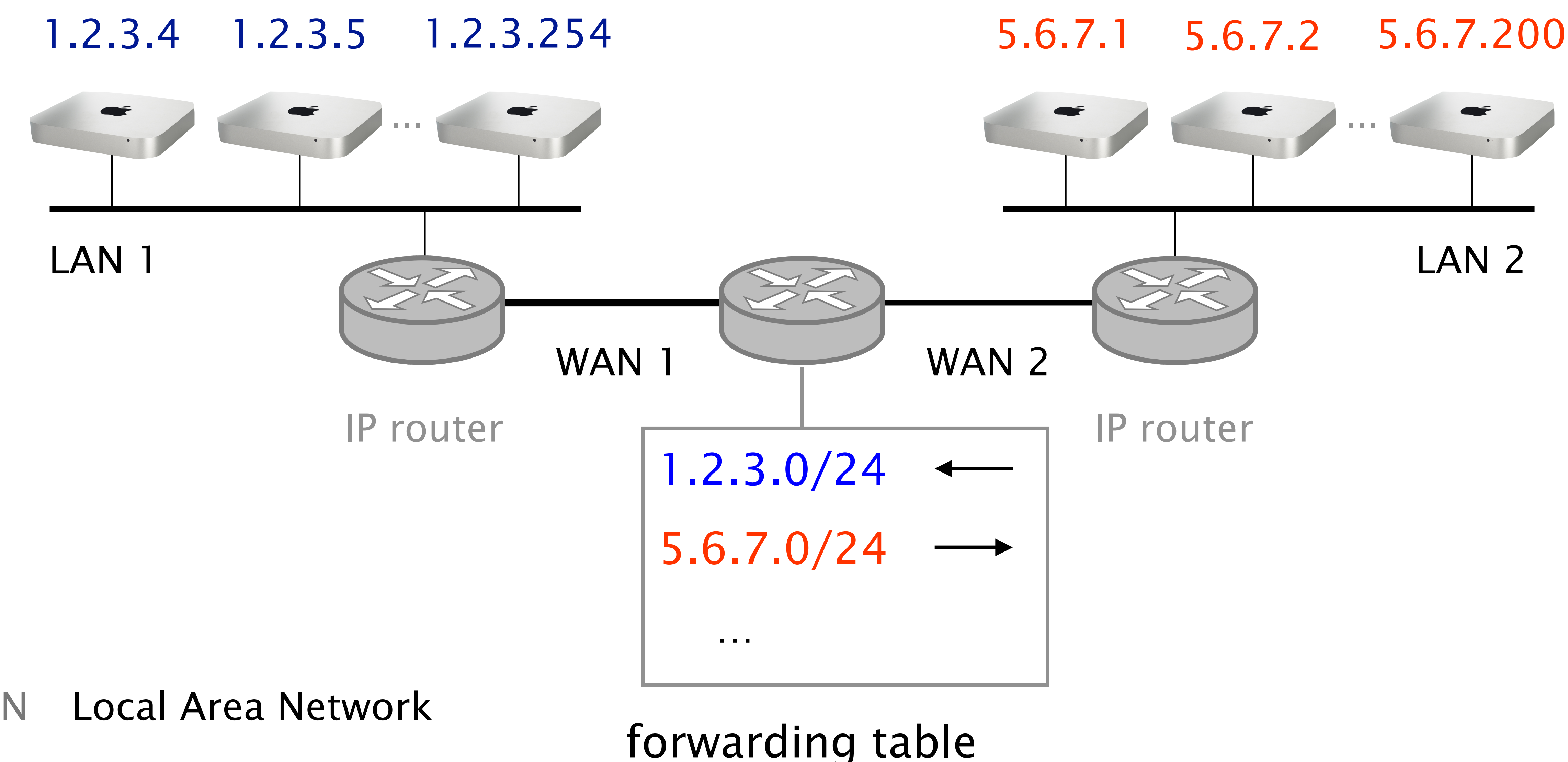
0001000010000000 0100000101111010

IP addressing is hierarchical, composed of a prefix (network address) and a suffix (host address)



Routers forward packet to their destination according to the network part, *not* the host part

Doing so enables to scale the forwarding tables



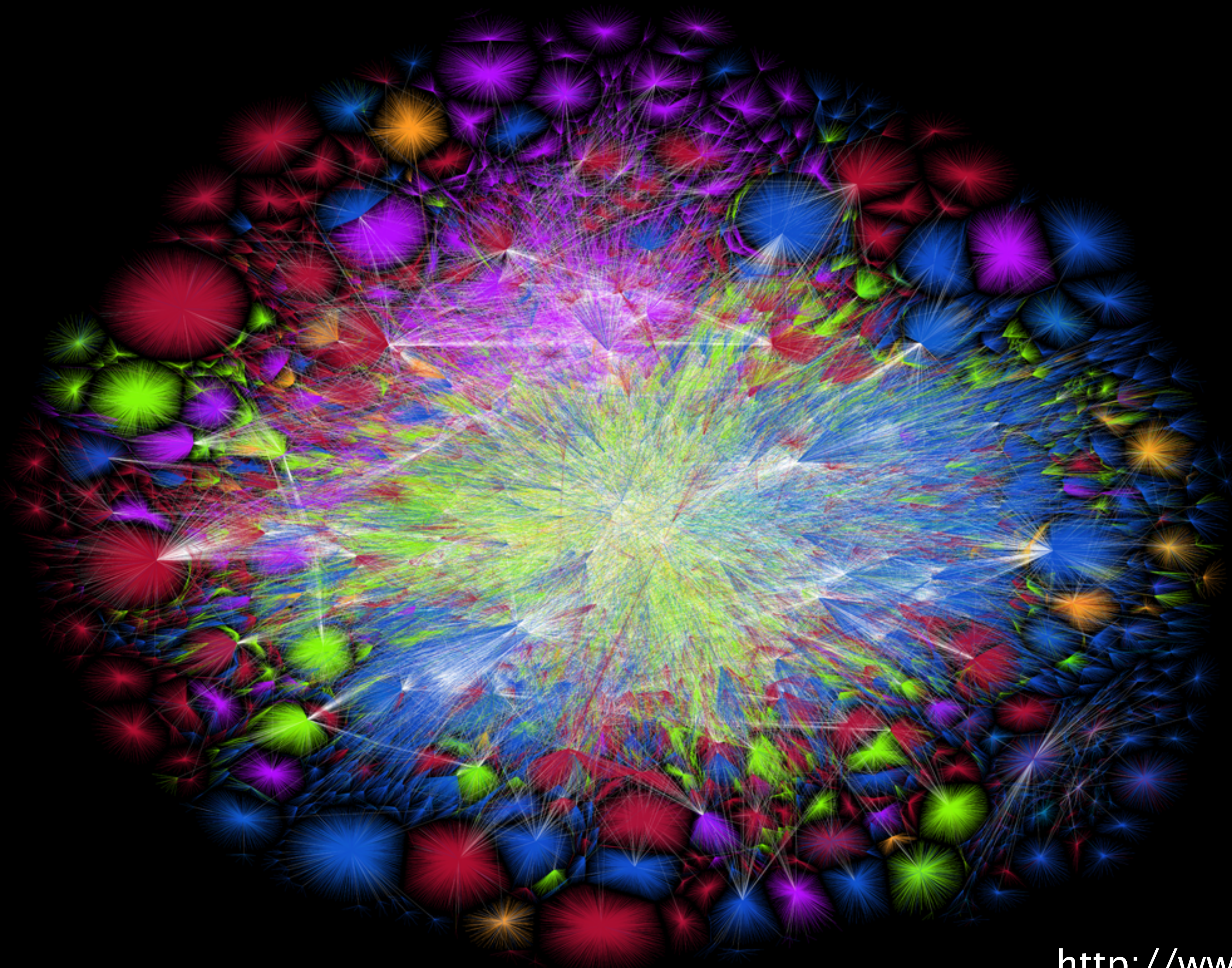
LAN Local Area Network

WAN Wide Area Network

This week on

Communication Networks

Internet routing



http://www.opte.org

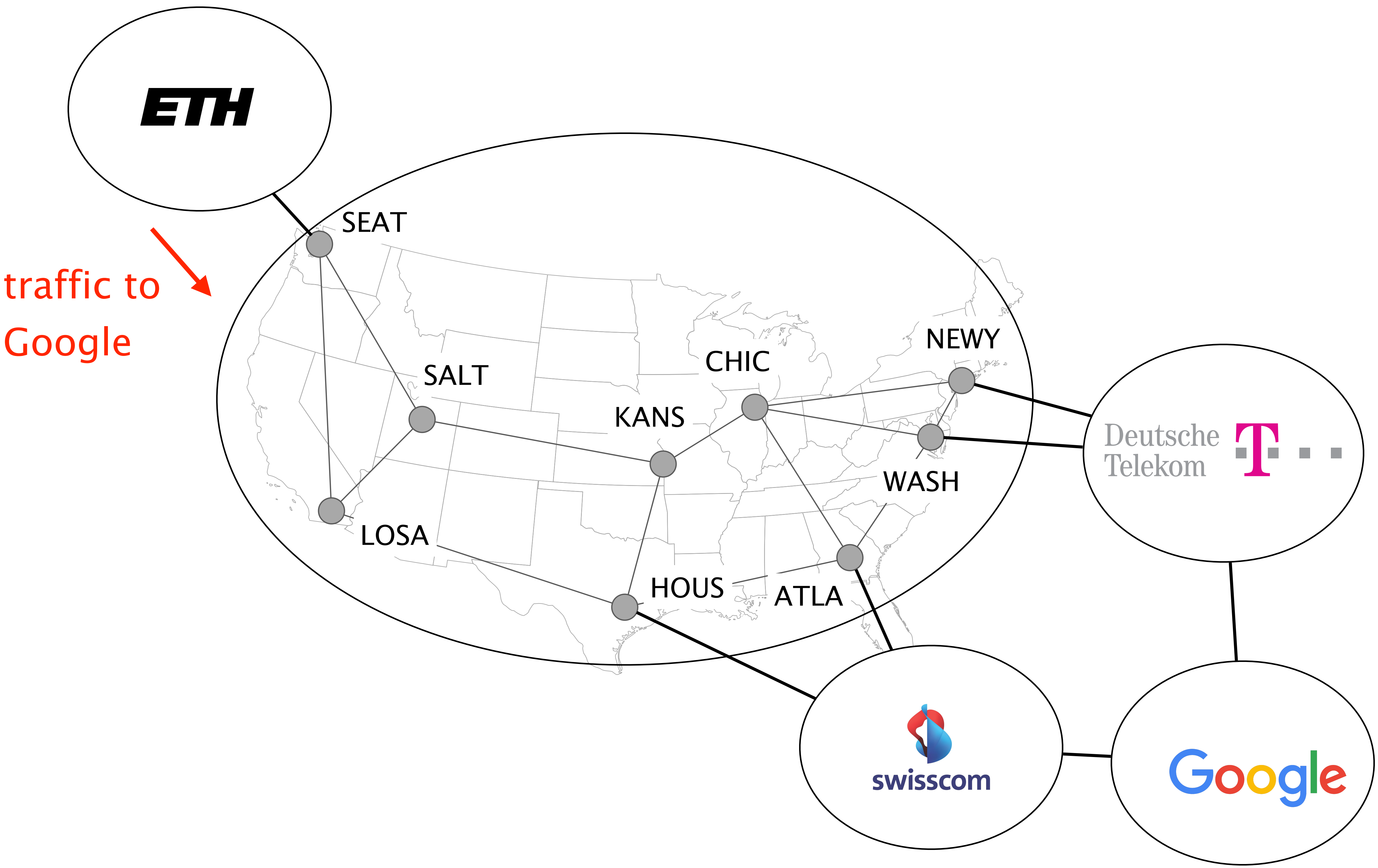
Internet routing comes into two flavors:
intra- and *inter-domain* routing

inter-domain routing	intra-domain routing
Find paths between networks	Find paths within a network

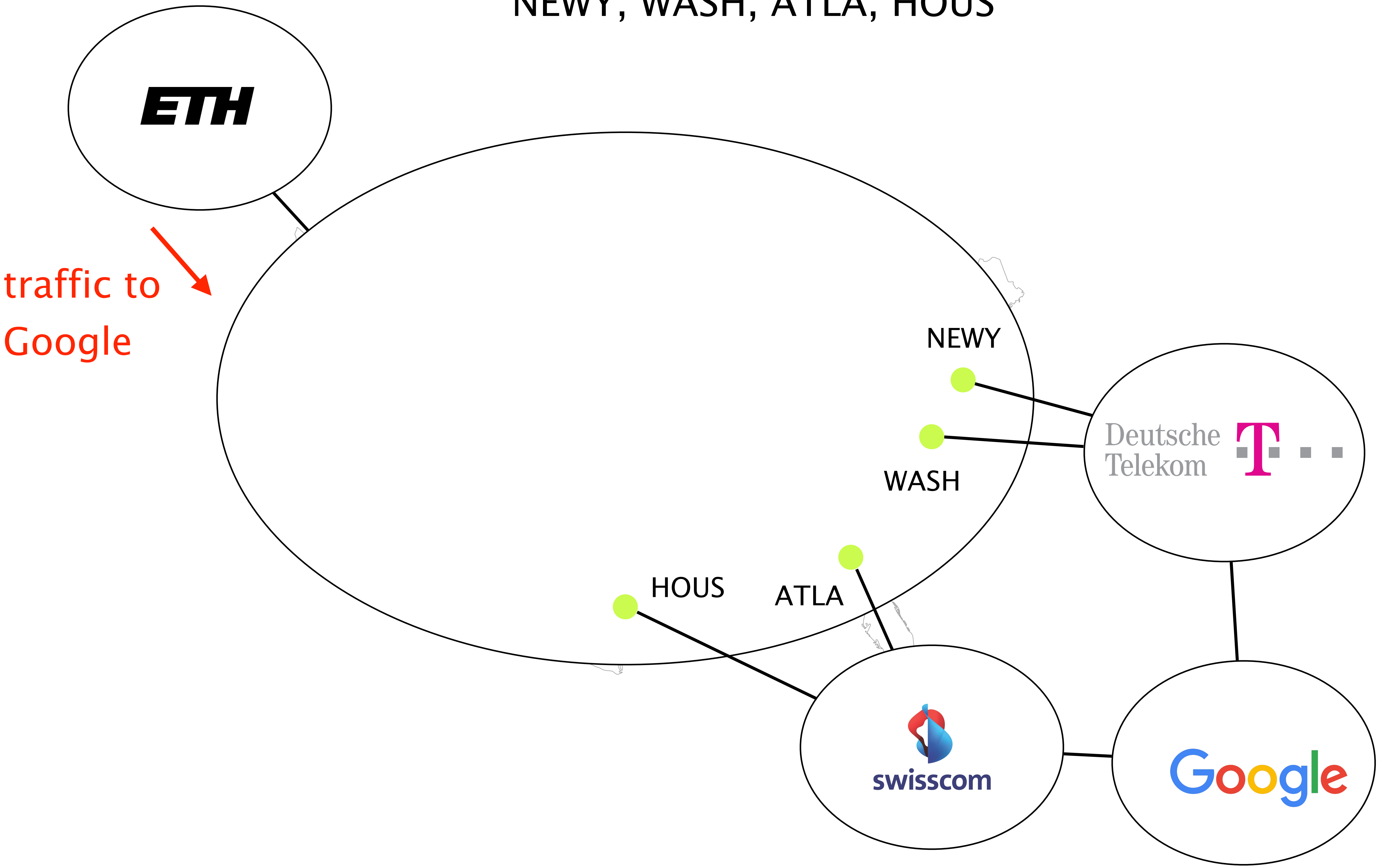
inter-domain
routing

intra-domain
routing

Find paths between networks


traffic to
Google
ETH
SEAT
SALT
LOSA
KANS
CHIC
NEWY
WASH
HOUS
ATLA
Deutsche
Telekom
swisscom
Google

