Communication Networks

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Communication Networks

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Slides from

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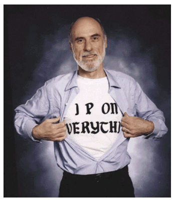
Material inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

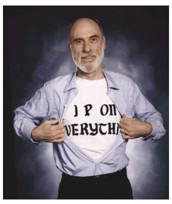
Internet Protocol and Forwarding



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

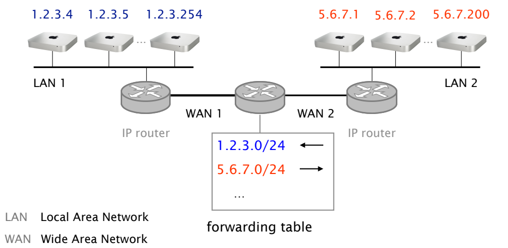
prefix length (in bits)

Prefixes are also sometimes specified using an address and a mask

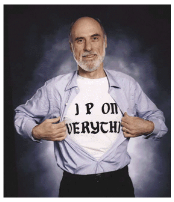
Address	82.130.102.0
	01010010.10000010.01100110. 00000000
	11111111.11111111.11111111. 00000000
Mask	255.255.255.0

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

Doing so enables to scale the forwarding tables



Internet Protocol and Forwarding



IP addresses
use, structure, allocation

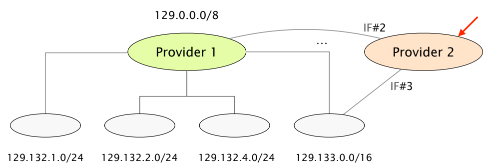
2 IP forwarding
longest prefix match rule

IP header
IPv4 and IPv6, wire format

Routers maintain forwarding entries for each Internet prefix

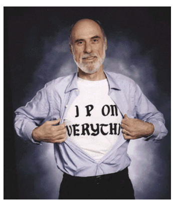
Provider 2's Forwarding table

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

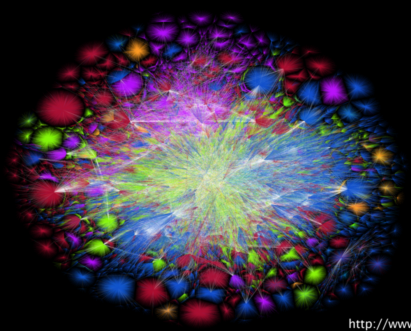
3 IP header
IPv4 and IPv6, wire format

32 bits

4	4	8	3	13
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)

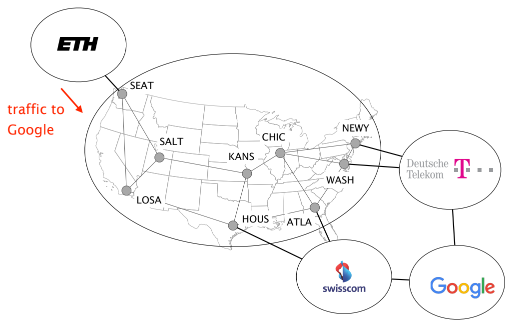
Internet routing comes into two flavors:
intra- and *inter-domain* routing

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

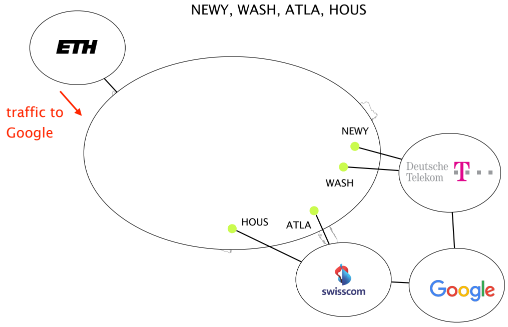
inter-domain routing

intra-domain routing

Find paths between networks



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



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

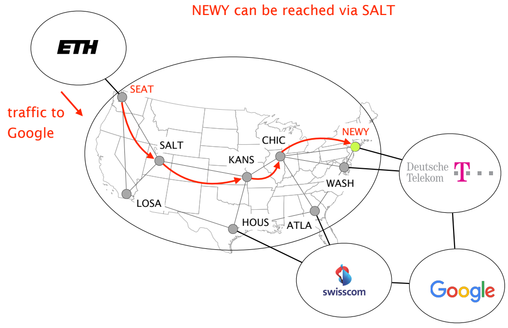
best exit point
based on money, performance, …

