CSC 525:
Computer Networks

Why Network Topology?

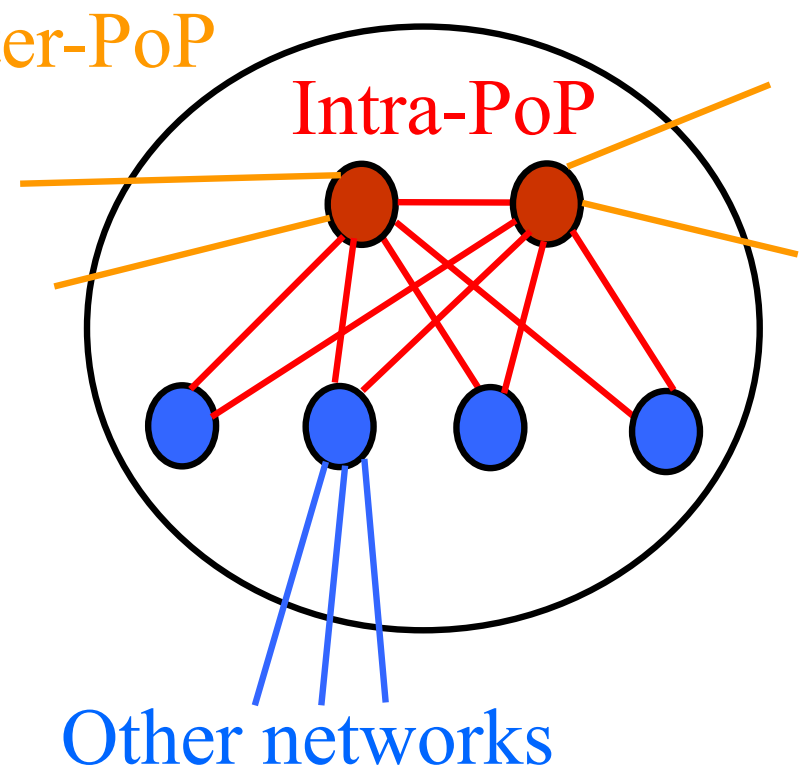
- Business analysis
  - Comparison with competitors
  - Selecting a provider or peer
- Scientific curiosity
  - Understand the structure and the evolution of large-scale, complex networks such as the Internet.
- Input to research studies
  - Network design, routing protocols, simulations …
- Interesting research problem in its own right
  - How to measure/infer the topology and its properties.

Network Topology

- A topology is a set of nodes and links.
- A node or link may represent different network entities, resulting in topologies of different granularity.
  - Switch
  - Router
  - PoP (Point of Presence)
  - AS (Autonomous System)
  - ISP

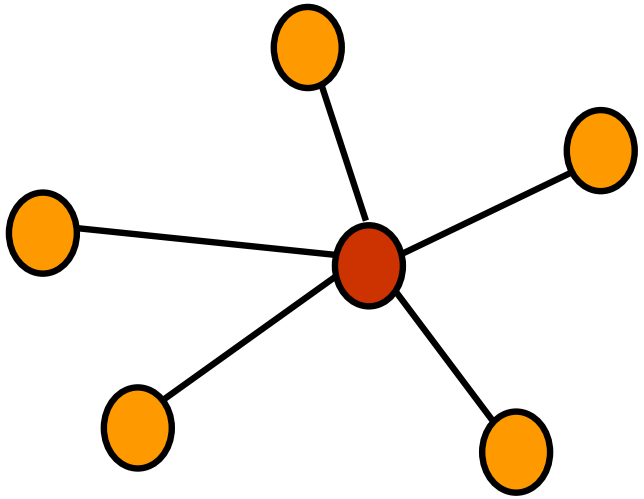
PoP (Point of Presence)

- Inter-PoP links
  - Long distances
  - High bandwidth
- Intra-PoP links
  - Short cables between racks or floors
  - Aggregated bandwidth
- Links to other networks
  - Wide range of media and bandwidth



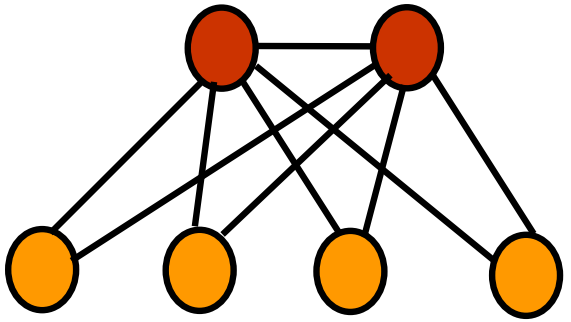
Hub-and-Spoke

- Single hub node
  - Common in enterprise networks
  - Main location and satellite sites
  - Simple design and trivial routing
- Problems (especially when the network is large)
  - Single point of failure
  - Bandwidth limitations
  - High delay between sites
  - Costs to backhaul to hub

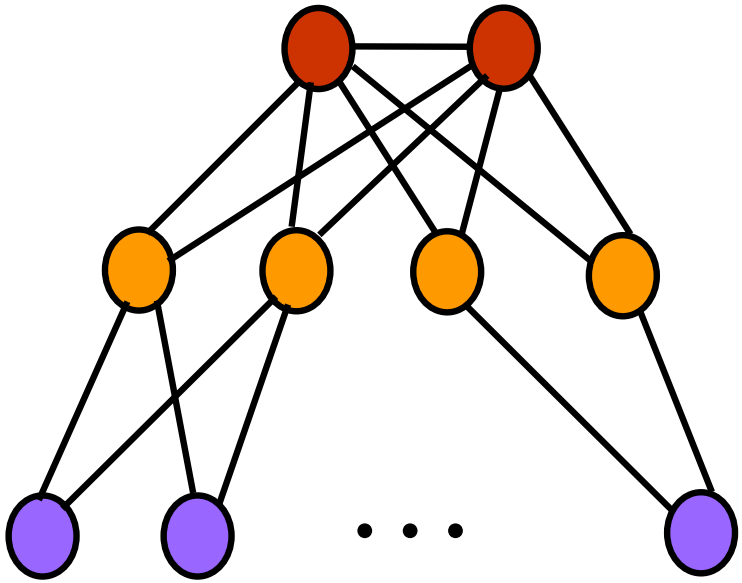


Simple Alternatives

- Dual hub-and-spoke
  - Higher reliability
  - Higher cost
  - Good building block



- Levels of hierarchy
  - Reduce backhaul cost
  - Aggregate the bandwidth
  - Shorter site-to-site delay