Google can be reached via
NEWY, WASH, ATLA, HOUS



Google can be reached via

NEWY, WASH, ATLA, HOUS

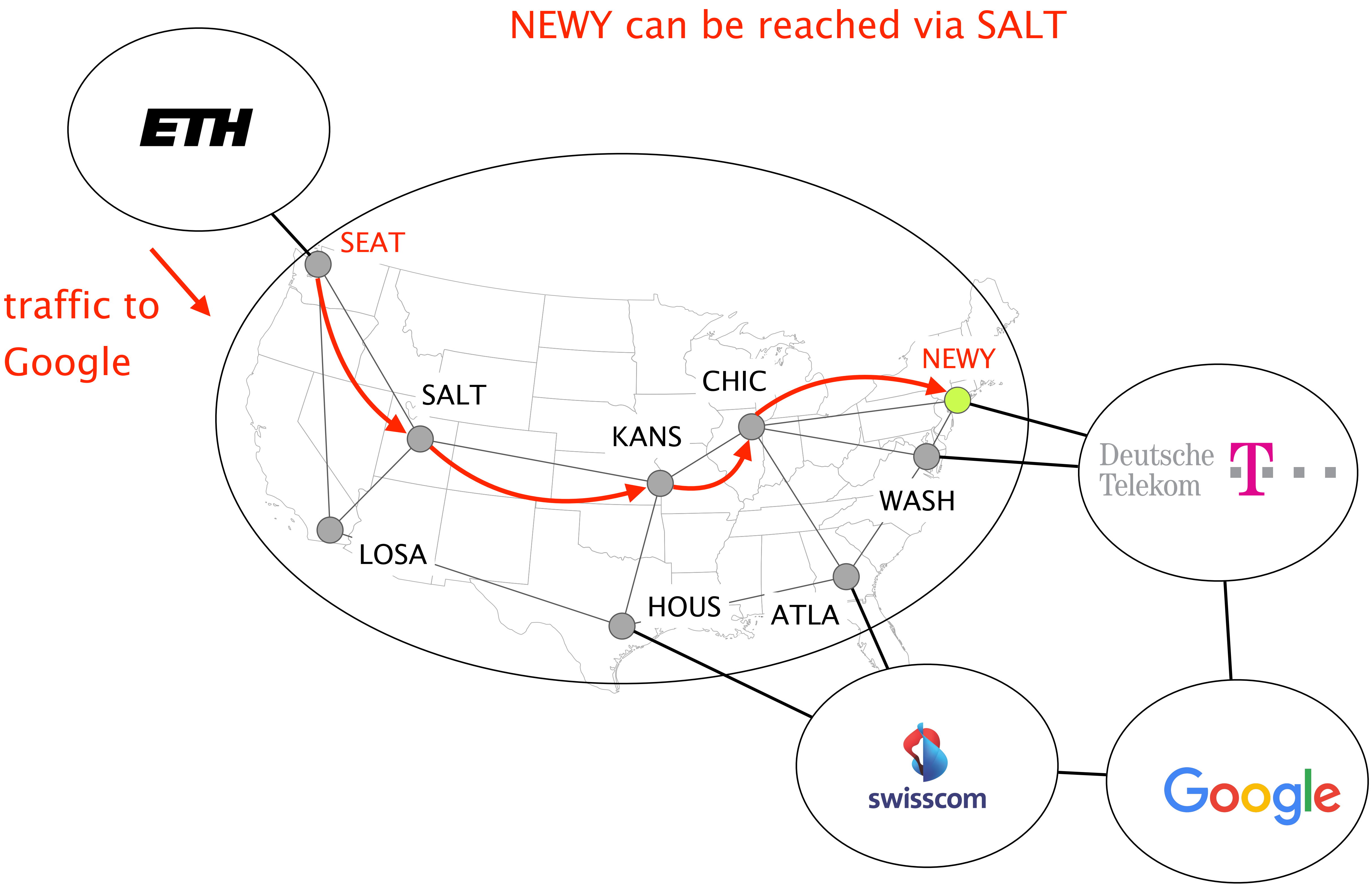
best exit point

based on money, performance, …

inter-domain
routing

intra-domain
routing

Find paths within a network


NEWY can be reached via SALT
ETH
traffic to Google
SEAT
SALT
LOSA
KANS
CHIC
NEWY
WASH
HOUS
ATLA
Deutsche Telekom
swisscom
Google

› traceroute **www.google.ch**

rou-etx-1-ee-tik-etx-dock-1
rou-ref-rz-bb-ref-rz-etx
rou-fw-rz-ee-tik
rou-fw-rz-gw-rz

intra-domain routing

swiix1-10ge-1-4.switch.ch
swiez2
swiix2-p1.switch.ch

intra-domain routing

equinix-zurich.net.google.com
66.249.94.157
zrh04s06-in-f24.1e100.net

intra-domain routing

› traceroute **www.google.ch**

rou-etx-1-ee-tik-etx-dock-1

rou-ref-rz-bb-ref-rz-etx

rou-fw-rz-ee-tik

rou-fw-rz-gw-rz

swiix1-10ge-1-4.switch.ch

swiez2

swiix2-p1.switch.ch

equinix-zurich.net.google.com

66.249.94.157

zrh04s06-in-f24.1e100.net

inter-domain routing

inter-domain 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

Intra-domain routing enables routers to compute forwarding paths to any internal subnet

what kind of paths?

Network operators don't want arbitrary paths, they want good paths

definition

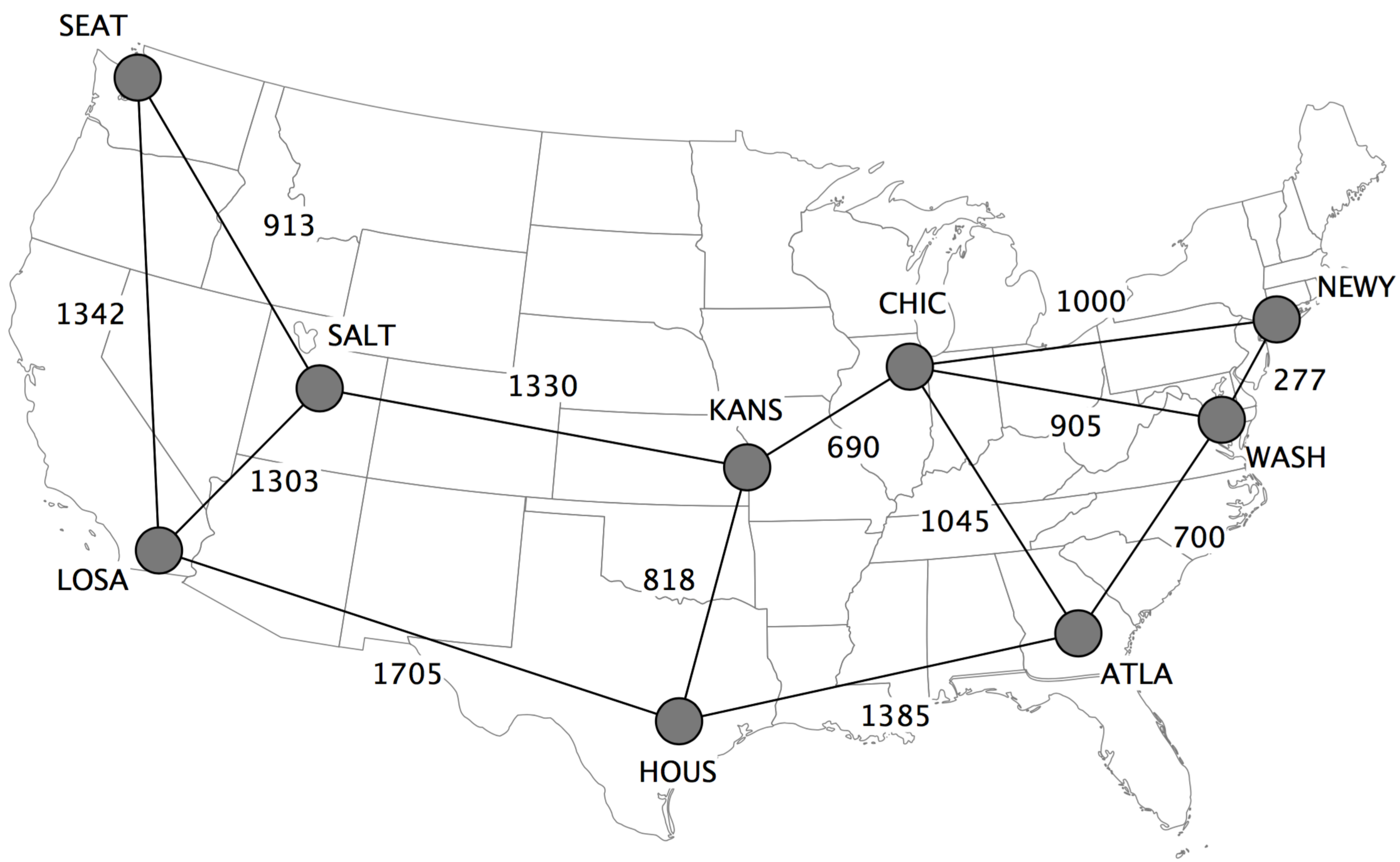
A good path is a path that minimizes some network-wide metric

typically delay, load, loss, cost

approach

Assign to each link a weight (usually static), compute the *shortest-path* to each destination

When weights are assigned proportionally to the distance, shortest-paths will minimize the end-to-end delay



Internet2, the US-based research network

When weights are assigned proportionally to the distance, shortest-paths will minimize the end-to-end delay

if traffic is such that there is no congestion

When weights are assigned inversely proportionally to each link capacity, throughput is maximized

if traffic is such that there is no congestion

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

Flooding is performed as in L2 learning

Node sends its link-state
on all its links

Next node does the same,
except on the one where
the information arrived

Flooding is performed as in L2 learning

except that it is reliable

Node sends its link-state
on all its links

Next node does the same,
except on the one where
the information arrived

All nodes are ensured to
receive the *latest version*
of all link-states

challenges

packet loss

out of order arrival

Flooding is performed as in L2 learning
except that it is reliable

Node sends its link-state
on all its links

Next node does the same,
except on the one where
the information arrived

All nodes are ensured to
receive the *latest version*
of all link-states

solutions

ACK & retransmissions

sequence number

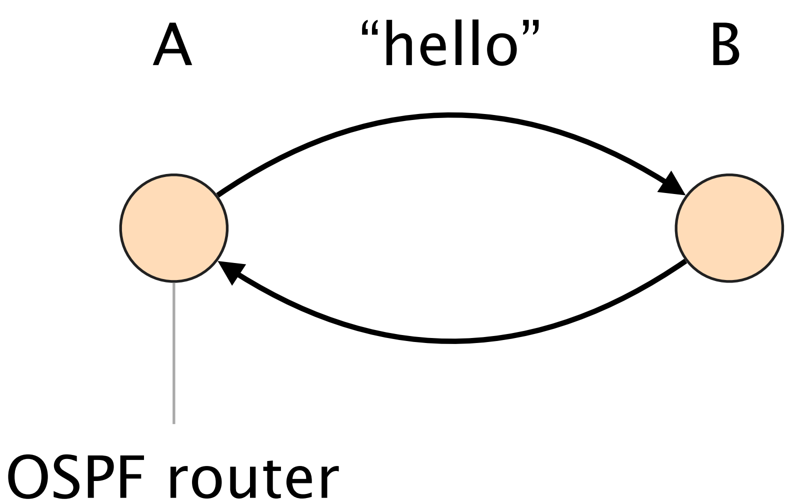
time-to-live for each link-state

A link-state node initiate flooding in 3 conditions

Topology change	link or node failure/recovery
Configuration change	link cost change
Periodically	refresh the link-state information every (say) 30 minutes account for possible data corruption

Once a node knows the entire topology,
it can compute shortest-paths using Dijkstra's algorithm

By default, Link-State protocols detect topology changes using software-based beaconing



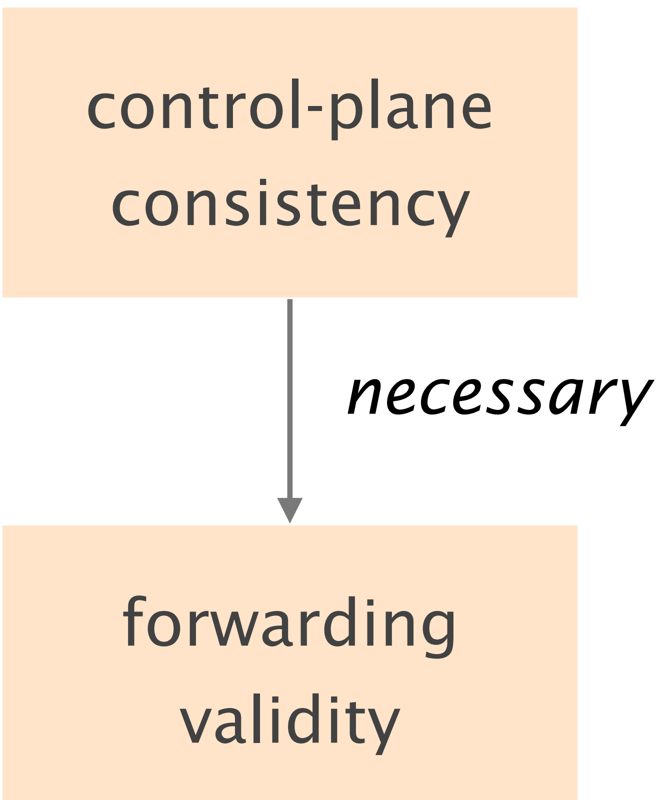
Routers periodically exchange "Hello" in both directions (*e.g.* every 30s)

Trigger a failure after few missed "Hellos" (*e.g.*, after 3 missed ones)

Tradeoffs between:

- detection speed
- bandwidth and CPU overhead
- false positive/negatives

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

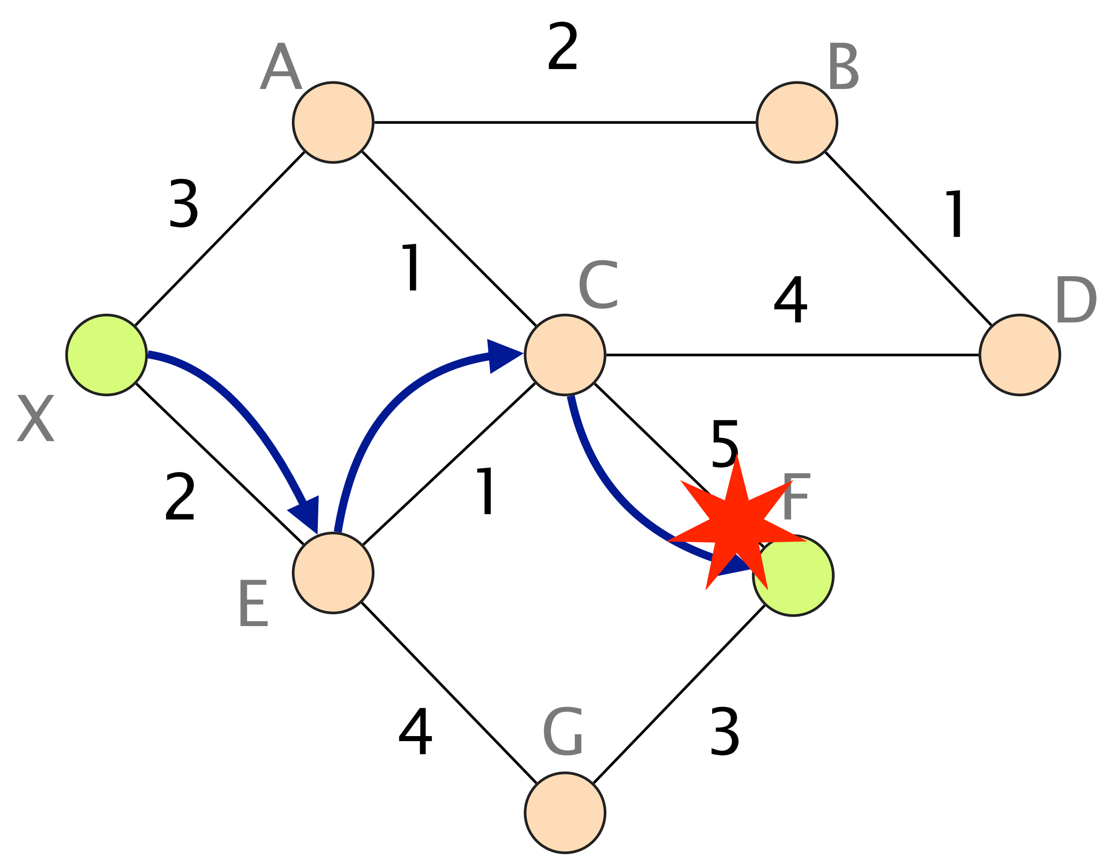


all nodes have the same link-state database

the global forwarding state directs packet to its destination

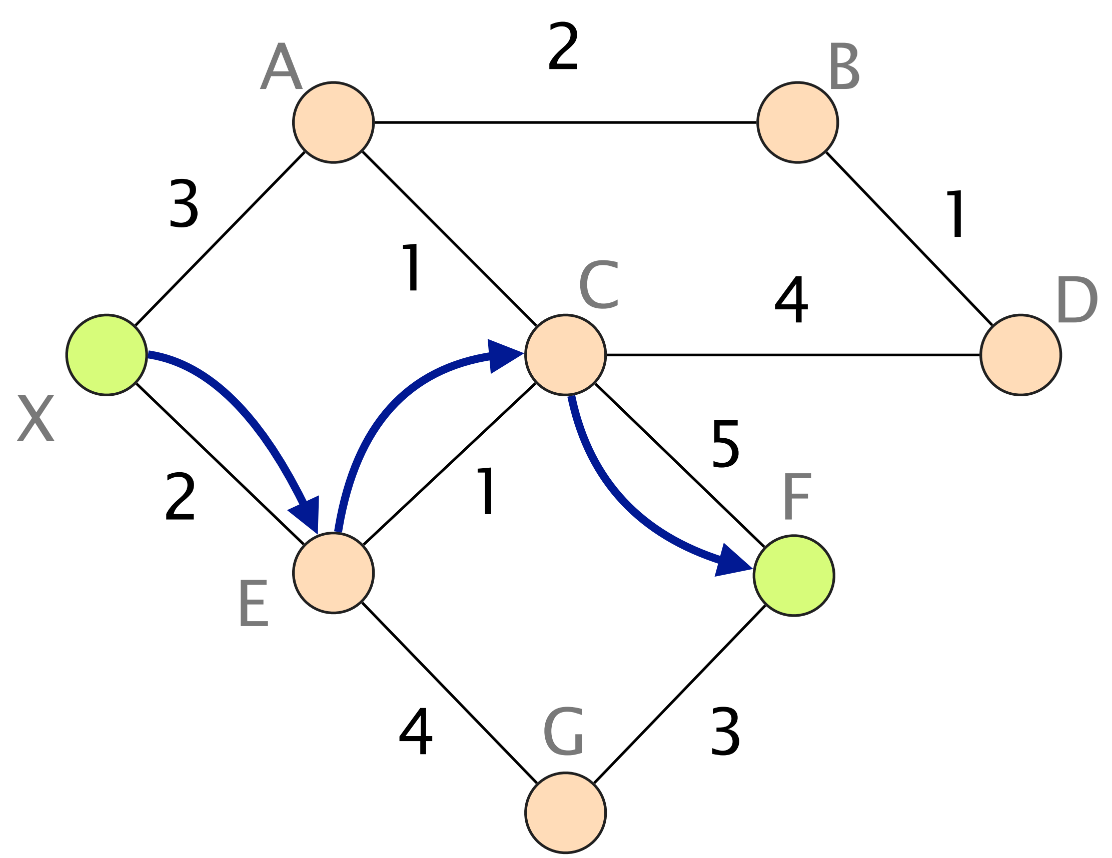
Inconsistencies lead to transient disruptions
in the form of blackholes or forwarding loops

