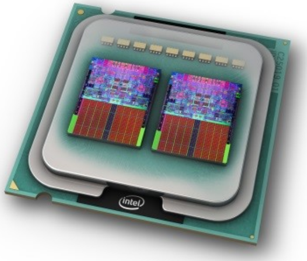
Large-scale Distributed Systems and Networks

(Storskaliga Distribuerade System och Nätverk)

Slides by Niklas Carlsson (including slides based on slides by P. Gill and Y. Shavitt)

Systems thinking

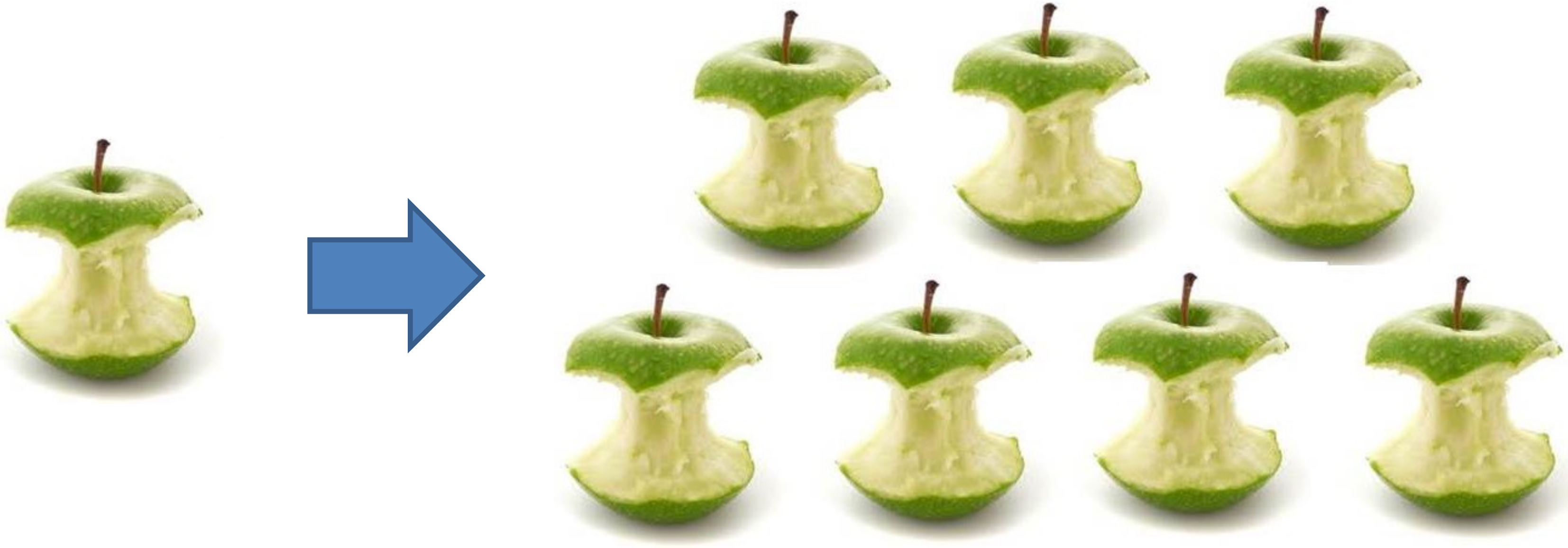
- We want to understand the full system and the ecosystem it operates within; e.g.,
  - Understanding the full system
  - Looking at the parts and how they interact
- This course provide many examples ...



Measurements

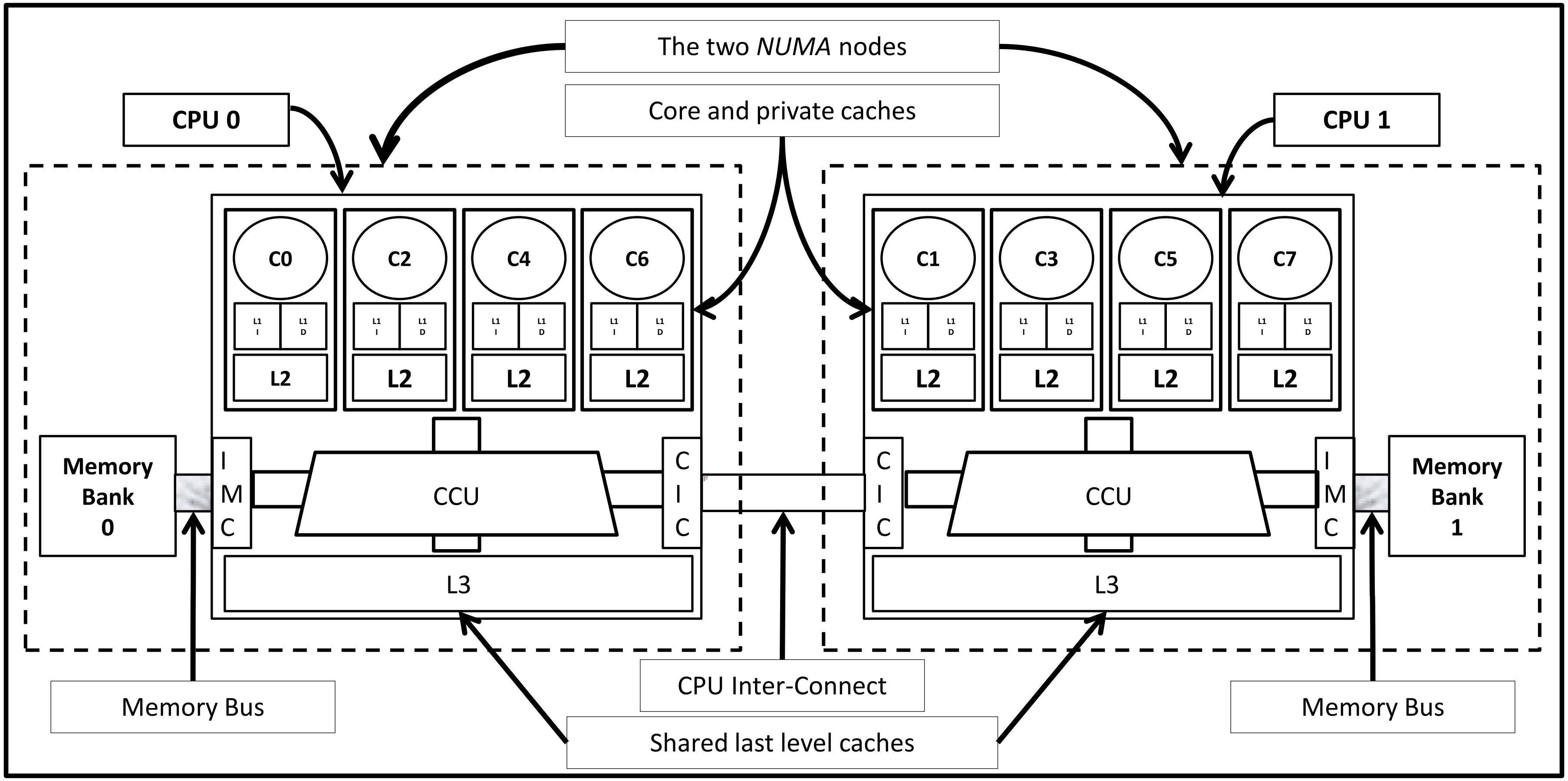
- It has often been stated that
  - “you can’t manage what you can’t measure” ...
- Effective tool to understand, model, test, and improve existing systems …
  - E.g., often want to identify (and fix) system bottlenecks

Multicore systems



NUMA Architecture

An example of a two processor eight core NUMA system



The two *NUMA* nodes

Core and private caches

CPU 0

CPU 1

Memory Bus

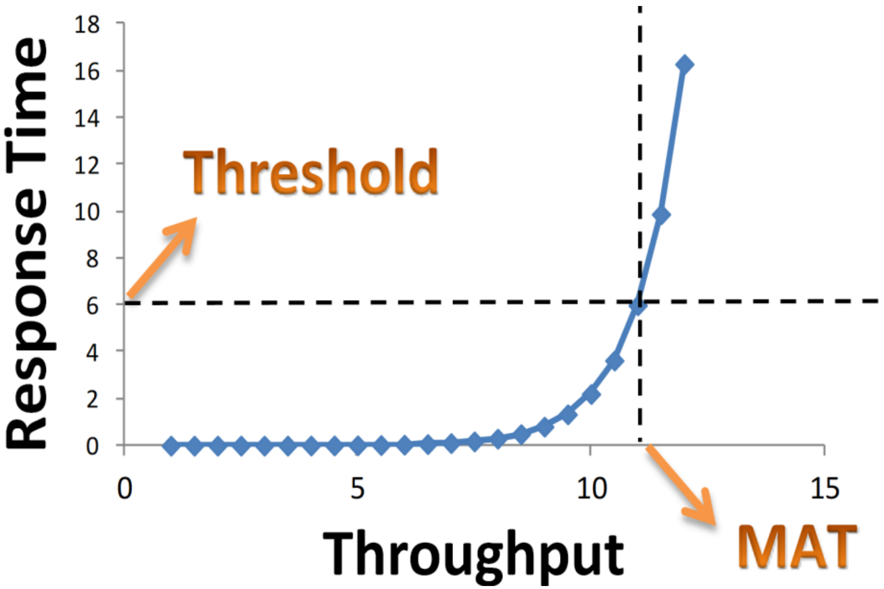
CPU Inter-Connect

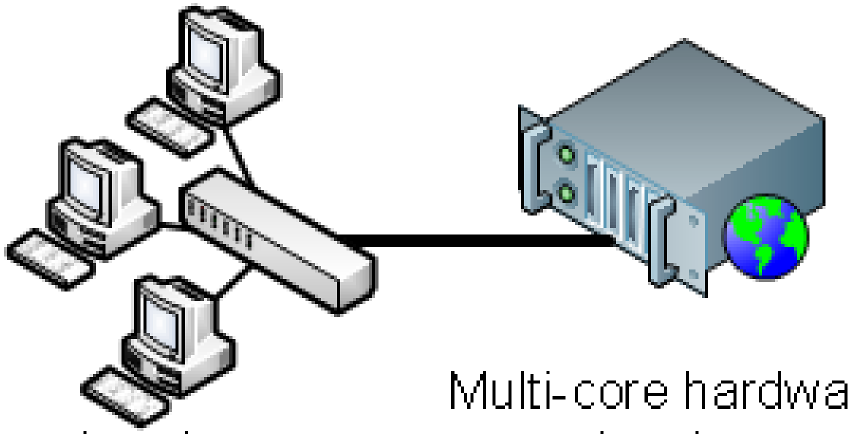
Shared last level caches

Memory Bus

Scalability Evaluation Measurements

- E.g., Measure Web server scalability for workloads [ICPE ‘13]
  - Typically want to provide some 99% response time
  - Example scalability measure: Maximum Achievable Throughput (MAT)