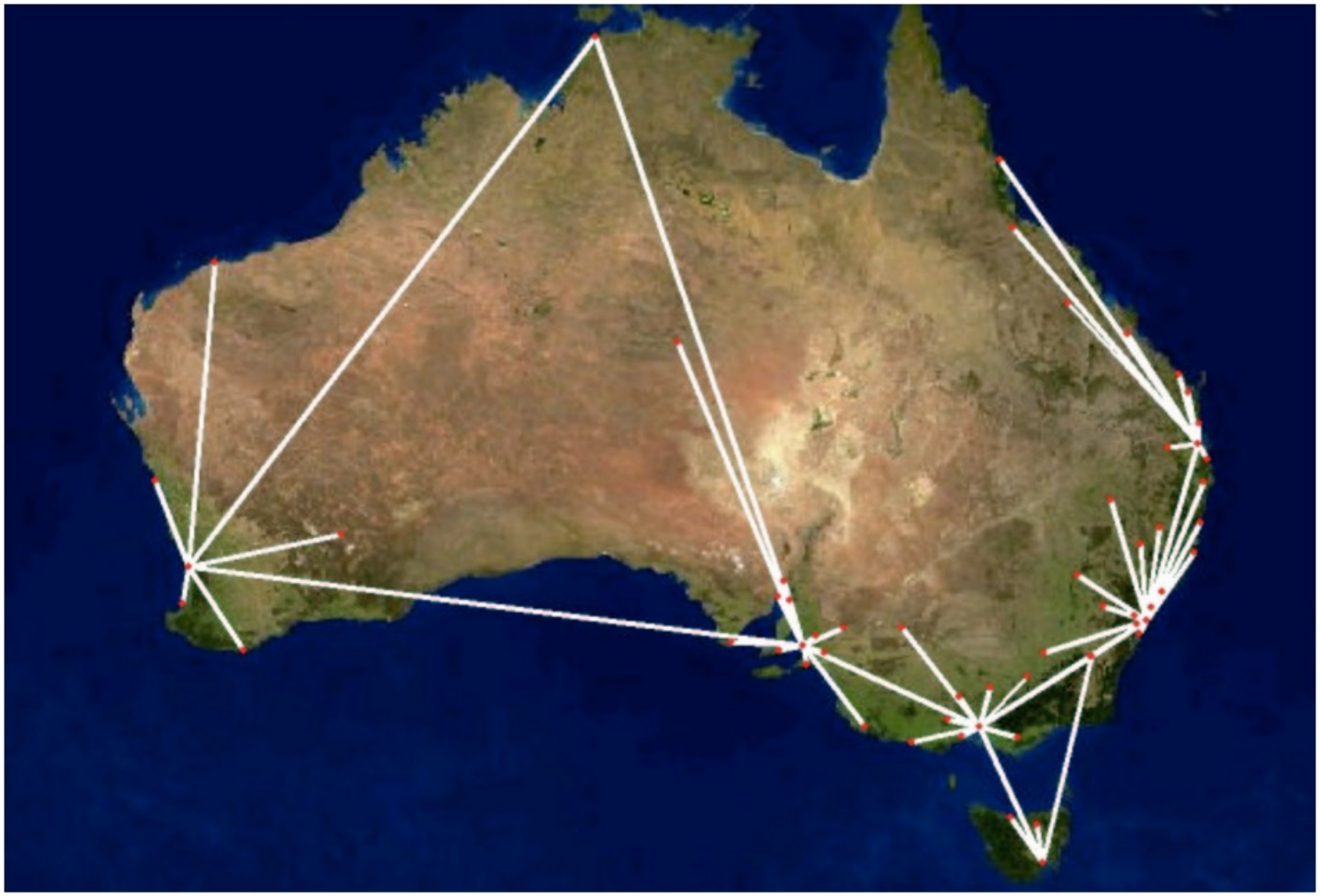


Backbone Networks

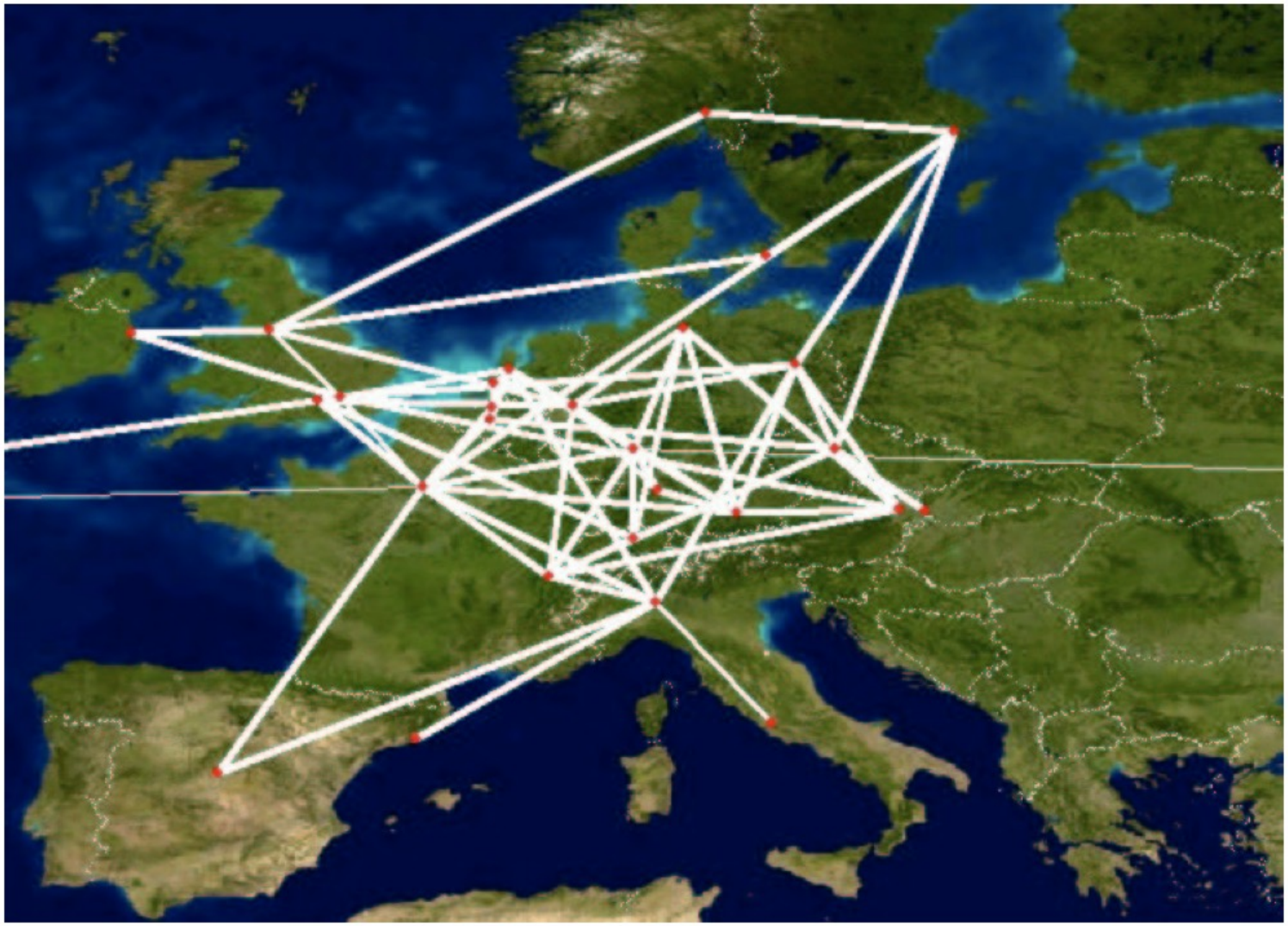
- Backbone networks
  - Multiple Points-of-Presence (PoPs)
  - Lots of communication between PoPs
  - Need to accommodate diverse traffic demands
  - Need to limit propagation delay

  - Take a great effort to design and provision the network, considering the financial costs, the projected traffic volume, and technical properties to ensure good quality of service.