Blackholes appear due to detection delay,
as nodes do not immediately detect failure

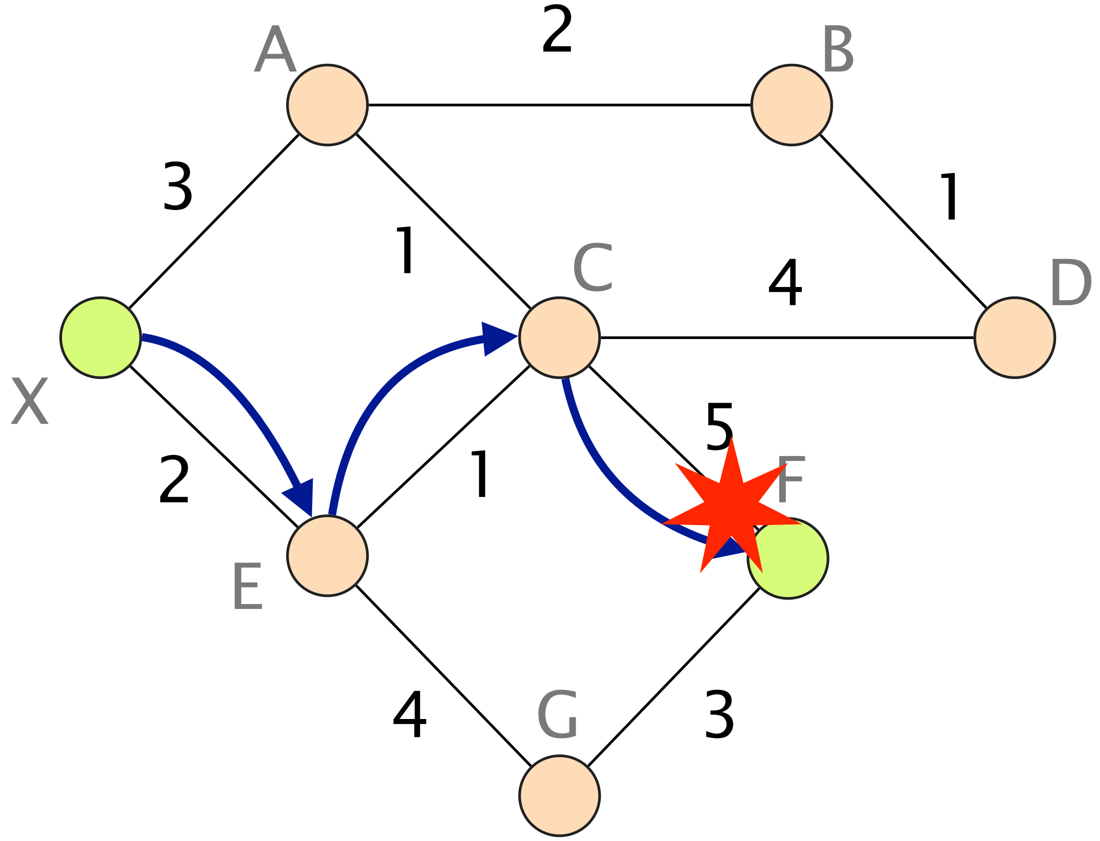


depends on the timeout for detecting lost hellos

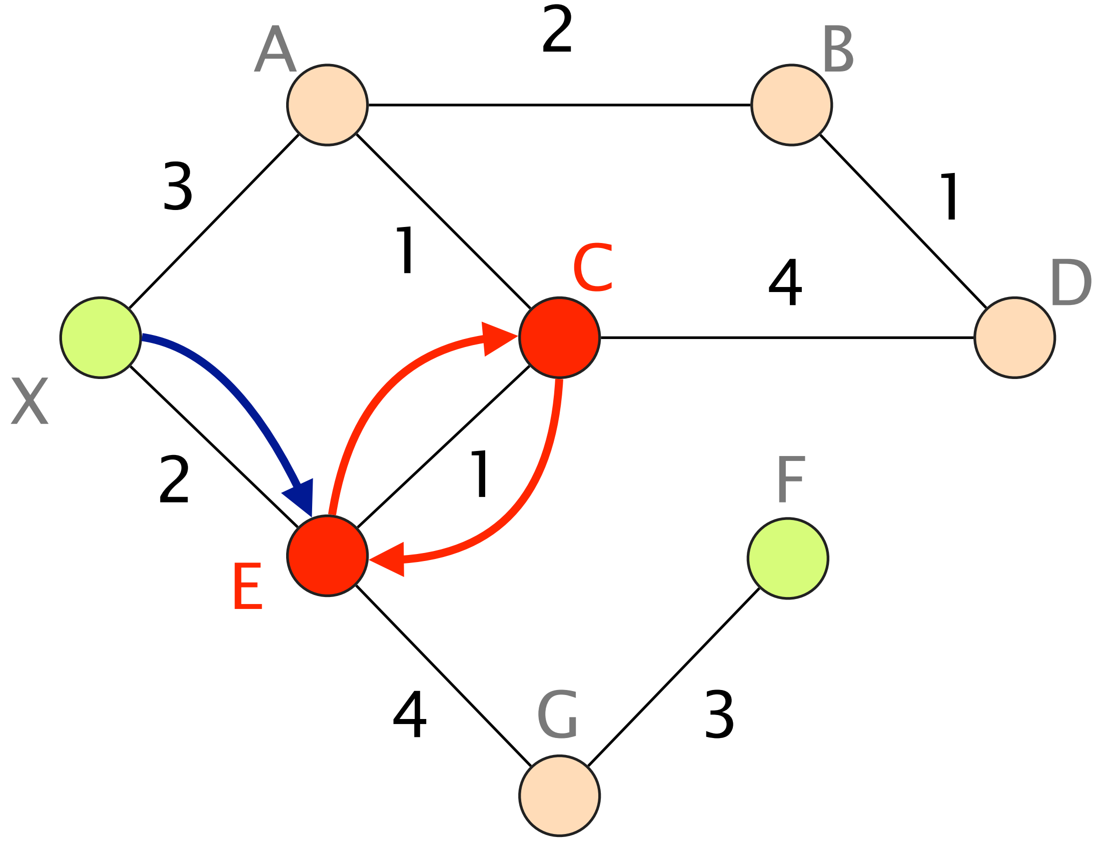
Transient loops appear due to inconsistent link-state databases



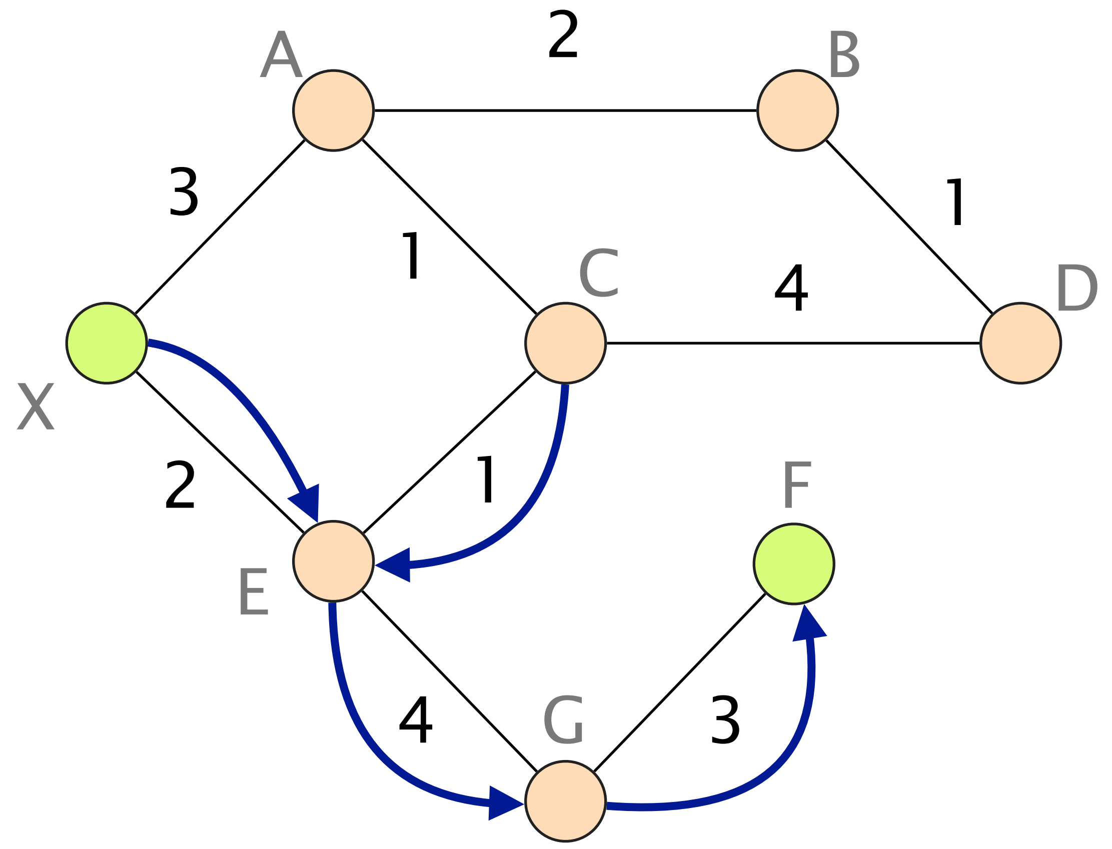
Initial forwarding state



C learns about the failure
and immediately reroute to E



A loop appears as E
isn't yet aware of the failure



The loop disappears as soon as
E updates its forwarding table

Convergence is the process during which the routers seek to actively regain a consistent view of the network

Today, two Link-State protocols are widely used:

OSPF and IS-IS

OSPF

IS-IS

Open Shortest Path First

Intermediate Systems[2]

OSPF

Open Shortest Path First

used in many enterprise & ISPs

work on top of IP

only route IPv4 by default

IS-IS

Intermediate Systems^2

OSPF

IS-IS

Open Shortest Path First

Intermediate Systems²

used mostly in large ISPs

work on top of link-layer

network protocol agnostic

Internet routing

from here to there, and back

1 Intra-domain routing

Link-state protocols

Distance-vector protocols

Inter-domain routing

Path-vector protocols

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

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

until convergence

Each node bundles these distances into one message (called a vector) that it repeatedly sends to all its neighbors

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

until convergence

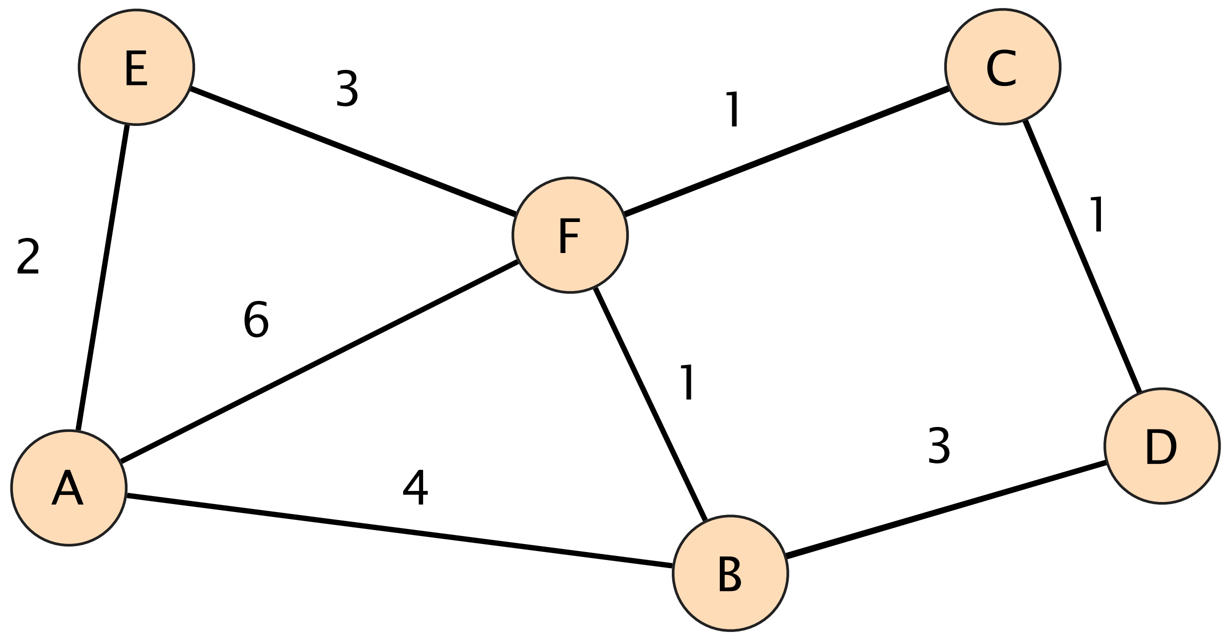
Each node bundles these distances into one message (called a vector) that it repeatedly sends to all its neighbors

Each node updates its distances based on neighbors' vectors:

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

Similarly to Link-State, 3 situations cause nodes to send new DVs

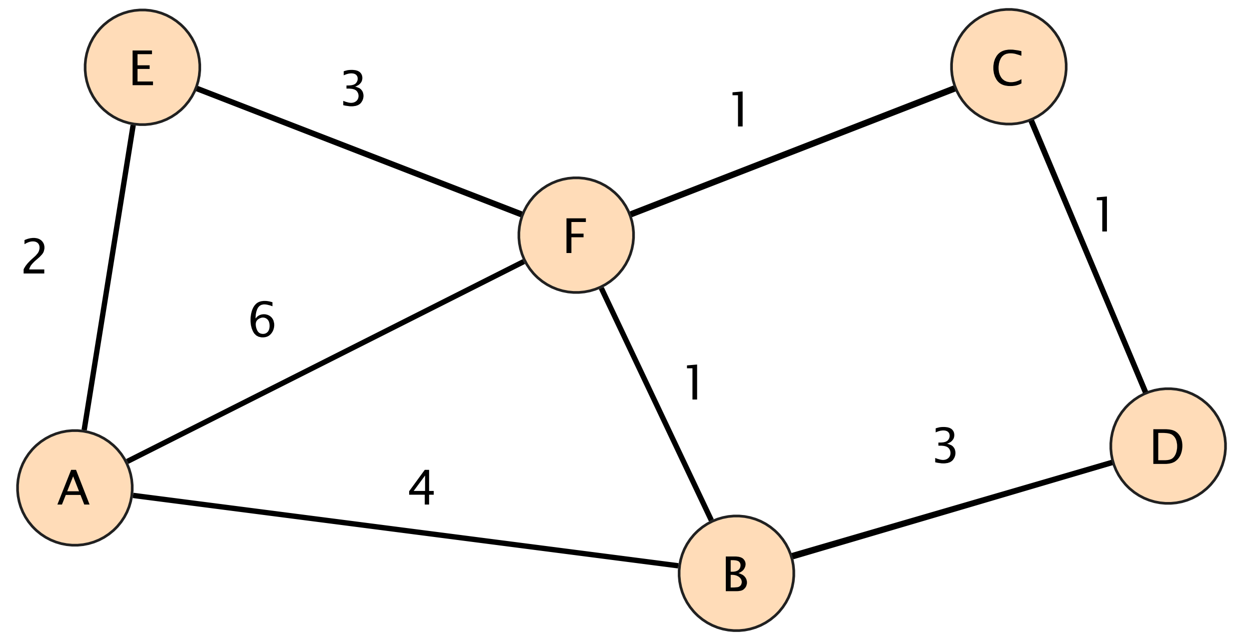
Topology change	link or node failure/recovery
Configuration change	link cost change
Periodically	refresh the link-state information every (say) 30 minutes account for possible data corruption