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
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

intra-domain routing

intra-domain routing

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

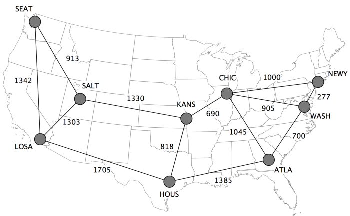
what kind of paths?

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 configuration-free	mandate a spanning-tree 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

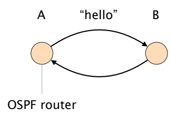
time-to-live for each link-state

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

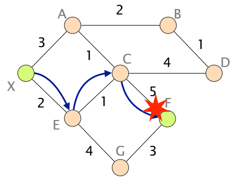
control-plane consistency — all nodes have the same link-state database

necessary

forwarding validity — the global forwarding state directs packet to its destination

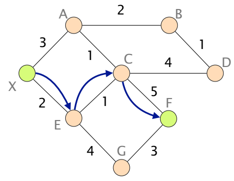
Inconsistencies lead to transient disruptions in the form of blackholes or forwarding loops

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

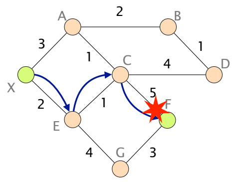


depends on the timeout for detecting lost hellos

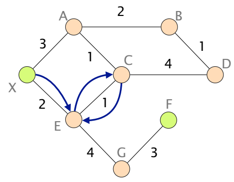
Transient loops appear due to inconsistent link-state databases



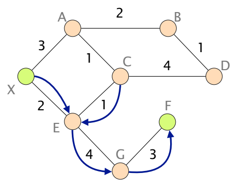
Initial forwarding state



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

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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

---

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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

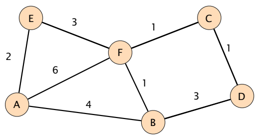
Each node updates its distances
based on neighbors' vectors:

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

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

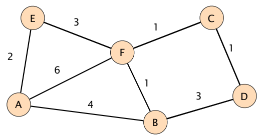
Topology change	link or node failure/recovery
Configuration change	link cost change
Periodically	refresh the link-state information every (say) 30 minutes account for possible data corruption



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

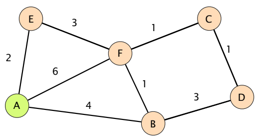
C			D			E			F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	∞	-	A	∞	-	A	2	A	A	6	A
B	∞	-	B	3	B	B	∞	-	B	1	B
C	0	C	C	1	C	C	∞	-	C	1	C
D	1	D	D	0	D	D	∞	-	D	∞	-
E	∞	-	E	∞	-	E	0	E	E	3	E
F	1	F	F	∞	-	F	3	F	F	0	F



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

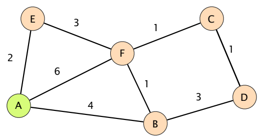
C			D			E			F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	∞	-	A	∞	-	A	2	A	A	6	A
B	∞	-	B	3	B	B	∞	-	B	1	B
C	0	C	C	1	C	C	∞	-	C	1	C
D	1	D	D	0	D	D	∞	-	D	∞	-
E	∞	-	E	∞	-	E	0	E	E	3	E
F	1	F	F	∞	-	F	3	F	F	0	F