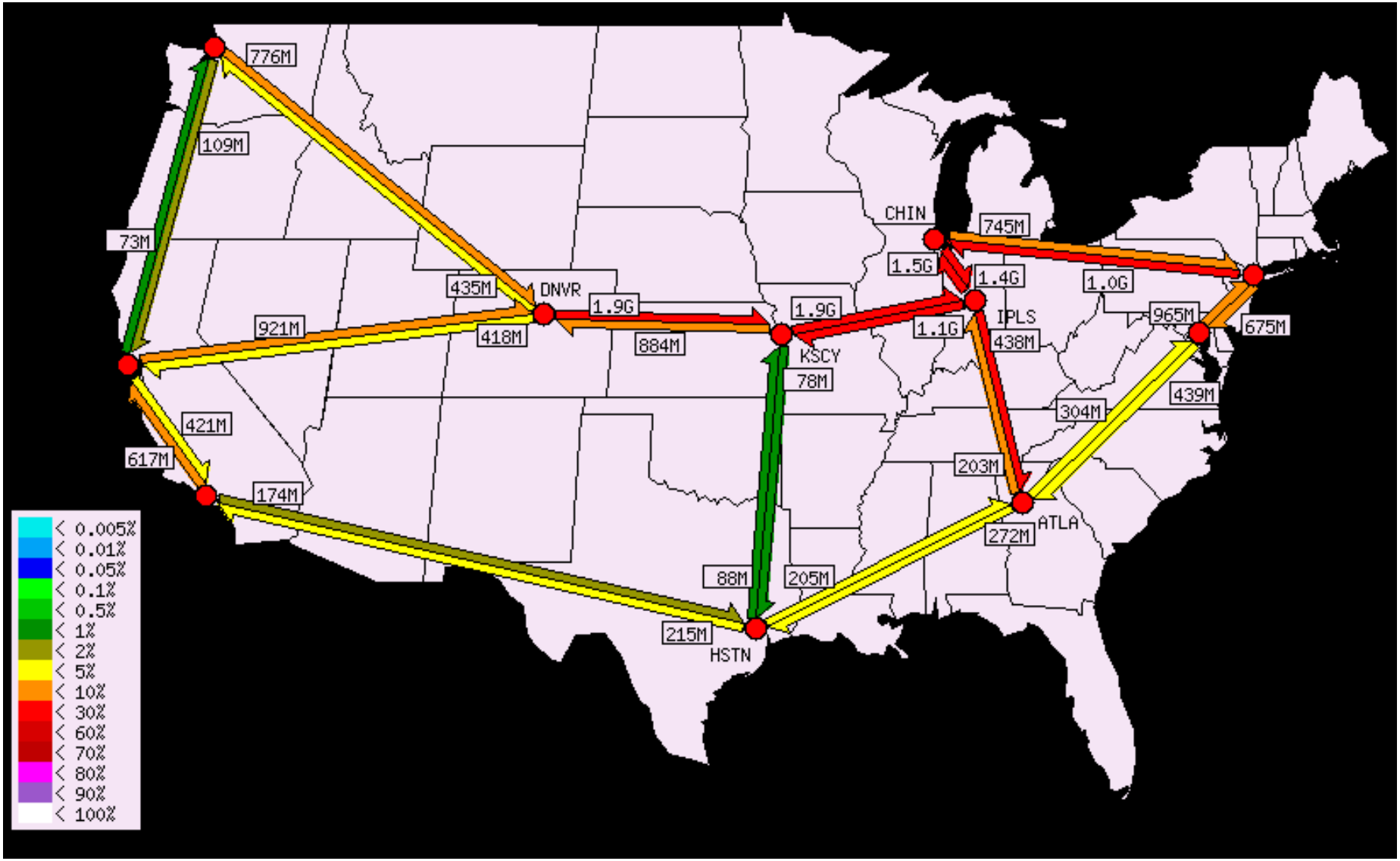
Telstra

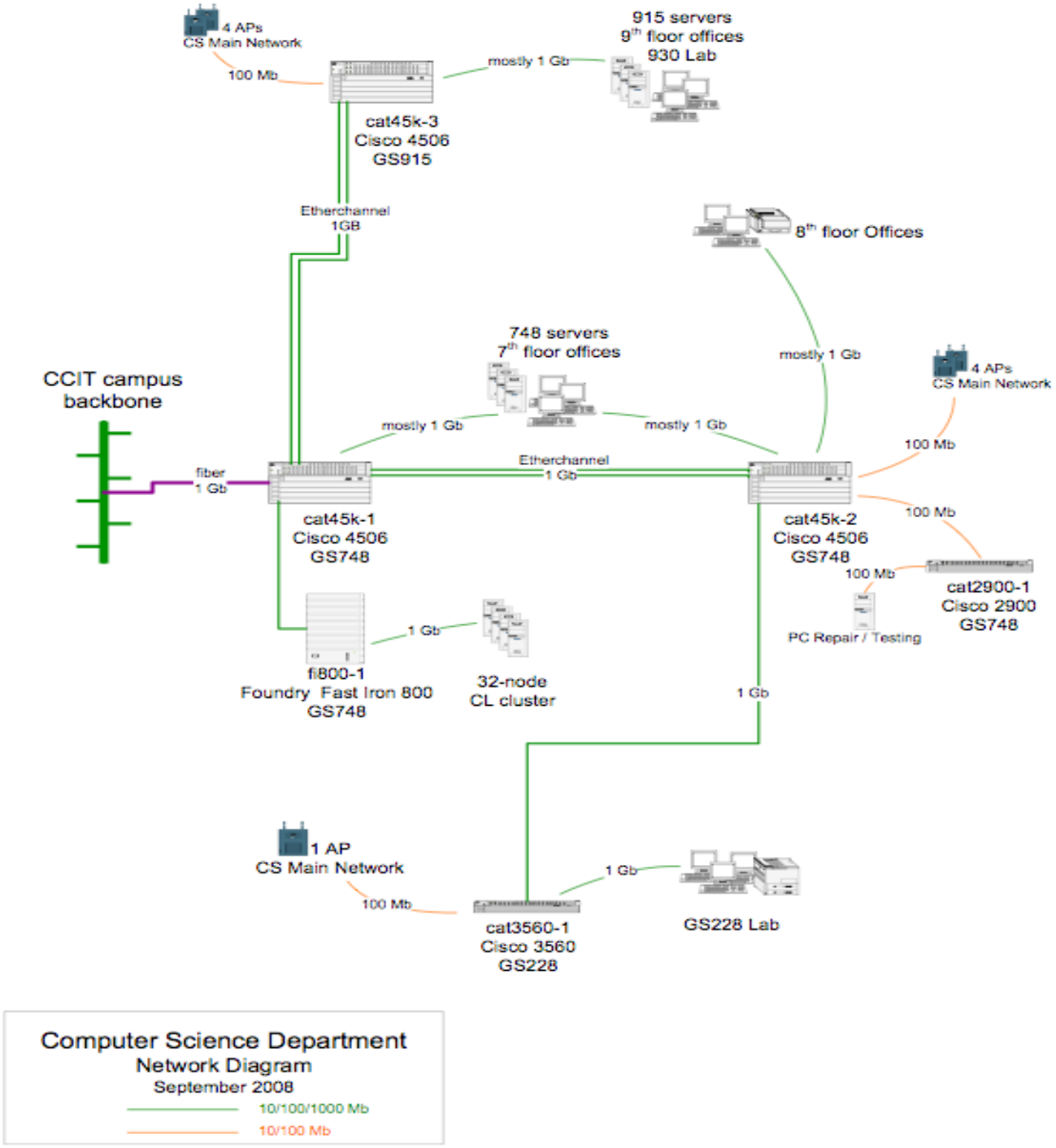


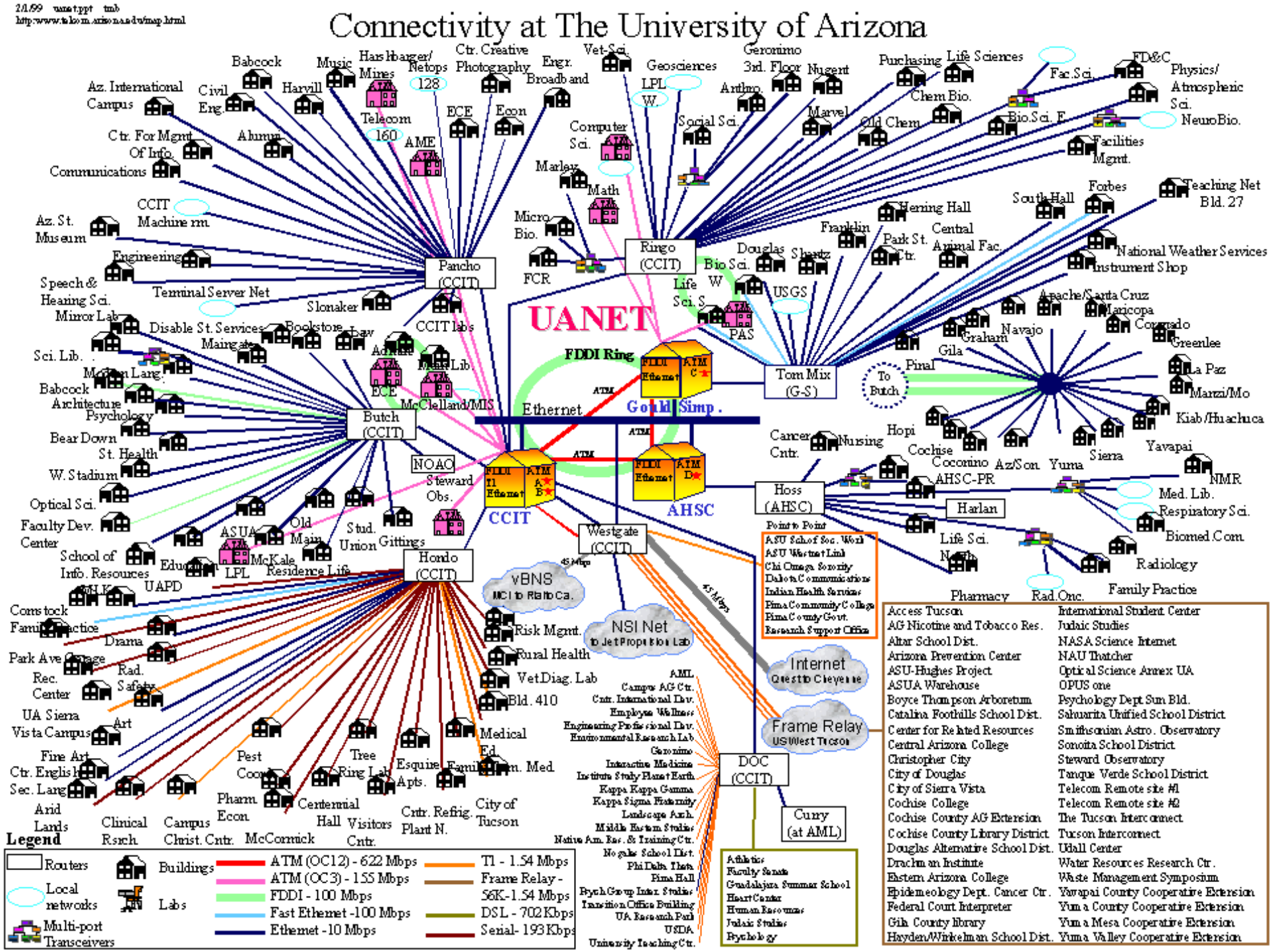
EBone



Abilene


776M
109M
73M
435M
DNVR
1.9G
921M
418M
884M
1.9G
CHIN
745M
1.5G
1.4G
1.0G
IPLS
965M
675M
1.1G
438M
KSCY
78M
439M
304M
421M
617M
203M
174M
ATLA
272M
88M
205M
215M
HSTN
< 0.005%
< 0.01%
< 0.05%
< 0.1%
< 0.5%
< 1%
< 2%
< 5%
< 10%
< 30%
< 60%
< 70%
< 80%
< 90%
< 100%


4 APs
CS Main Network
100 Mb
mostly 1 Gb
915 servers
9th floor offices
930 Lab
cat45k-3
Cisco 4506
GS915
Etherchannel
1GB
8th floor Offices
748 servers
7th floor offices
mostly 1 Gb
mostly 1 Gb
mostly 1 Gb
4 APs
CS Main Network
100 Mb
CCIT campus
backbone
fiber
1 Gb
Etherchannel
1 Gb
cat45k-1
Cisco 4506
GS748
cat45k-2
Cisco 4506
GS748
100 Mb
100 Mb
cat2900-1
Cisco 2900
GS748
PC Repair / Testing
1 Gb
fi800-1
Foundry Fast Iron 800
GS748
32-node
CL cluster
1 Gb
1 AP
CS Main Network
100 Mb
1 Gb
cat3560-1
Cisco 3560
GS228
GS228 Lab
Computer Science Department
Network Diagram
September 2008
10/100/1000 Mb
10/100 Mb