E
3
1
C
2
F
1
6
1
3
D
A
4
B

Optimum 1-hop path

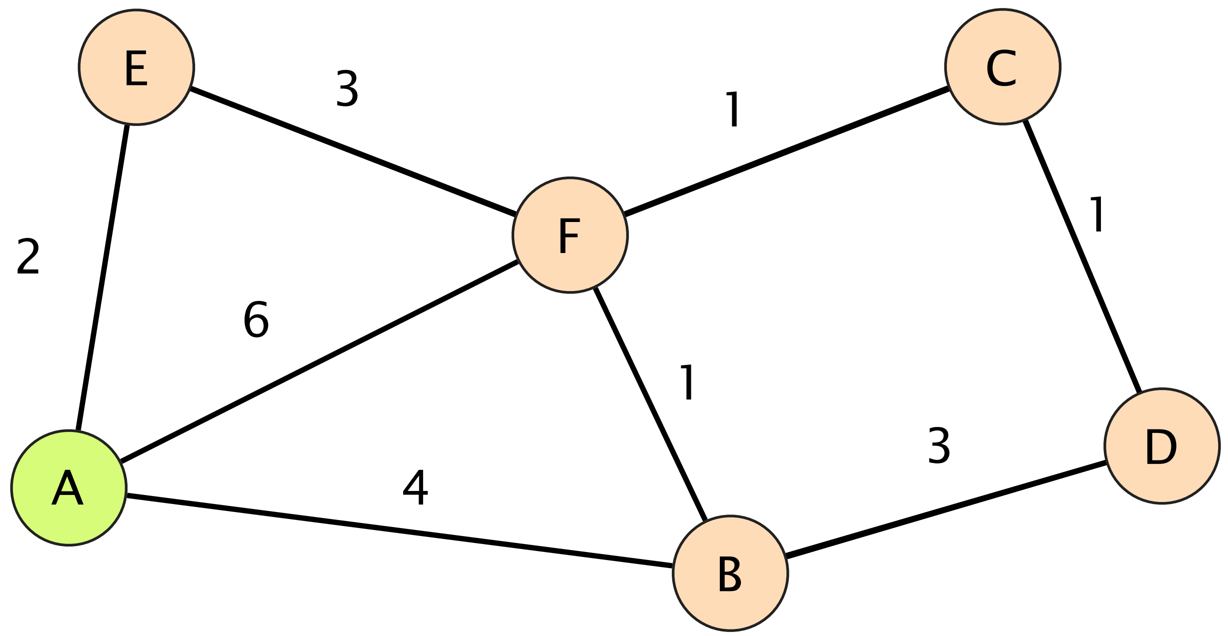
A			B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	∞	–	C	∞	–
D	∞	–	D	3	D
E	2	E	E	∞	–
F	6	F	F	1	F



C			D			E			F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	∞	–	A	∞	–	A	2	A	A	6	A
B	∞	–	B	3	B	B	∞	–	B	1	B
C	0	C	C	1	C	C	∞	–	C	1	C
D	1	D	D	0	D	D	∞	–	D	∞	–
E	∞	–	E	∞	–	E	0	E	E	3	E
F	1	F	F	∞	–	F	3	F	F	0	F

Optimum 1-hop path

A			B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	**4**	**B**	B	0	B
C	∞	–	C	∞	–
D	∞	–	D	3	D
E	**2**	**E**	E	∞	–
F	**6**	**F**	F	1	F

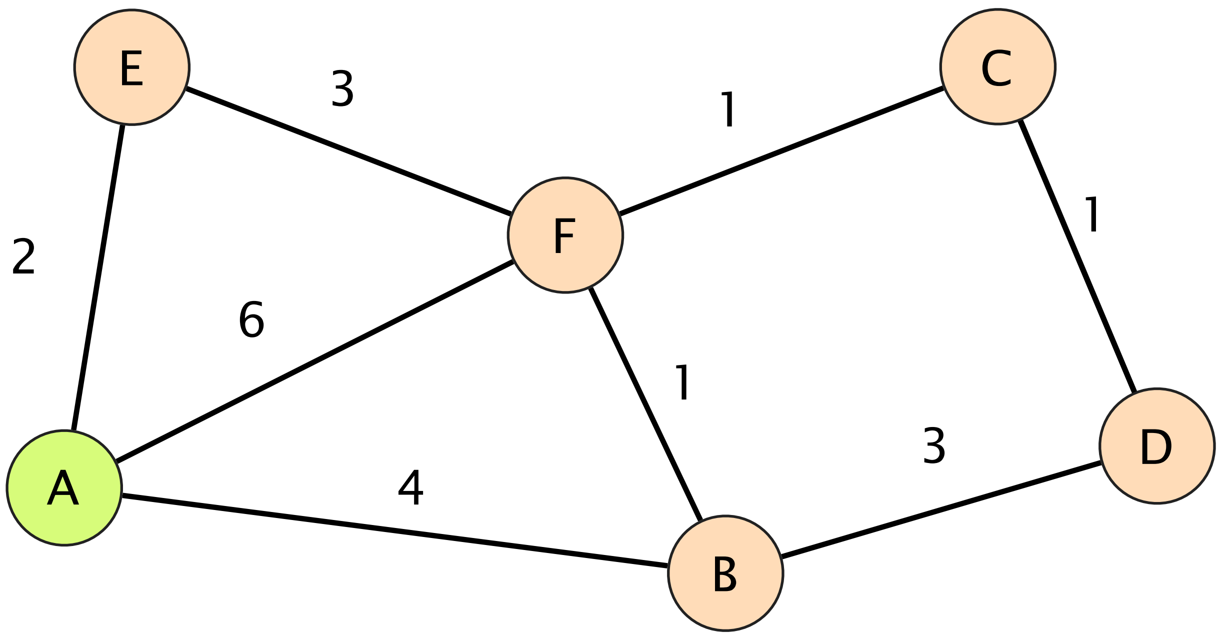


C			D			E			F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	∞	–	A	∞	–	A	2	A	A	6	A
B	∞	–	B	3	B	B	∞	–	B	1	B
C	0	C	C	1	C	C	∞	–	C	1	C
D	1	D	D	0	D	D	∞	–	D	∞	–
E	∞	–	E	∞	–	E	0	E	E	3	E
F	1	F	F	∞	–	F	3	F	F	0	F

Optimum 2-hops path

A		
Dst	Cst	Hop
A	0	A
B	4	B
C	7	F
D	7	B
E	2	E
F	5	E

B		
Dst	Cst	Hop
A	4	A
B	0	B
C	2	F
D	3	D
E	4	F
F	1	F



C		
Dst	Cst	Hop
A	7	F
B	2	F
C	0	C
D	1	D
E	4	F
F	1	F

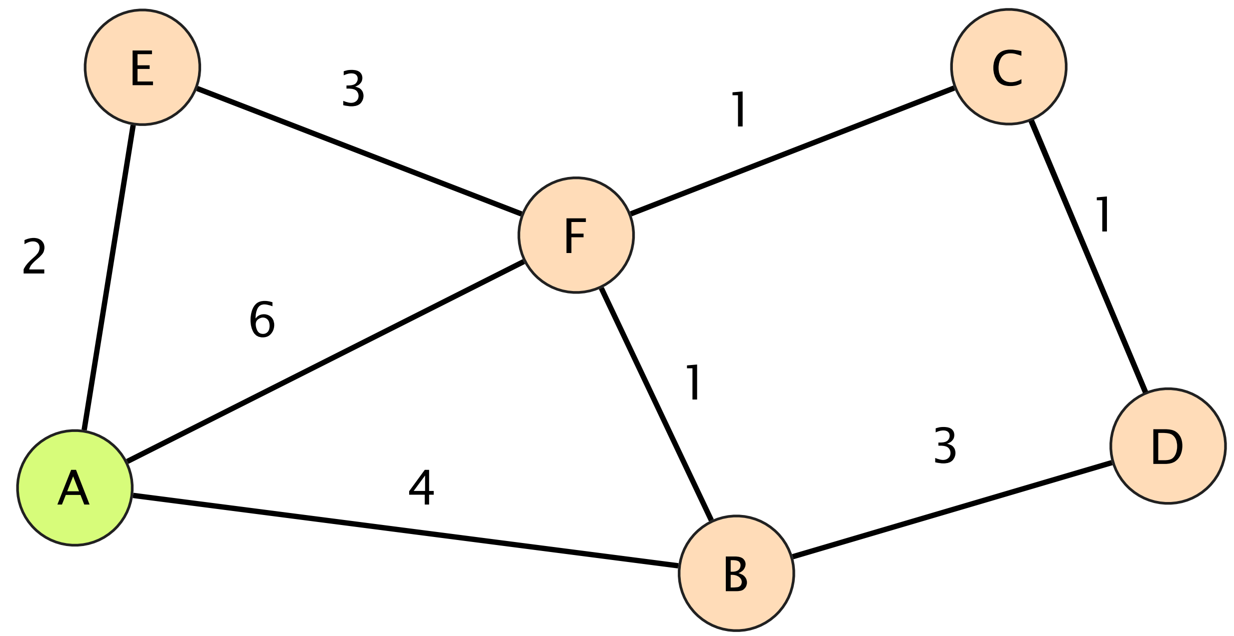
D		
Dst	Cst	Hop
A	7	B
B	3	B
C	1	C
D	0	D
E	∞	–
F	2	C

E		
Dst	Cst	Hop
A	2	A
B	4	F
C	4	F
D	∞	–
E	0	E
F	3	F

F		
Dst	Cst	Hop
A	5	B
B	1	B
C	1	C
D	2	C
E	3	E
F	0	F

Optimum 3-hops path

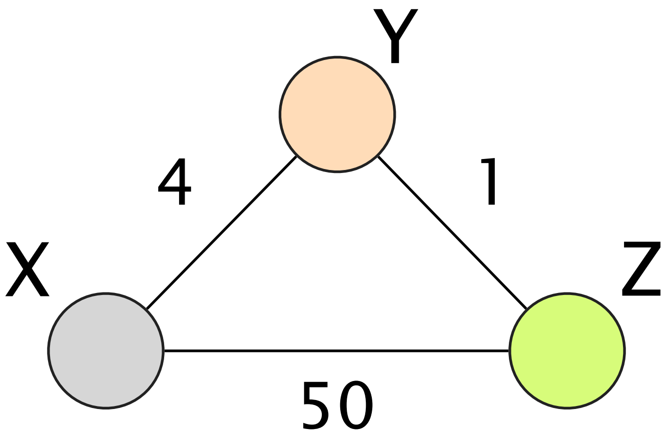
A			B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	6	E	C	2	F
D	7	F	D	3	D
E	2	E	E	4	F
F	5	E	F	1	F



C			D			E			F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	6	F	A	7	B	A	2	A	A	5	B
B	2	F	B	3	B	B	4	F	B	1	B
C	0	C	C	1	C	C	4	F	C	1	C
D	1	D	D	0	D	D	5	F	D	2	C
E	4	F	E	5	C	E	0	E	E	3	E
F	1	F	F	2	C	F	3	F	F	0	F

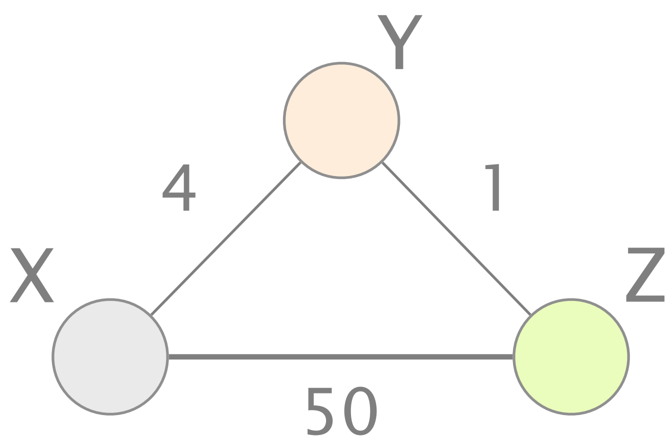
Let's consider the convergence process after a link cost change

Consider the following network



Consider the following network

leading to the following vectors



Y vector

dest.	via X	via Z
X	4	6

Y reaches X directly

Z vector

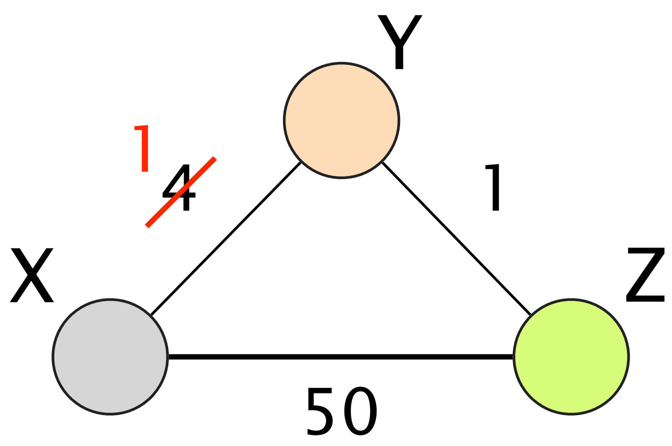
dest.	via X	via Y
X	50	5

Z reaches X via Y

t = 0

(X,Y) weight changes

from 4 to 1



time t=0

Y vector

dest.	via X	via Z
X	4	6

Z vector

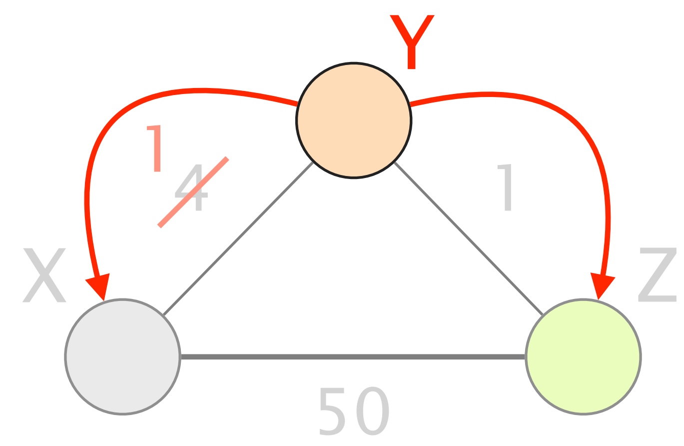
dest.	via X	via Y
X	50	5

Node detects local cost change, update their vectors, and notify their neighbors if it has changed

t = 1

Y updates its vector,

sends it to X and Z



t=0

Y vector

dest.	via X	via Z
X	4	6

Z vector

dest.	via X	via Y
X	50	5

t=1

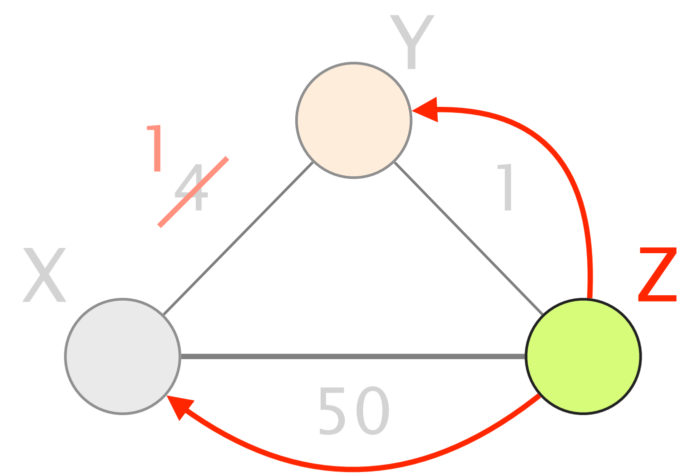
Y vector

dest.	via X	via Z
X	1	6

t = 2

Z updates its vector,

sends it to X and Y



t=0

Y vector

dest.	via X	via Z
X	4	6

Z vector

dest.	via X	via Y
X	50	5

t=1

Y vector

dest.	via X	via Z
X	1	6

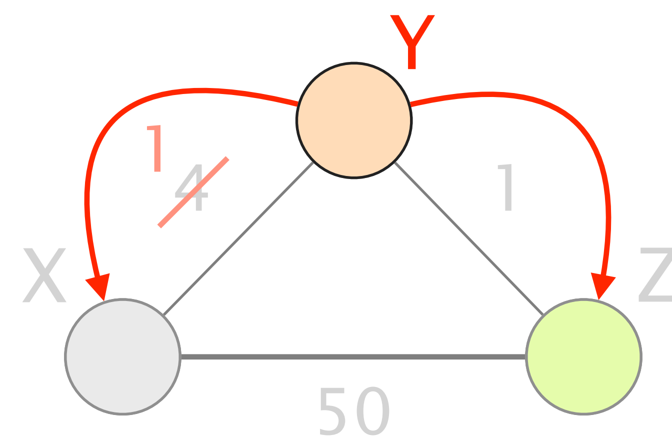
t=2

Z vector

dest.	via X	via Y
X	50	2

t = 3

Y updates its vector, sends it to X and Z



Y vector

	t=0			t=1			t=2			t=3		
	dest.	via X	via Z	dest.	via X	via Z				dest.	via X	via Z
	X	4	6	X	1	6				X	1	3