Optimum 2-hops path

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

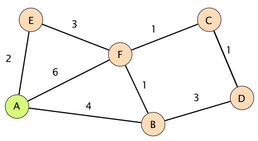
C			D			E			F		
Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop	Dst	Cst	Hop
A	7	F	A	7	B	A	2	A	A	5	B
B	2	F	B	3	B	B	4	F	B	1	B
C	0	C	C	1	C	C	4	F	C	1	C
D	1	D	D	0	D	D	∞	-	D	2	C
E	4	F	E	∞	-	E	0	E	E	3	E
F	1	F	F	2	C	F	3	F	F	0	F



Optimum 3-hops path

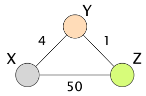
A			B		
Dst	Cst	Hop	Dst	Cst	Hop
A	0	A	A	4	A
B	4	B	B	0	B
C	6	E	C	2	F
D	7	F	D	3	D
E	2	E	E	4	F
F	5	E	F	1	F

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

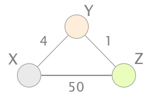


Let’s consider the convergence process
after a link cost change

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

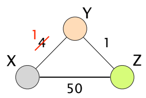
Z vector

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

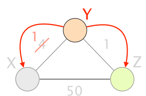
Z vector

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



Y vector

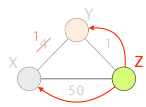
	t=0			t=1	
dest.	via X	via Z	dest.	via X	via Z
X	4	6	X	1	6

Z vector

	t=0	
dest.	via X	via Y
X	50	5

---

t = 2
Z updates its vector,
sends it to X and Y



Y vector

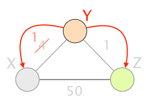
	t=0			t=1	
dest.	via X	via Z	dest.	via X	via Z
X	4	6	X	1	6

Z vector

	t=0			t=2	
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

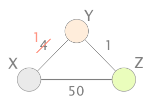
	t=0			t=1			t=3	
dest.	via X	via Z	dest.	via X	via Z	dest.	via X	via Z
X	4	6	X	1	6	X	1	3

Z vector

	t=0			t=2	
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!



Y vector

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

The algorithm terminates
after 3 iterations

Good news travel fast!

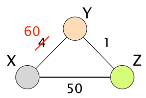
Good news travel fast!

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

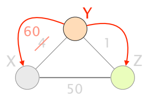
Z vector

dest.	via X	via Y
X	50	5

---

t = 1

Y updates its vector,
sends it to X and Z



Y vector

time	dest.	via X	via Z
t=0	X	4	6
t=1	X	60	6

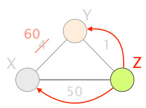
Z vector

time	dest.	via X	via Y
t=0	X	50	5

---

t = 2

Z updates its vector,
sends it to X and Y



Y vector

time	dest.	via X	via Z
t=0	X	4	6
t=1	X	60	6

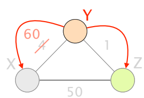
Z vector

time	dest.	via X	via Y
t=0	X	50	5
t=2	X	50	7

---

t = 3

Y updates its vector,
sends it to X and Z



Y vector

time	dest.	via X	via Z
t=0	X	4	6
t=1	X	60	6
t=3	X	60	8

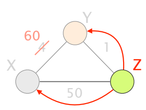
Z vector

time	dest.	via X	via Y
t=0	X	50	5
t=2	X	50	7

---

t = 4

Z updates its vector,
sends it to X and Y…

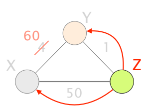


t=4

Y vector

Z vector

dest.	via X	via Y
X	50	9



… many iterations later …

Y vector

time	dest.	via X	via Z
t=44	X	60	51

Z vector

time	dest.	via X	via Y
t=4	X	50	9
t=44	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?