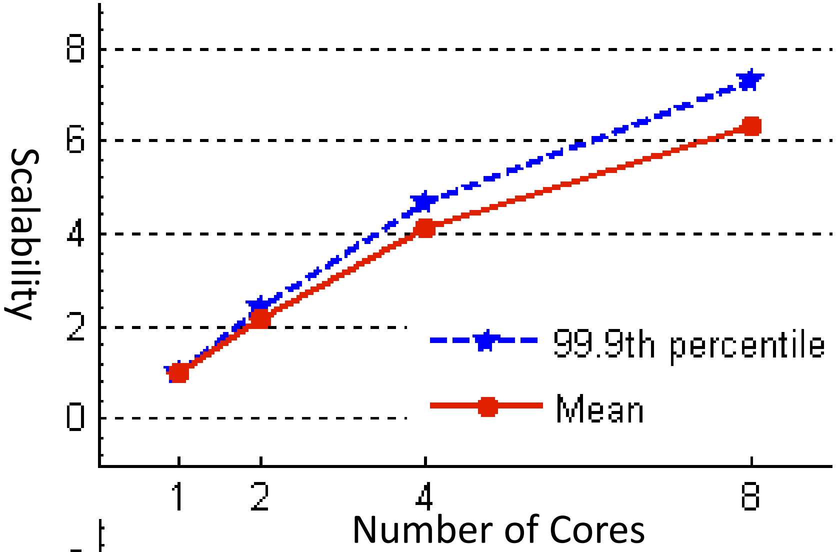
Load Generators

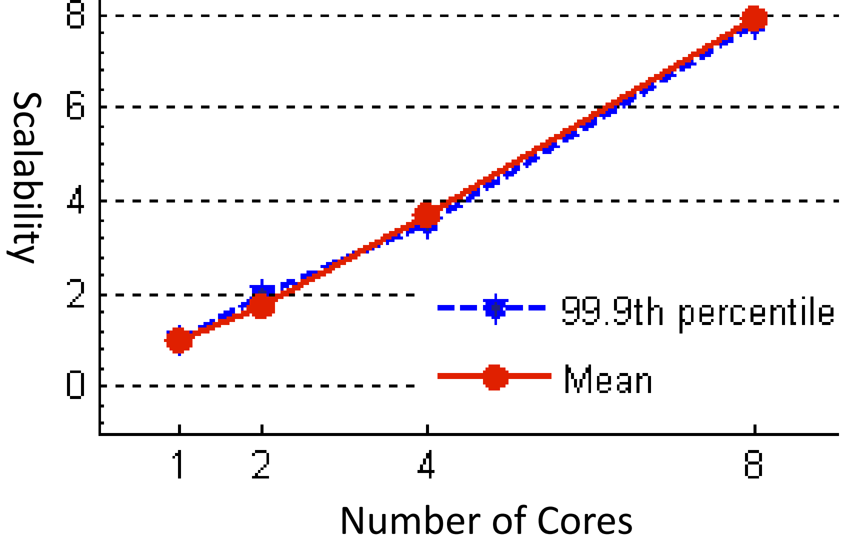
Multi-core hardware hosting Web/Application server

SCALABILITY EVALUATION

RESULTS

- TCP/IP Intensive workload
  - Sub-linear
    - Maximum Achievable Throughput
      - 146,000 req/sec
- SPECweb Support workload
  - Almost linear
    - Maximum Achievable Throughput
      - 23,000 req/sec



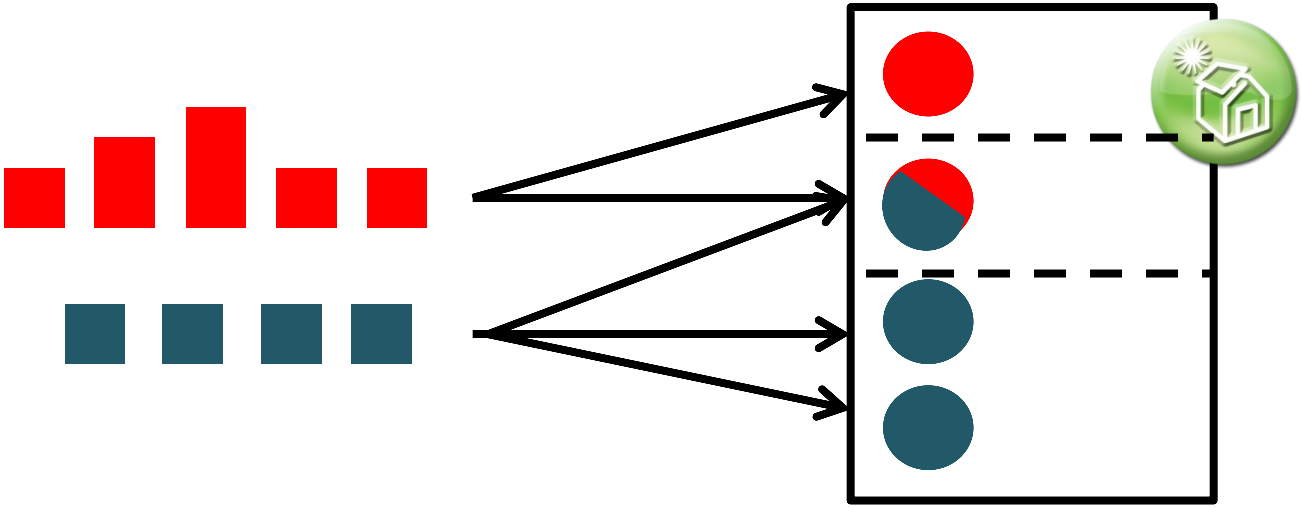


Identification of bottlenecks

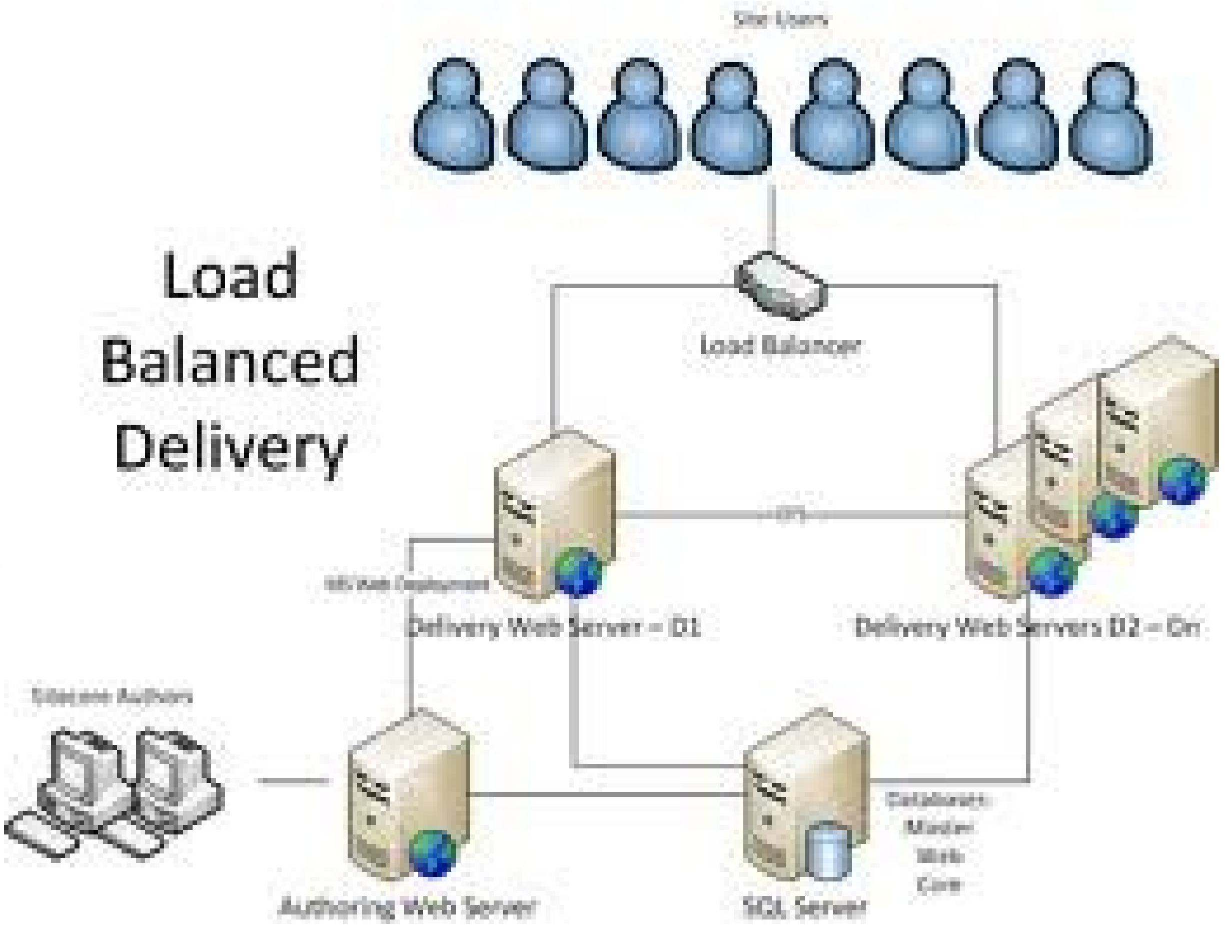
- E.g., memory, CPU, network, cache hierarchy, interconnect bus, scheduler, …
  - Black-box testing
  - Low-level instrumentation

Identification of bottlenecks

- E.g., memory, CPU, network, cache hierarchy, interconnect bus, scheduler, …
  - – Black-box testing
  - – Low-level instrumentation
- Multiple workloads …



Often many servers (and racks)



... and data centers …

$G(-x^*)/[xH(-x^*)]$
$\Delta_L \arg f(z) = (\pi/2)(S_1$
$= \prod_{k=1} (u + u_k)G_0(u),$
$\rho(x) = -G(-x^*)/[xH($
$(1/2)[1 - \operatorname{sg} A_1]$
$G(u)$

… cost-efficient delivery ...

