Communication Networks

Spring 2017

Tobias Bühler, TA

Slides from

Laurent Vanbever

www.vanbever.eu

ETH Zürich (D-ITET)

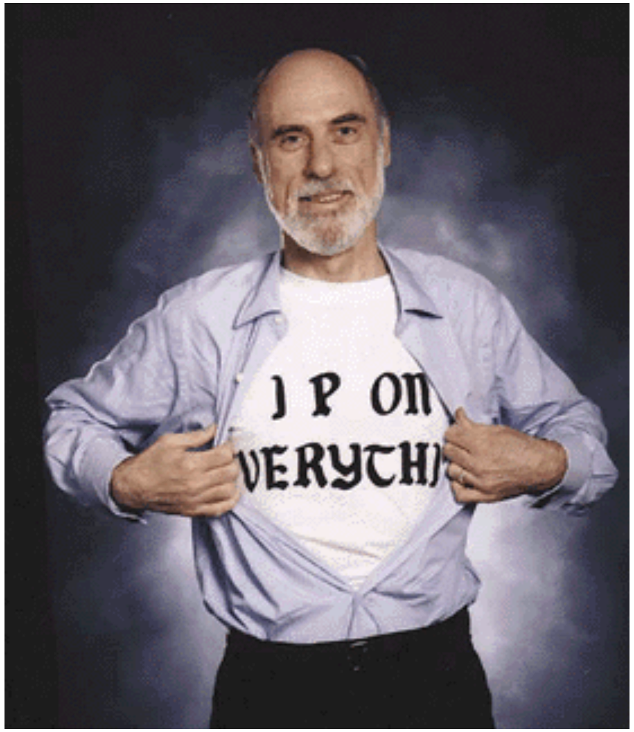
April, 3 2017

Material inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

Internet Protocol and Forwarding



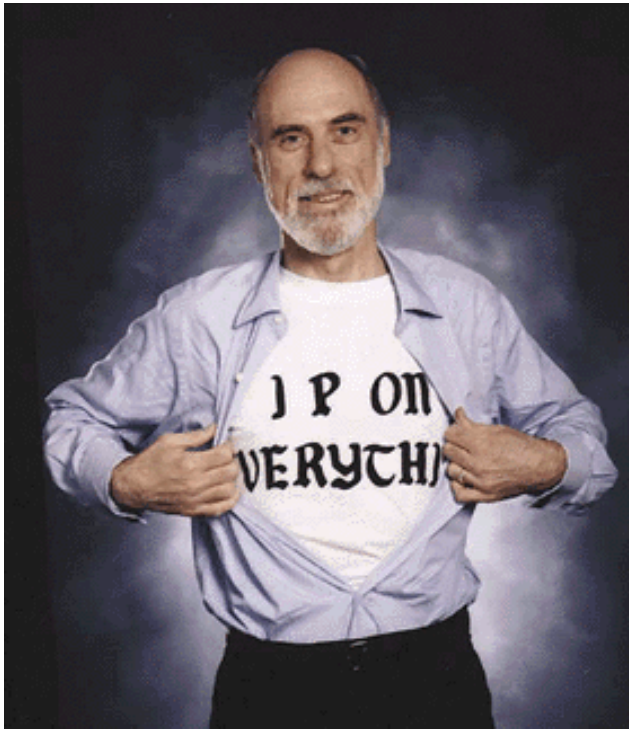
source: Boardwatch Magazine

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

IPv4 addresses are unique 32-bits number associated to a network interface (on a host, a router, …)

IP addresses are usually written using dotted-quad notation

82.130.102.10

01010010 10000010 01100110 00001010

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

32 bits

01010010.10000010.01100110.00001010

prefix
identifies the network

suffix
identifies the hosts
in the network

Each prefix has a given length,
usually written using a "slash notation"

IP prefix 82.130.102.0 /24

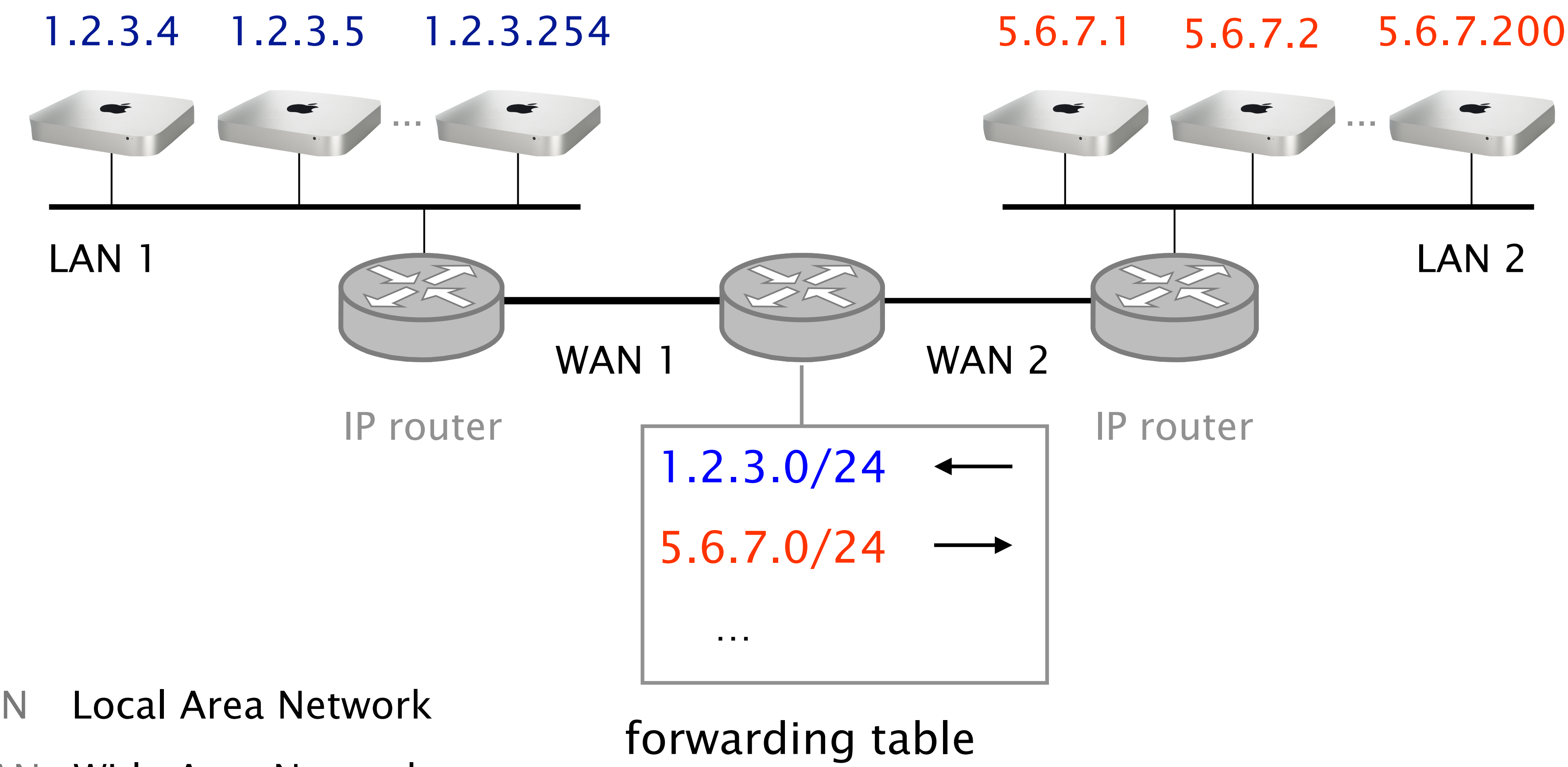
prefix length (in bits)

Prefixes are also sometimes specified using an address and a mask

Address	82.130.102.0
	01010010.10000010.01100110. 00000000
	11111111.11111111.11111111. 00000000
Mask	255.255.255.0

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

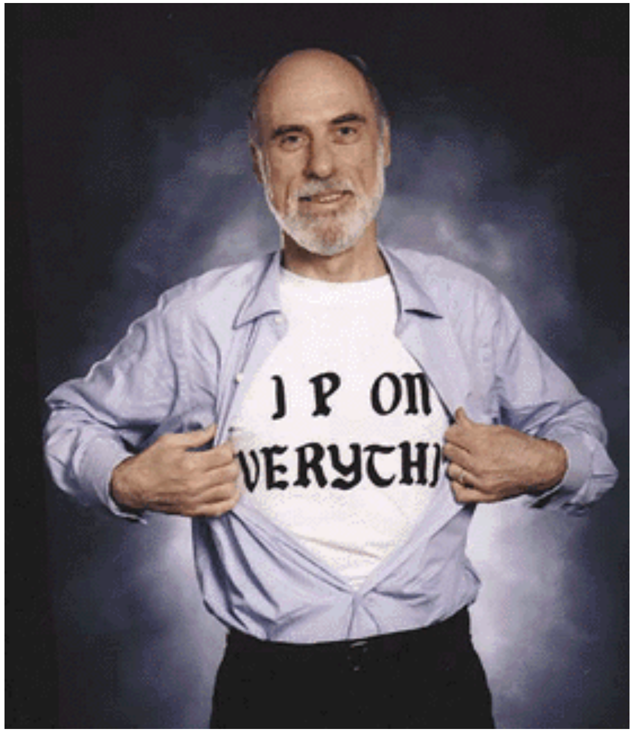
Doing so enables to scale the forwarding tables



LAN Local Area Network

WAN Wide Area Network

Internet Protocol and Forwarding



IP addresses

use, structure, allocation

2 IP forwarding

longest prefix match rule

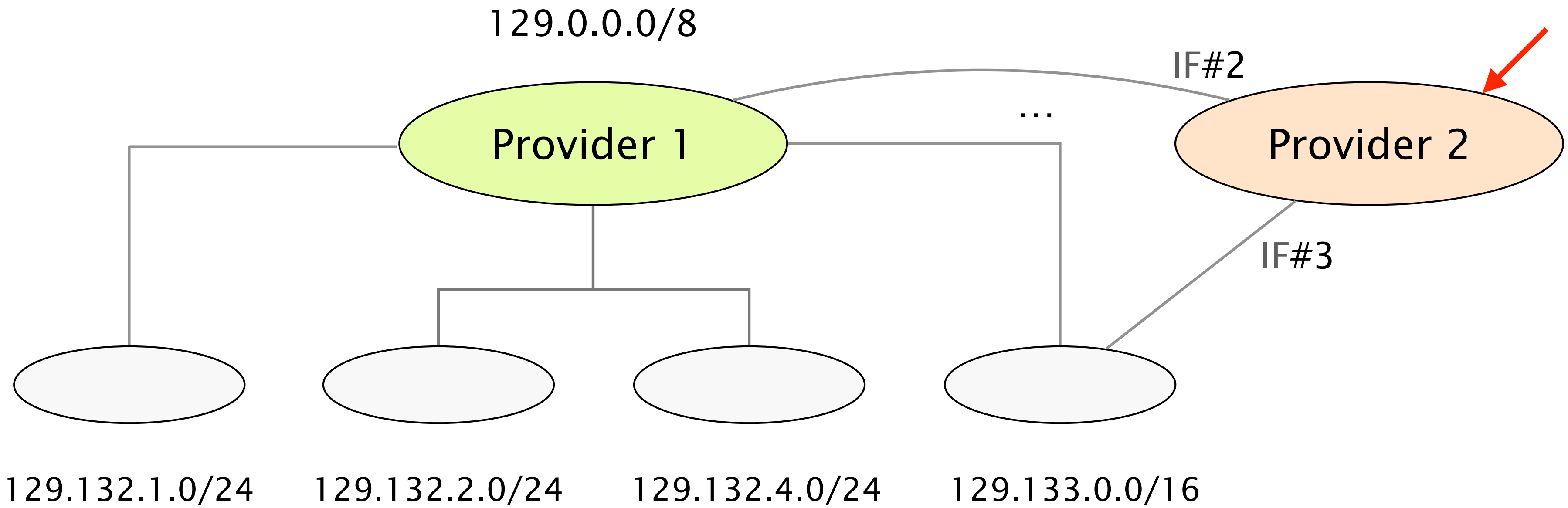
IP header

IPv4 and IPv6, wire format

Routers maintain forwarding entries
for each Internet prefix

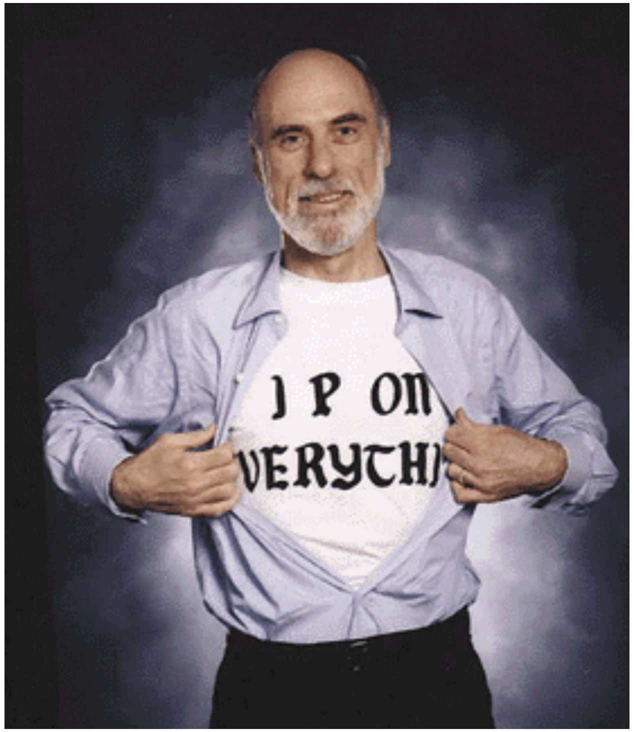
Provider 2's Forwarding table

IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3



To resolve ambiguity, forwarding is done along the *most specific* prefix (*i.e.*, the longer one)