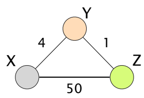
Routers don't know when neighbors use them

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	∞

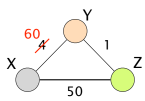
As Z uses Y to reach X,
it announces to Y an infinite cost

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

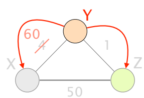
dest.	via X	via Z
X	4	∞

Z vector

dest.	via X	via Y
X	50	5

t = 1

Y updates its vector,
sends it to X and Z



Y vector

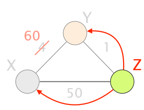
	t=0 dest.	via X	via Z	t=1 dest.	via X	via Z
	X	4	∞	X	60	∞

Z vector

	t=0 dest.	via X	via Y
	X	50	5

t = 2

Z updates its vector,
sends it to X and Y



Y vector

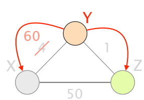
t=0 dest.	via X	via Z	t=1 dest.	via X	via Z
X	4	∞	X	60	∞

Z vector

t=0 dest.	via X	via Y	t=2 dest.	via X	via Y
X	50	5	X	50	61

t = 3

Y updates its vector,
sends it to X and Z



Y vector

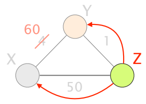
t=0 dest.	via X	via Z	t=1 dest.	via X	via Z	t=3 dest.	via X	via Z
X	4	∞	X	60	∞	X	60	51

Z vector

t=0 dest.	via X	via Y	t=2 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

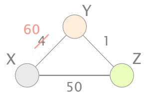
dest.	via X	via Y
X	50	∞

---

t > 4

no one moves

network has converged!



t=4 | t>4

Y vector (t>4)

dest.	via X	via Z
X	60	51

Z vector (t=4)

dest.	via X	via Y
X	50	∞

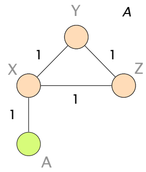
Z vector (t>4)

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

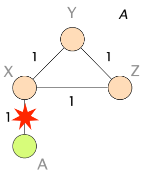


dest.	via A	via Y	via Z
A	1	∞	∞

dest.	via X	via Z
A	2	3

dest.	via X	via Y
A	2	3

What happens if link (X,A) fails?



dest.	via A	via Y	via Z
A	1	∞	∞

dest.	via X	via Z
A	2	3

dest.	via X	via Y
A	2	3

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

↓

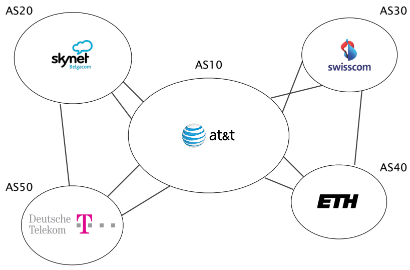
A network of *networks*

Internet

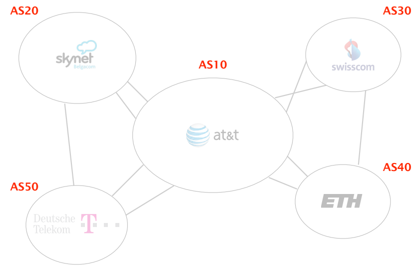
↓

Border Gateway Protocol (BGP)

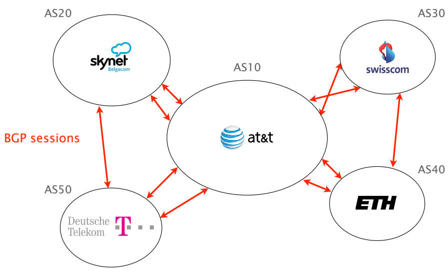
The Internet is a network of networks,
referred to as Autonomous Systems (AS)



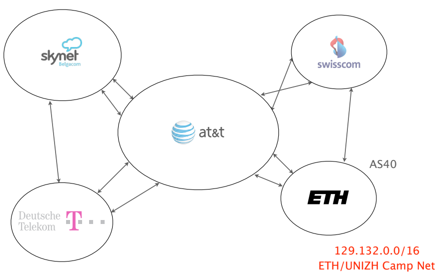
Each AS has a number (encoded on 16 bits)
which identifies it