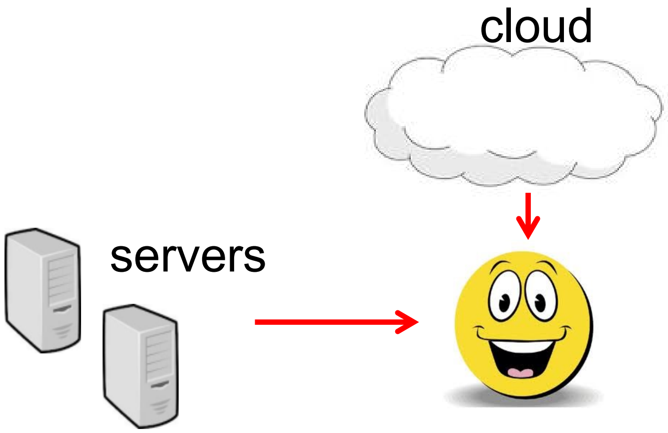
$\rho(x) = -G(-x^2)/[xH(-x^2)]$.
$-\alpha_0 \leq \pi/2 + 2\pi k$, $p = 2\mathscr{V}_0 + (1/2)[\mathrm{sg}\,A_1 - \mathrm{sg}$
$\Delta_L \arg f(z) = (\pi/2)(S_1$
$(u) = \prod_{k=1}^{\mu} (u + u_k)G_0(u)$,
$\rho(x) = -G(-x^2)/[xH(-x^2)]$.
$p = 2\mathscr{V}_0$ $\rho^s > \sum_{j=0, j\neq p}^{n} A_j\rho^j$, $-\pi/2 + 2\pi k \leq$
$(1/2)[1 - \mathrm{sg}\,A_1]$
$(S_1 - S_2)$ $G(u)$

… and different flexibility …

- Minimize content delivery costs

	Bandwidth	Cost
Cloud-based	Elastic/flexible	$$$
Dedicated servers	Capped	$

How to get the best of two worlds?



… and from who?

Measurements of Distributed Systems and Networks

Let’s consider the Internet itself

- We are very reliant on the Internet
  - Today, it is hard to imagine a world without the internet
  - Yet it is growing increasingly complex ...

- Today: Wide area network that is too complex to fully grasp
  - Many protocols at various levels interact and effect behavior

- Many applications have performance requirements
  - End-to-end delay, loss, reliability, …

- It is an interesting complex system with emergent characteristics like many living systems
    - Biological systems
    - Social networks

Internet Measurement Challenges

- Network size [quick “guestimates” …]
  - ~ O(1B) hosts in DNS, billions of users (and routers), ~O(100K) ASes, 20-30 billion connected devices ...
- Network Complexity
  - Interaction between components, protocols, applications, users
- All change over time
  - New applications are added
  - New protocol versions (TCP, QUIC, …)
  - New router design (AQM)

Why do we measure the Internet?

- Already mentioned
  - Because it is there!
  - Operational reasons

- We cannot improve the Internet if we don’t understand it
  - We cannot understand it if we don’t measure
  - We cannot build effective models or simulators if we don’t measure

What can we measure on the Internet?

- Structure
  - Topology (router/network) connectivity, link capacities, link loss, available bandwidth, routing, …
- Traffic
  - End-to-end performance, packet arrival process (congestion built-up), …
- Users and applications
  - WWW, peer-to-peer, streaming, gaming, …
- Malicious behavior (and vulnerabilities)
  - Attack patterns, port scans, …

Where can we measure the Internet?

How to chose representative measurement points?

Example: traffic samples

- LAN traffic vs. WAN traffic
- Inside an ISP vs. between continents
- Country biases
- Commercial location vs. educational
- More locations is better, BUT most of all, one point is better than no point

How can we measure the Internet?

- Active measurements
  - Probes: Traceroute, ping, packet trains
  - Application simulation

- Passive measurement
  - Logs (WWW)
  - Monitors, sniffers

When should we measure the Internet?

- Diurnal and weekly traffic cycles
- Time scales depend on “what” and “how”
- Passive measurement are typically continuous
  - Can generate **huge** datasets
  - Log access problems
  - Privacy concerns
- Active measurements are typically discrete
  - Important characteristics can be missed
  - Probes can be filtered and/or detected

Who is measuring the Internet?

- Businesses do a great deal of measurement
  - Mostly do not share with the research community
  - examples:
    - Akamai: http delay from server side
    - Google: everything
- Academia and Research institutes
  - Publish papers, but data may not always be available
  - Inform public and make recommendations
- Governments and their affiliates (e.g., MSB)

Publishing Internet Measurement Studies

- All major networking conferences & journals accept measurement papers
  - ACM SIGCOMM, IEEE INFOCOM, ACM SIGMETRICS
  - IEEE/ACM ToN, IEEE TPDS
- Dedicated meetings
  - ACM Internet Measurement Conf. (IMC)
  - Passive & Active Measurements Conf. (PAM)

E.g., PAM 2024 (2 weeks ago, on YouTube soon ...)

Active Measurement Techniques

Active Probes

- Active probes send stimulus (packets) into the network and then measure the response
  - Done on network, transport and application layers

- Active probes are useful to measure various things:
  - Delay, delay jitter, and loss
  - Topology and routing behavior
  - Capacity, bandwidth, and throughput

Example: RTT

ICMP

ICMP is the IP error diagnosis protocol.

<table>
<tr><td colspan="2">IP header</td></tr>
<tr><td>Type</td><td>Code</td></tr>
<tr><td colspan="2">Checksum</td></tr>
<tr><td colspan="2">Sequence number</td></tr>
<tr><td colspan="2">Any ICMP data</td></tr>
</table>

ICMP Message Types

Type No.	Meaning
0	Echo reply
3	Destination unreachable
4	Source quench
5	Redirect
8	Echo
9	Router advertisement
10	Router solicitation
11	Time exceeded
12	Parameter problem
13	Timestamp
14	Timestamp reply
15	Information requeste
16	Information reply

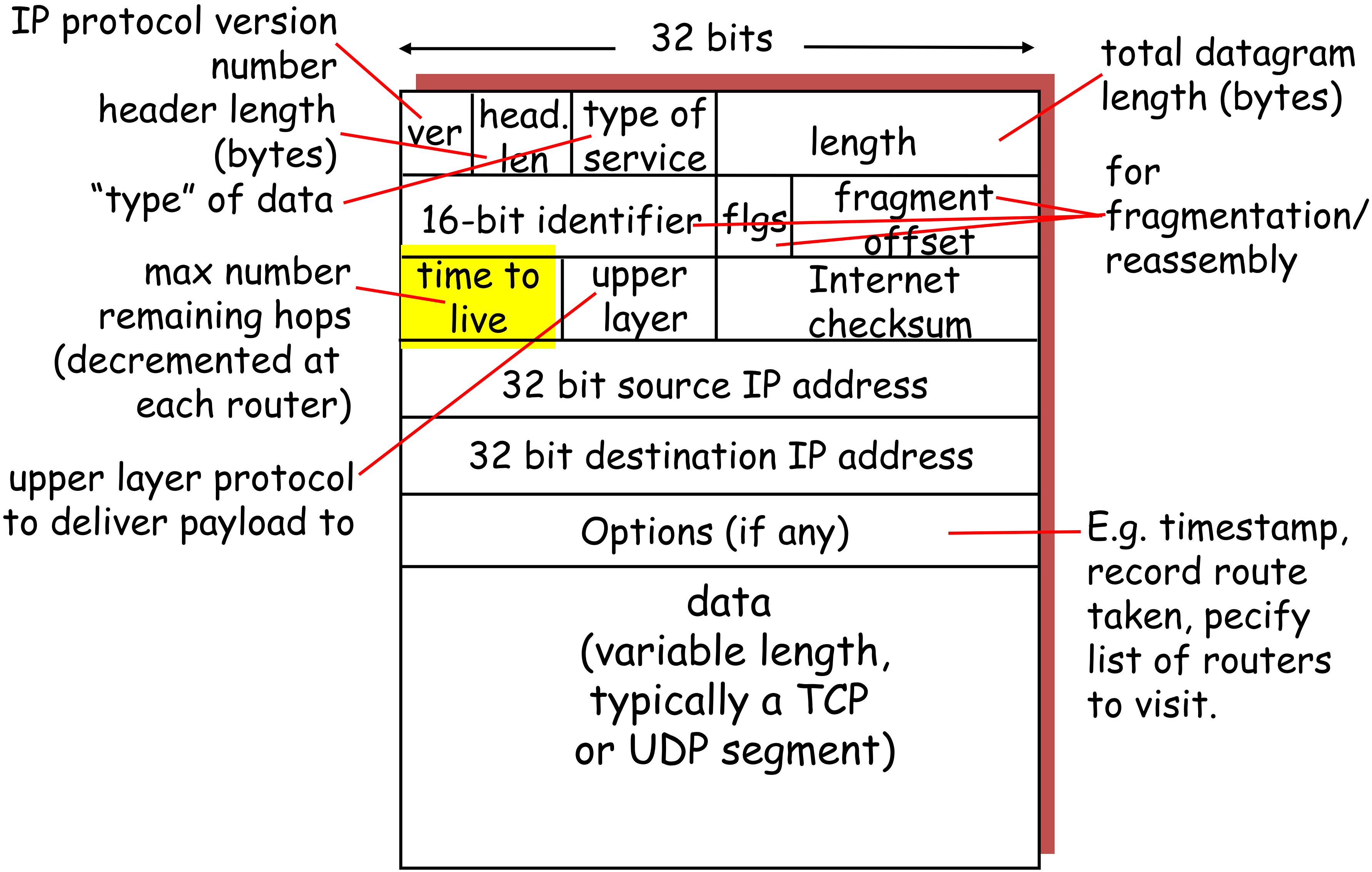
PING

Application layer “ping”

- One can generate application layer messages to test application reaction time
- Most common:
  - TCP SYN message to port 80

Example: Path

IP datagram format



IP protocol version number

header length (bytes)

“type” of data

max number remaining hops (decremented at each router)

upper layer protocol to deliver payload to

32 bits

ver	head. len	type of service	length	
16-bit identifier			flgs	fragment offset
time to live	upper layer		Internet checksum	
32 bit source IP address				
32 bit destination IP address				
Options (if any)				
data (variable length, typically a TCP or UDP segment)				

total datagram length (bytes)

for fragmentation/ reassembly

E.g. timestamp, record route taken, pecify list of routers to visit.