Internet Protocol and Forwarding



IP addresses

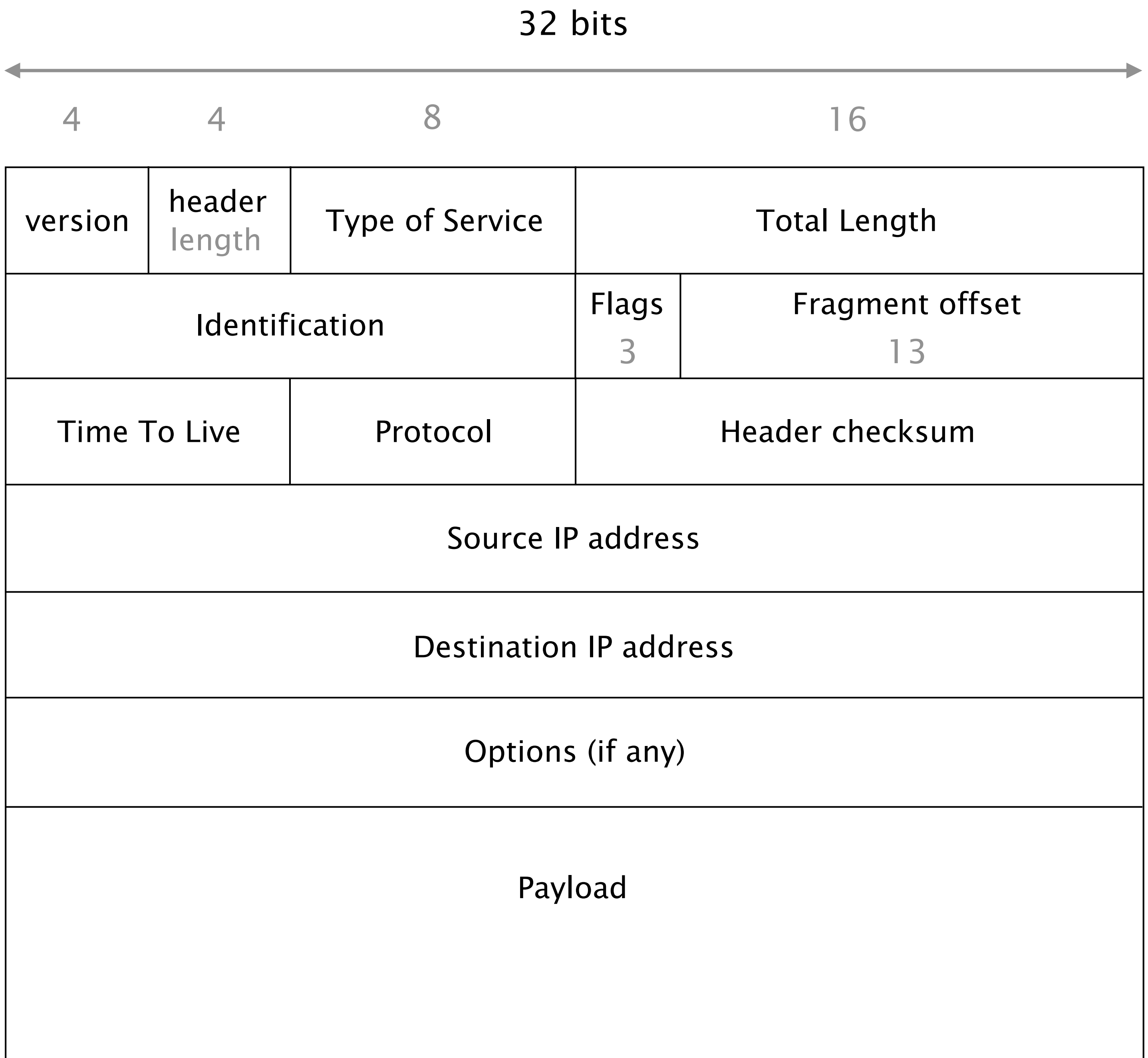
use, structure, allocation

IP forwarding

longest prefix match rule

3 IP header

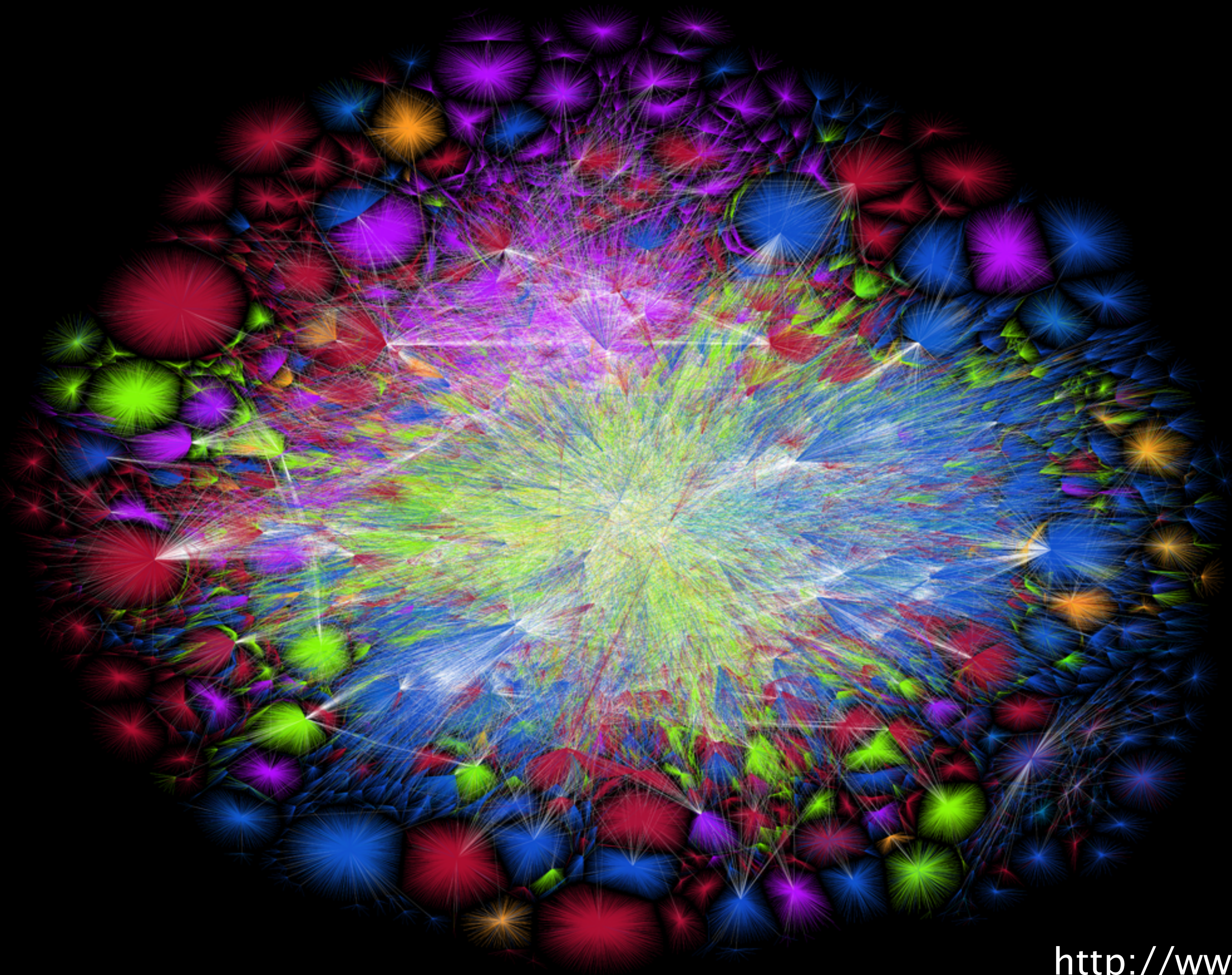
IPv4 and IPv6, wire format


32 bits
4
4
8
16
version
header length
Type of Service
Total Length
Identification
Flags
3
Fragment offset
13
Time To Live
Protocol
Header checksum
Source IP address
Destination IP address
Options (if any)
Payload

This week on

Communication Networks

Internet routing



http://www.opte.org

› traceroute www.google.ch

› traceroute www.google.ch

1 **rou-etx-1-ee-tik-etx-dock-1** (82.130.102.1)

2 **rou-ref-rz-bb-ref-rz-etx** (10.10.0.41)

3 **rou-fw-rz-ee-tik** (10.1.11.129)

4 **rou-fw-rz-gw-rz** (192.33.92.170)

5 **swiix1-10ge-1-4.switch.ch** (130.59.36.41)

6 **swiez2** (192.33.92.11)

7 **swiix2-p1.switch.ch** (130.59.36.250)

8 **equinix-zurich.net.google.com** (194.42.48.58)

9 **66.249.94.157** (66.249.94.157)

10 **zrh04s06-in-f24.1e100.net** (173.194.40.88)