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

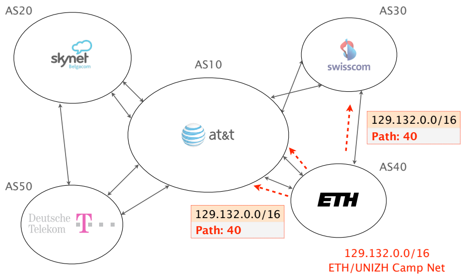
cons — **It still minimizes some common distance**
impossible to achieve in an inter domain setting

It converges slowly
counting-to-infinity problem

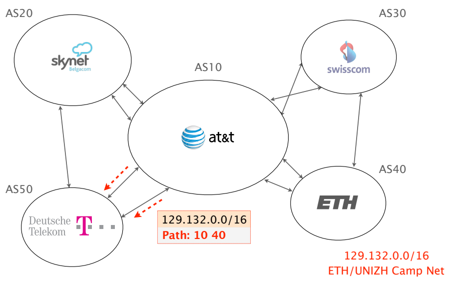
BGP relies on path-vector routing to support flexible routing policies and avoid count-to-infinity

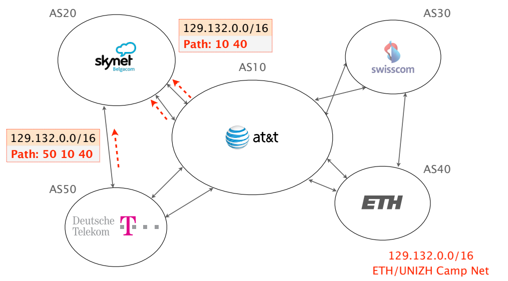
key idea — advertise the entire path instead of distances

BGP announcements carry complete path information instead of distances

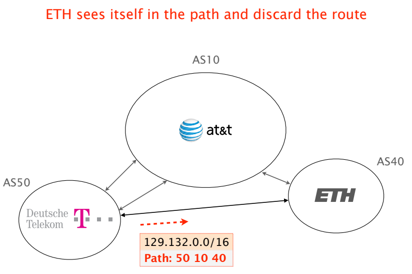


Each AS appends itself to the path when it propagates announcements





Complete path information enables ASes to easily detect a loop



Life of a BGP router is made of three consecutive steps

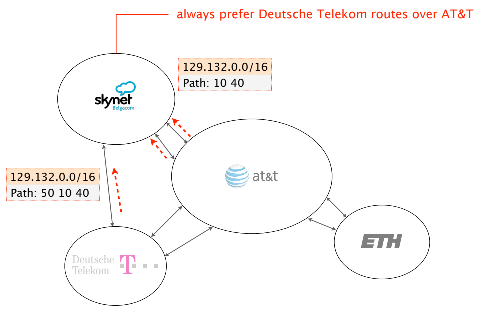
while true:

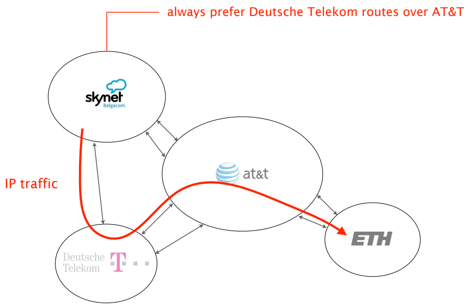
- **receives routes** from my neighbors
- **select one best route** for each prefix
- **export the best route** to my neighbors

Each AS can apply local routing policies

Each AS is **free to**

- **select and use any path**
  preferably, the cheapest one

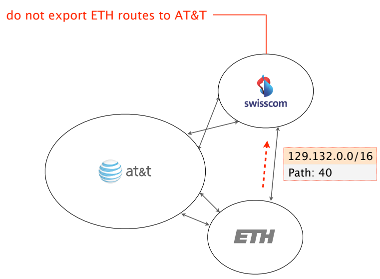


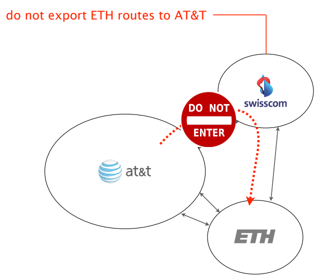


Each AS can apply local routing policies

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





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