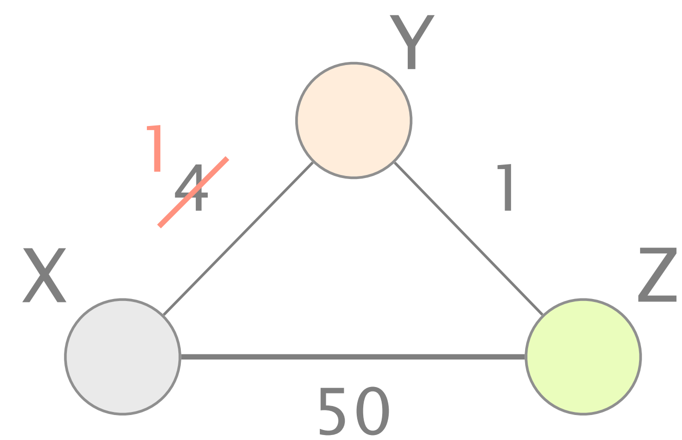
Z vector

	t=0			t=1			t=2			t=3		
	dest.	via X	via Y				dest.	via X	via Y			
	X	50	5				X	50	2			

t > 3

no one moves anymore

network has converged!



t=0 | t=1 | t=2 | t>3

Y vector

t=0

dest.	via X	via Z
X	4	6

t=1

dest.	via X	via Z
X	1	6

t>3

dest.	via X	via Z
X	1	3

Z vector

t=0

dest.	via X	via Y
X	50	5

t=2

dest.	via X	via Y
X	50	2

t>3

dest.	via X	via Y
X	50	2

The algorithm terminates after 3 iterations

Good news travel fast!

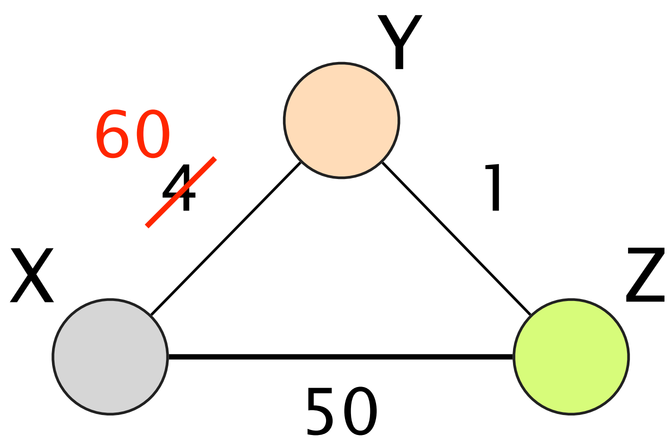
Good news travel fast!

What about bad ones?

t = 0

(X,Y) weight changes

from 4 to 60



time t=0

Y vector

dest.	via X	via Z
X	4	6

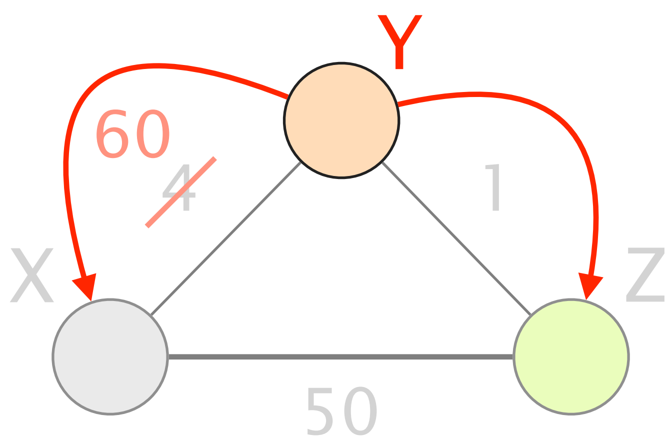
Z vector

dest.	via X	via Y
X	50	5

t = 1

Y updates its vector,

sends it to X and Z



t=0

Y vector

dest.	via X	via Z
X	4	6

Z vector

dest.	via X	via Y
X	50	5

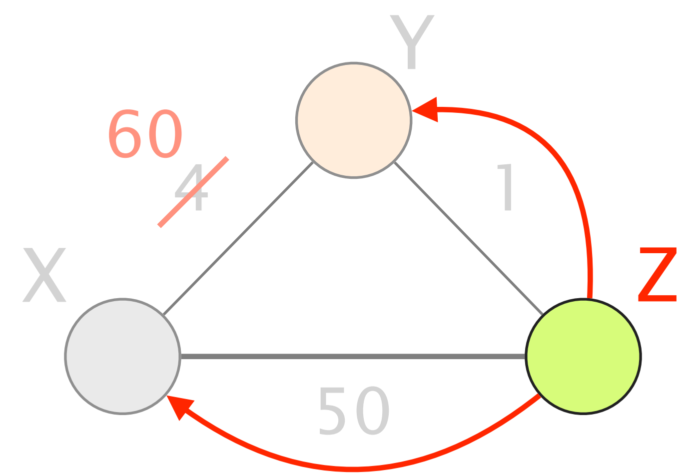
t=1

Y vector

dest.	via X	via Z
X	60	6

t = 2

Z updates its vector, sends it to X and Y

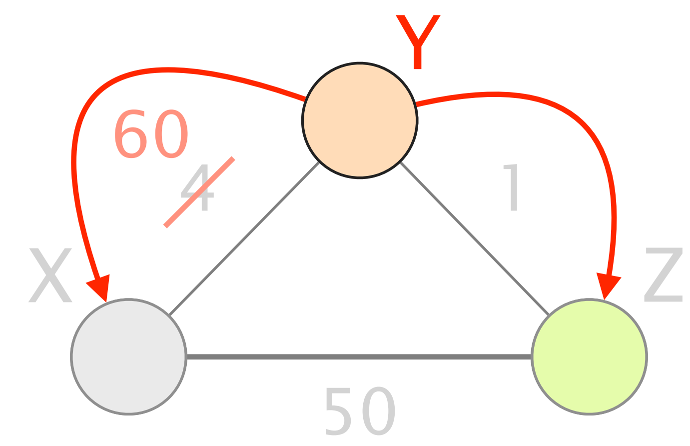


	t=0			t=1			t=2		
Y vector	dest.	via *X*	via *Z*	dest.	via *X*	via *Z*			
	X	4	6	*X*	60	6			
Z vector	dest.	via *X*	via *Y*				dest.	via *X*	via *Y*
	X	50	5				*X*	50	7

t = 3

Y updates its vector,

sends it to X and Z



Y vector

t=0

dest.	via X	via Z
X	4	6

t=1

dest.	via X	via Z
X	60	6

t=3

dest.	via X	via Z
X	60	8

Z vector

t=0

dest.	via X	via Y
X	50	5

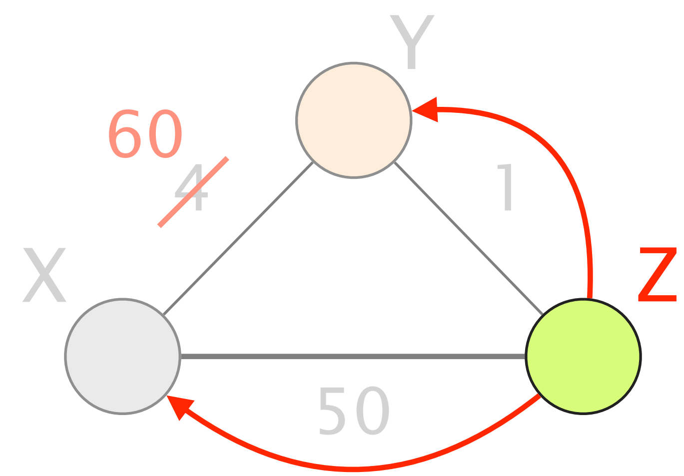
t=2

dest.	via X	via Y
X	50	7

t = 4

Z updates its vector,

sends it to X and Y…

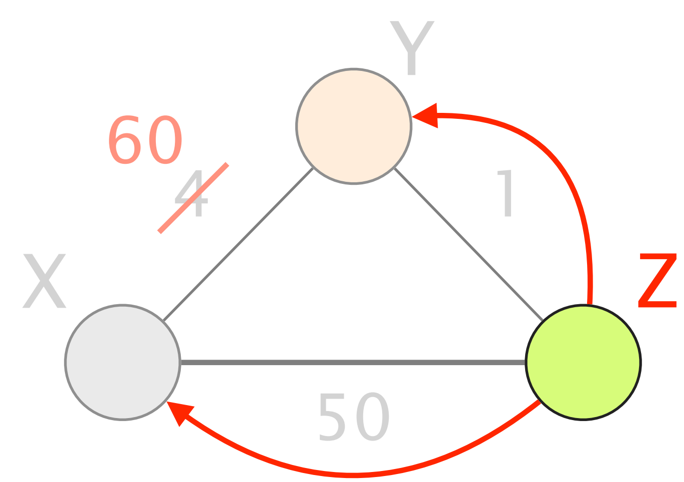


t=4

Y
vector

Z
vector

dest.	via X	via Y
X	50	9



t=4

t=44

Y
vector

... many iterations later ...

dest.	via X	via Z
X	60	51

Z
vector

dest.	via X	via Y
X	50	9

dest.	via X	via Y
X	50	52

The algorithm terminates
after 44 iterations!

Bad news travel slow!

This problem is known as count-to-infinity, a type of routing loop

Count-to-infinity leads to very slow convergence

what if the cost had changed from 4 to 9999?

Routers don't know when neighbors use them

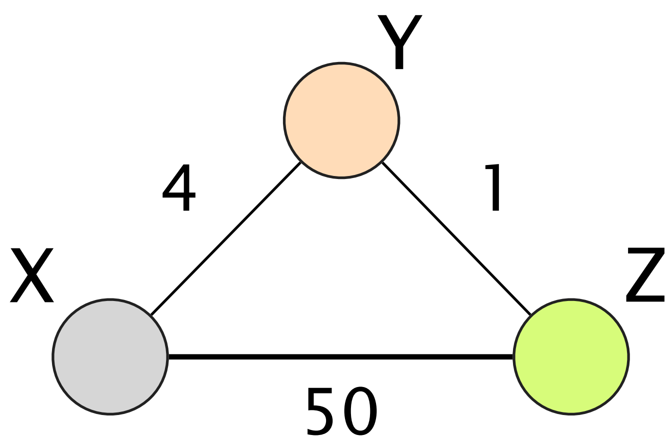
Z does not know that Y has switched to use it

Let's try to fix that

Whenever a router uses another one,

it will announce it an infinite cost

The technique is known as poisoned reverse



Y vector

dest.	via X	via Z
X	4	∞

As Z uses Y to reach X,

it announces to Y an infinite cost

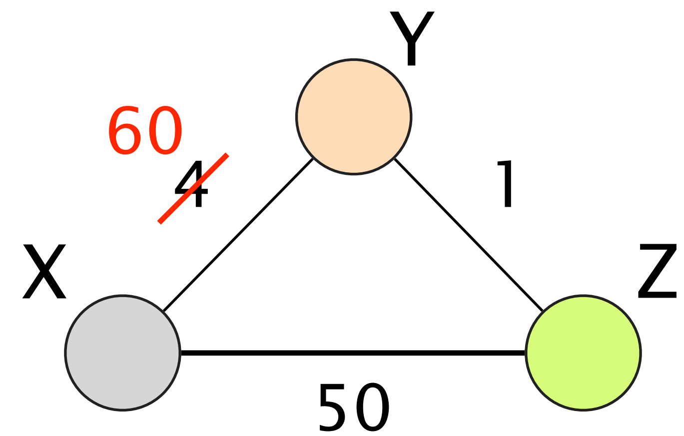
Z vector

dest.	via X	via Y
X	50	5

t = 0

(X,Y) weight changes

from 4 to 60



time t=0

Y vector

dest.	via X	via Z
X	4	∞

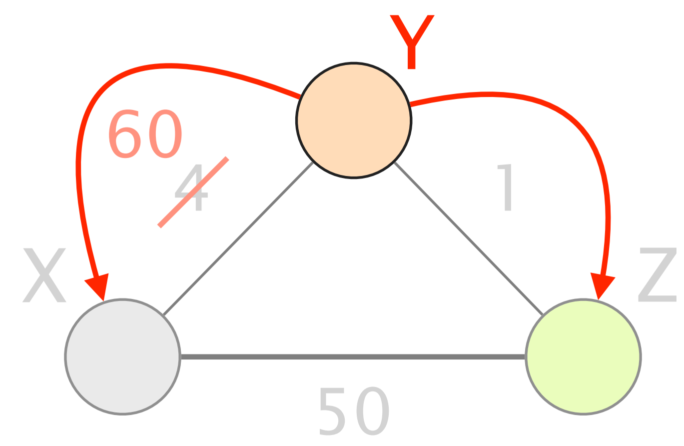
Z vector

dest.	via X	via Y
X	50	5

t = 1

Y updates its vector,

sends it to X and Z



t=0

Y vector

dest.	via X	via Z
X	4	∞

Z vector

dest.	via X	via Y
X	50	5

t=1

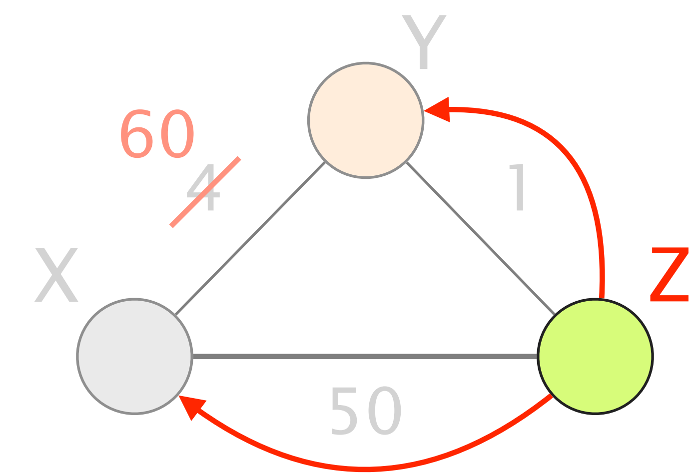
Y vector

dest.	via X	via Z
X	60	∞

t = 2

Z updates its vector,

sends it to X and Y



t=0 | t=1 | t=2

Y vector

t=0:

dest.	via X	via Z
X	4	∞

t=1:

dest.	via X	via Z
X	60	∞

Z vector

t=0:

dest.	via X	via Y
X	50	5

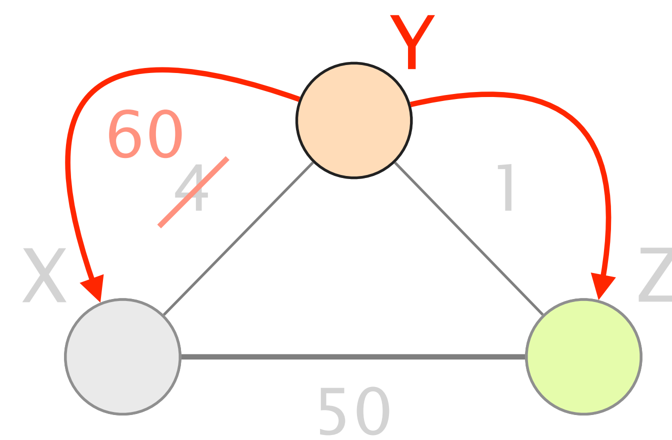
t=2:

dest.	via X	via Y
X	50	61

t = 3

Y updates its vector,

sends it to X and Z

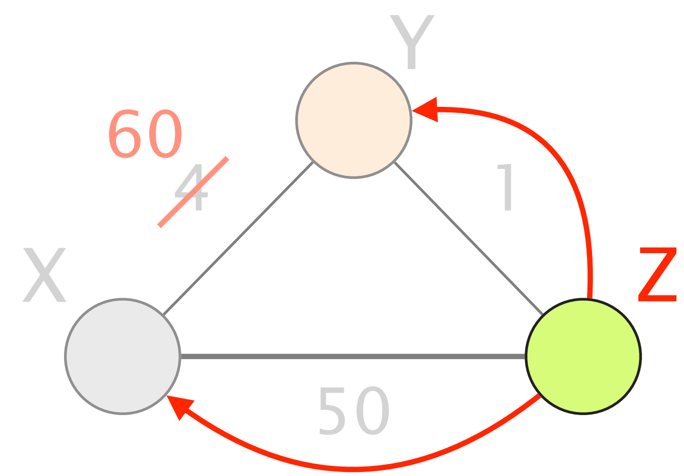


	t=0			t=1			t=2			t=3		
Y vector	dest.	via X	via Z	dest.	via X	via Z				dest.	via X	via Z
	X	4	∞	X	60	∞				X	60	51
Z vector	dest.	via X	via Y				dest.	via X	via Y			
	X	50	5				X	50	61			

t = 4

Z updates its vector,

sends it to X and Y



t=4

Y
vector

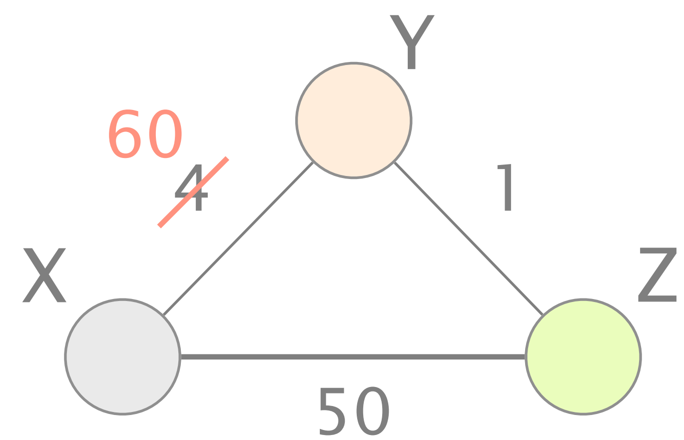
Z
vector

dest.	via X	via Y
X	50	∞

t > 4

no one moves

network has converged!



	t=4			t>4		
Y vector				dest.	via X	via Z
				X	60	51
Z vector	dest.	via X	via Y	dest.	via X	via Y
	X	50	∞	X	50	∞

While poisoned reverse solved this case,

it does not solve loops involving 3 or more nodes…

see exercise session

Actual distance-vector protocols mitigate this issue by using small “infinity”, *e.g.* 16

Link-State *vs* Distance-Vector routing

	Message complexity	Convergence speed	Robustness
Link-State	O(nE) message sent n: #nodes E: #links	relatively fast	node can advertise incorrect link cost nodes compute their own table
Distance-Vector	between neighbors only	slow	node can advertise incorrect path cost errors propagate

Internet routing

from here to there, and back

Intra-domain routing

Link-state protocols

Distance-vector protocols

2 Inter-domain routing

Path-vector protocols

Internet

Internet

Internet

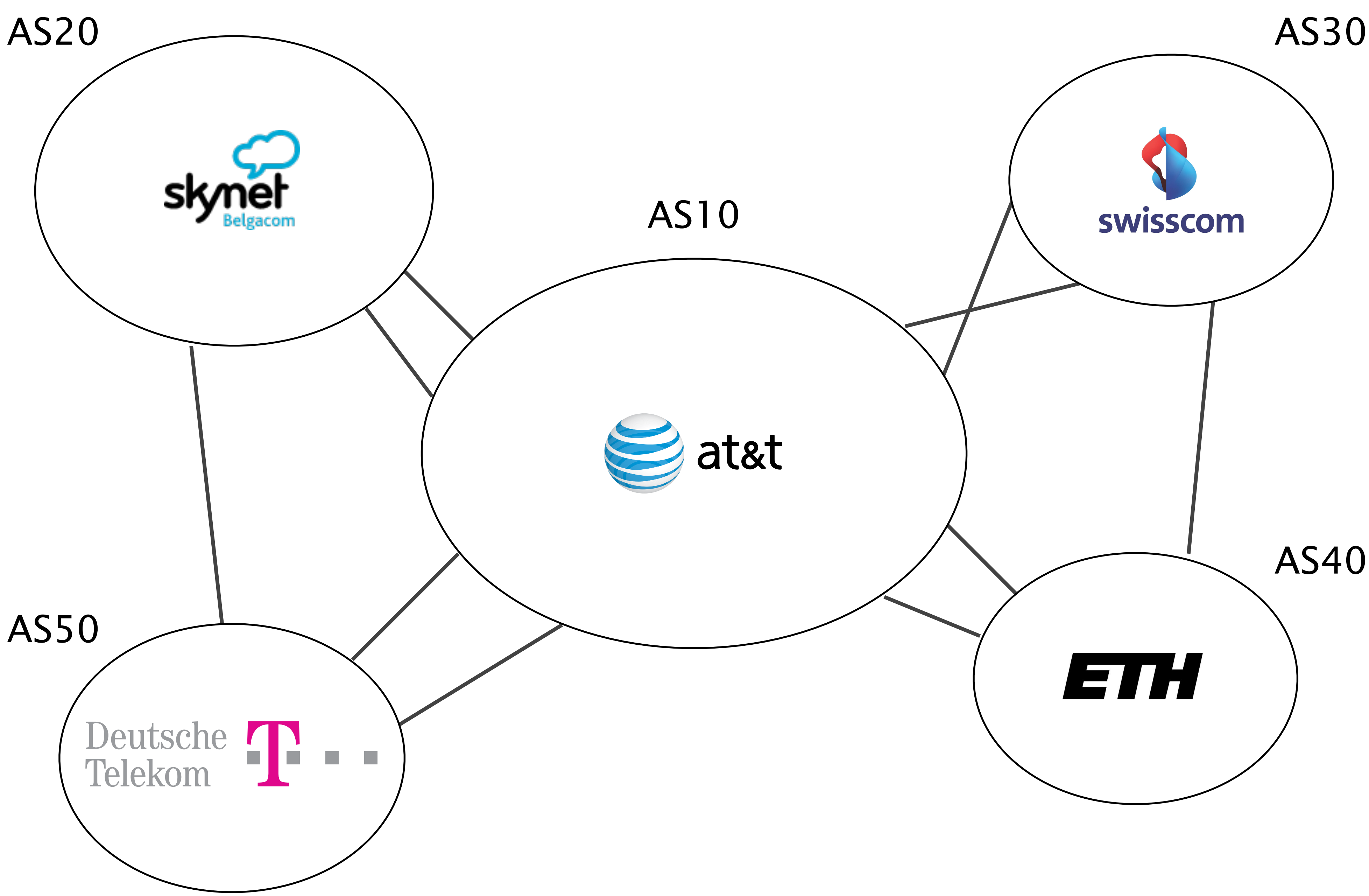
A network of *networks*

Internet

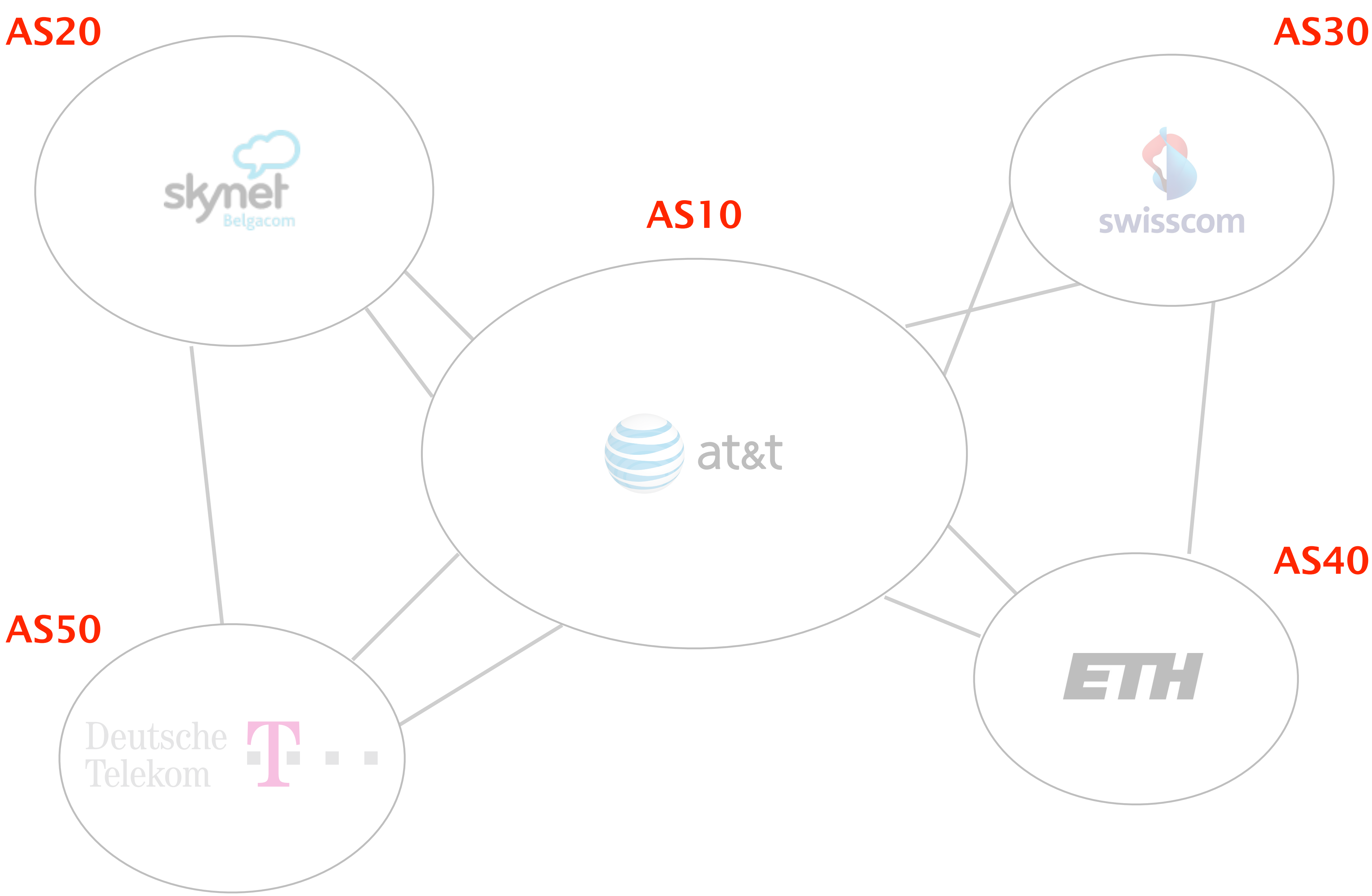
↓

Border Gateway Protocol (BGP)

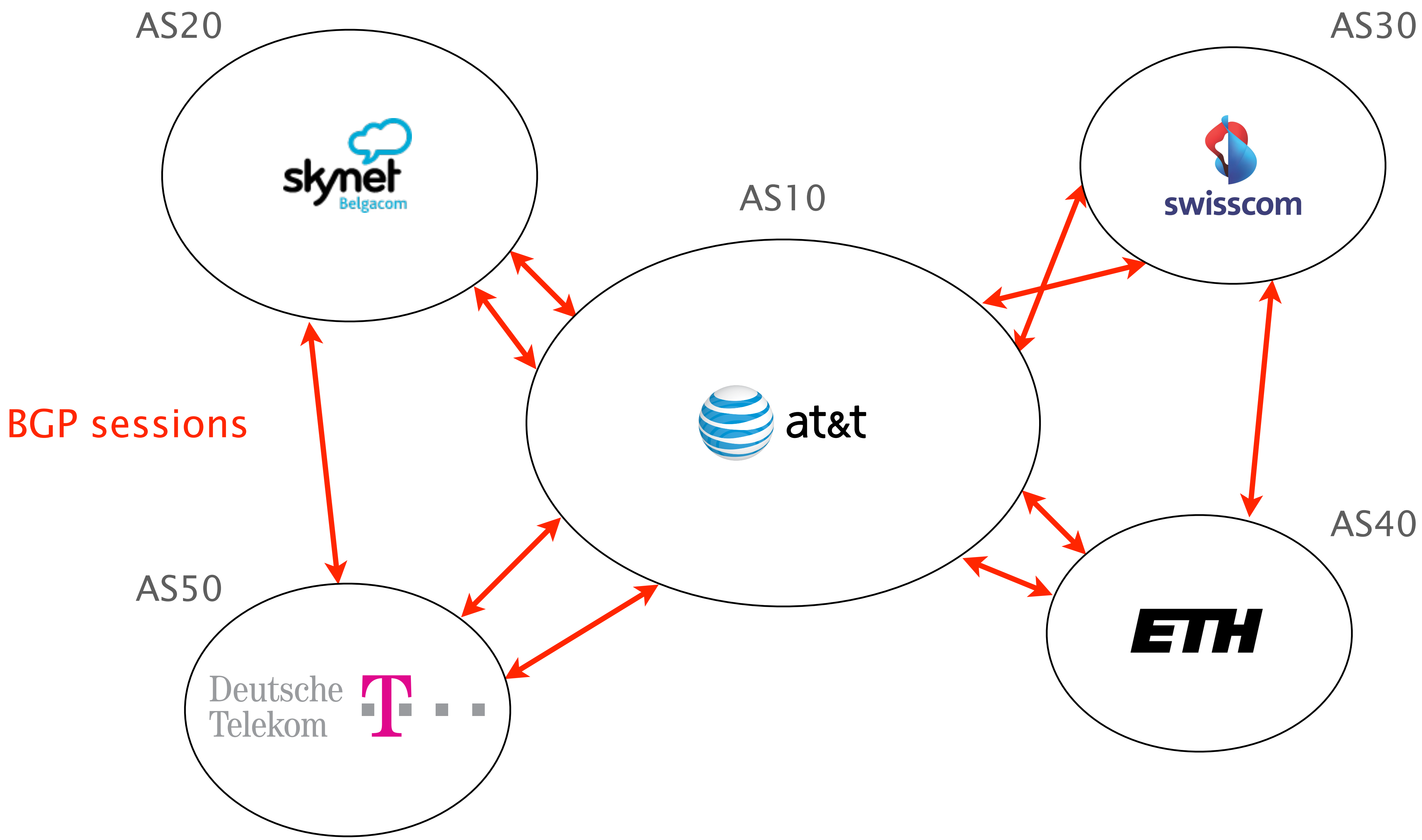
The Internet is a network of networks, referred to as Autonomous Systems (AS)