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Type	Code	description
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	3	dest port unreachable
3	6	dest network unknown
3	7	dest host unknown

traceroute

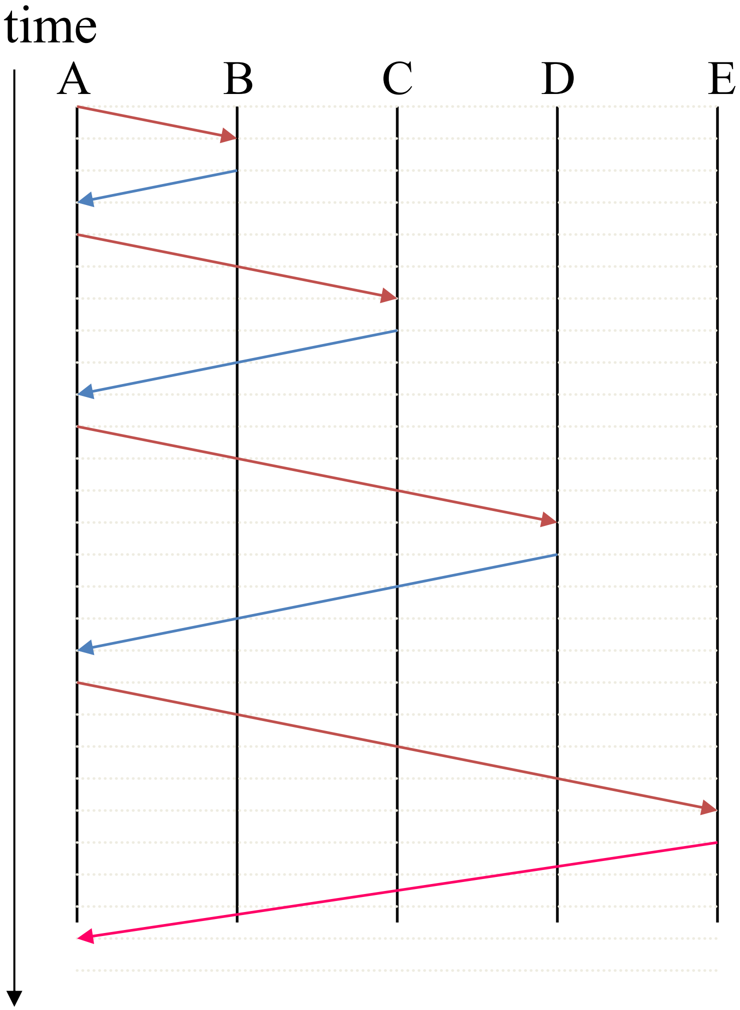
traceroute

Regular UDP packets

- successive TTLs

ICMP “TTL expired” message

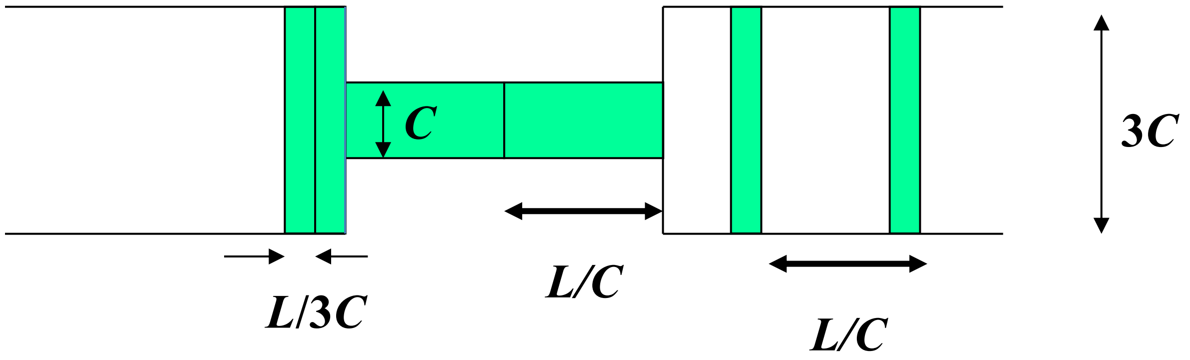
ICMP “port unreachable” message



Example: Bottleneck capacity

Packet Dispersion to Estimate Capacity

- Packet transmission time: τ=*L*/*C*
- Send two packets back-to-back
- Measure dispersion Δ at the receiver
- Estimate *C* as *L*/Δ

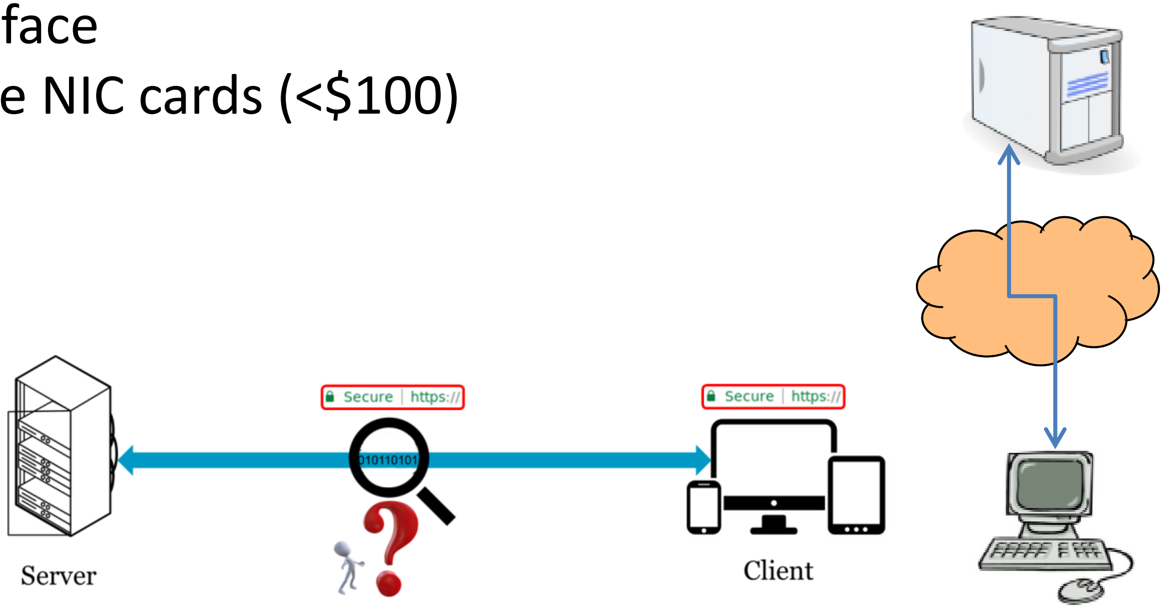


- But cross-traffic 'noise' can effect Δ.
- E.g., patchar "allows any user to find (estimate) the bandwidth, delay, average queue and loss rate of every hop between any source & destination on the Internet"

Passive Measurement Techniques

Passive packet measurement

- Capture packets as they pass by
  - Packet capture applications (e.g., tcpdump) on hosts use packet capture filter
    - Requires access to the wire
    - Promiscuous mode or mirror ports to see other traffic
  - Hardware-based solutions
    - Endace, Inc.'s DAG cards for monitoring almost every type of network interface
    - Programmable NIC cards (<$100)
- Example issues:
  - Timestamps
  - Data volumes
  - Privacy



Passive IP flow measurement

- An IP flow is defined by the five-tuple:
  - src addr, src port, dst addr, dst port, protocol
- Cisco’s NetFlow
  - Provide template-based flow records
- Many tools can manipulate NetFlow data

tcpdump

- Can capture entire packet or *n* first bytes
- Timestamps each packet
- Can filter based on any combination of header field

HTTP Logs

- Have data about the client IP, transaction time, command (GET/POST), return code, bytes transferred, referrer, metadata (browser type, OS, languages, etc.)

- Tools are available to analyze HTTP logs
  - Webalizer

```
[root@jupiter httpd]# grep "GET / " access_log |tail -10
68.54.223.47 - - [19/May/2005:12:36:20 +0300] "GET / HTTP/1.1" 200 14067 "-" "Mozilla/4.0 (compatible;
    MSIE 6.0; Windows NT 5.1; .NET CLR 1.1.4322)"
132.76.80.118 - - [19/May/2005:12:49:44 +0300] "GET / HTTP/1.1" 304 -
    "http://www.eng.tau.ac.il/~shavitt/" "Mozilla/4.0 (compatible; MSIE 6.0; Windows NT 5.1; .NET CLR
    1.1.4322)"
24.169.148.213 - - [19/May/2005:13:06:58 +0300] "GET / HTTP/1.1" 200 14067 "-" "Mozilla/5.0 (Windows;
    U; Windows NT 5.1; en-US; rv:1.7.8) Gecko/20050511 Firefox/1.0.4"
84.170.181.64 - - [19/May/2005:13:07:14 +0300] "GET / HTTP/1.1" 200 14067
    "http://www.google.de/search?hl=de&q=dimes&meta=" "Mozilla/4.0 (compatible; MSIE 6.0; Windows
    NT 5.1; SV1)"
130.240.136.220 - - [19/May/2005:13:07:25 +0300] "GET / HTTP/1.1" 304 - "-" "Mozilla/4.0 (compatible;
    MSIE 6.0; Windows NT 5.1; SV1; .NET CLR 1.1.4322)"
81.72.13.30 - - [19/May/2005:13:11:00 +0300] "GET / HTTP/1.1" 200 14067
    "http://www.miranet.it/php/Articolo.php?id=708" "Mozilla/4.0 (compatible; MSIE 6.0; Windows 98)"
194.78.199.123 - - [19/May/2005:13:13:44 +0300] "GET / HTTP/1.1" 200 14067 "-" "Mozilla/4.0 (compatible;
    MSIE 6.0; Windows NT 5.0; .NET CLR 1.1.4322)"
82.152.182.12 - - [19/May/2005:13:23:10 +0300] "GET / HTTP/1.1" 200 14067 "-" "Mozilla/4.0 (compatible;
    MSIE 6.0; Windows NT 5.1; SV1)"
80.119.126.44 - - [19/May/2005:13:38:08 +0300] "GET / HTTP/1.1" 200 14067 "-" "Mozilla/5.0 (Windows; U;
    Windows NT 5.1; en-US; rv:1.7.8) Gecko/20050511 Firefox/1.0.4"
80.250.186.101 - - [19/May/2005:13:46:14 +0300] "GET / HTTP/1.1" 200 14067
    "http://distributed.ru/forum/?a=topic&topic=583" "Mozilla/5.0 (Windows; U; Windows NT 5.1; en-US;
    rv:1.7.8) Gecko/20050511 Firefox/1.0.4"
```