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

inter-domain
routing

Find paths between networks

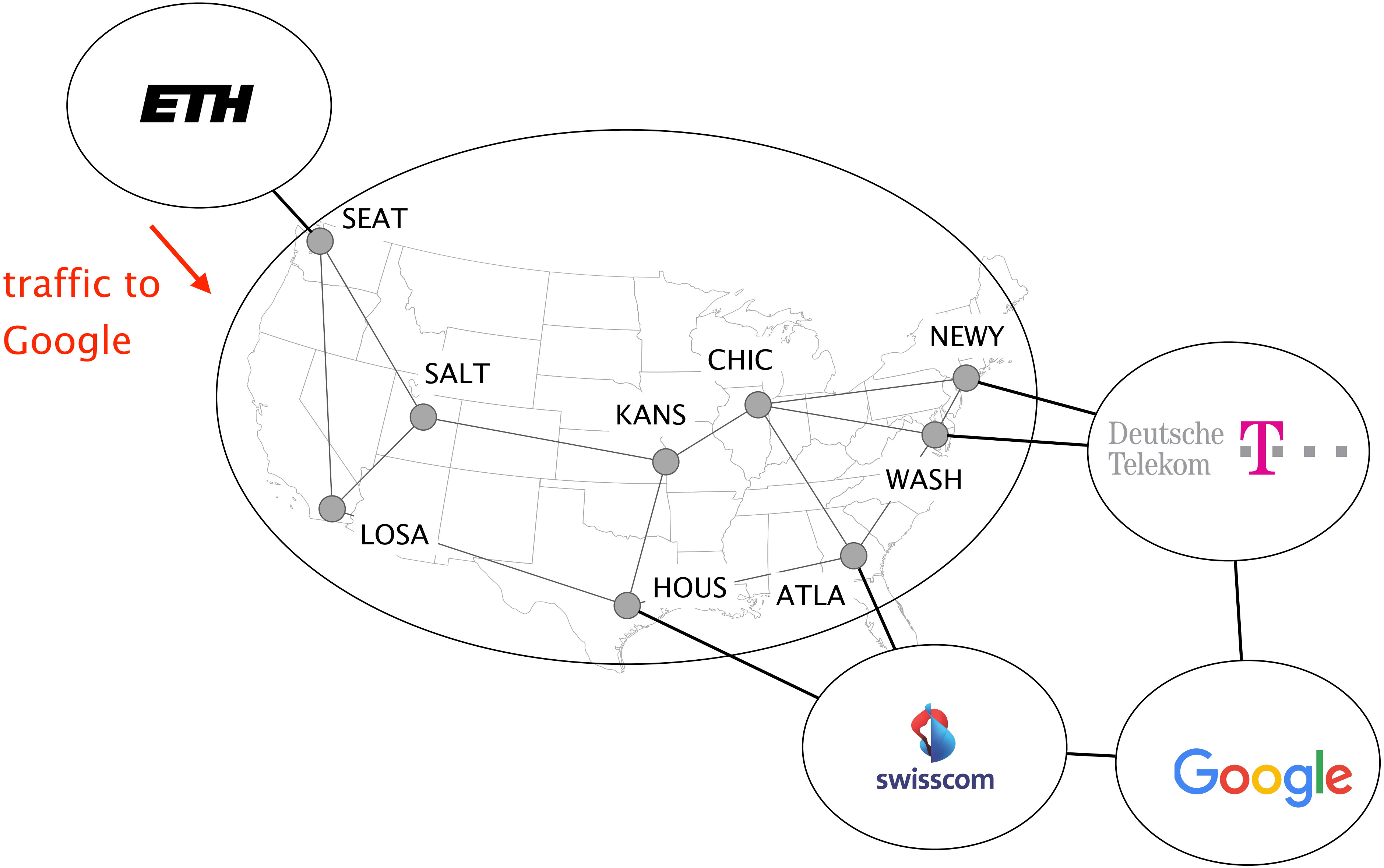
intra-domain
routing

Find paths within a network

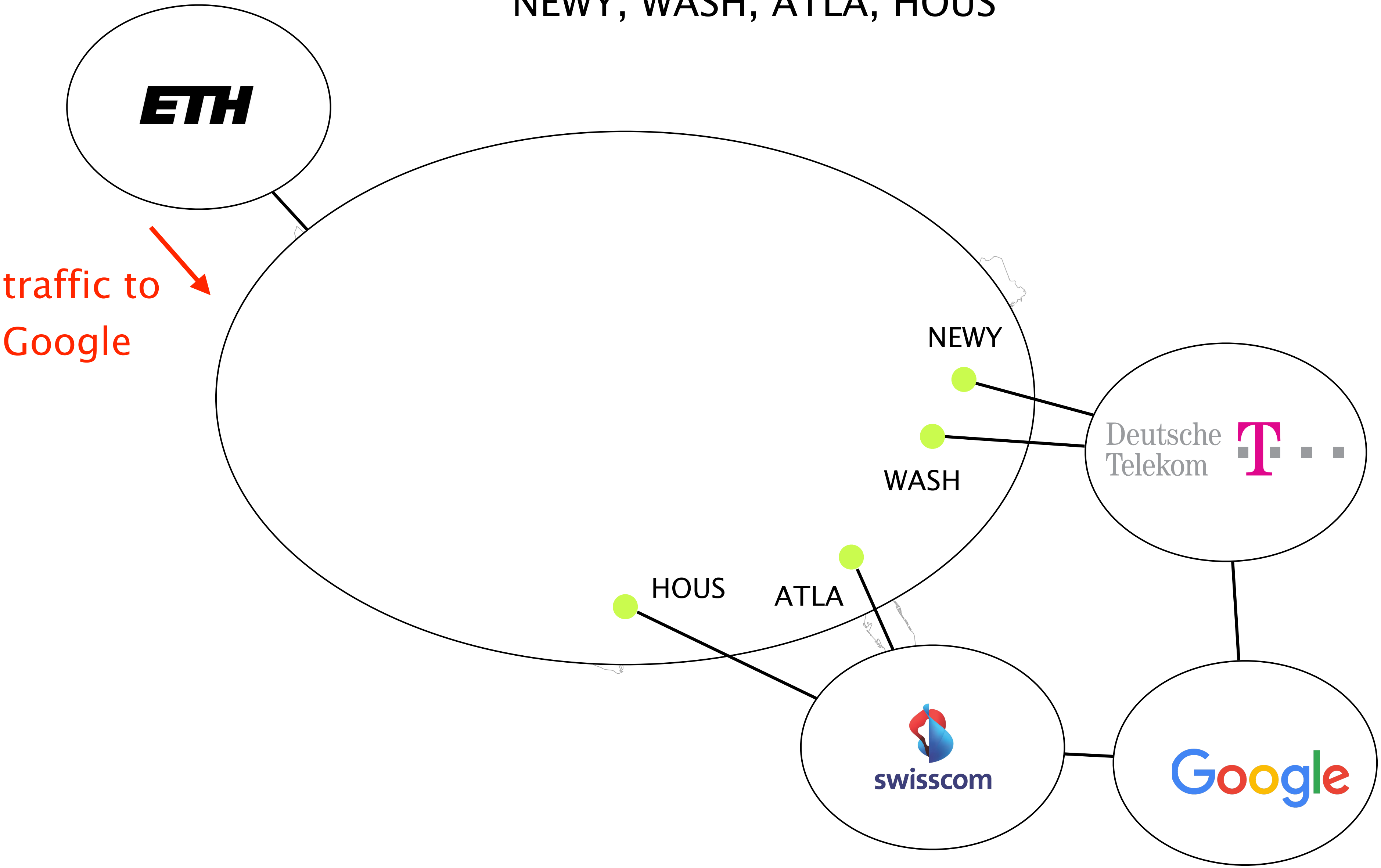
inter-domain
routing

intra-domain
routing

Find paths between networks


ETH
traffic to Google
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

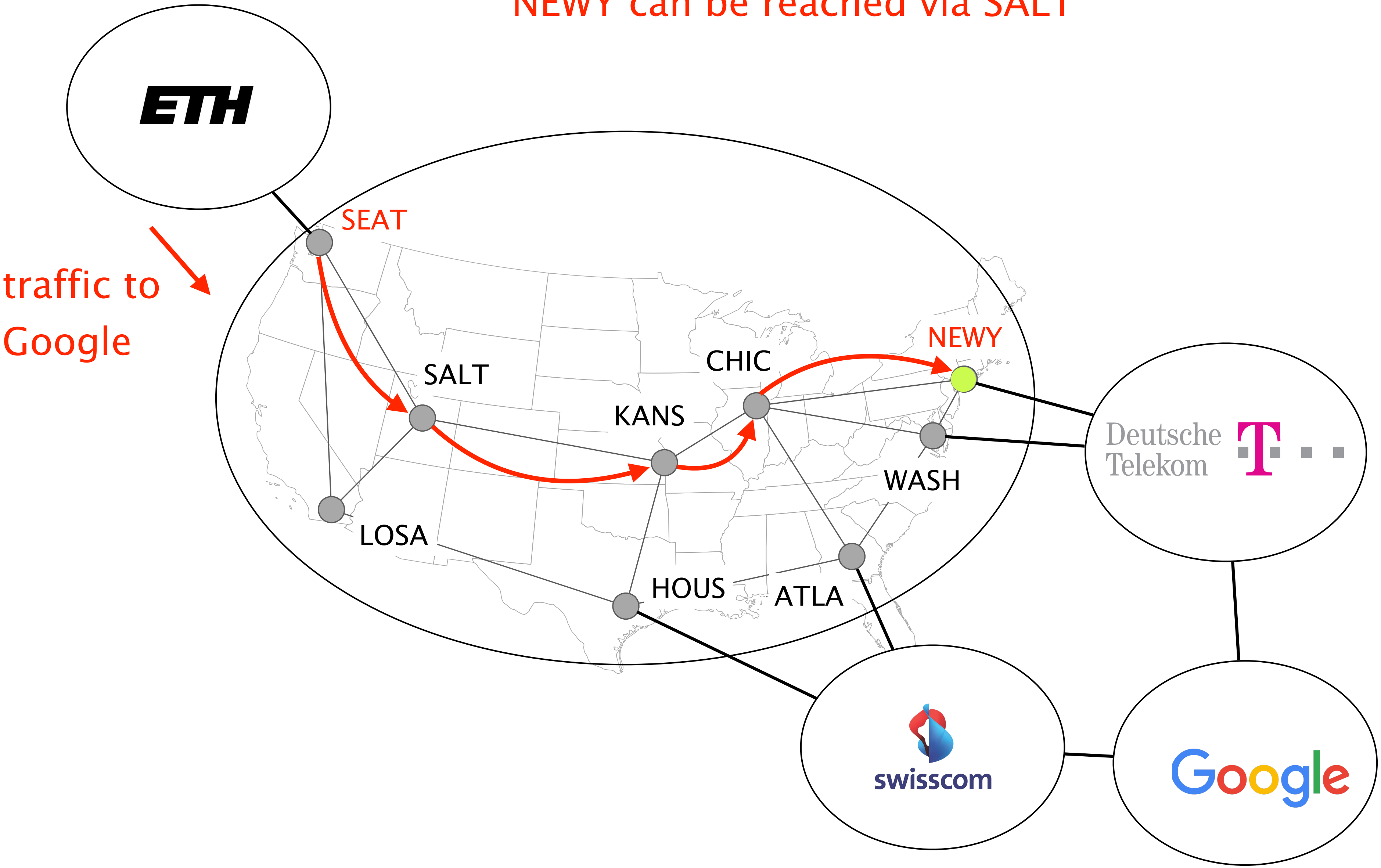
based on money, performance, …

inter-domain
routing

intra-domain
routing

Find paths within a network

NEWY can be reached via SALT



› 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

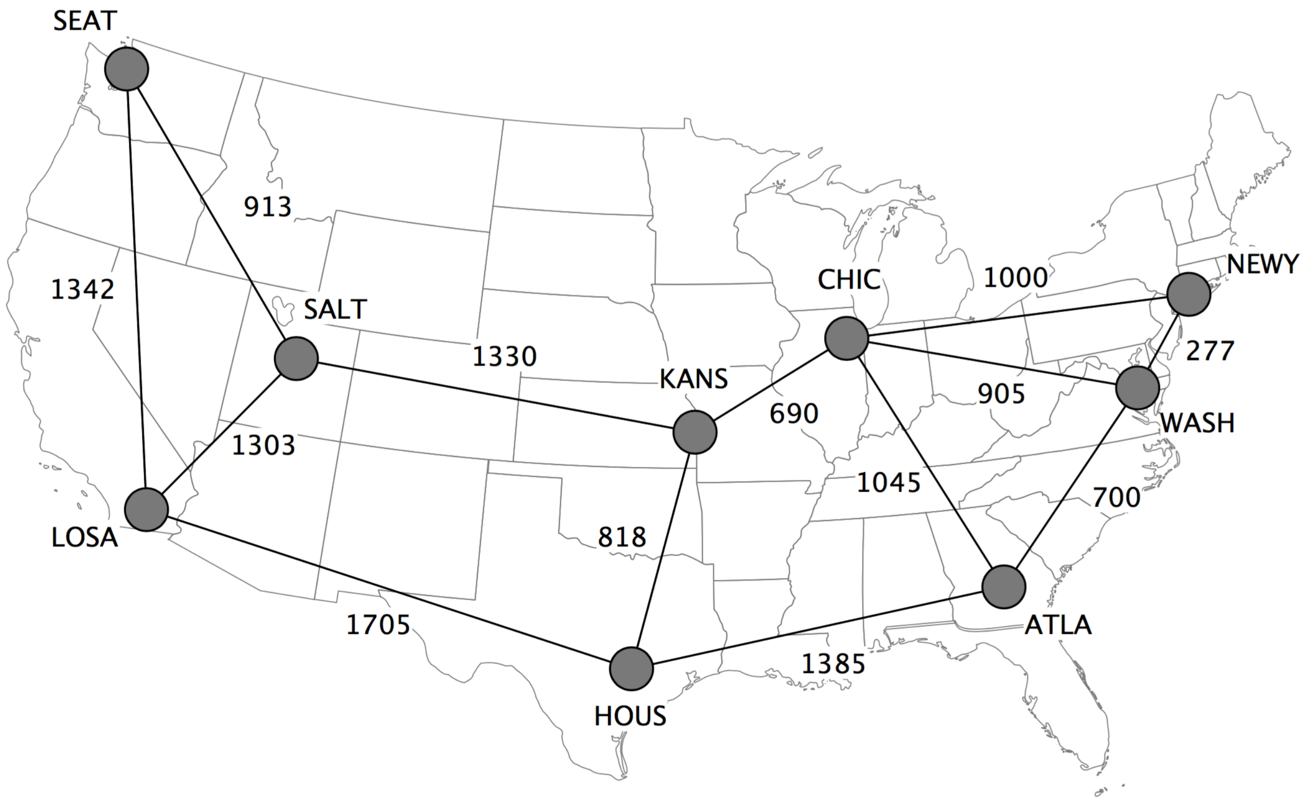
A good path is a path that minimizes some network-wide metric

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 inversely proportionally to each link capacity, throughput is maximized

How do routers compute shortest-paths?

#1	Use tree-like topologies	Spanning-tree
#2	Rely on a global network view	Link-State SDN
#3	Rely on distributed computation	Distance-Vector BGP

In practice tree-based forwarding is only used within a LAN

advantages	disadvantages
plug-and-play	mandate a spanning-tree
configuration-free	eliminate many links from the topology
automatically adapts to moving host	slow to react to failures host movement

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

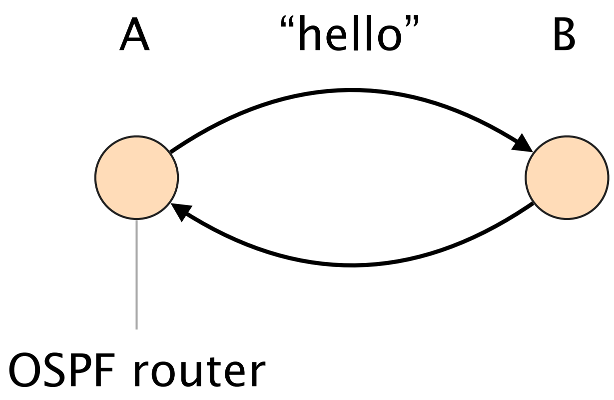
time-to-live for each link-state

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

control-plane consistency

all nodes have the same link-state database

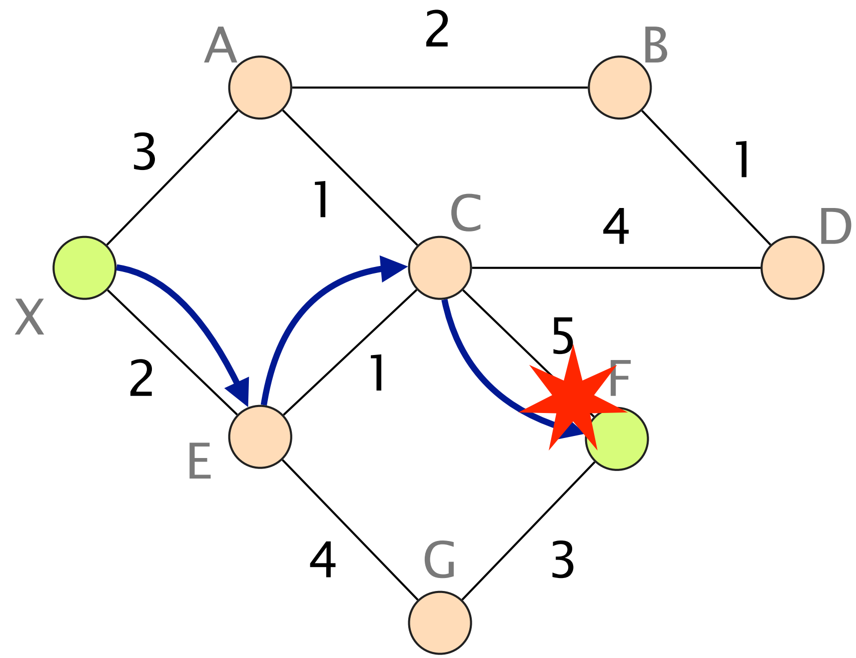
necessary

forwarding validity

the global forwarding state directs packet to its destination

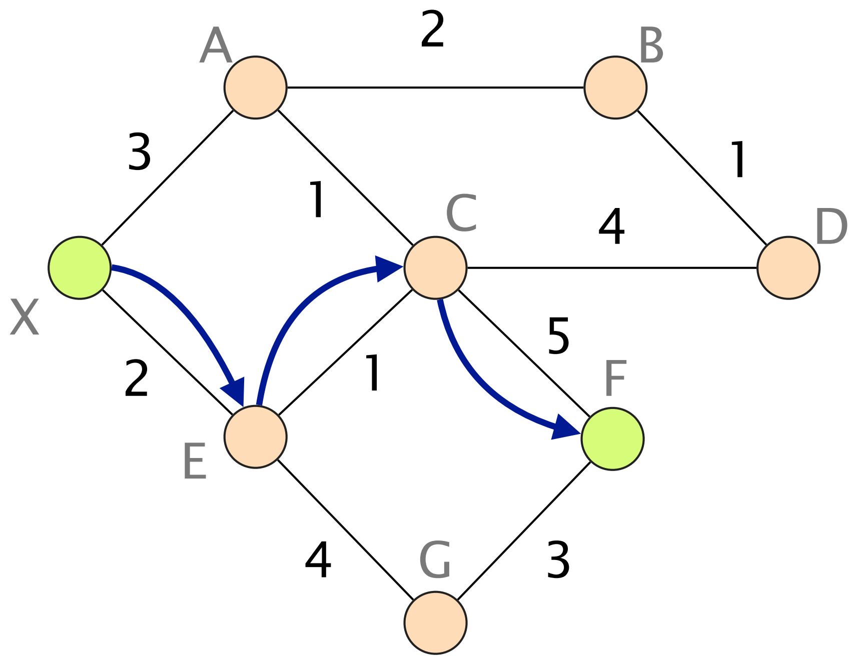
Inconsistencies lead to transient disruptions
in the form of blackholes or forwarding loops

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

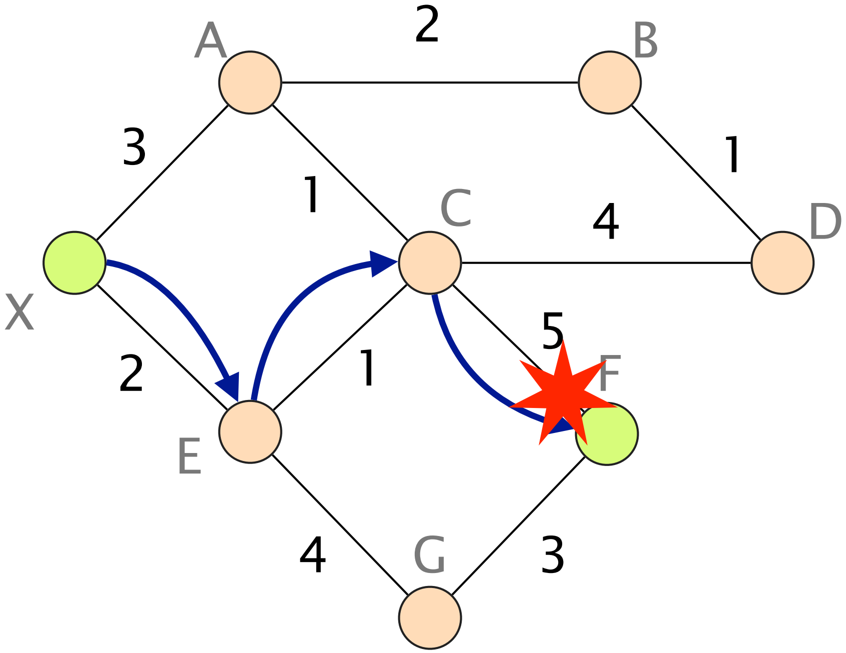


depends on the timeout for detecting lost hellos

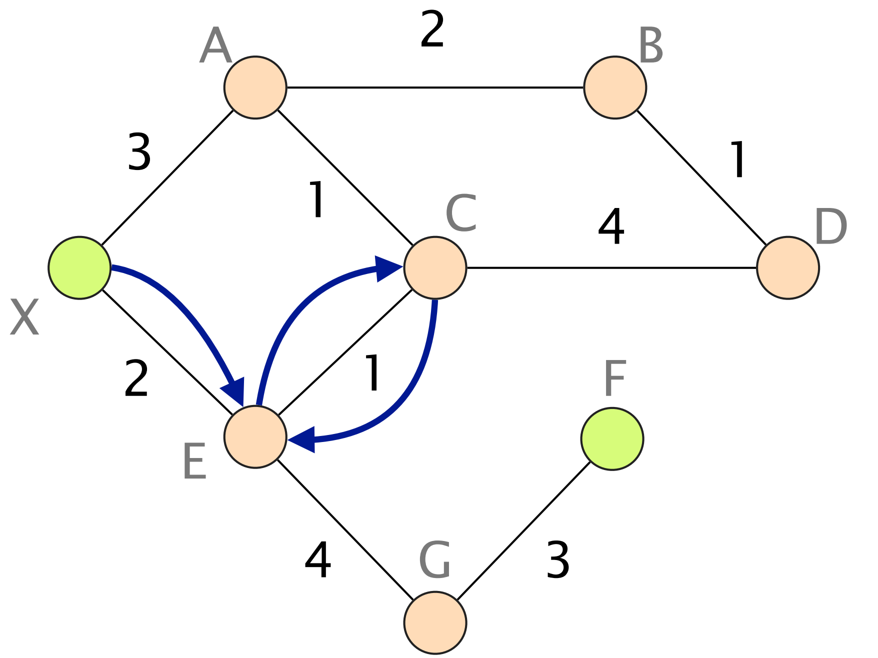
Transient loops appear due to inconsistent link-state databases