2/1/99 uanet.ppt tmb
http:www.telcom.arizona.edu/map.html
Connectivity at The University of Arizona
UANET
FDDI Ring
Ethernet
Gould Simp.
ATM
CCIT
AHSC
NOAO
Steward Obs.
Pancho (CCIT)
Ringo (CCIT)
Butch (CCIT)
Hondo (CCIT)
Westgate (CCIT)
Tom Mix (G-S)
Hoss (AHSC)
DOC (CCIT)
Curry (at AML)
Babcock
Music
Harshbarger/ Mines
Netops 128
Ctr. Creative Photography
Engr. Broadband
Vet Sci.
Geosciences
LPL W.
Geronimo 3rd. Floor
Nugent
Purchasing
Life Sciences
Fac.Sci.
FD&C
Physics/ Atmospheric Sci.
NeuroBio.
Facilities Mgmt.
Az. International Campus
Civil Eng.
Harvill
Telecom 160
ECE
Econ
AME
Computer Sci.
Social Sci.
Anthro.
Marvel
Old Chem
Chem Bio.
Bio.Sci. E
Ctr. For Mgmt Of Info.
Alumni
Communications
Marley
Math
Micro Bio.
FCR
CCIT Machine rm.
Az. St. Museum
Engineering
Speech & Hearing Sci.
Terminal Server Net
Slonaker
CCIT labs
Mirror Lab
Disable St. Services
Bookstore
Law
Maingate
Sci. Lib.
McClelland Lang.
Babcock
Architecture
Psychology
Bear Down
St. Health
W. Stadium
Optical Sci.
Faculty Dev. Center
School of Info. Resources
Admin
Main Lib
ECE
McClelland/MIS
Life Sci. S
Bio Sci. W
USGS
PAS
Douglas
Shantz
Franklin
Park St. Ctr.
Central Animal Fac.
Hering Hall
South Hall
Forbes
Teaching Net Bld. 27
National Weather Services
Instrument Shop
Apache/Santa Cruz
Maricopa
Navajo
Graham
Gila
Pinal
Greenlee
La Paz
Marizi/Mo
Kiab /Huachuca
Yavapai
Sierra
Yuma
Az/Son.
Cochise
Cocorino
AHSC-PR
Hopi
Cancer Cntr.
Nursing
NMR
Med. Lib.
Respiratory Sci.
Biomed.Com.
Radiology
Family Practice
Rad.Onc.
Pharmacy
Harlan
Life Sci. North
To Butch
ASUA
Old Main
Stud. Union
Gittings
McKale
Residence Life
LPL
UAPD
Educ.
Comstock Family Practice
Drama
Park Ave Garage
Rec. Center
Rad. Safety
UA Sierra Vista Campus
Art
Fine Art
Ctr. English as a Sec. Lang
Arid Lands
Clinical Rsrch.
Campus Christ. Cntr.
McCormick
Pharm. Econ.
Pest Control
Centennial Hall
Visitors Cntr.
Tree Ring Lab
Esquire Apts.
Cntr. Refrig. Plant N.
City of Tucson
Medical Ed.
Fam. Hlth. Med.
Bld. 410
Vet Diag. Lab
Rural Health
Risk Mgmt.
vBNS
MCI to Rsrch Ca.
NSI Net
to Jet Propulsion Lab
Internet
Qwest to Cheyenne
Frame Relay
US West Tucson
45 Mbps
AML
Campus AG Ctr.
Cntr. International Dev.
Employee Wellness
Engineering Professional Dev.
Environmental Research Lab
Geronimo
Interactive Medicine
Institute Study Planet Earth
Kappa Kappa Gamma
Kappa Sigma Fraternity
Landscape Arch.
Middle Eastern Studies
Native Am. Res. & Training Ctr.
Nogales School Dist.
Phi Delta Theta
Pima Hall
Psych Group Inter. Studies
Transition Office Building
UA Research Park
USDA
University Teaching Ctr.
Athletics
Faculty Senate
Guadalajara Summer School
Heart Center
Human Resources
Judaic Studies
Psychology
Point to Point
ASU School Soc. Work
ASU Westnet Link
Chi Omega Sorority
Dakota Communications
Indian Health Service
Pima Community College
Pima County Govt.
Research Support Office
Access Tucson
AG Nicotine and Tobacco Res.
Altar School Dist.
Arizona Prevention Center
ASU-Hughes Project
ASUA Warehouse
Boyce Thompson Arboretum
Catalina Foothills School Dist.
Center for Related Resources
Central Arizona College
Christopher City
City of Douglas
City of Sierra Vista
Cochise College
Cochise County AG Extension
Cochise County Library District
Douglas Alternative School Dist.
Drachman Institute
Eastern Arizona College
Epidemeology Dept. Cancer Ctr.
Federal Court Interpreter
Gila County library
Hayden/Winkelman School Dist.
International Student Center
Judaic Studies
NASA Science Internet
NAU Thatcher
Optical Science Annex UA
OPUS one
Psychology Dept Sun Bld.
Sahuarita Unified School District
Smithsonian Astro. Observatory
Sonoita School District
Steward Observatory
Tanque Verde School District
Telecom Remote site #1
Telecom Remote site #2
The Tucson Interconnect
Tucson Interconnect
Udall Center
Water Resources Research Ctr.
Waste Management Symposium
Yavapai County Cooperative Extension
Yuma County Cooperative Extension
Yuma Mesa Cooperative Extension
Yuma Valley Cooperative Extension
Legend
Routers
Local networks
Multi-port Transceivers
Buildings
Labs
ATM (OC12) - 622 Mbps
ATM (OC3) - 155 Mbps
FDDI - 100 Mbps
Fast Ethernet -100 Mbps
Ethernet -10 Mbps
T1 - 1.54 Mbps
Frame Relay - 56K-1.54 Mbps
DSL - 702Kbps
Serial- 193Kbps