Other examples

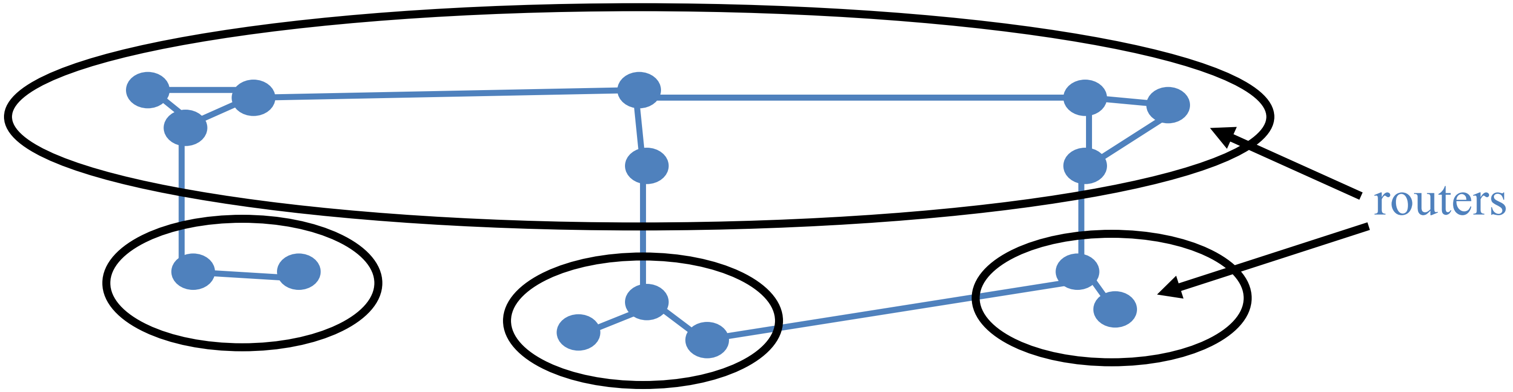
- Zeek (formerly Bro)
  - Open-source network security monitoring tool that allows easy extraction of information from the network traffic
  - Flexible and powerful when wanting to extract information from the various network layers
  - Typically use scripts to create logs
- Wireshark (used in labs)
  - Has “cute” user interface, is more “plug-and-play”, and faster to get up-to-speed

Measuring the Internet’s topology

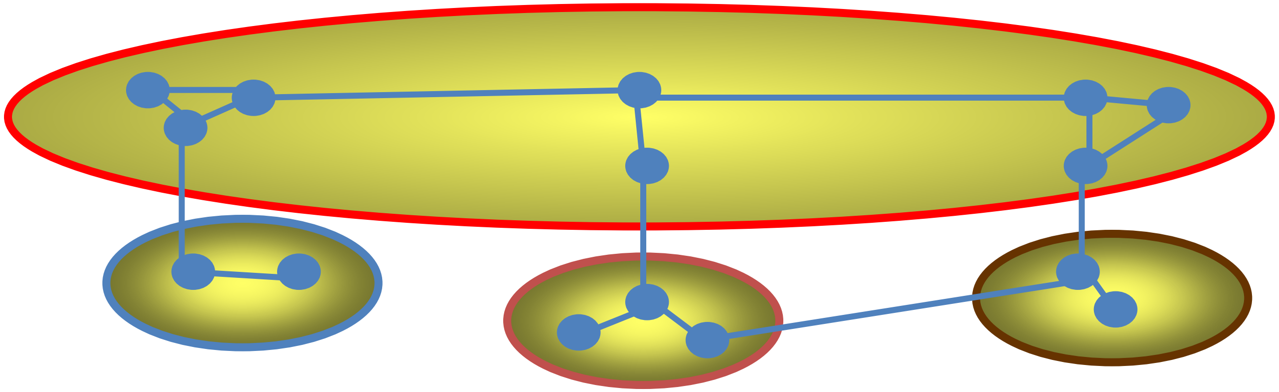
Outline

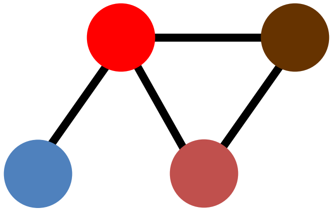
- Background
- Then, both active and passive examples ...