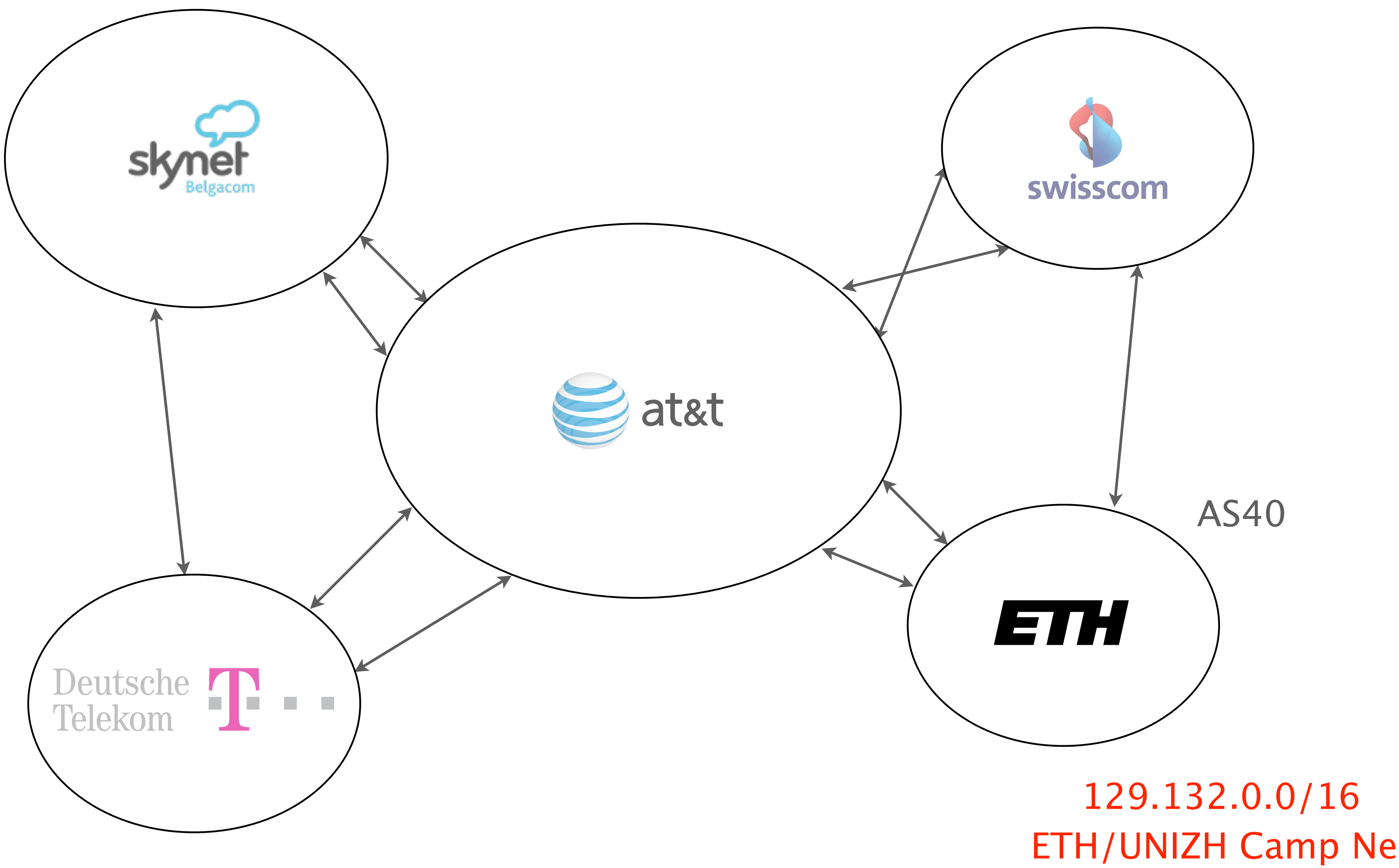
Each AS has a number (encoded on 16 bits) which identifies it



BGP is the routing protocol "glueing" the entire 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

700k prefixes, >50,000 networks, millions (!) of routers

Networks don't want to divulge internal topologies

or their business relationships

Networks need 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

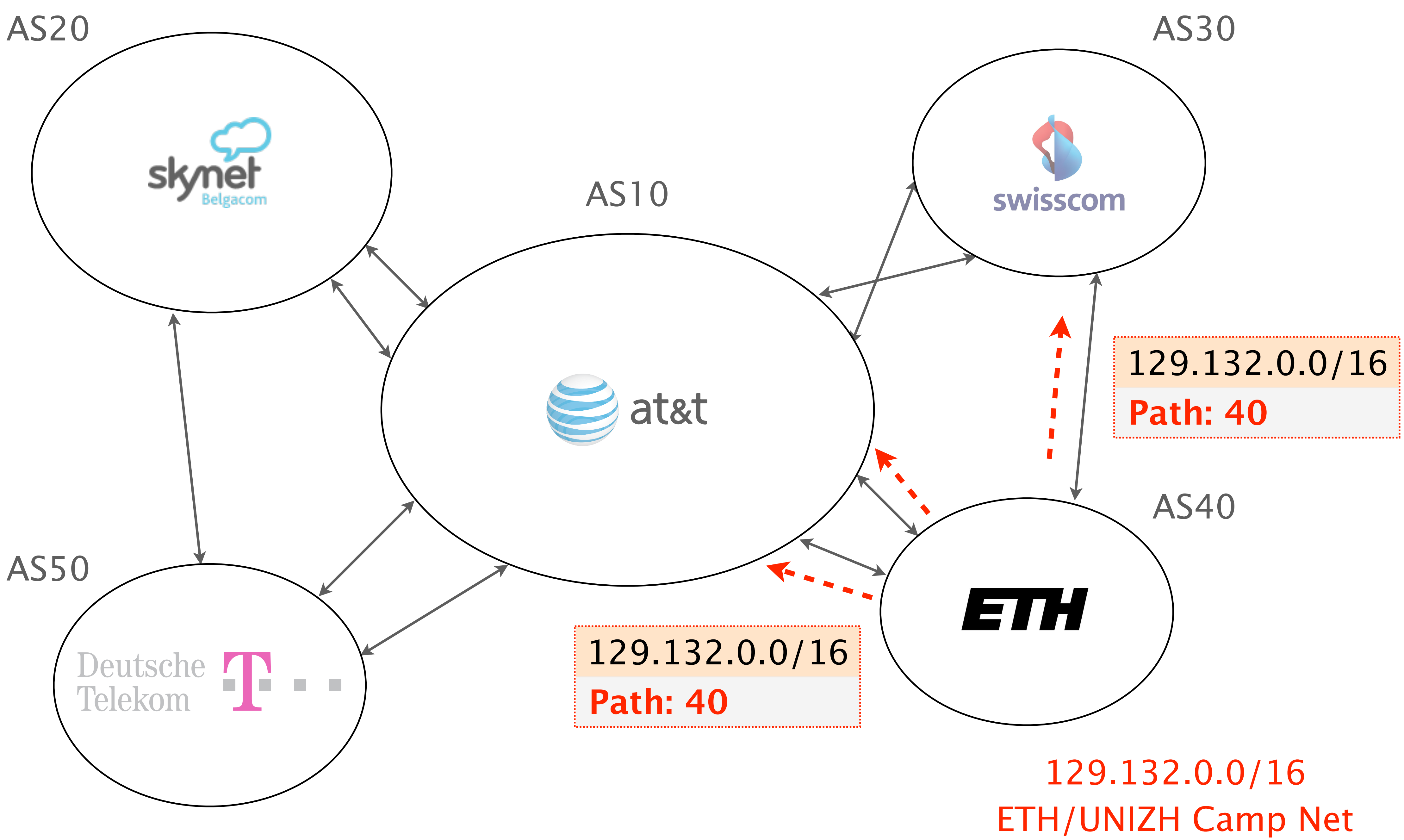
Distance-Vector routing is on the right track,
but not really there yet…

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

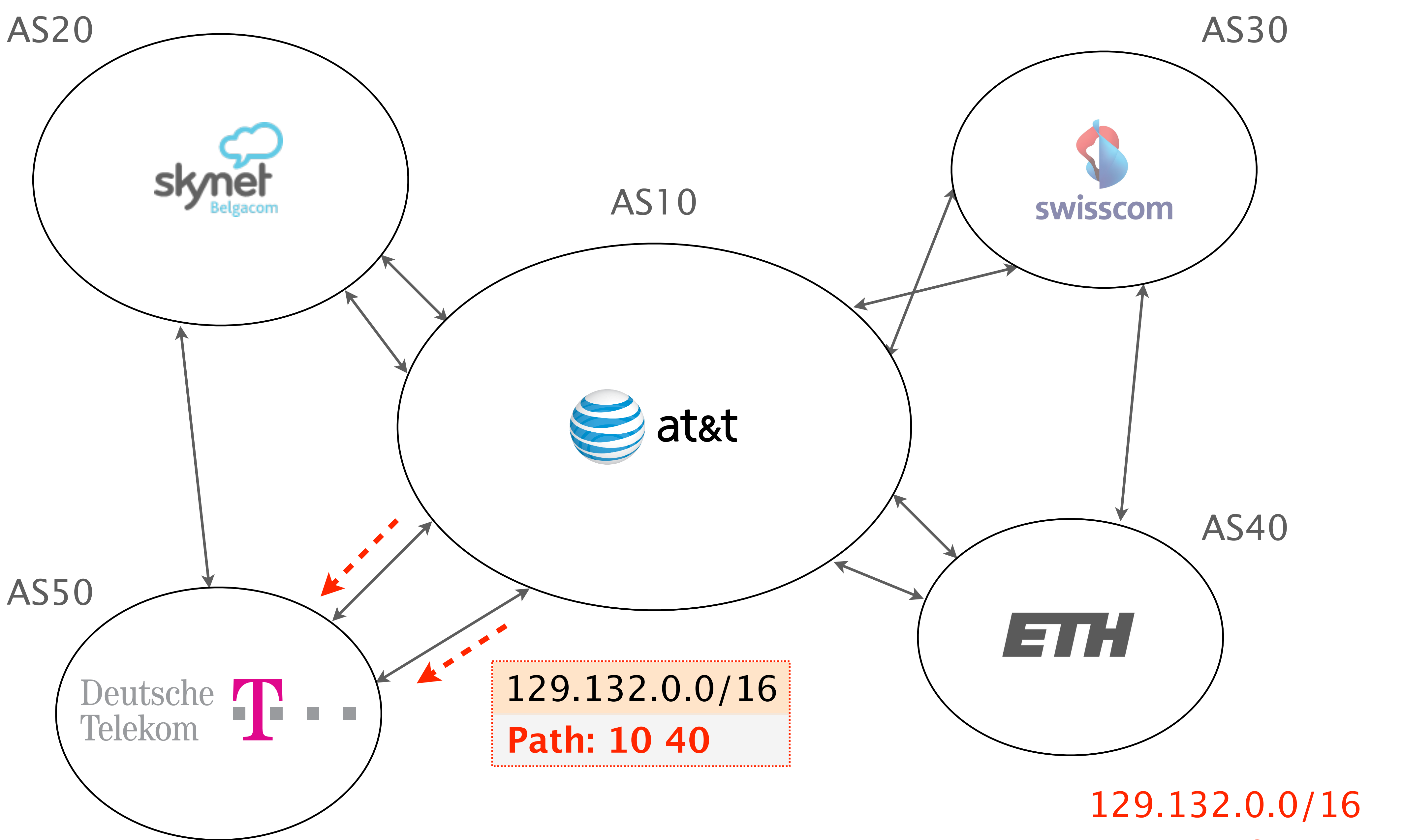
BGP relies on path-vector routing to support flexible routing policies and avoid count-to-infinity

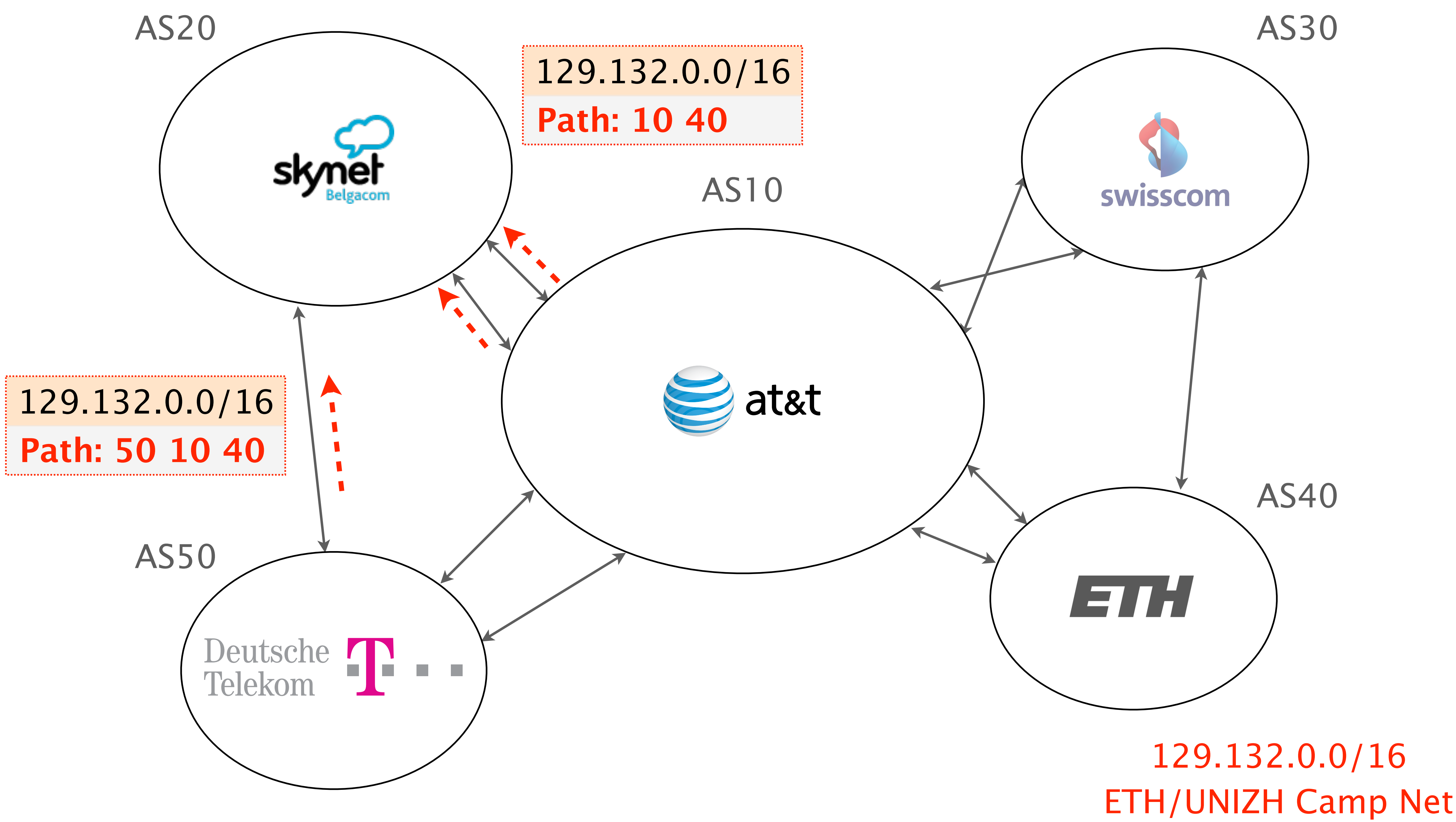
key idea advertise the entire path instead of distances

BGP announcements carry complete path information instead of distances

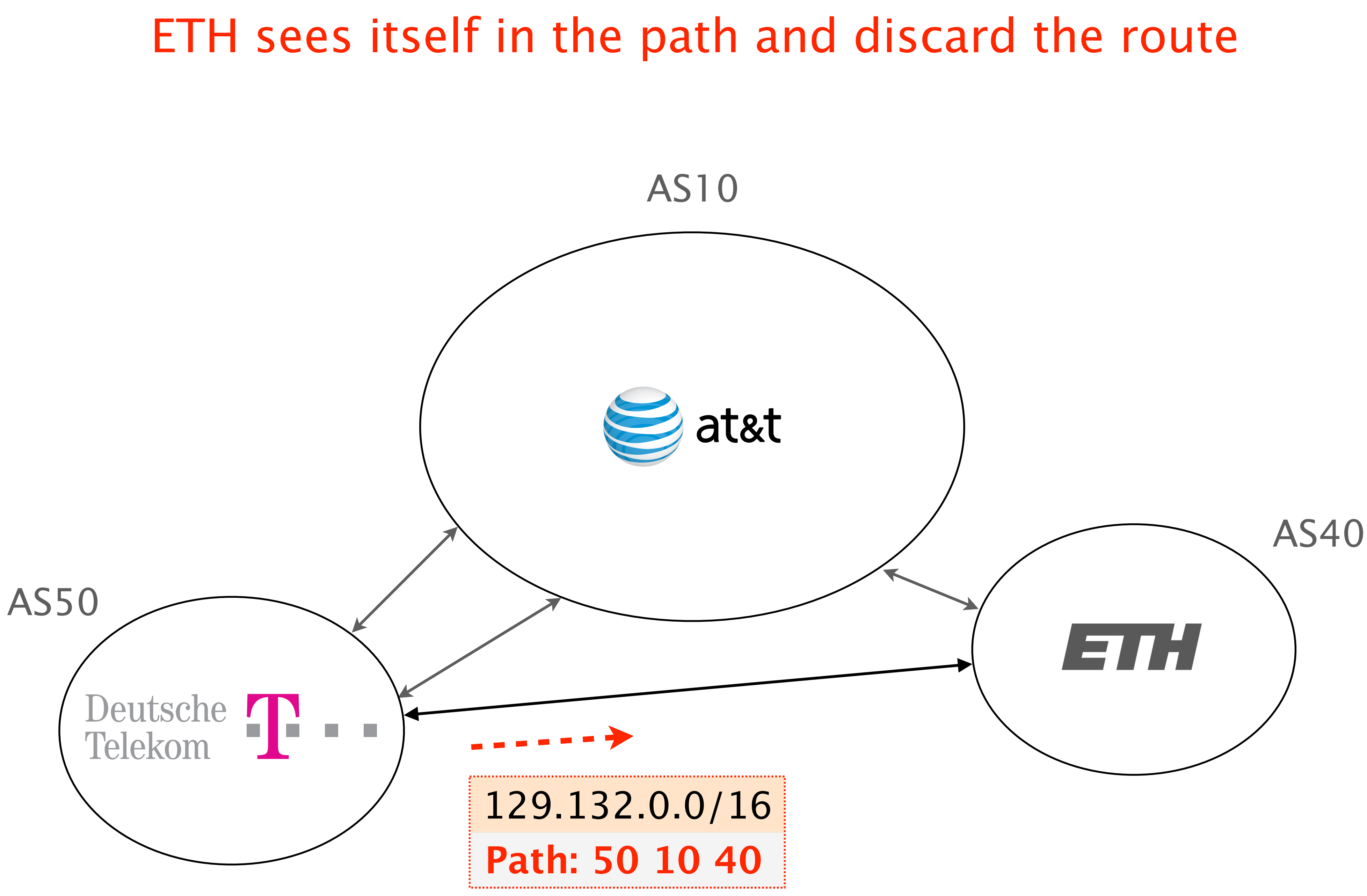


Each AS appends itself to the path when it propagates announcements




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

Complete path information enables ASes to easily detect a loop



Life of a BGP router is made of three consecutive steps

while true:

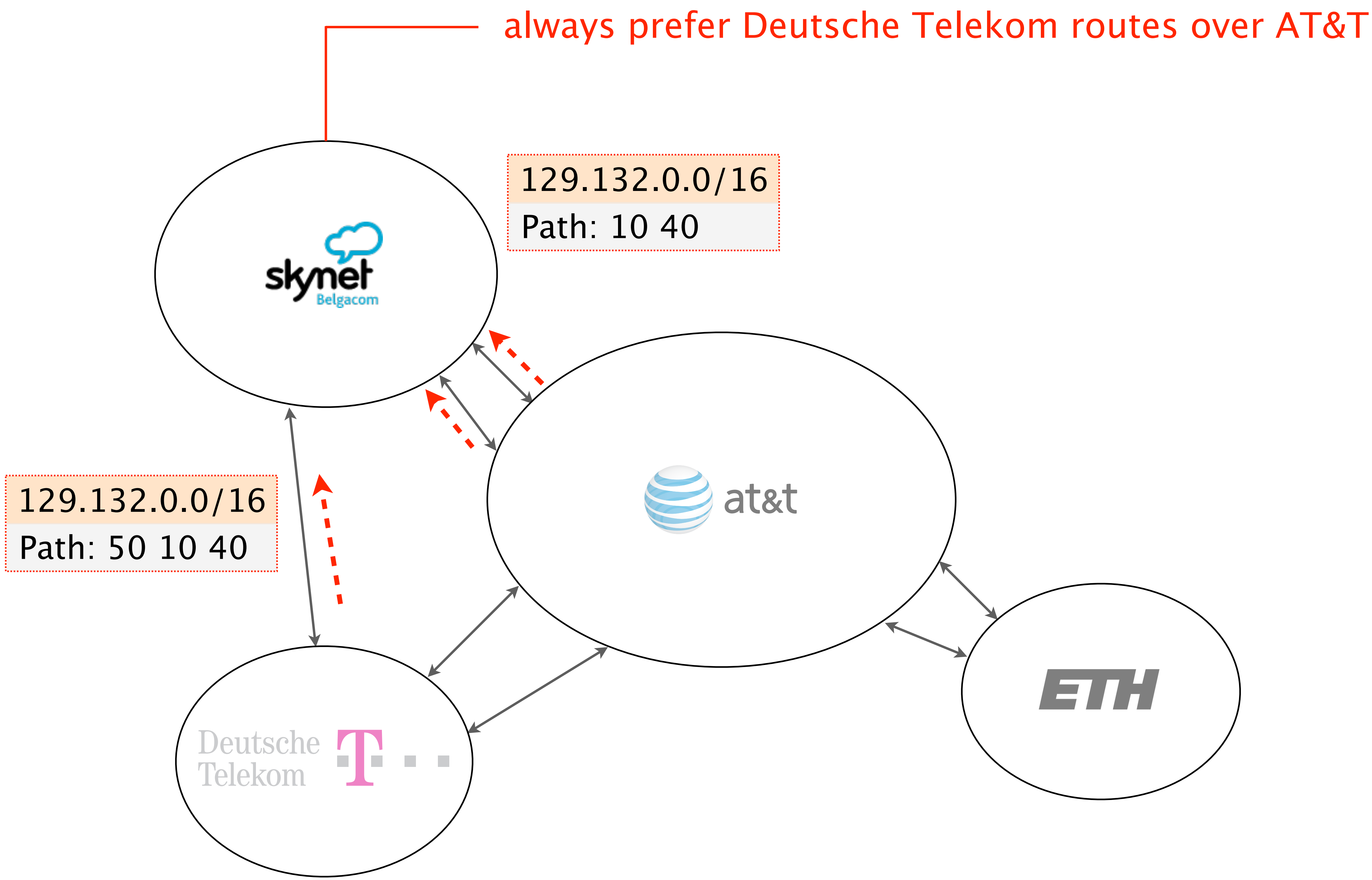
- receives routes from my neighbors
- select one best route for each prefix
- export the best route to my neighbors

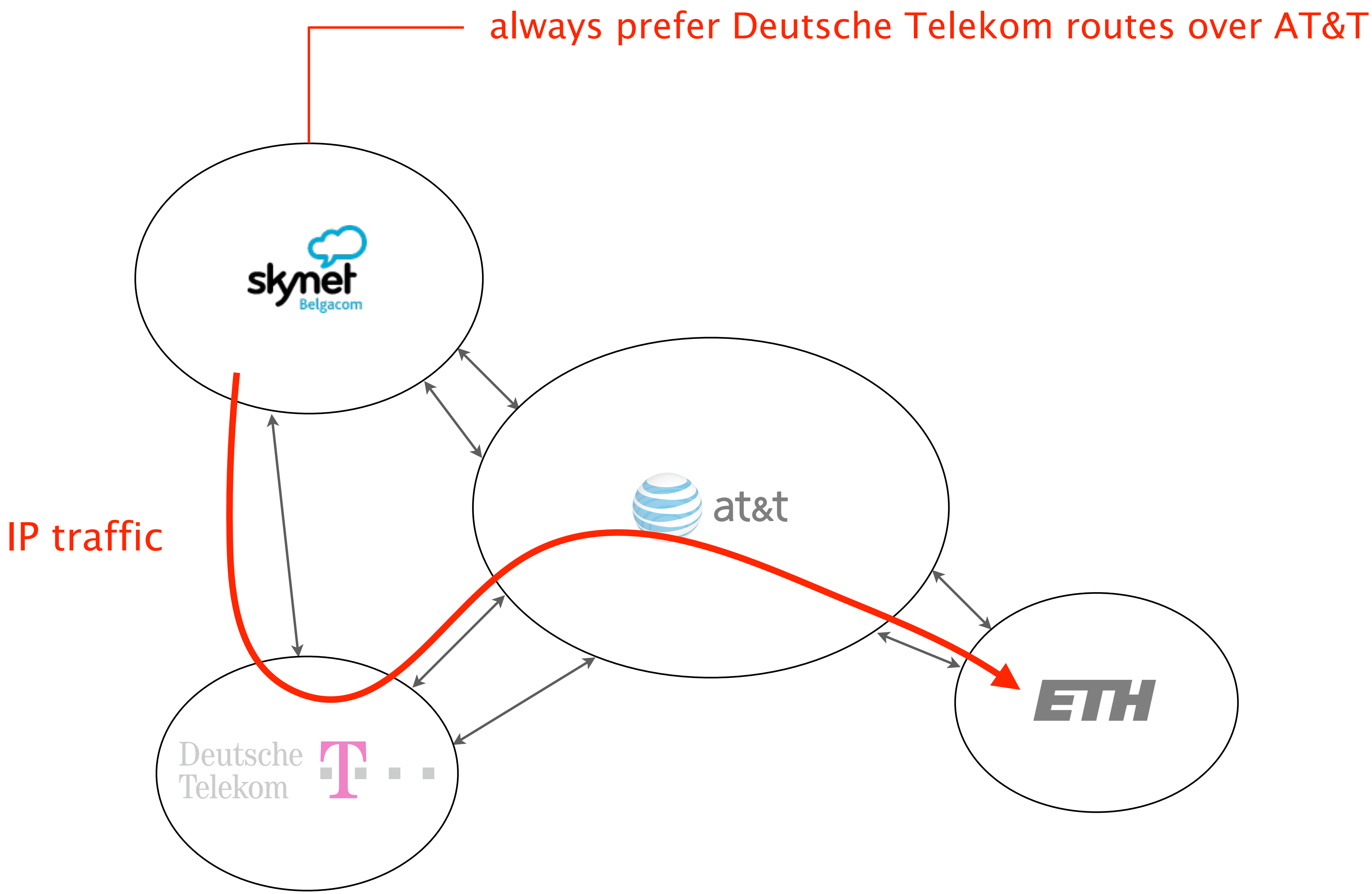
Each AS can apply local routing policies

Each AS is free to

- select and use any path

  preferably, the cheapest one


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
ETH


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

Each AS can apply local routing policies

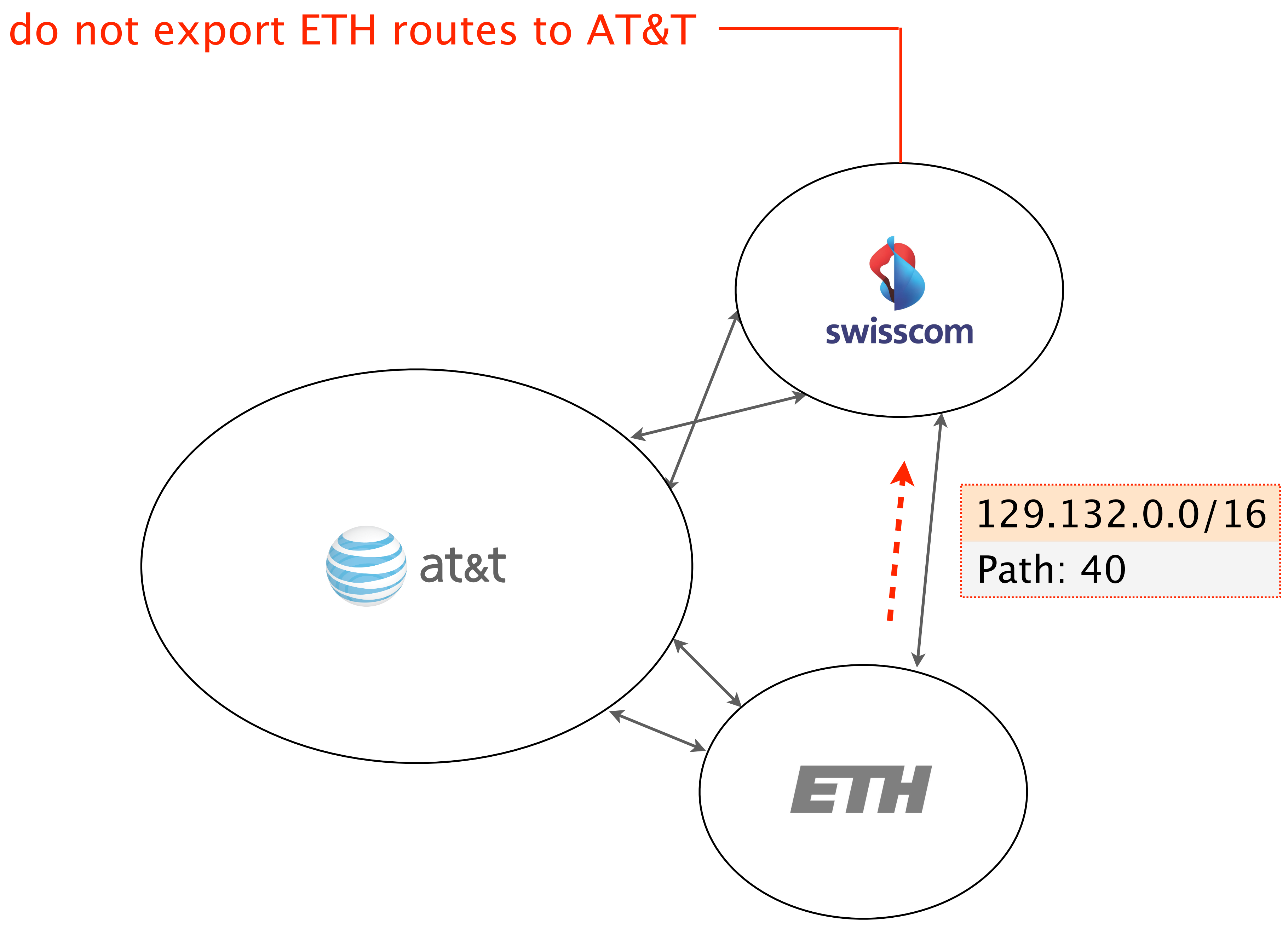
Each AS is free to

- select and use any path

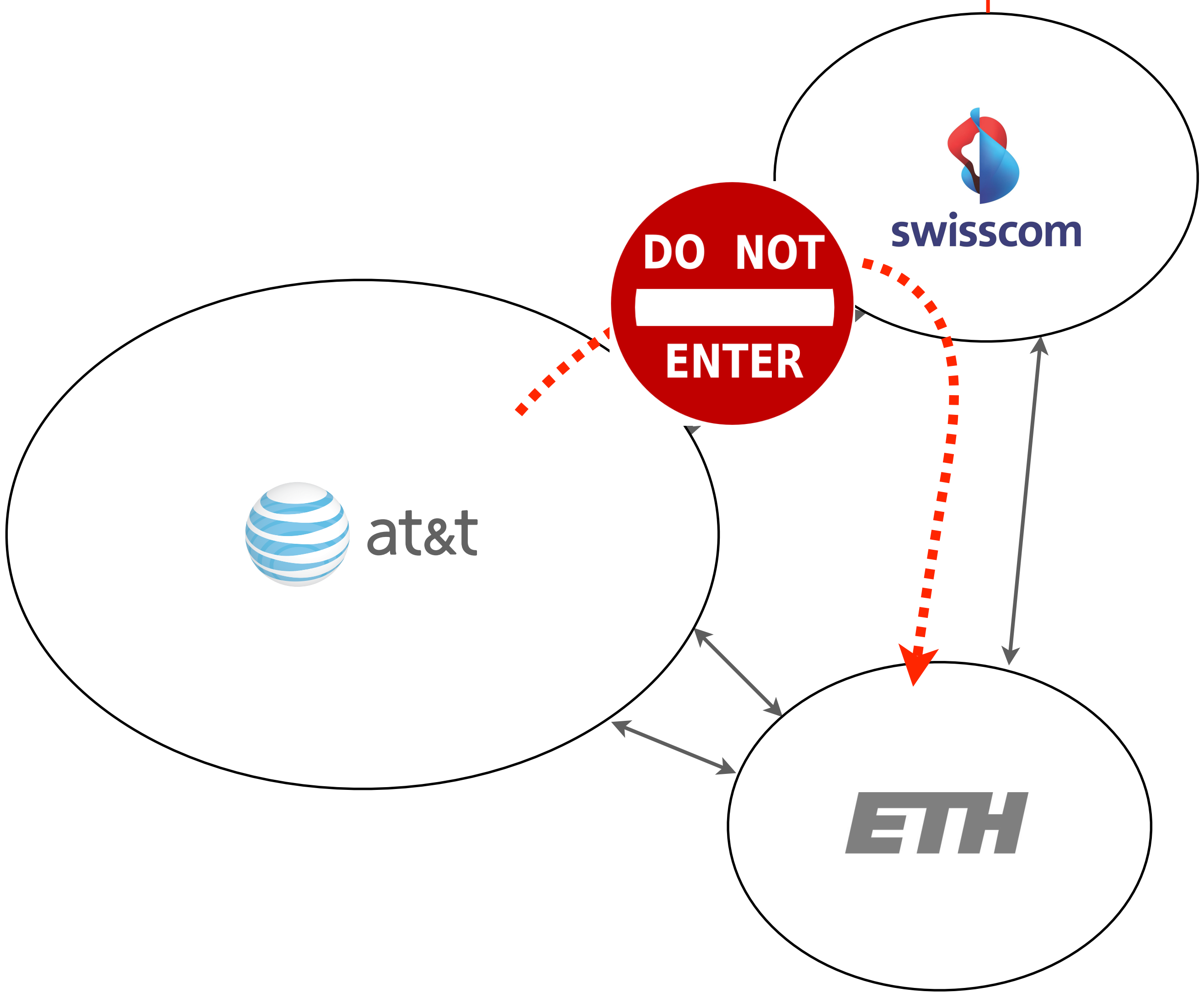
  preferably, the cheapest one

- decide which path to export (if any) to which neighbor

  preferably, none to minimize carried traffic


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

do not export ETH routes to AT&T



Communication Networks

Spring 2021

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April 12 2021