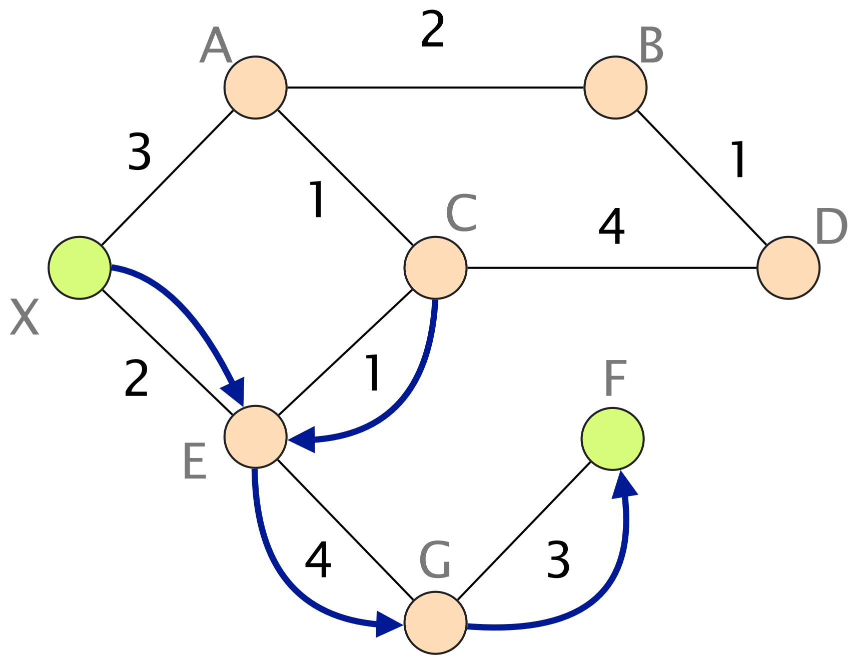
Initial forwarding state



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

Network convergence time depends on 4 main factors

factors	time the routers take for…
detection	realizing that a link or a neighbor is down
flooding	flooding the news to the entire network
computation	recomputing shortest-paths using Dijkstra
table update	updating their forwarding table

In practice, network convergence time is mostly driven by table updates

	time	improvements
detection	few ms	smaller timers
flooding	few ms	high-priority flooding
computation	few ms	incremental algorithms
table update	potentially, *minutes!*	better table design

Today, two Link-State protocols are widely used:

OSPF and IS-IS

OSPF

IS-IS

Open Shortest Path First

Intermediate Systems^2

OSPF	IS-IS
Open Shortest Path First	Intermediate Systems^2

used in many enterprise & ISPs

work on top of IP

only route IPv4 by default

OSPF

IS-IS

Open Shortest Path First

Intermediate Systems^2

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

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

until convergence

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:

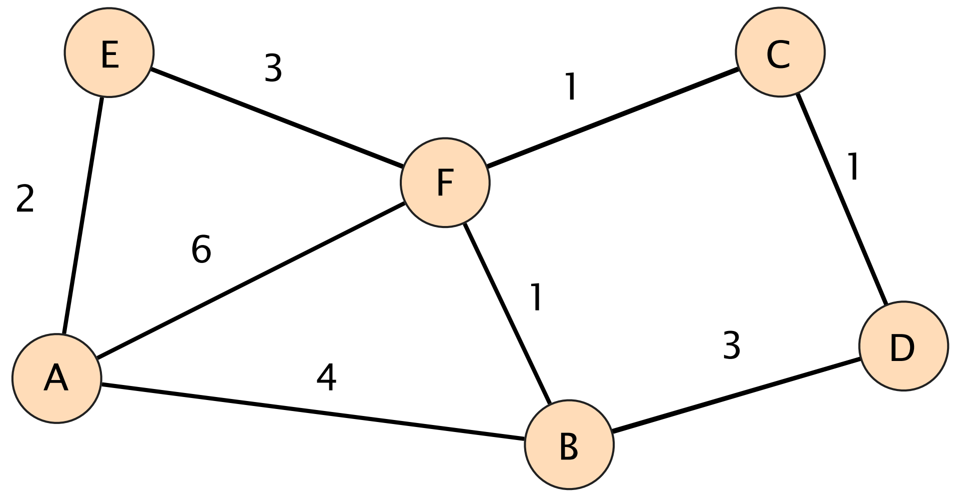
$d_x(y) = \min\{ c(x,v) + d_v(y) \}$ over all neighbors v

Over time, $d_x(y)$ converges to

the shortest-path distances and next-hops

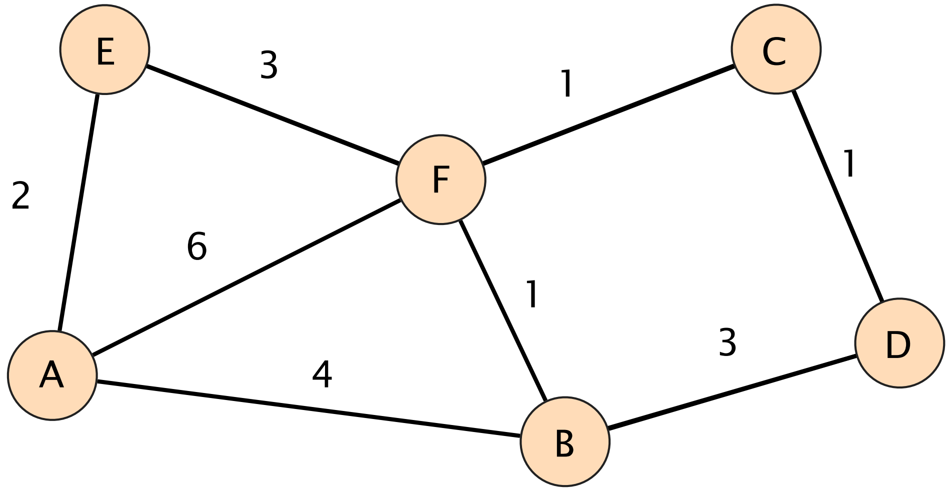
Similarly to Link-State,
3 situations cause nodes to send new DVs

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

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

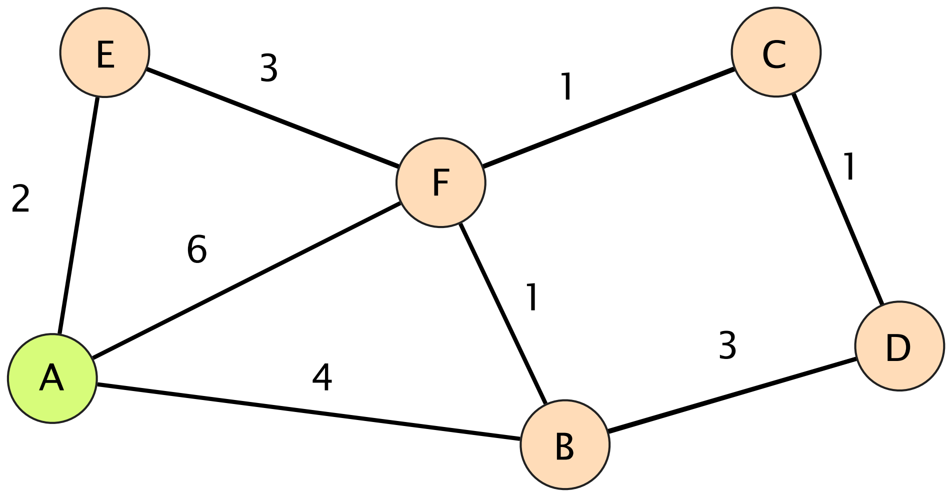


C			D			E			F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	∞	–	A	∞	–	A	2	A	A	6	A
B	∞	–	B	3	B	B	∞	–	B	1	B
C	0	C	C	1	C	C	∞	–	C	1	C
D	1	D	D	0	D	D	∞	–	D	∞	–
E	∞	–	E	∞	–	E	0	E	E	3	E
F	1	F	F	∞	–	F	3	F	F	0	F

Optimum 1-hop path

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

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



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

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

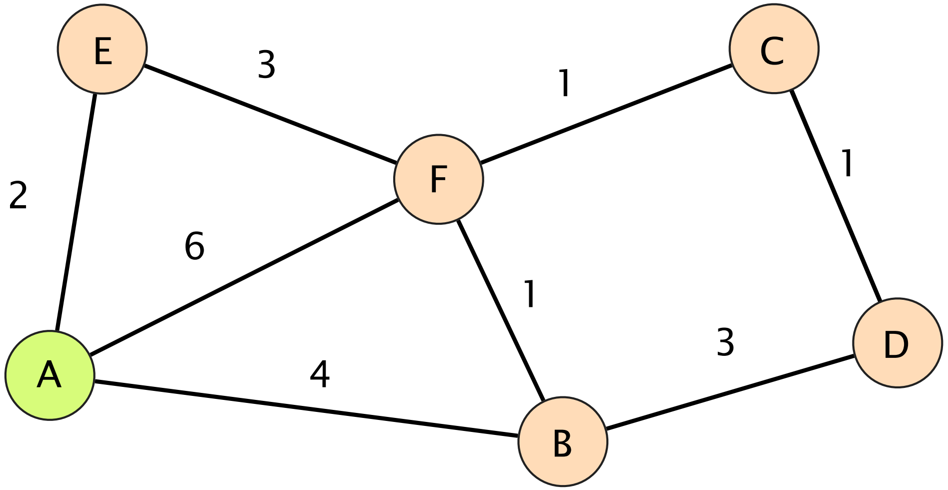
E		
Dst	Cst	Hop
A	2	A
B	∞	–
C	∞	–
D	∞	–
E	0	E
F	3	F

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

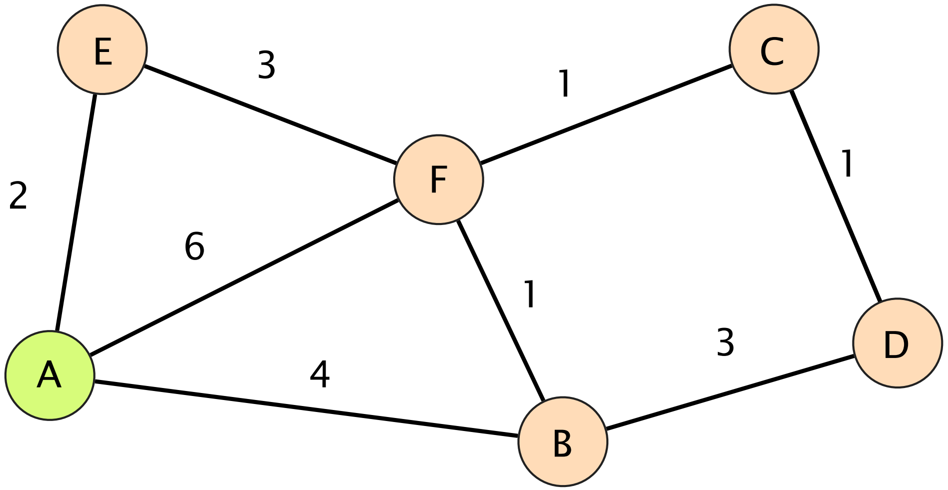
D		
Dst	Cst	Hop
A	7	B
B	3	B
C	1	C
D	0	D
E	∞	–
F	2	C

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

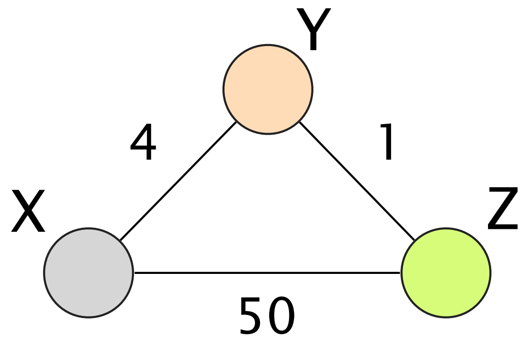
A			B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	6	E	C	2	F
D	7	F	D	3	D
E	2	E	E	4	F
F	5	E	F	1	F



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

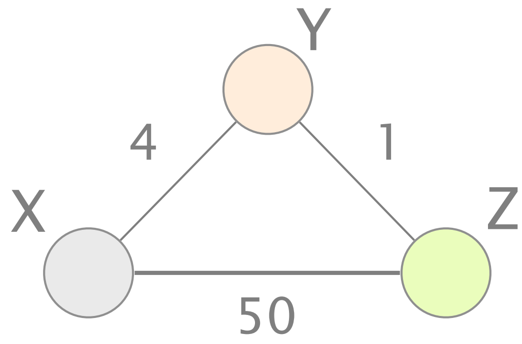
Let’s consider the convergence process
after a link cost change

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

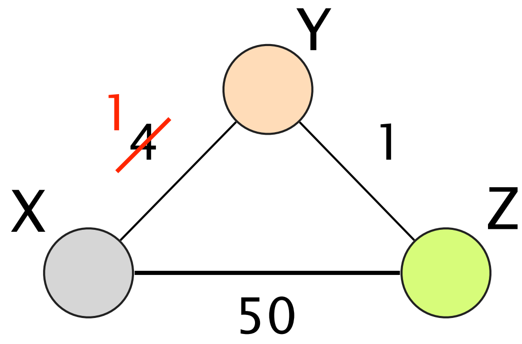
Z
vector

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

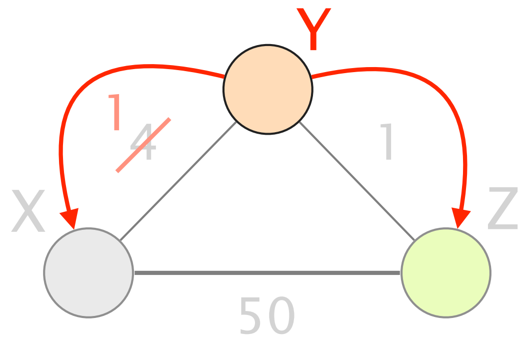
dest.	via *X*	via *Y*
X	50	5

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

t=1

Y vector

dest.	via X	via Z
X	4	6

dest.	via X	via Z
X	1	6

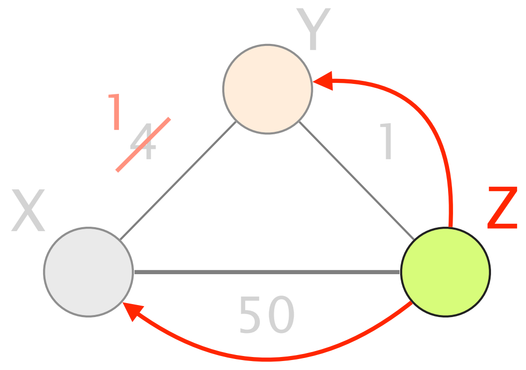
Z vector

dest.	via X	via Y
X	50	5

t = 2

Z updates its vector,

sends it to X and Y

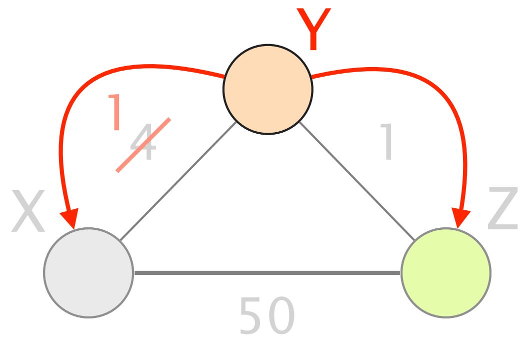


	t=0			t=1			t=2		
Y vector	dest.	via X	via Z	dest.	via X	via Z			
	X	4	6	*X*	1	6			
Z vector	dest.	via X	via Y				dest.	via X	via Y
	X	50	5				*X*	50	2

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	1	6

t=3

dest.	via X	via Z
X	1	3

Z vector

t=0

dest.	via X	via Y
X	50	5

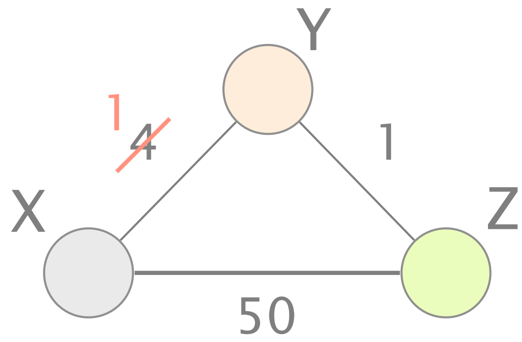
t=2

dest.	via X	via Y
X	50	2

t > 3

no one moves anymore

network has converged!