The Internet Structure



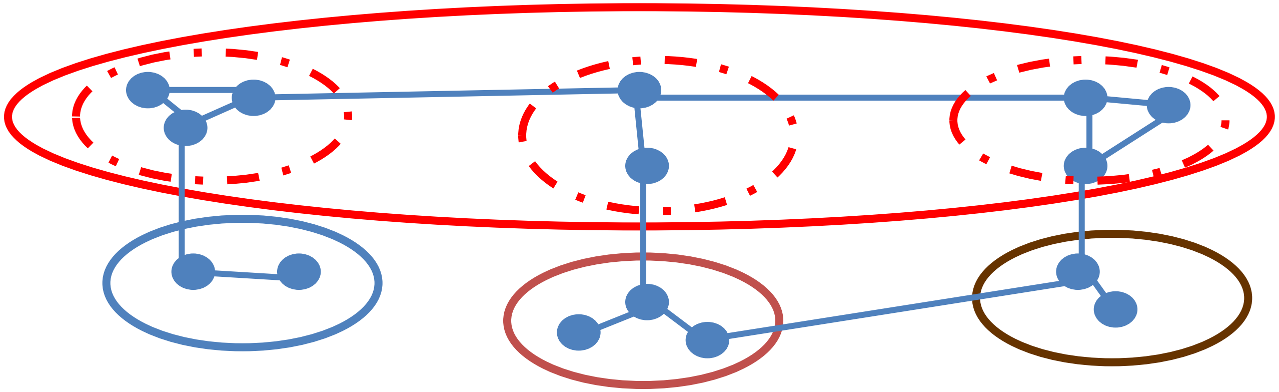
The Internet Structure

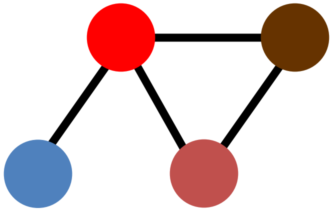




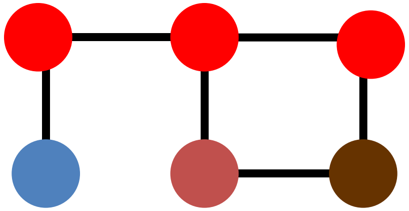
The **AS** graph

The Internet Structure





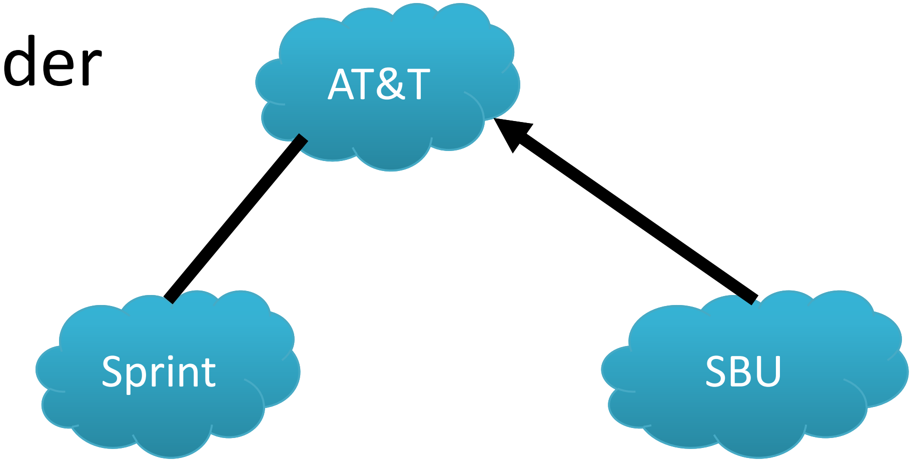
The **AS** graph



The **PoP level** graph

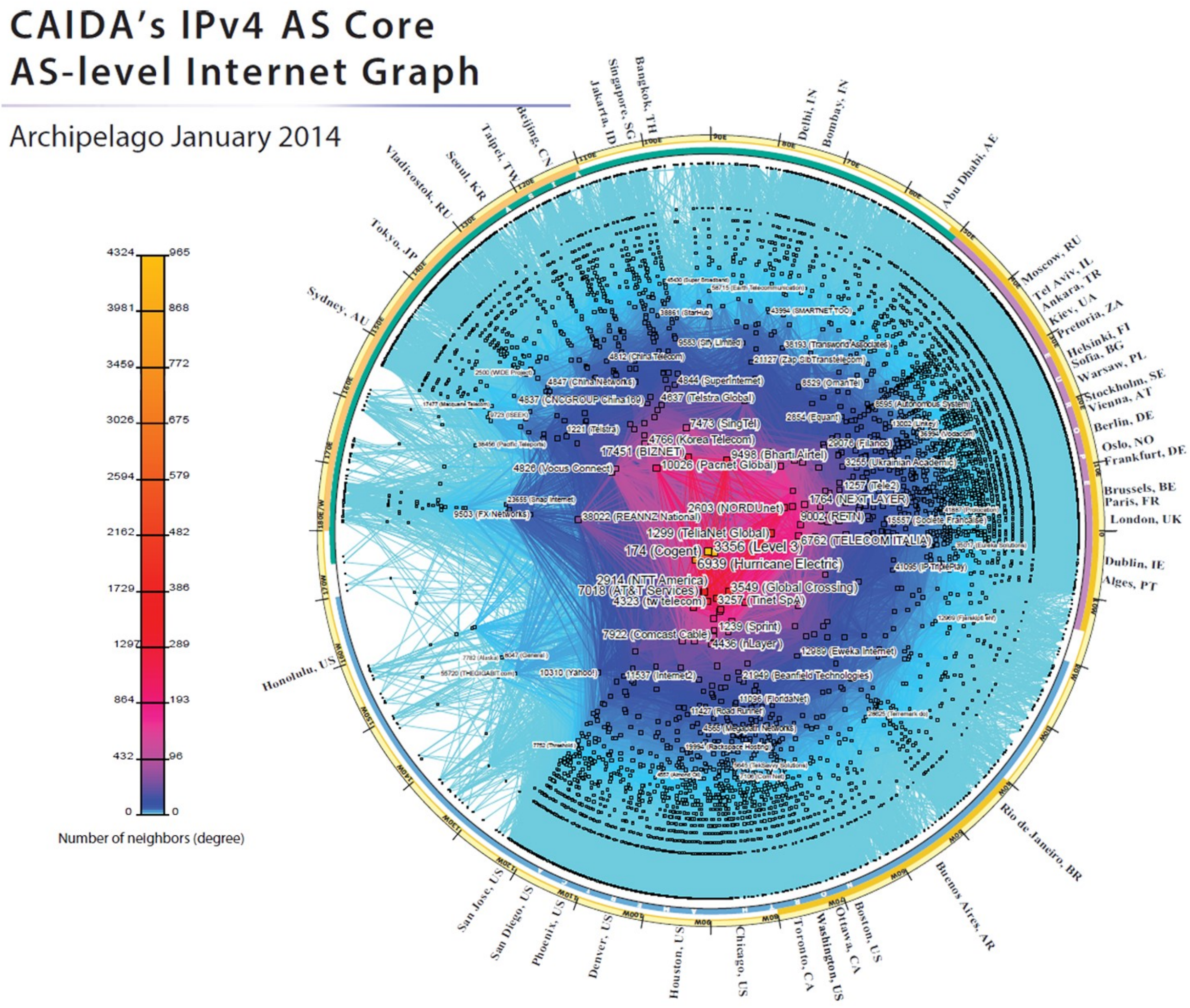
Measuring the Internet’s topology

- What do we mean by topology?
  - – Internet as graph
  - – Edges? Nodes?
    - Node = Autonomous System (AS)
    - Edge = connection.
- Edges labeled with business relationship
  - – Customer → Provider
  - – Peer -- Peer



The outputs ….

15412	12041	p2c
15412	12486	p2c
15412	12880	p2c
15412	13810	p2c
15412	15802	p2c
15412	17408	p2c
15412	17554	p2c
15412	17709	p2c
15412	18101	p2c
15412	19806	p2c
15412	19809	p2c
15413…		

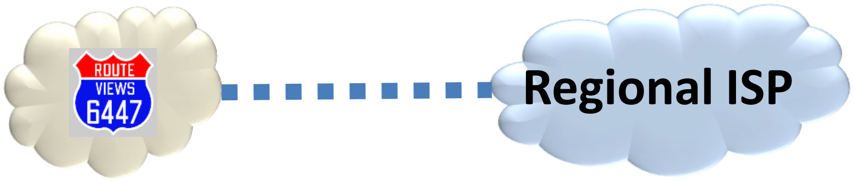


So how do we measure this graph?

- Passive approach: BGP route monitors
  - Coverage of the topology
  - Amount of visibility provided by each neighbor
- Active approach: Traceroute
  - From where?
  - Traceroute gives series of IP addresses not ASes

Passive approach: BGP Route Monitors

- Receive BGP announcements from participating ASes at multiple vantage points



www.routeviews.org

Going from BGP Updates to a Topology

Example update:

- TIME: 03/22/11 12:10:45
- FROM: 12.0.1.63 AS7018
- TO: 128.223.51.102 AS6447
- ASPATH: 7018 4134 9318 32934 32934 32934
- 69.171.224.0/20

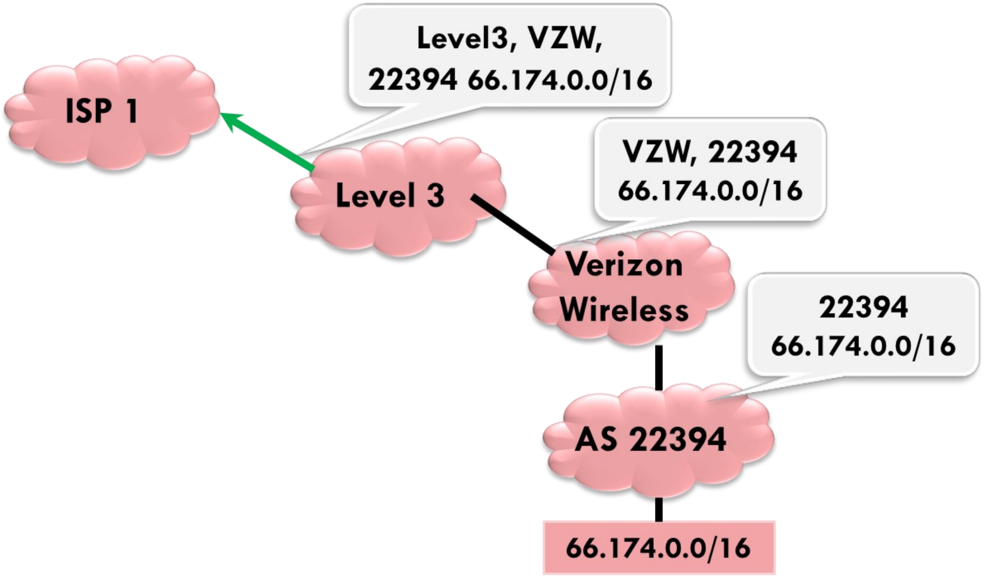
AT&T (AS7018) it telling Routeviews (AS 6447) about this route.

This /20 prefix can be reached via the above path

Going from BGP Updates to a Topology

- Key idea
  - The business relationships determine the routing policies
  - The routing policies determine the paths that are chosen
  - So, look at the chosen paths and infer the policies
- Example: AS path “7018 4134 9318” implies
  - AS 4134 allows AS 7018 to reach AS 9318
  - China Telecom allows AT&T to reach Hanaro Telecom
  - Each “triple” tells something about transit service

Traceroute vs Announced Path



Characterizing Large-scale Routing Anomalies: A Case Study of the China Telecom Incident,
R. Hiran et al., Proc. PAM 2013.

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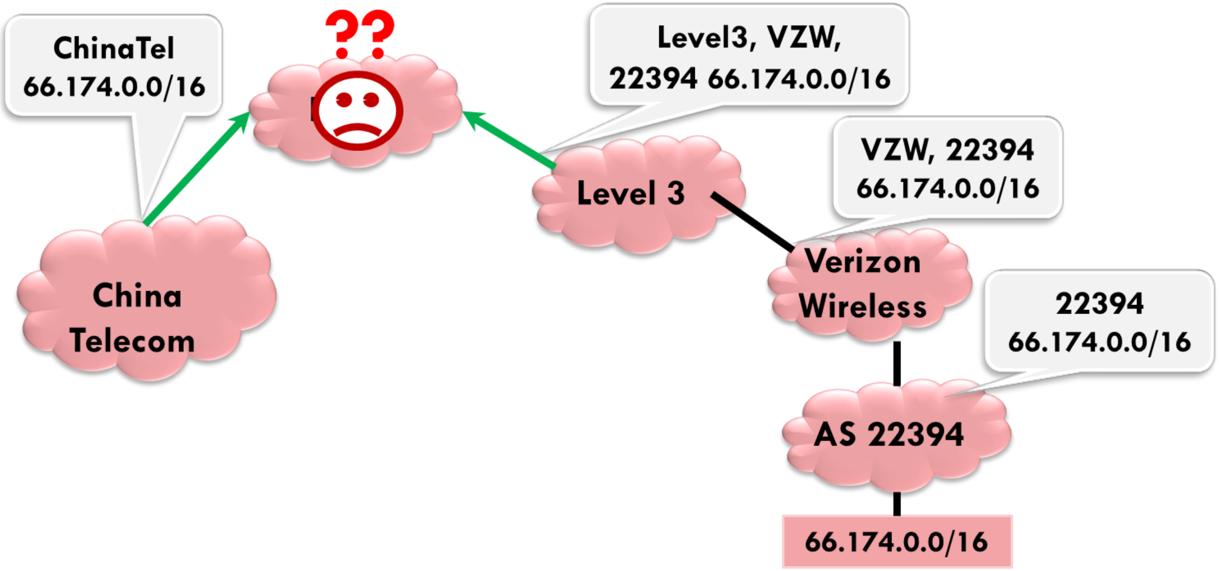

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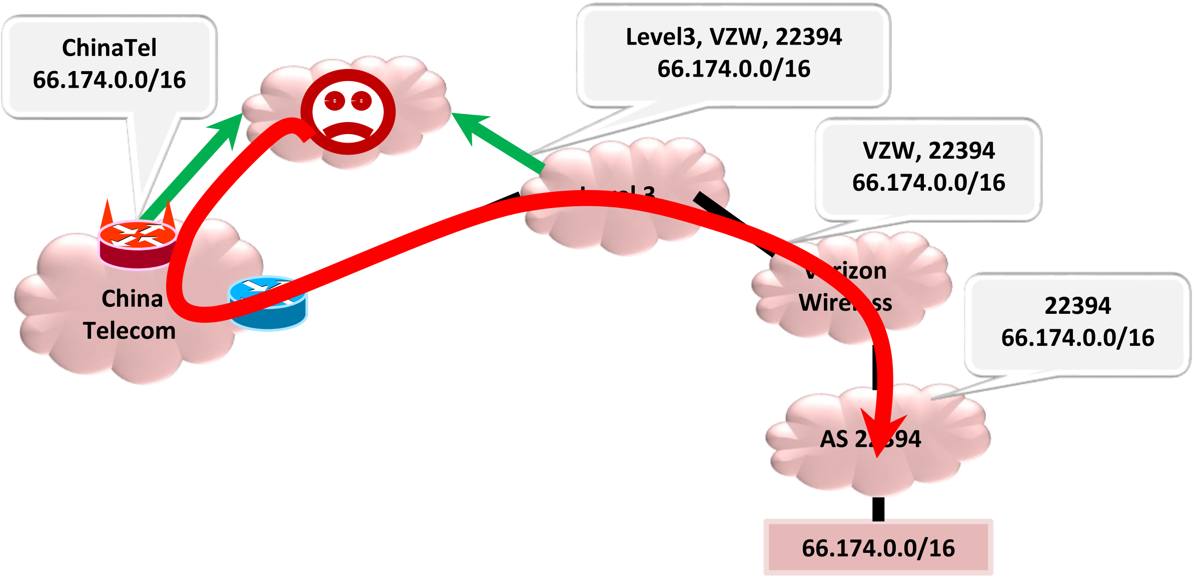