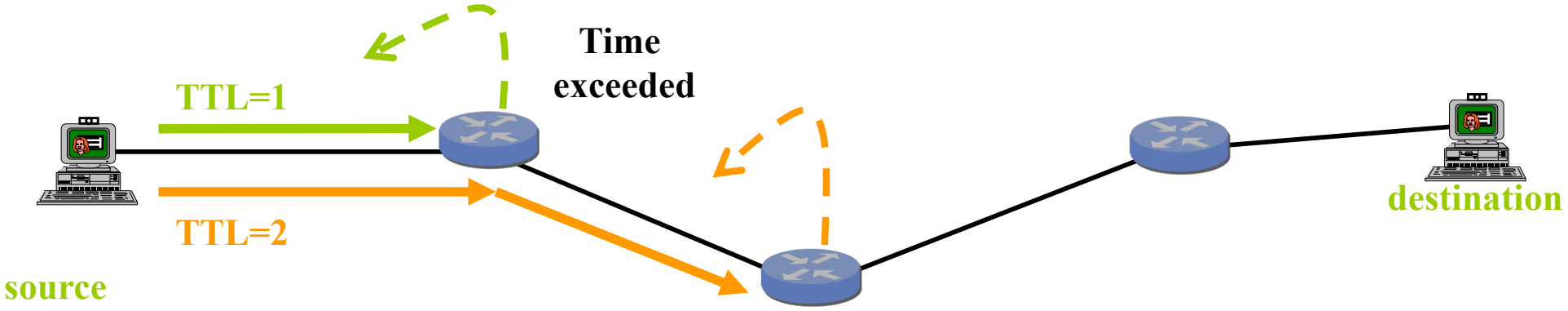
Topology Measurement

- Active Probing
  - E.g., traceroute probes
  - Better control on what to measure and when to measure.
  - Security concerns
  - Miss transient changes.

- Passive Collection
  - E.g, BGP monitoring
  - Always at work, receive all changes.
  - Only see what the routing protocol presents
  - Deployment is more difficult.

Traceroute

- Measuring the forwarding path
- Time-To-Live field in IP packet header
  - Source sends a packet with a TTL of *n*
  - Each router along the path decrements the TTL
  - "TTL exceeded" sent back when TTL reaches *0*
- Traceroute exploits this TTL behavior



Send packets with TTL=1, 2, 3, … and record source of "TTL exceeded" mesg

Example Output

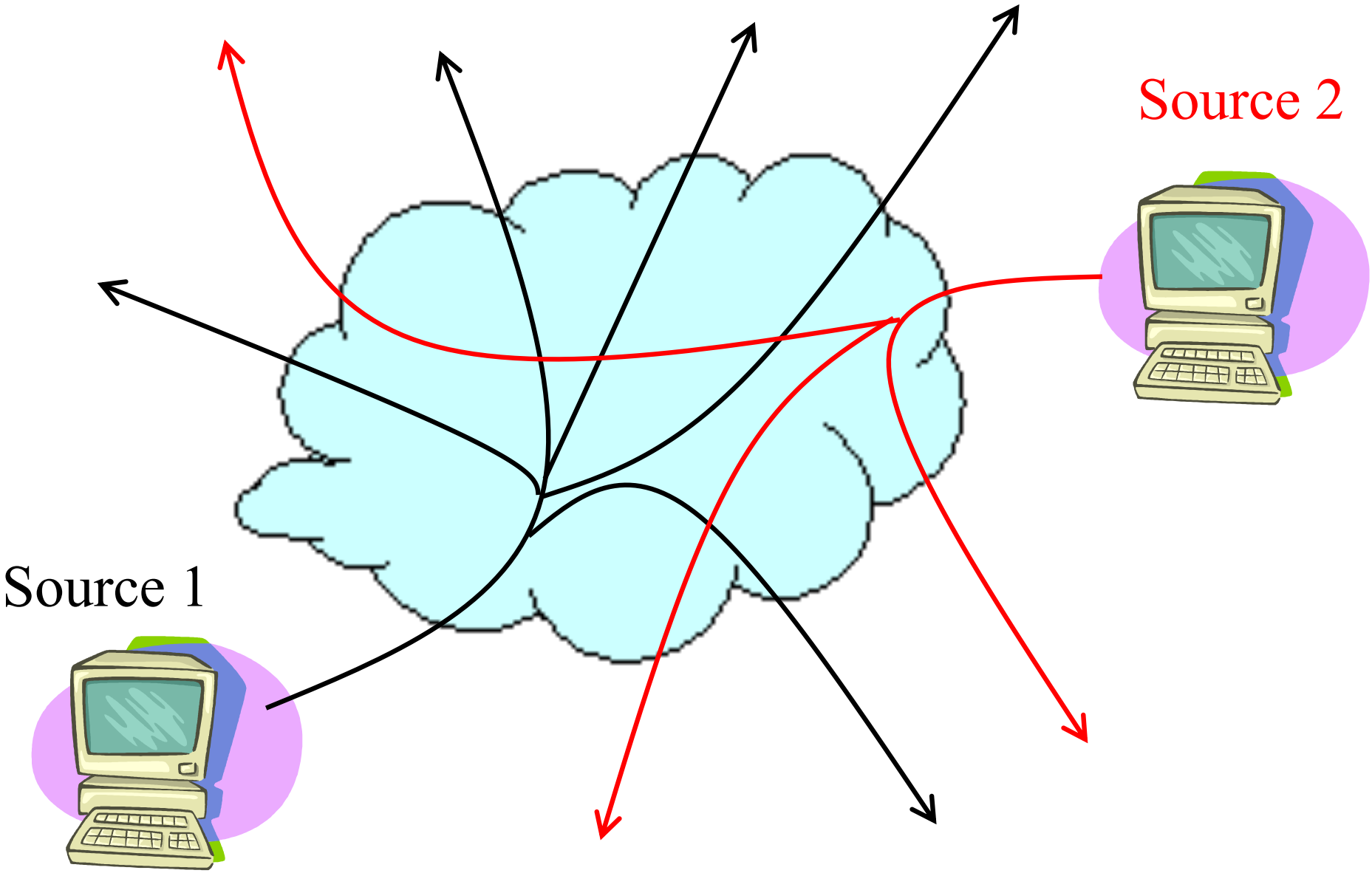
Hop number, IP address, DNS name

```
 1  169.229.62.1      inr-daedalus-0.CS.Berkeley.EDU
 2  169.229.59.225    soda-cr-1-1-soda-br-6-2
 3  128.32.255.169    vlan242.inr-202-doecev.Berkeley.EDU
 4  128.32.0.249      gigE6-0-0.inr-666-doecev.Berkeley.EDU
 5  128.32.0.66       qsv-juniper--ucb-gw.calren2.net
 6  209.247.159.109   POS1-0.hsipaccess1.SanJose1.Level3.net
 7  *                 ?
 8  64.159.1.46       ?
 9  209.247.9.170     pos8-0.hsa2.Atlanta2.Level3.net
10  66.185.138.33     pop2-atm-P0-2.atdn.net
11  *                 ?
12  66.185.136.17     pop1-atl-P4-0.atdn.net
13  64.236.16.52      www4.cnn.com
```

No response from router

No name resolution

Measure ISP topology from Many Angles



Where to Get Sources and Dests?