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!

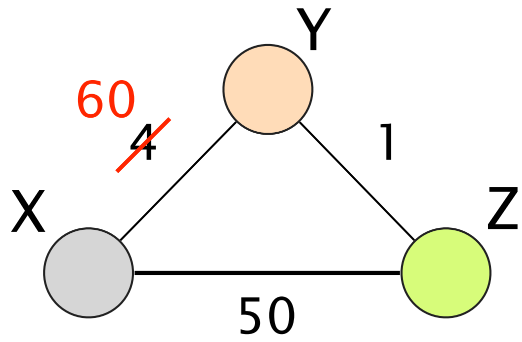
Good news travel fast!

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

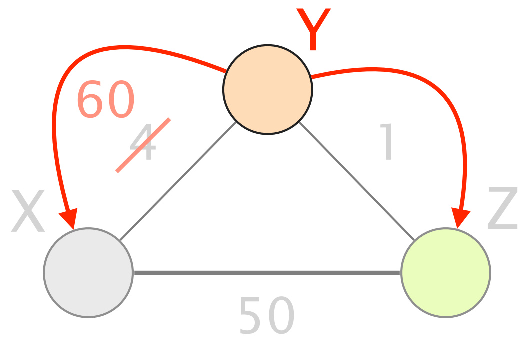
Z vector

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

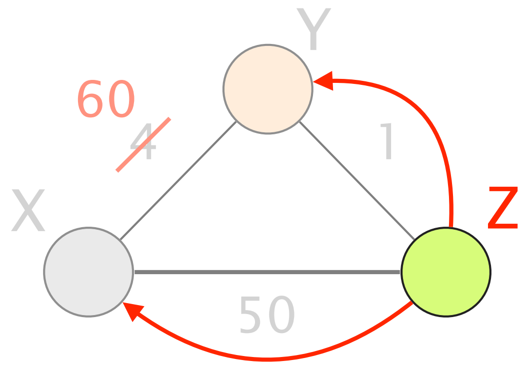
Y vector

dest.	via X	via Z
X	60	6

t = 2

Z updates its vector,

sends it to X and Y



t=0

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

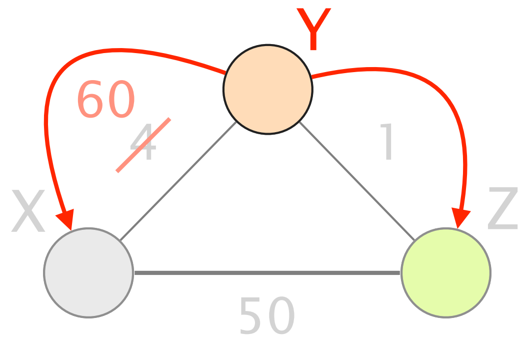
Z vector

dest.	via X	via Y
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

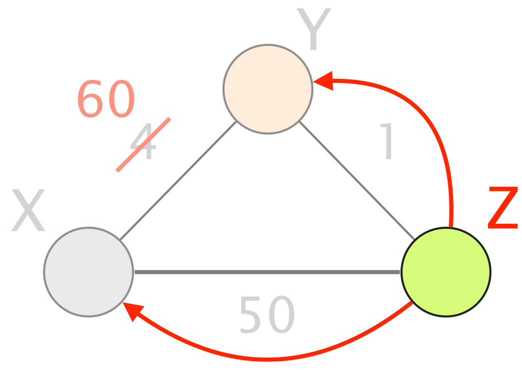
t=2

dest.	via X	via Y
X	50	7

t = 4

Z updates its vector,

sends it to X and Y…

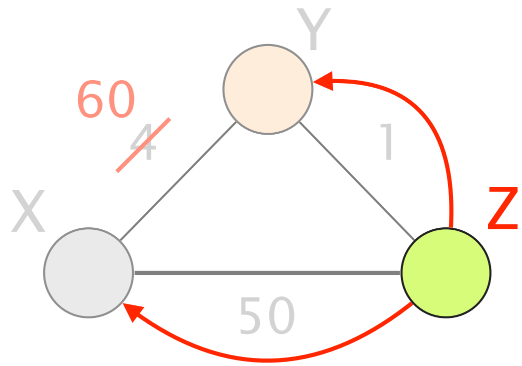


t=4

Y
vector

Z
vector

dest.	via *X*	via *Y*
X	50	9



t=4

t=44

… many iterations later …

Y vector (t=44)

dest.	via X	via Z
X	60	51

Z vector (t=4)

dest.	via X	via Y
X	50	9

Z vector (t=44)

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

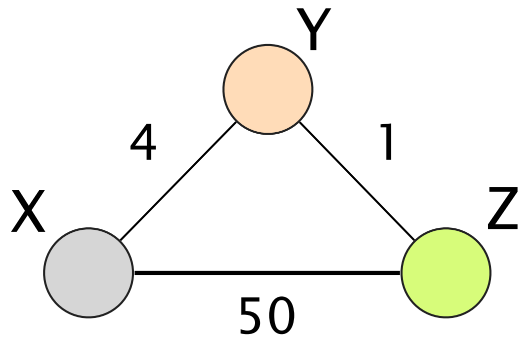
Z does not know that Y has switched to use it

Let's 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

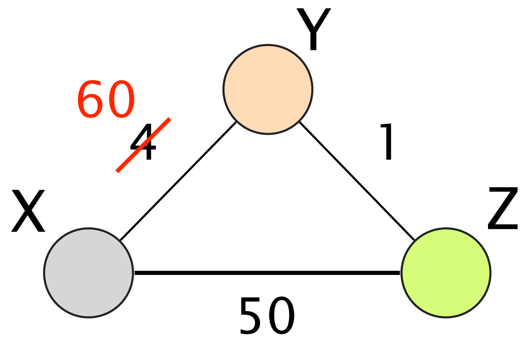
Z
vector

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	∞

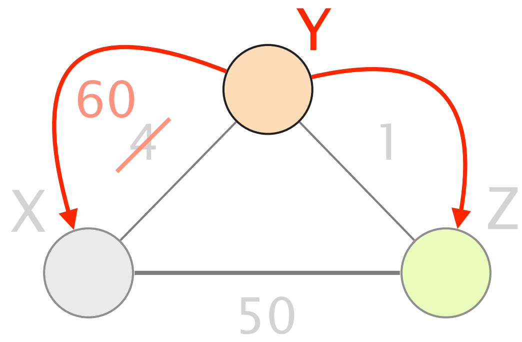
Z vector

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	∞

t=1

dest.	via X	via Z
X	60	∞

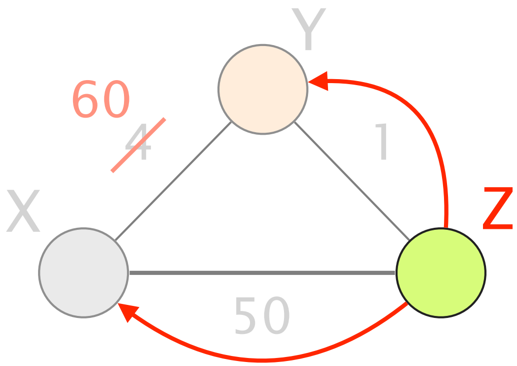
Z vector

dest.	via X	via Y
X	50	5

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

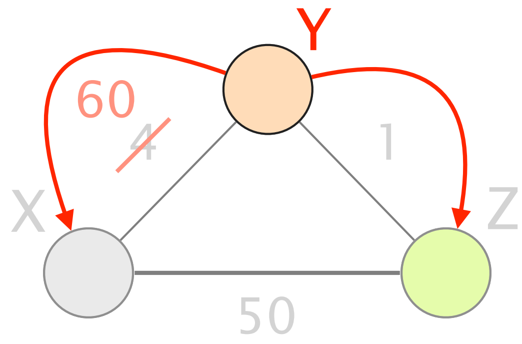
t=2:

dest.	via X	via Y
X	50	61

t = 3

Y updates its vector,

sends it to X and Z



t=0

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 vector

dest.	via X	via Y
X	50	61

t=3

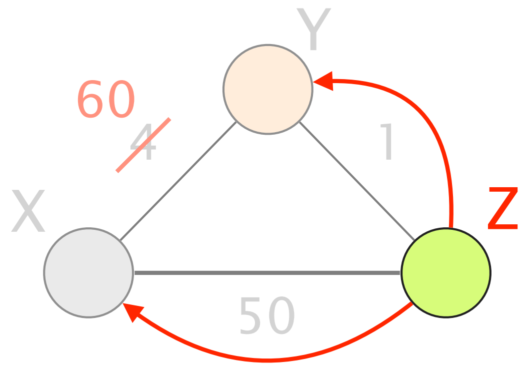
Y vector

dest.	via X	via Z
X	60	51

t = 4

Z updates its vector,

sends it to X and Y



t=4

Y
vector

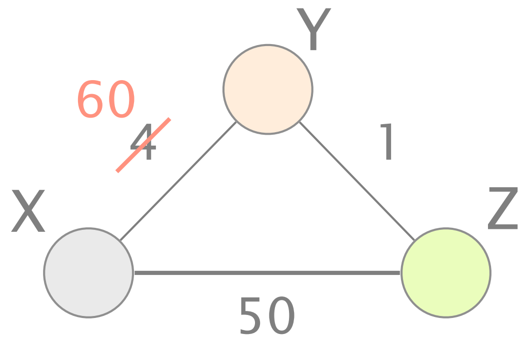
Z
vector

dest.	via X	via Y
X	50	∞

t > 4

no one moves

network has converged!



t=4 | t>4

Y vector

t>4:

dest.	via *X*	via *Z*
X	60	51

Z vector

t=4:

dest.	via *X*	via *Y*
X	50	∞

t>4:

dest.	via *X*	via *Y*
X	50	∞

While poisoned reverse solved this case,

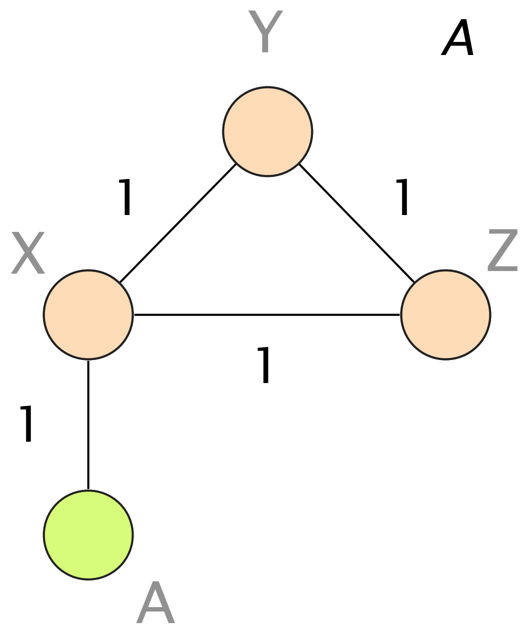
it does not solve loops involving 3 or more nodes…

Your turn!

Consider the following network

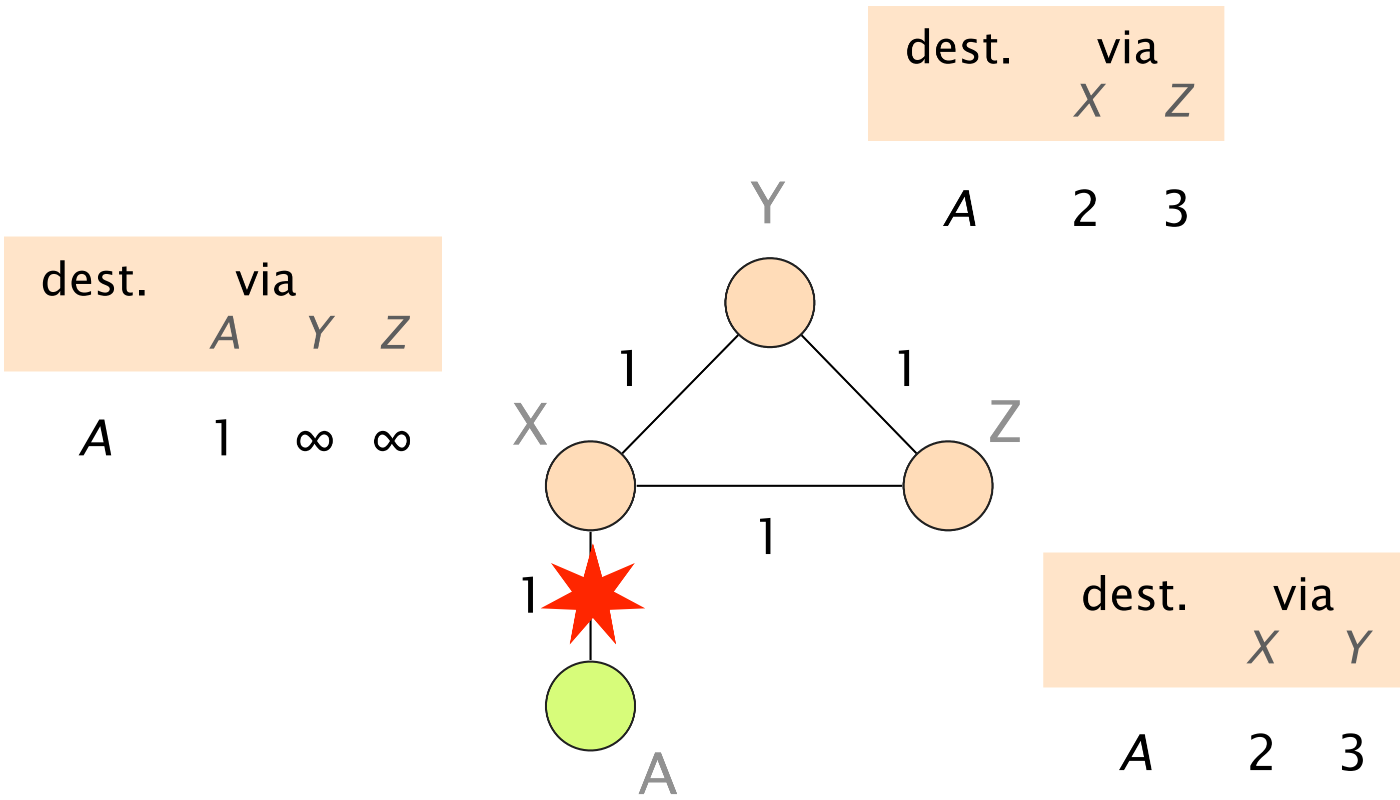
dest.	via X	via Z
A	2	3

dest.	via A	via Y	via Z
A	1	∞	∞



dest.	via X	via Y
A	2	3

What happens if link (X,A) fails?