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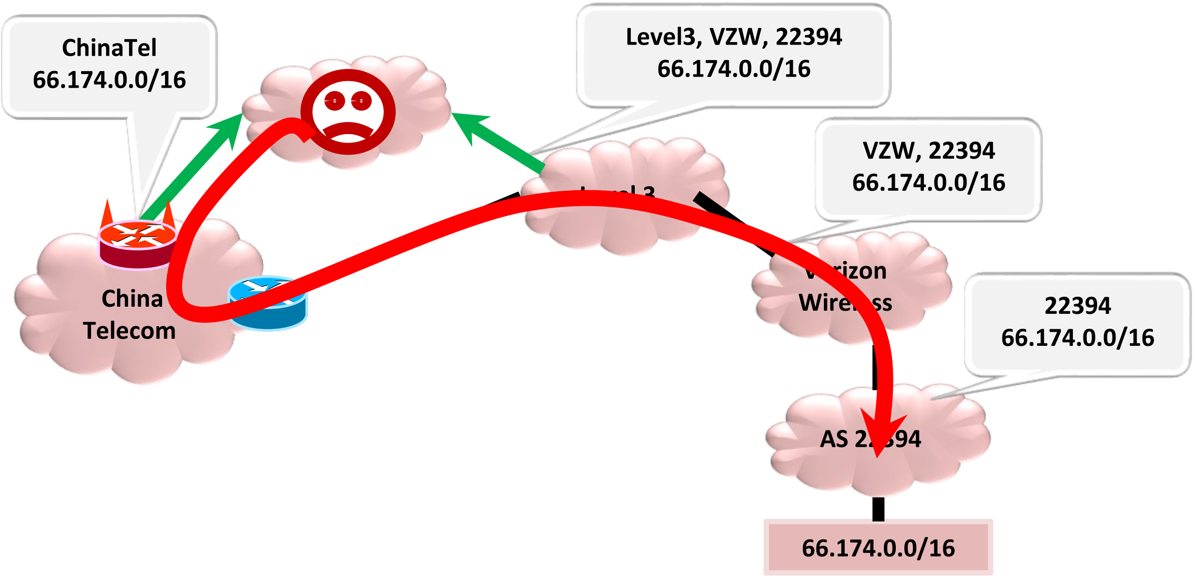

Interception typically results in differences between

- Announced AS-PATH
- Data path (traffic)

Policy checks if legit reason(s)

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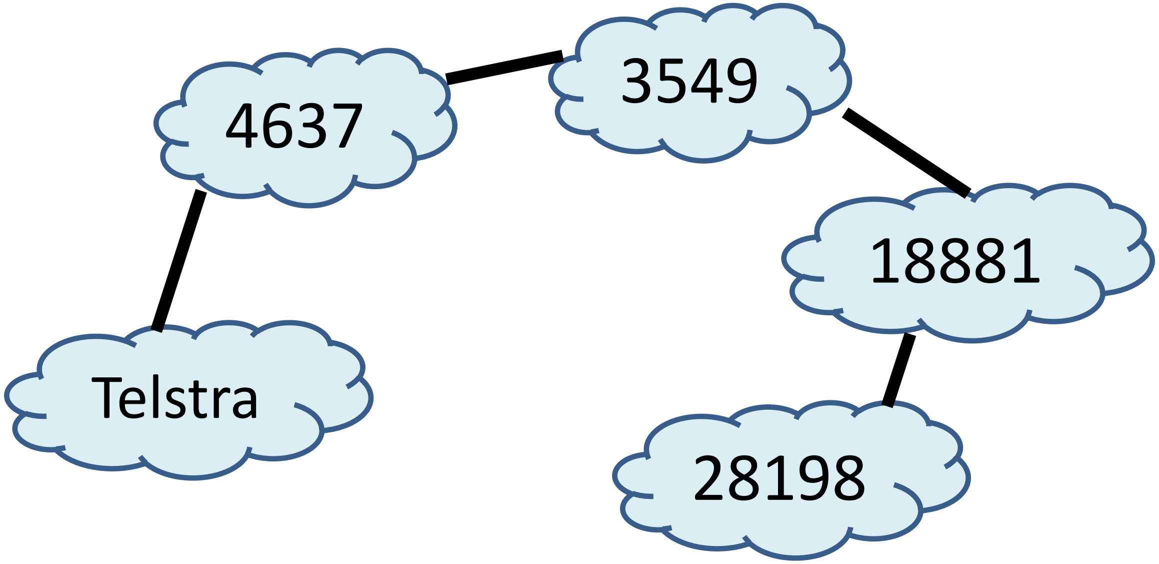
Traceroute vs Announced Path

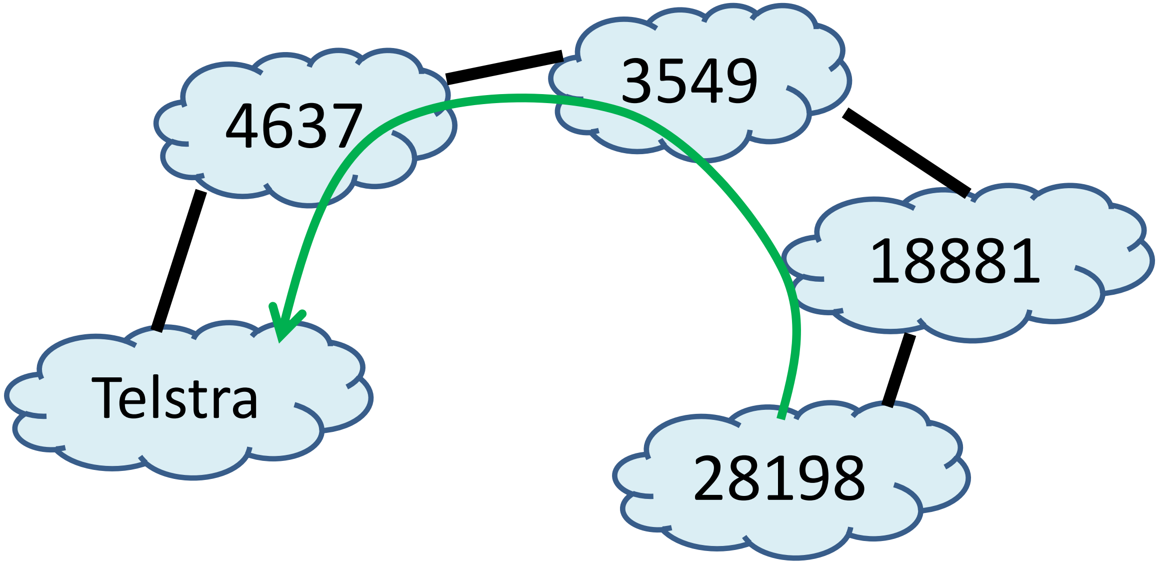


Sometimes differences

- Announced AS-PATH
- Data path (traffic)

Many legit reason(s)

Traceroute vs Announced Path



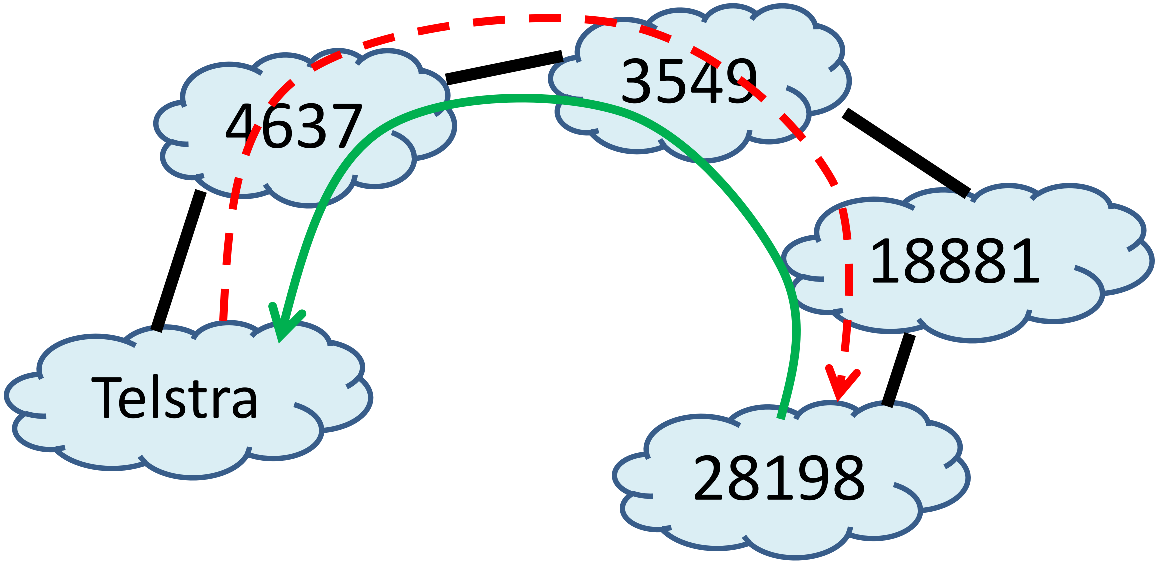
Sometimes differences

- Announced AS-PATH
- Data path (traffic)

Many legit reason(s)