- Source machines
  - Get accounts in many places
    - Good to have a lot of friends
  - Use an infrastructure like PlanetLab
    - Good to have friends who have lots of friends
  - Use public traceroute servers (http://www.traceroute.org)
    - Be nice to others
- Destination addresses to traceroute
  - Walk through the IP address space
    - One (or a few) IP addresses per prefix
  - Learn destination prefixes from public BGP tables
    - http://www.route-views.org

Problem with Traceroute

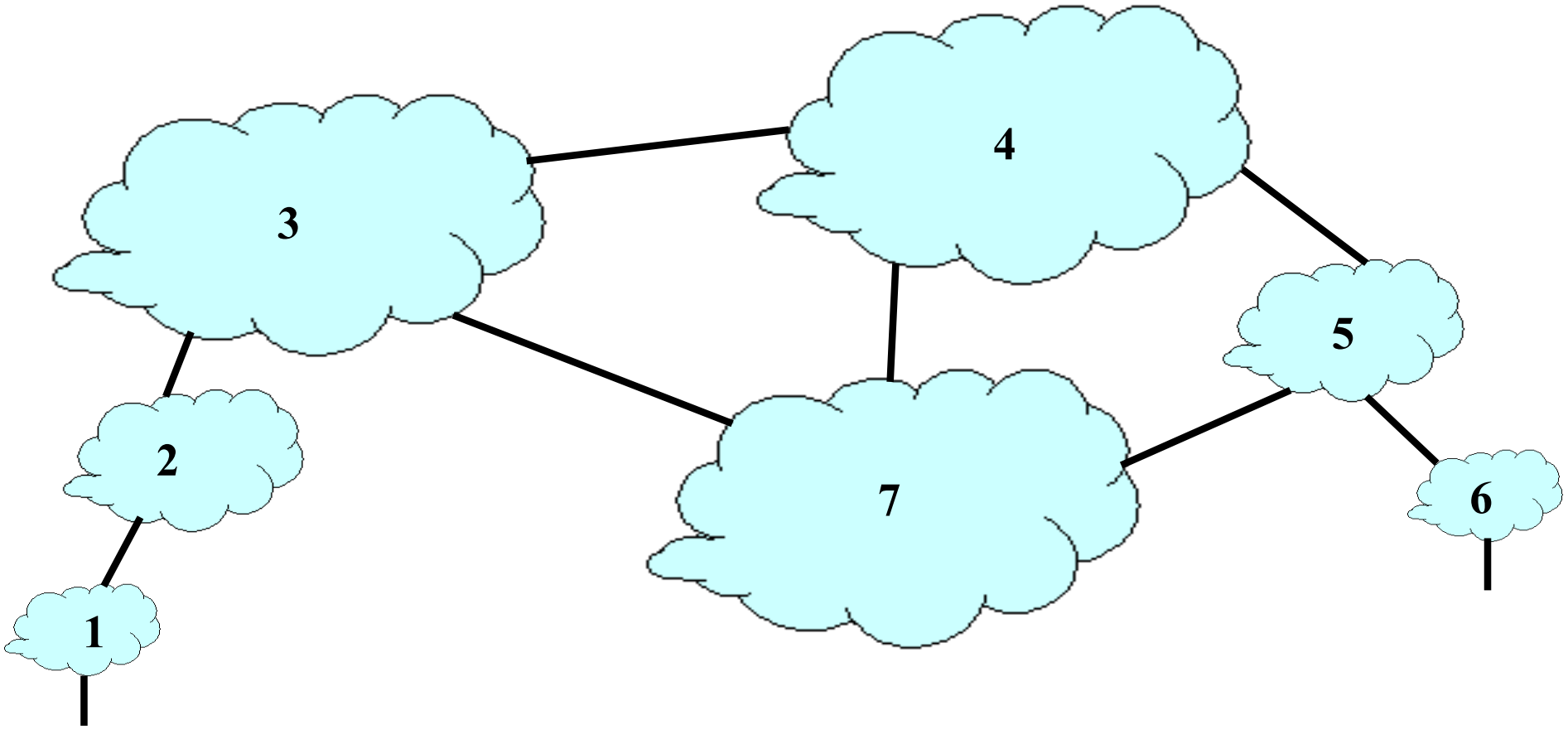
- Missing responses
  - Routers might not send "Time-Exceeded"
  - Firewalls may drop the probe packets
  - "Time-Exceeded" reply may be dropped
- Alias resolution
  - Mapping multiple interfaces to the same router
- Misleading IP addresses
  - How to map routers to an AS
- Angry operators who think this is an attack
  - Common problem with active probing
- It'll miss transient topological changes between probes.

Projects based on Traceroute

- Skitter/Ark
  - Global Internet topology
  - http://www.caida.org/tools/measurement/skitter/
- Rocketfuel
  - Individual ISP topology
  - http://www.cs.washington.edu/research/networking/rocketfuel/

AS Graph

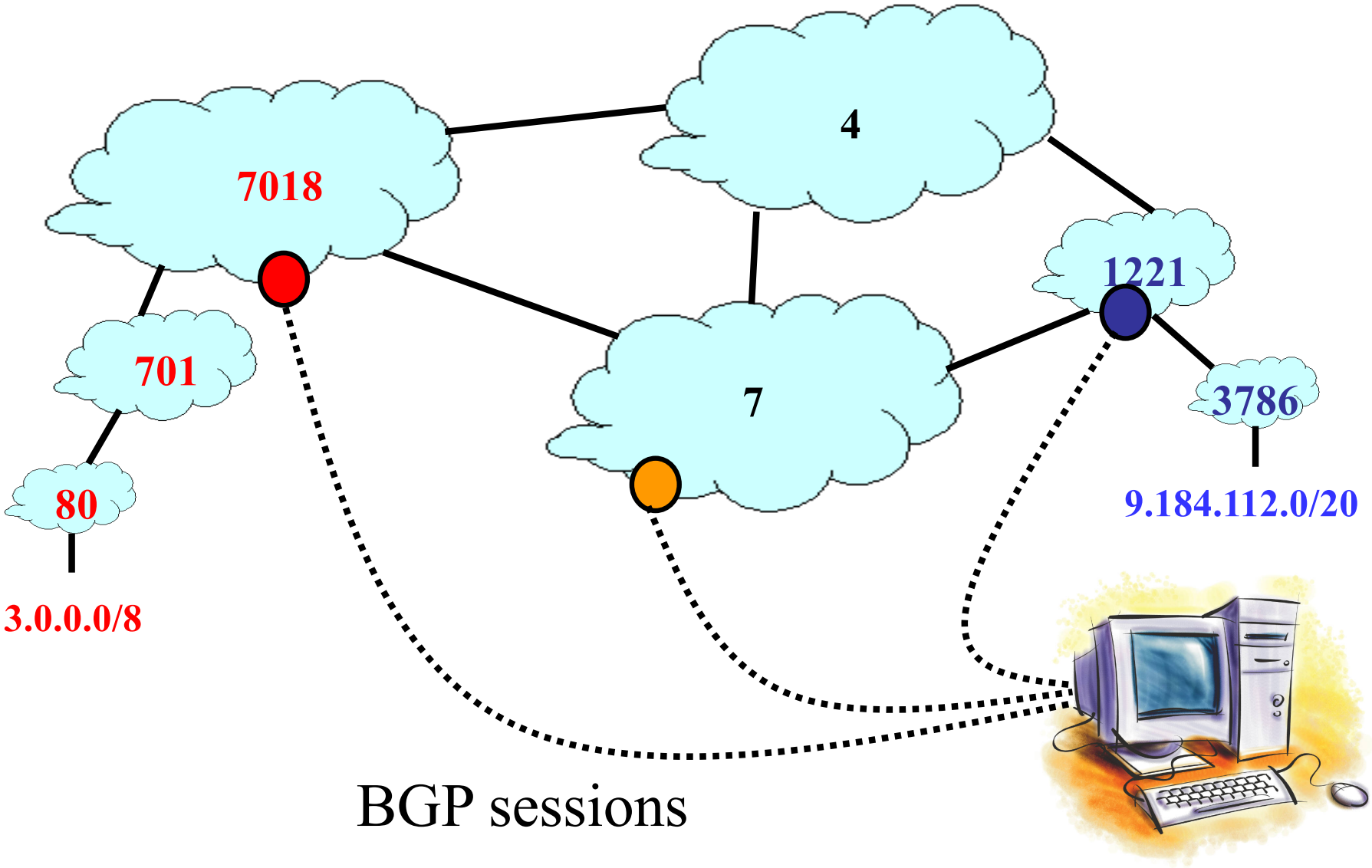
- Node: Autonomous System
- Link: between two ASes that speak BGP to each other
  - May correspond to multiple physical links or BGP sessions.