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

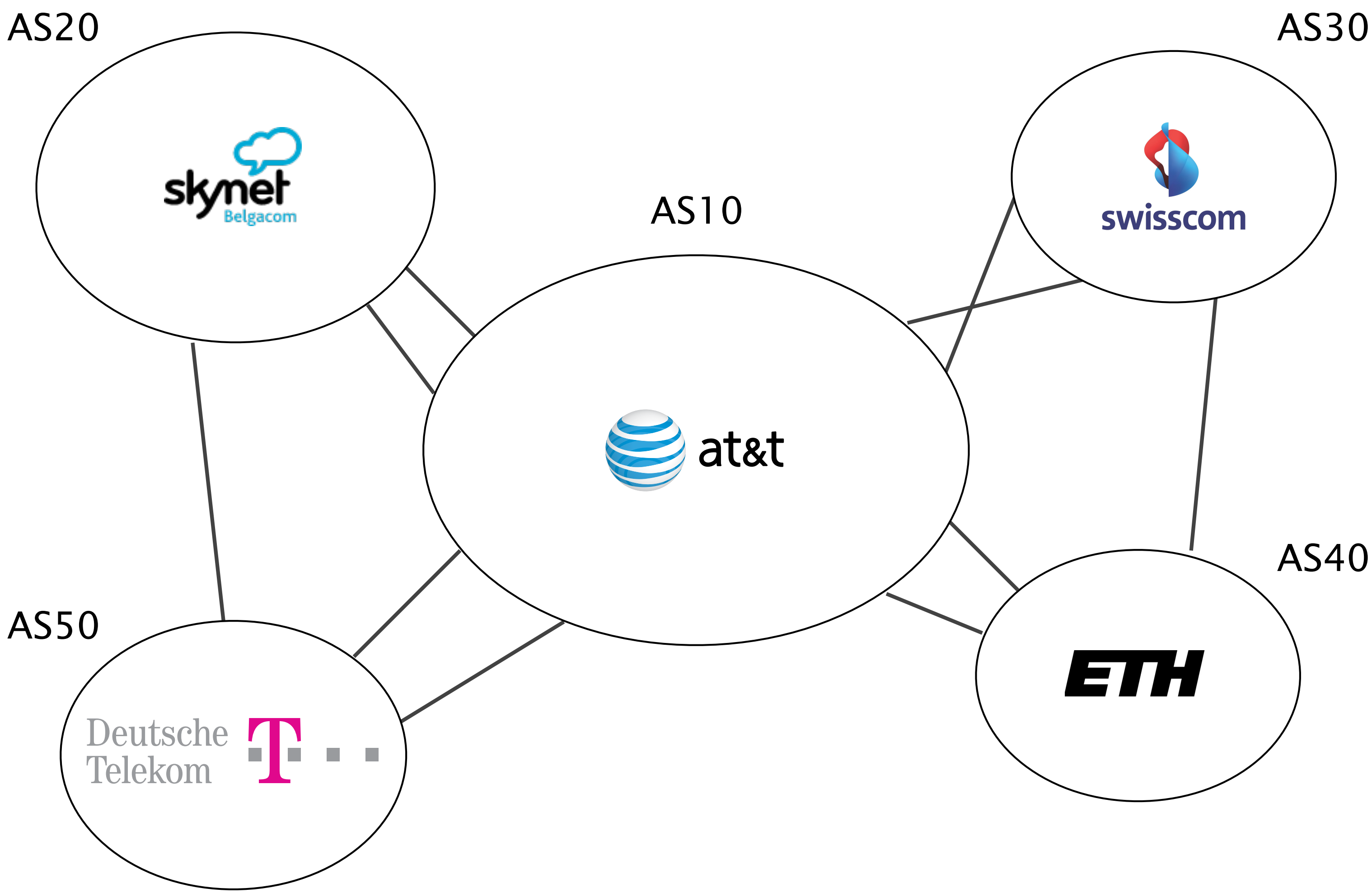
Internet

A network of *networks*

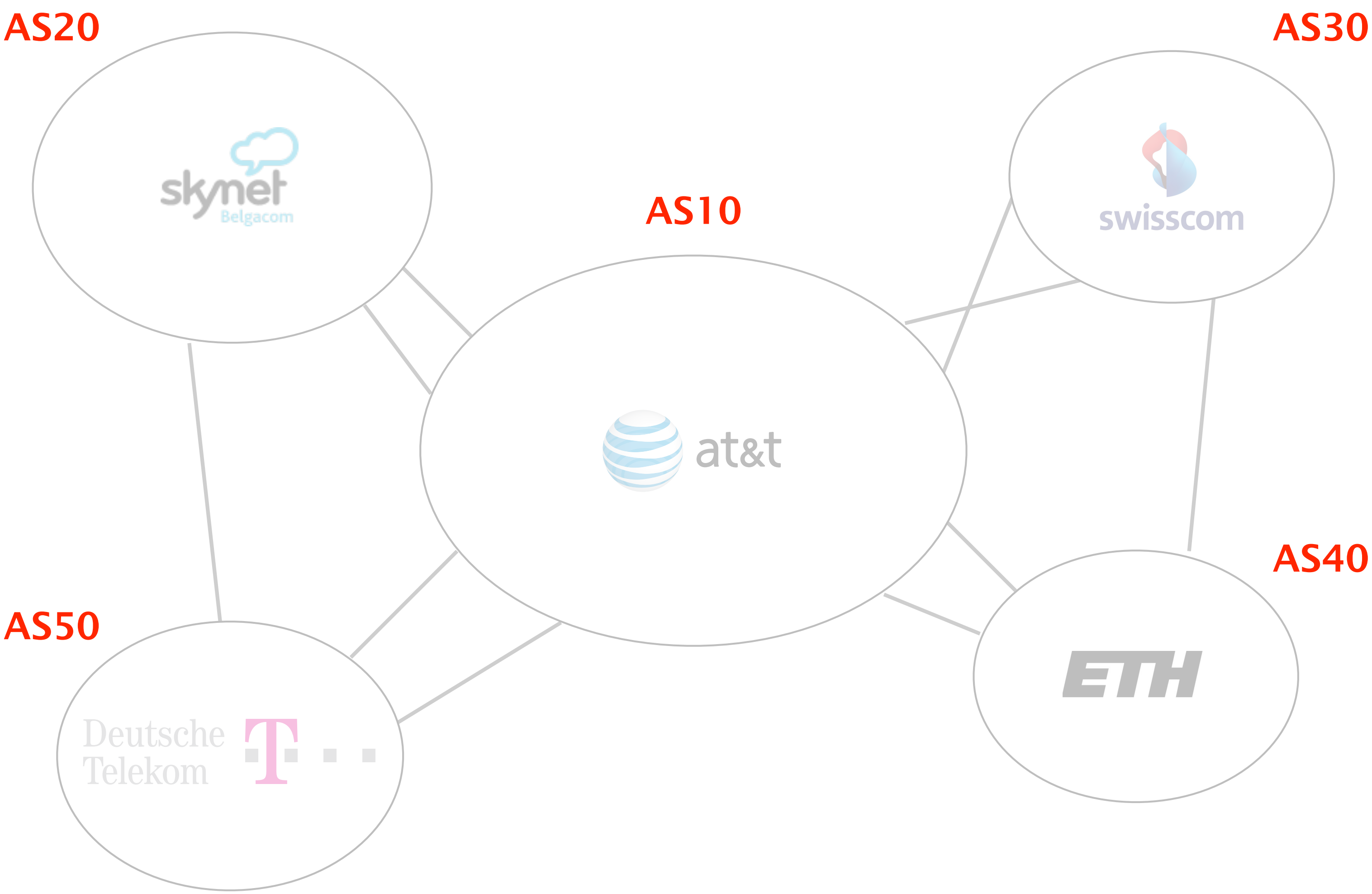
Internet

Border Gateway Protocol (BGP)

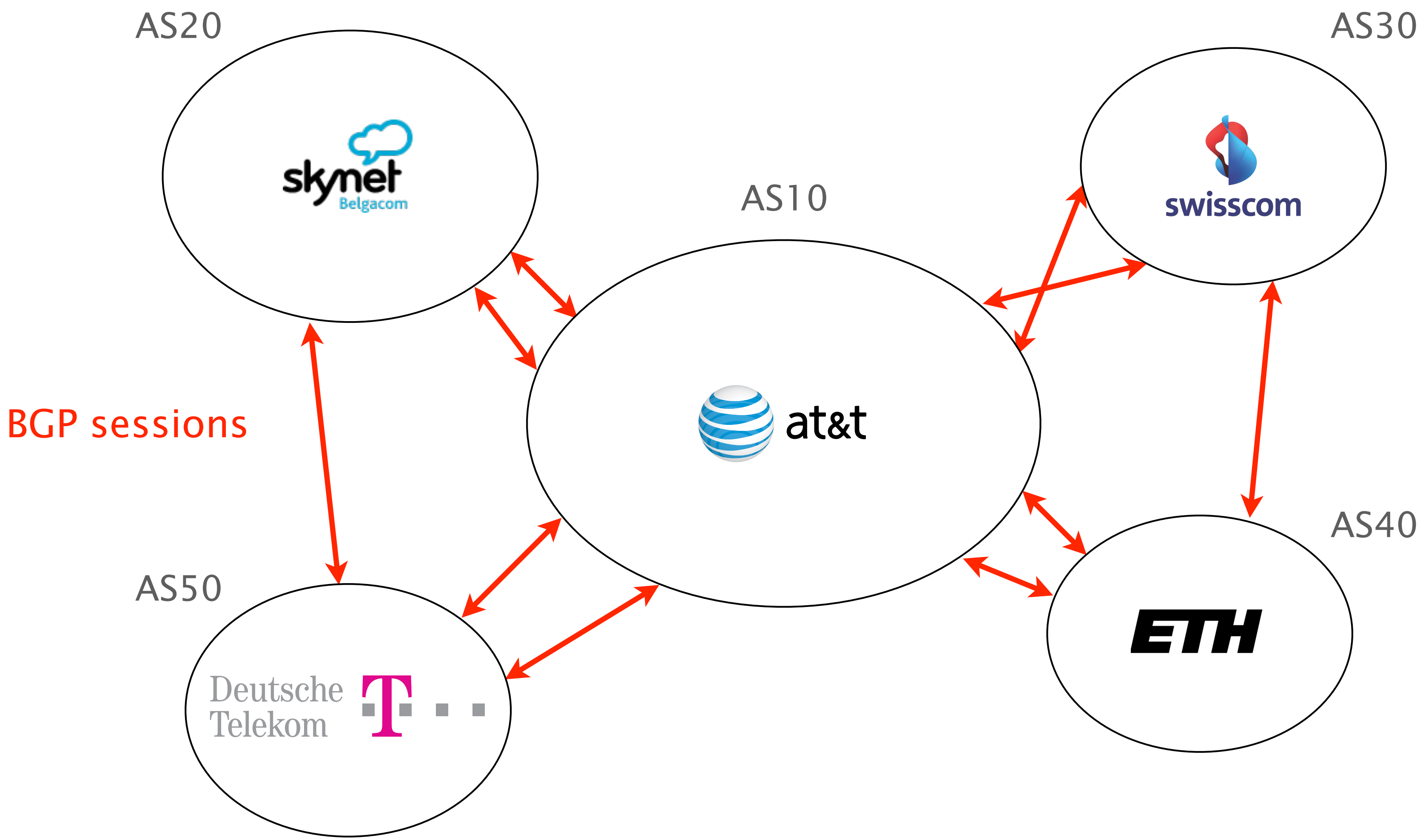
The Internet is a network of networks, referred to as Autonomous Systems (AS)



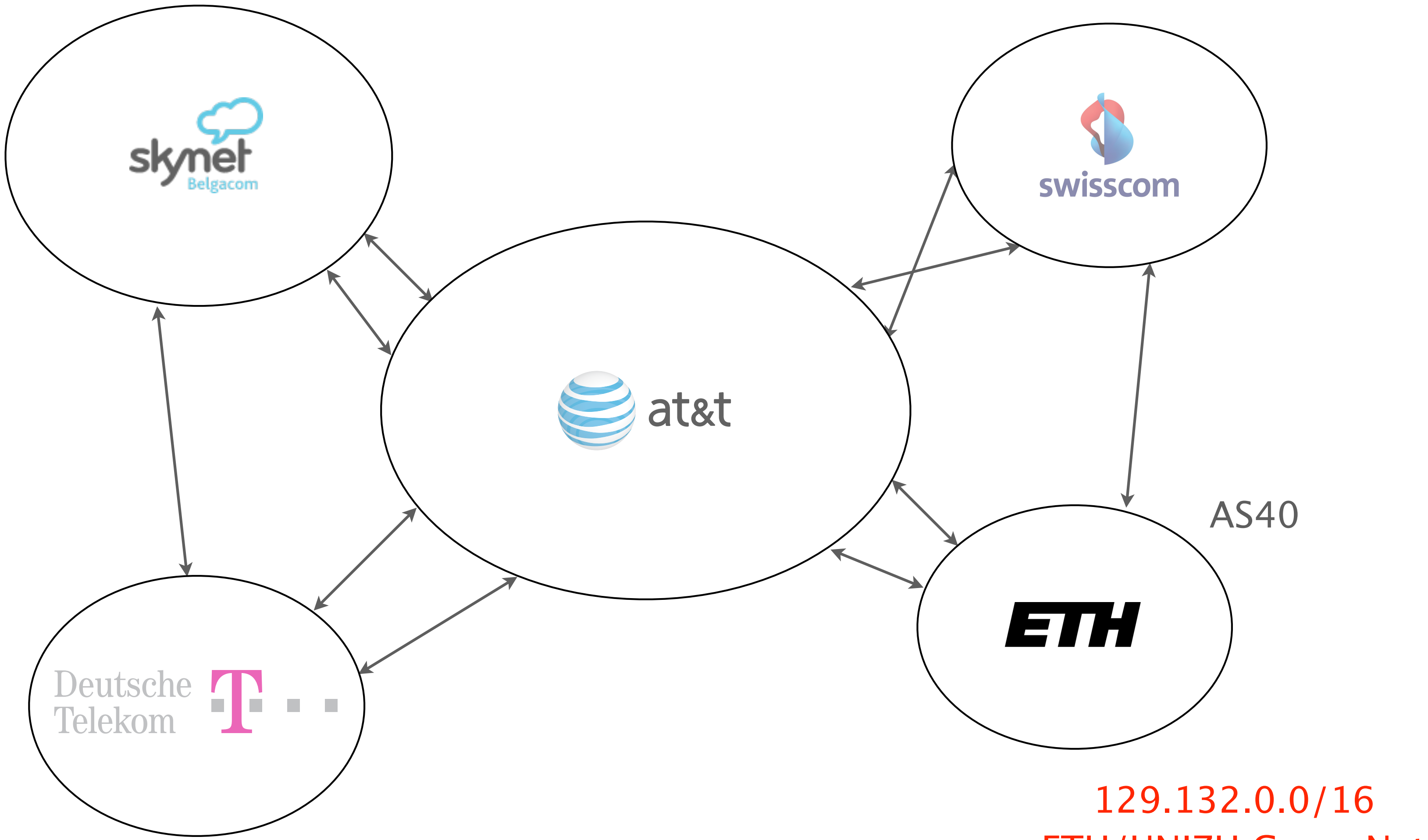
Each AS has a number (encoded on 16 bits) which identifies it



BGP is the routing protocol "glueing" the 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