AS-PATH: 177.52.48.0/21|1221 4637 3549 18881 28198

Traceroute vs Announced Path



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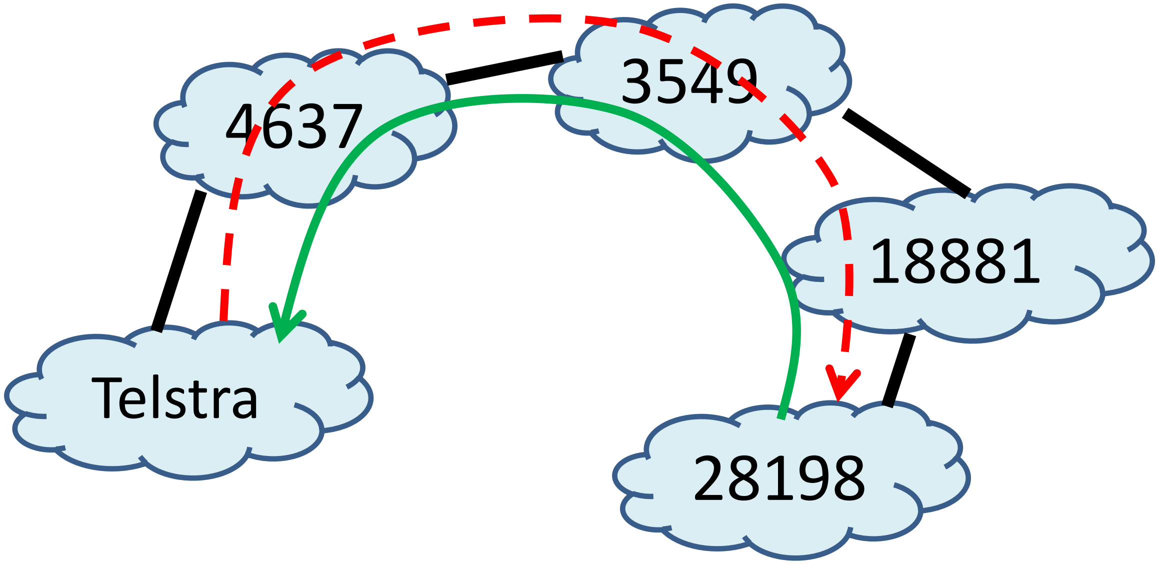
AS-PATH: 177.52.48.0/21|1221 4637 3549 18881 28198

Traceroute vs Announced Path



Sometimes differences

- Announced AS-PATH
- Data path (traffic)

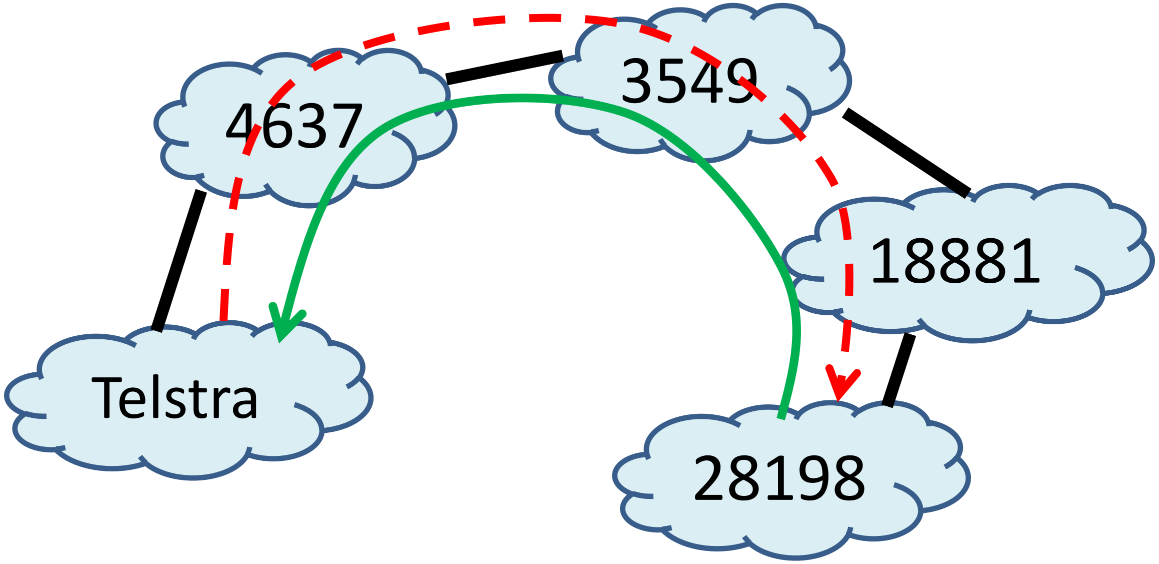
Many legit reason(s)

AS-PATH: 177.52.48.0/21|1221 4637 3549 18881 28198

Traceroute:

```
... (initial hops)
9.  telstraglobal.net (134.159.63.202)  164.905 ms
10  impsat.net.br (189.125.6.194)  337.434 ms
11  spo.gvt.net.br (187.115.214.217)  332.926 ms
12  spo.gvt.net.br (189.59.248.109)  373.021 ms
13  host.gvt.net.br (189.59.249.245)  343.685 ms
14  isimples.com.br (177.52.48.1)  341.172 ms
```

Traceroute vs Announced Path



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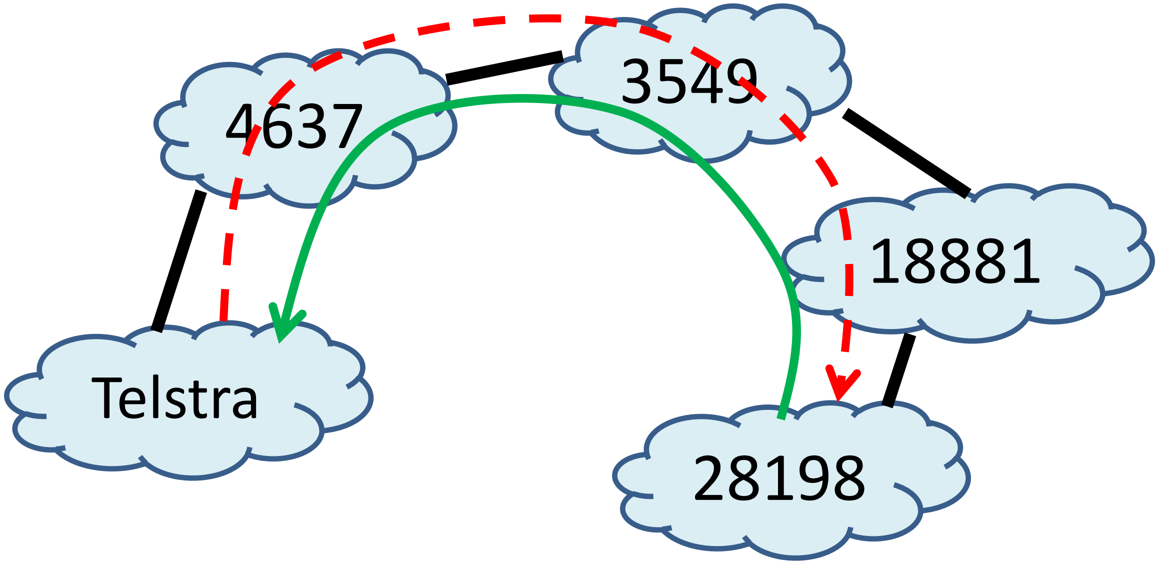
AS-PATH: 177.52.48.0/21|1221 4637 3549 18881 28198

AS HOPS in traceroute: 1221 1221 1221 1221 4637 4637 4637 4637 4637 3549 3549 3549 18881 18881 18881 18881 28198

Traceroute vs Announced Path



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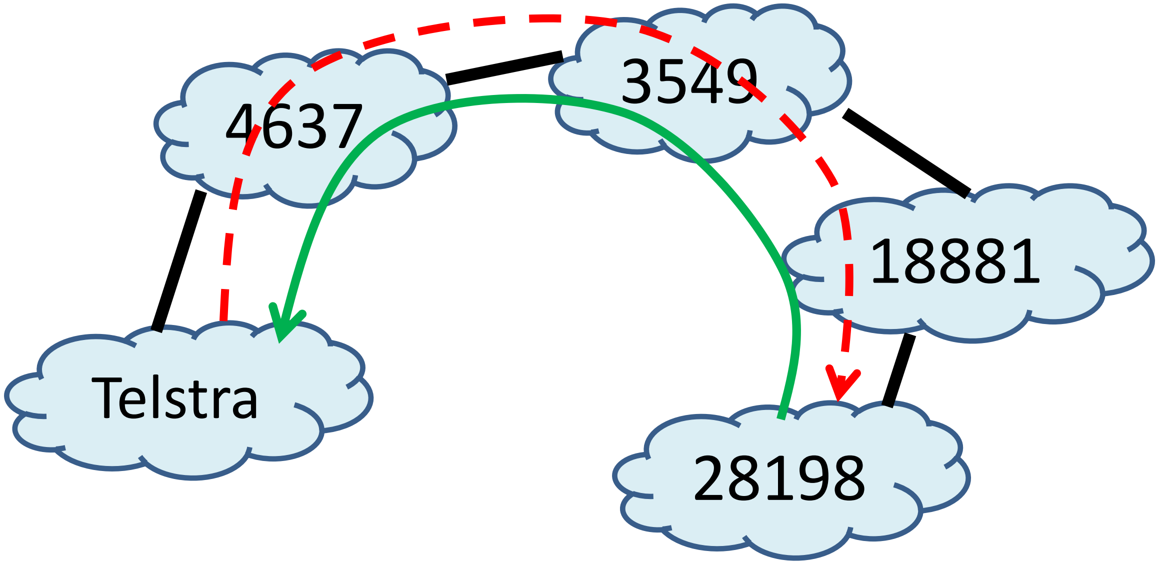
AS-PATH: 177.52.48.0/21|1221 4637 3549 18881 28198

AS HOPS in traceroute: 1221 1221 1221 1221 4637 4637 4637 4637 4637 3549 3549 3549 18881 18881 18881 18881 28198

Traceroute-PATH: 1221 4637 3549 18881 28198

Traceroute vs Announced Path



Sometimes differences

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AS-PATH: 177.52.48.0/21|1221 4637 3549 18881 28198

AS HOPS in traceroute: 1221 1221 1221 1221 4637 4637 4637 4637 4637 3549 3549 3549 18881 18881 18881 18881 28198

Traceroute-PATH: 1221 4637 3549 18881 28198