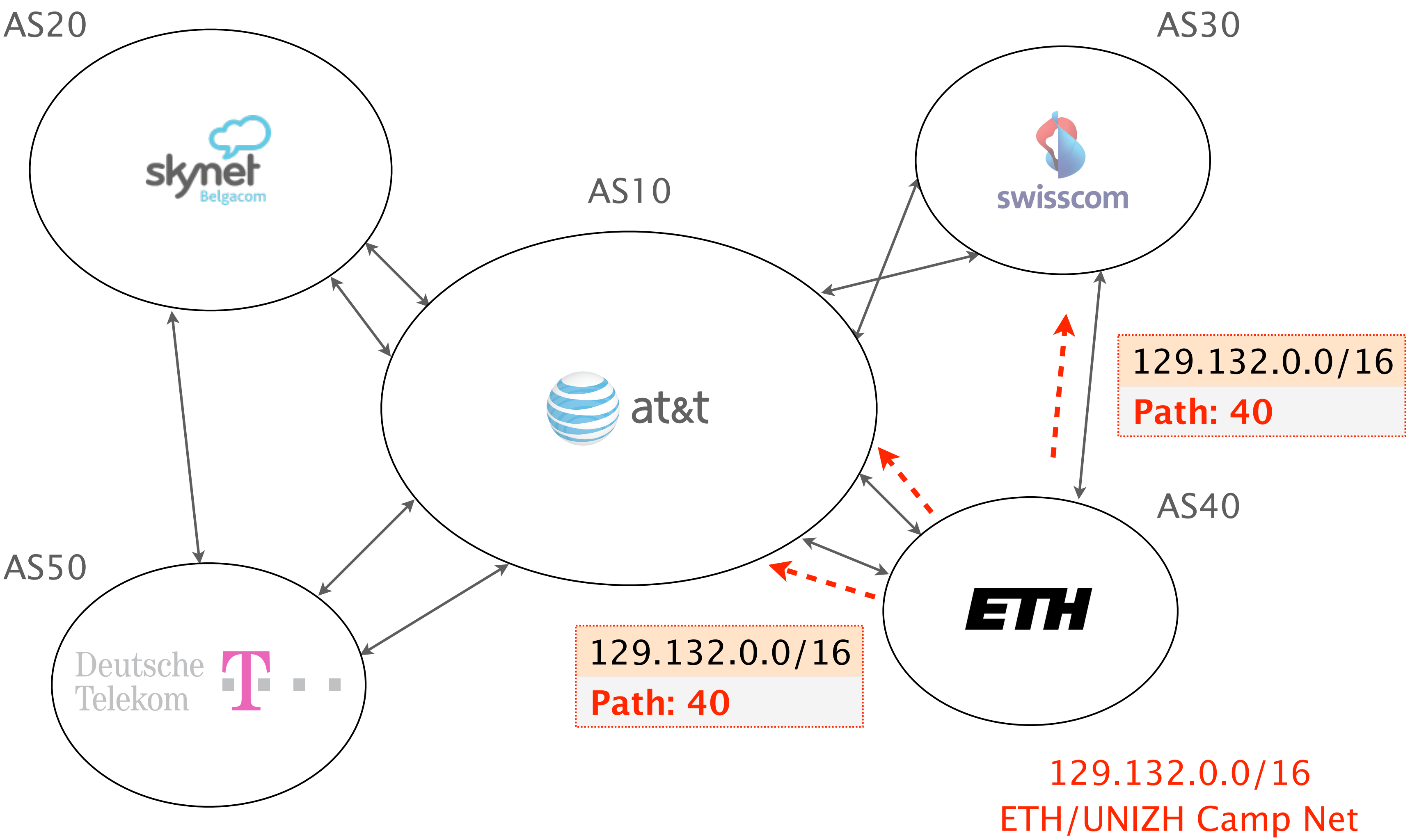
It converges slowly

counting-to-infinity problem

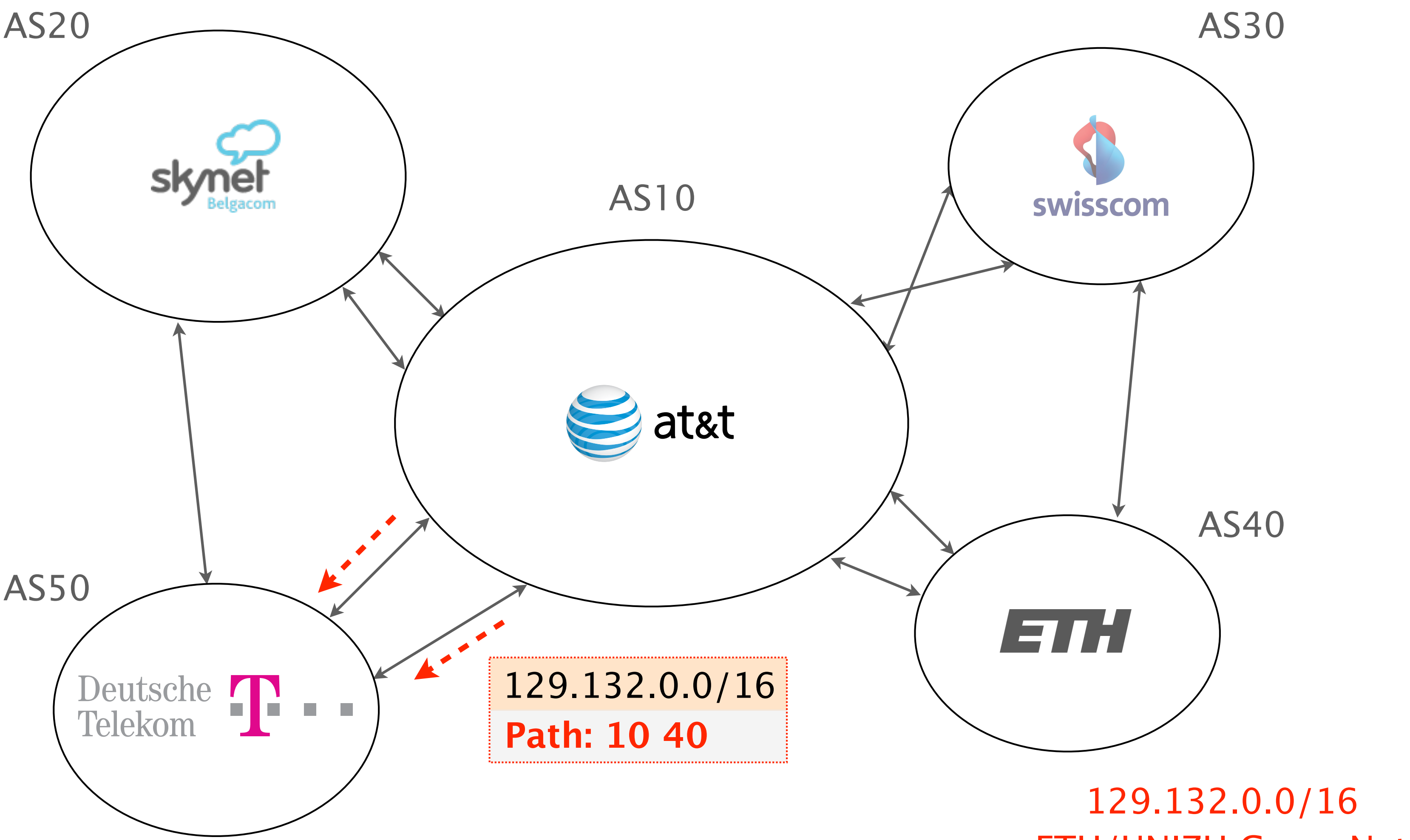
BGP relies on path-vector routing to support flexible routing policies and avoid count-to-infinity

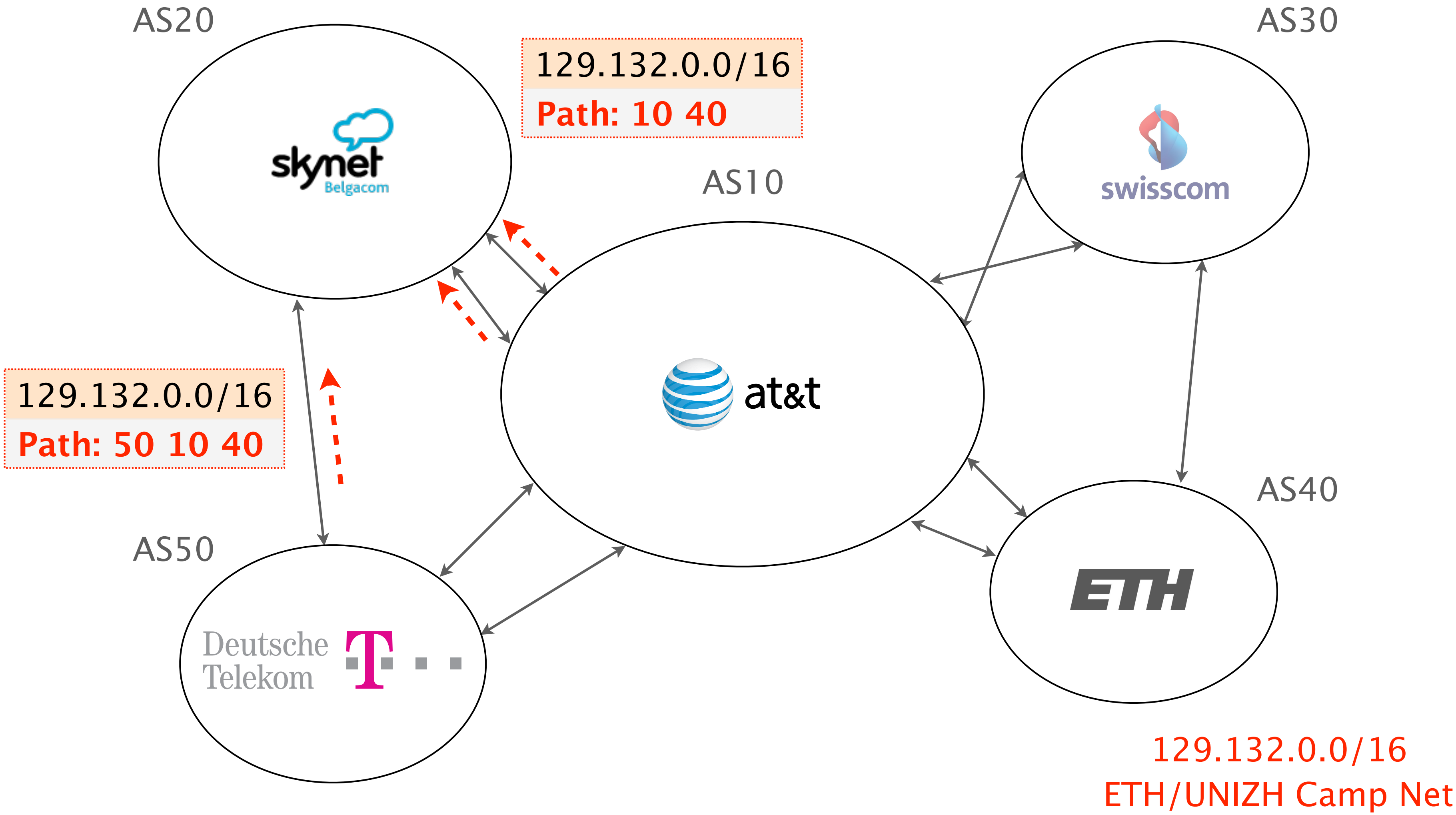
key idea advertise the entire path instead of distances

BGP announcements carry complete path information instead of distances



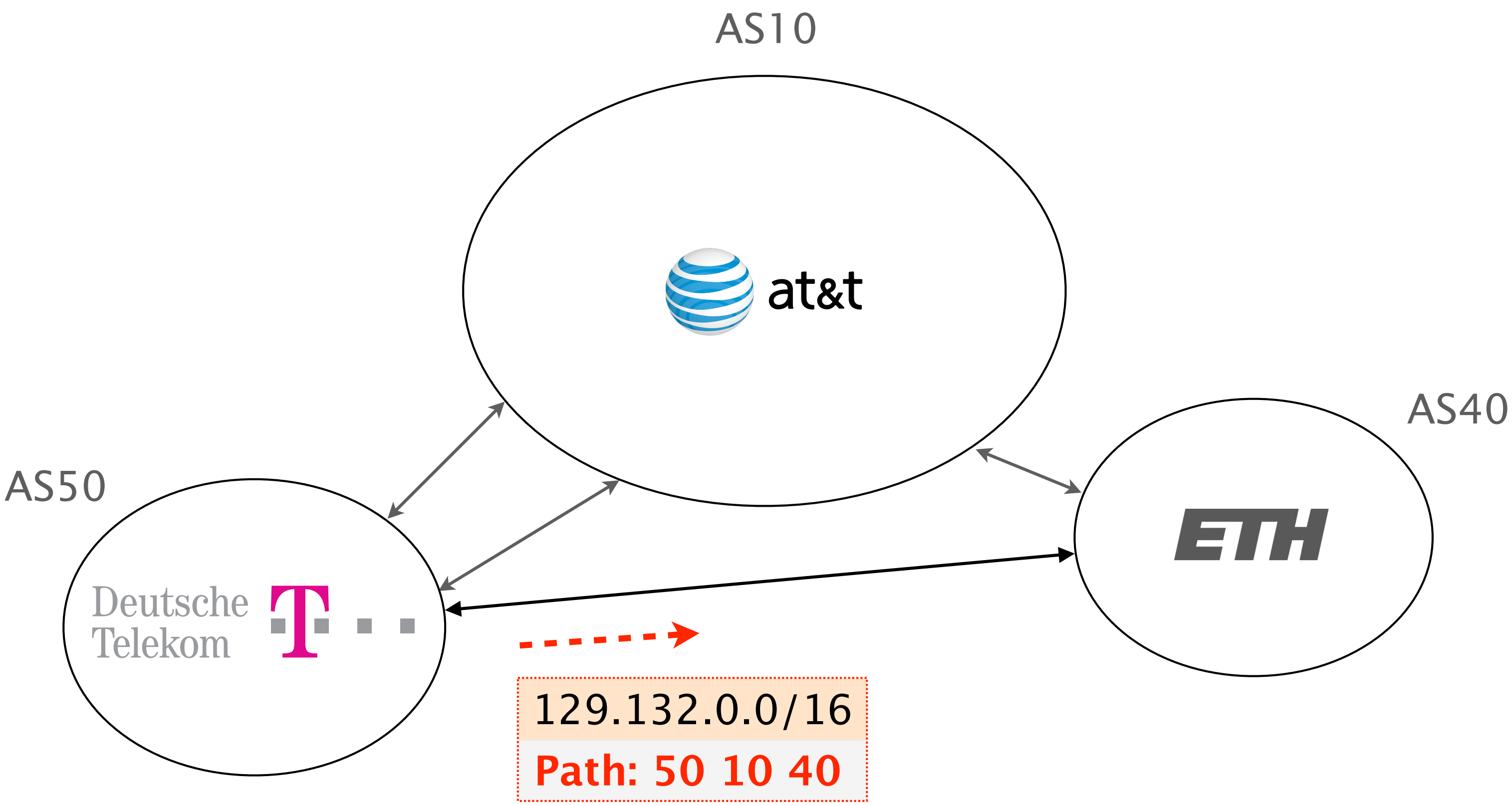
Each AS appends itself to the path when it propagates announcements




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

Complete path information enables ASes to easily detect a loop

ETH sees itself in the path and discard the route



Life of a BGP router is made of three consecutive steps

while true:

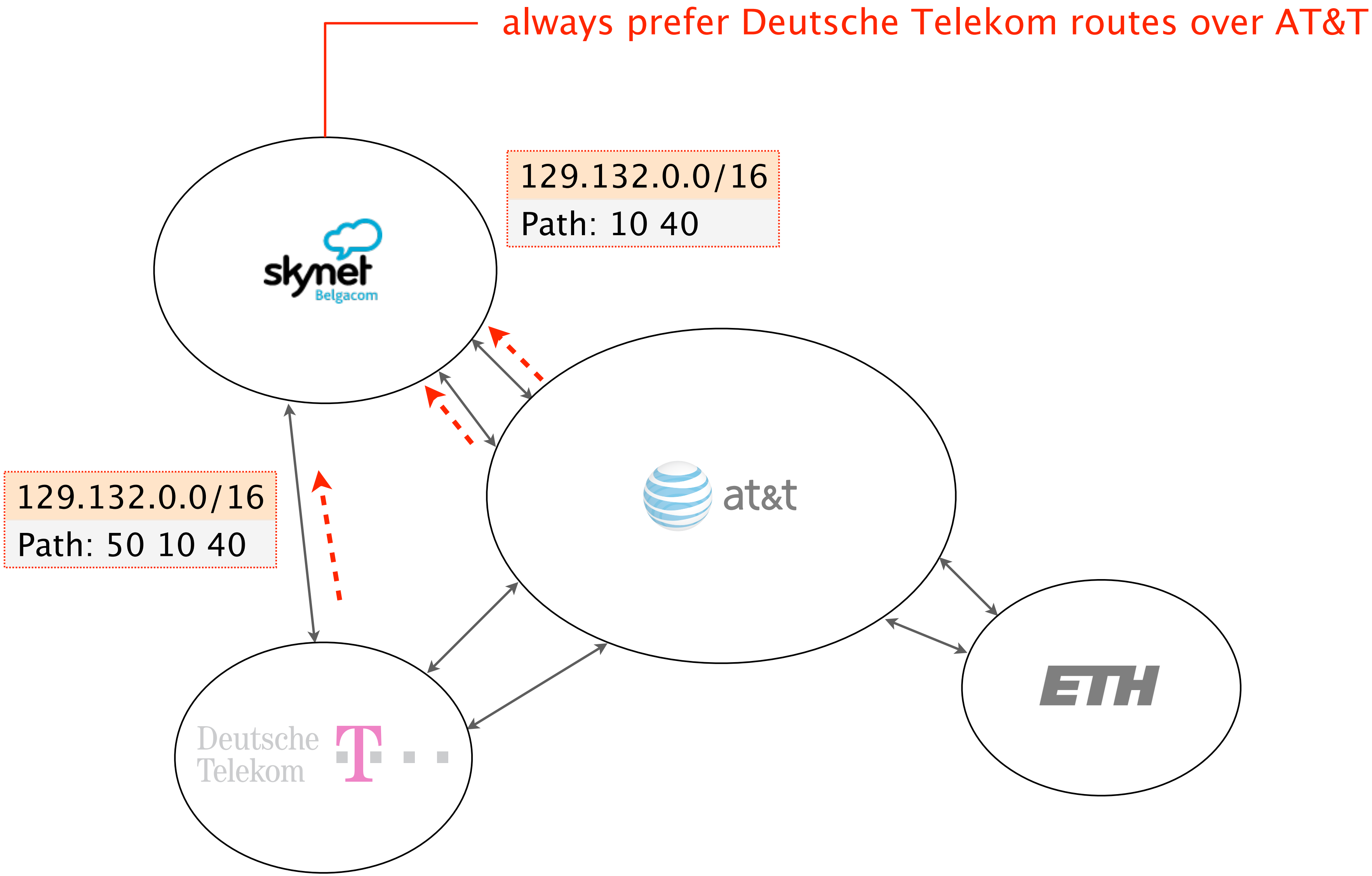
- receives routes from my neighbors
- select one best route for each prefix
- export the best route to my neighbors

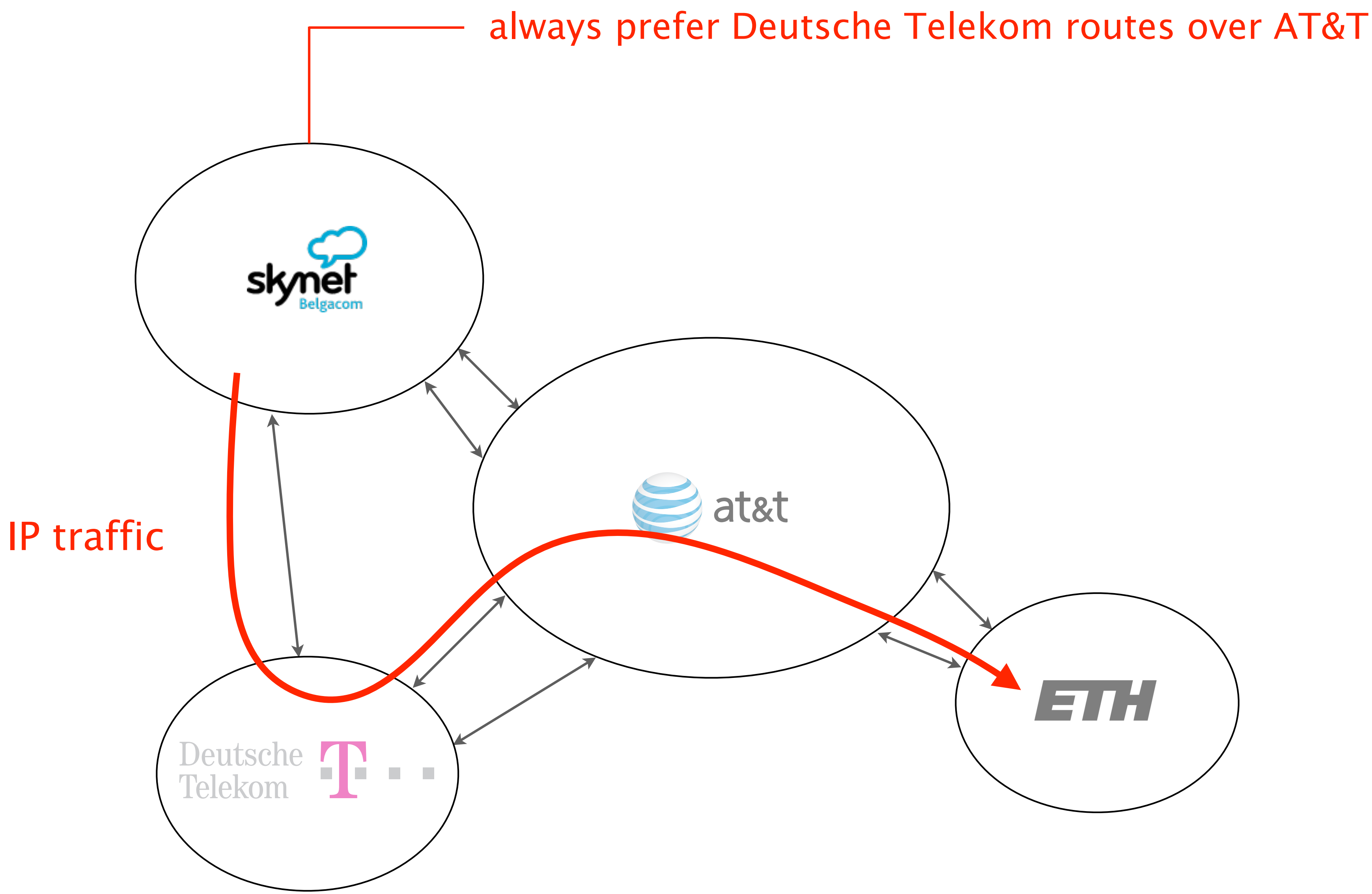
Each AS can apply local routing policies

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
IP traffic

Each AS can apply local routing policies

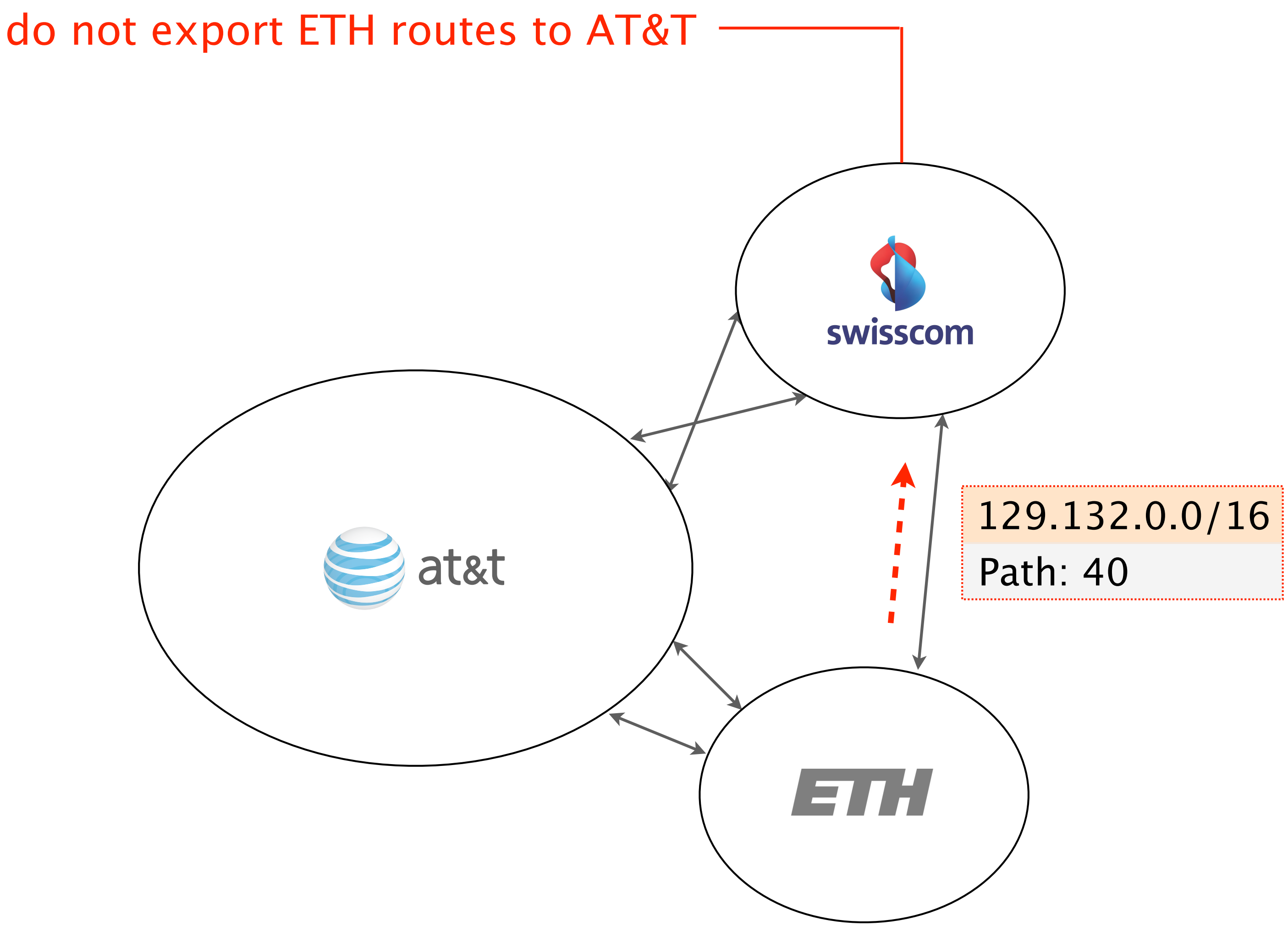
Each AS is free to

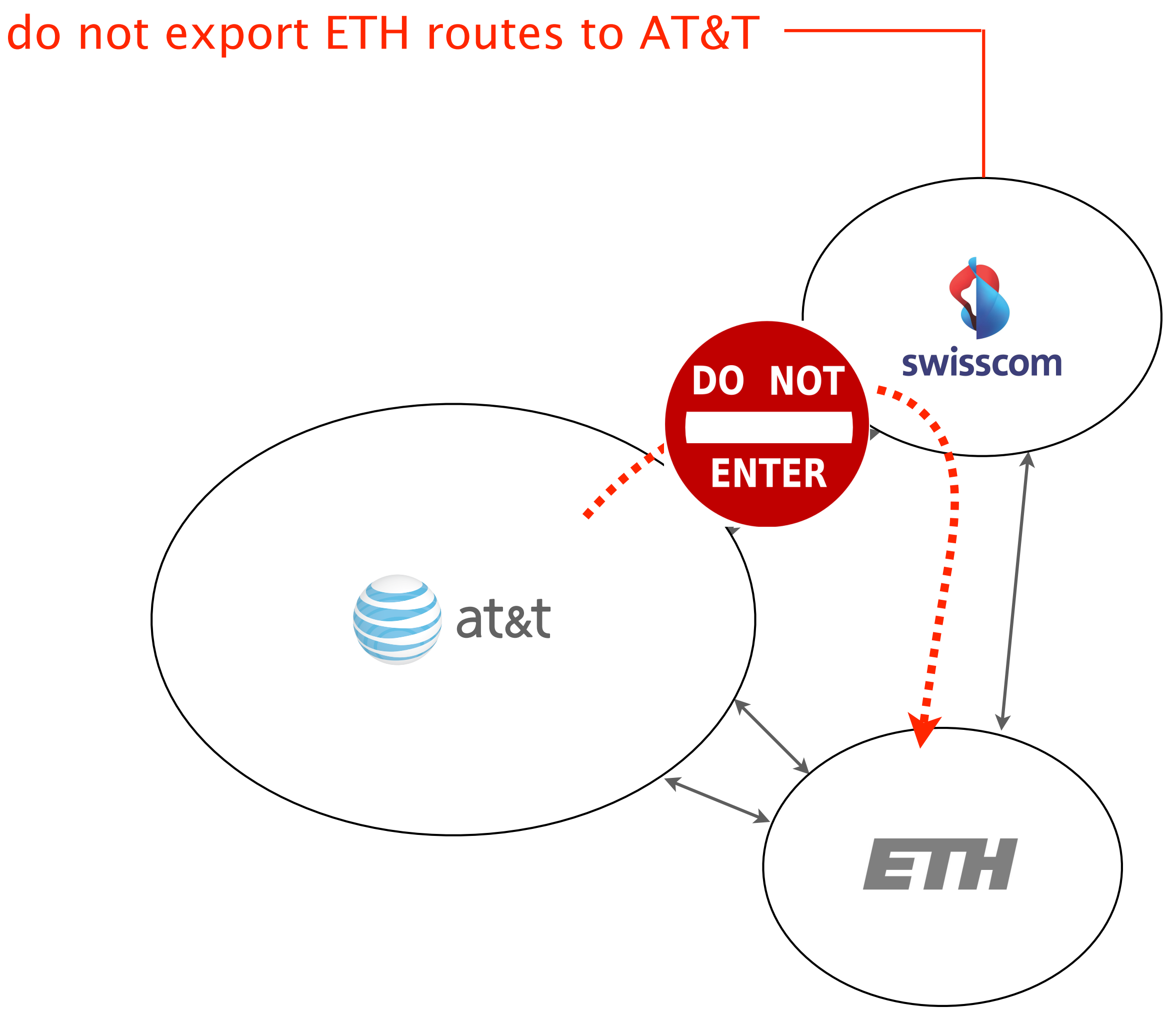
- select and use any path

  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
ETH
129.132.0.0/16
Path: 40


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

Next week on

Communication Networks

Internet routing policies

Communication Networks

Spring 2017

Tobias Bühler, TA

Slides from

Laurent Vanbever

www.vanbever.eu

ETH Zürich (D-ITET)

April, 3 2017