How to Discover a Node or Link?

- Consult the Registration Databases
  - WHOIS (IP, AS number, domain name, etc.)
  - Often out-of-date and/or incomplete
- Convert from traceroute results
  - Be careful of many pitfalls in converting IP addr to AS #.
- Extract from BGP routing data
  - Collect AS paths seen from routing data
  - Extract all the nodes and links
    - AS path "7018 1 88" implies that Nodes: 7018, 1, and 88, and links: (7018, 1) and (1, 88)
  - AS Path != Router Path

Public BGP Collectors



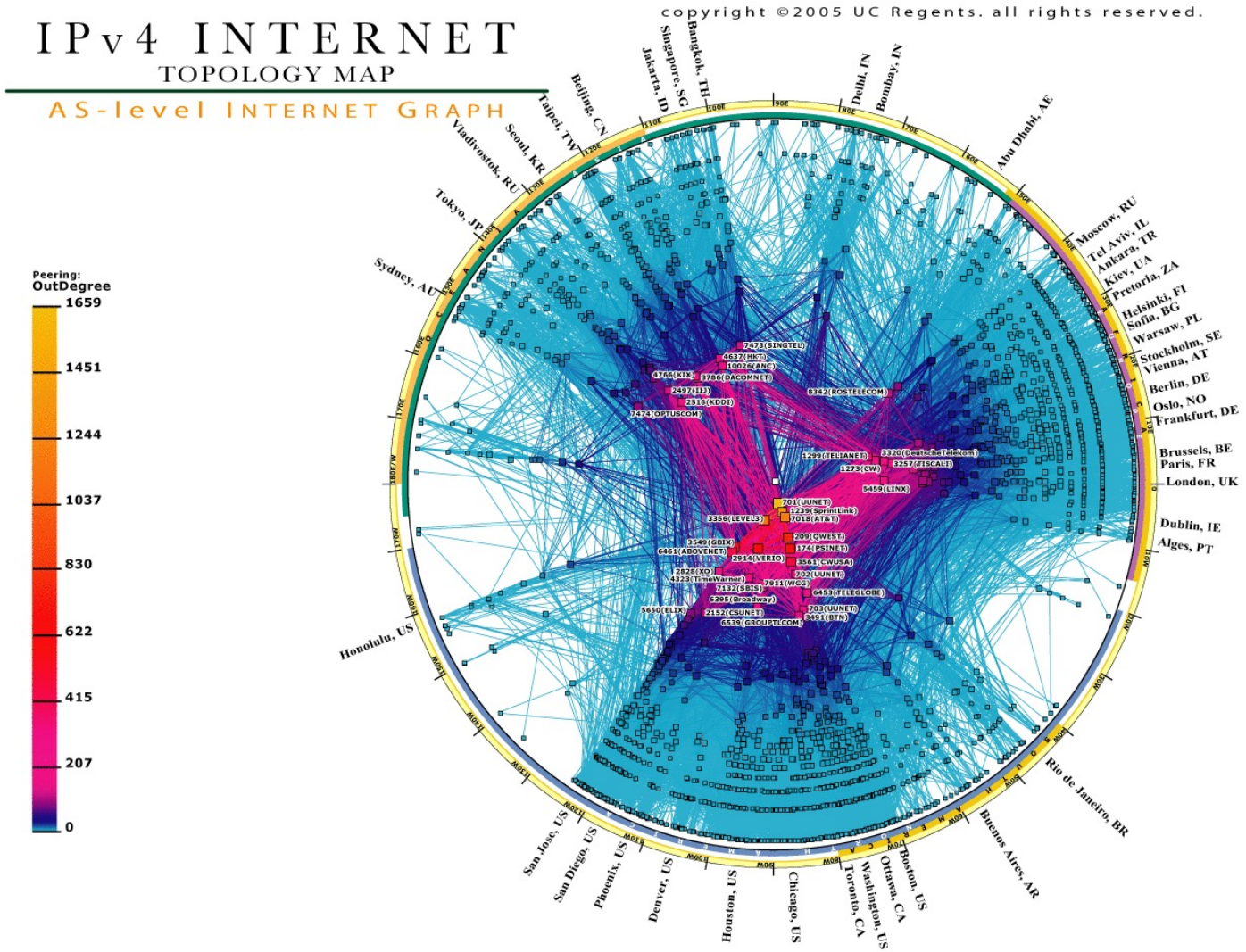
Sample BGP Table

Network	Next Hop	Metric	LocPrf	Weight	Path
* 3.0.0.0/8	205.215.45.50			0	4006 701 80 i
*	167.142.3.6			0	5056 701 80 i
*	157.22.9.7			0	715 1 701 80 i
*	195.219.96.239			0	8297 6453 701 80 i
*	195.211.29.254			0	5409 6667 6427 3356 701 80 i
*>	12.127.0.249			0	7018 701 80 i
*	213.200.87.254			0	3257 701 80 i
* 9.184.112.0/20	205.215.45.50			0	4006 6461 3786 i
*	195.66.225.254			0	5459 6461 3786 i
*>	203.62.248.4			0	1221 3786 i
*	167.142.3.6			0	5056 6461 6461 3786 i

Try it at home:
- telnet route-views.routeviews.org
- show ip bgp

Internet AS Topology Graph

(from CAIDA)



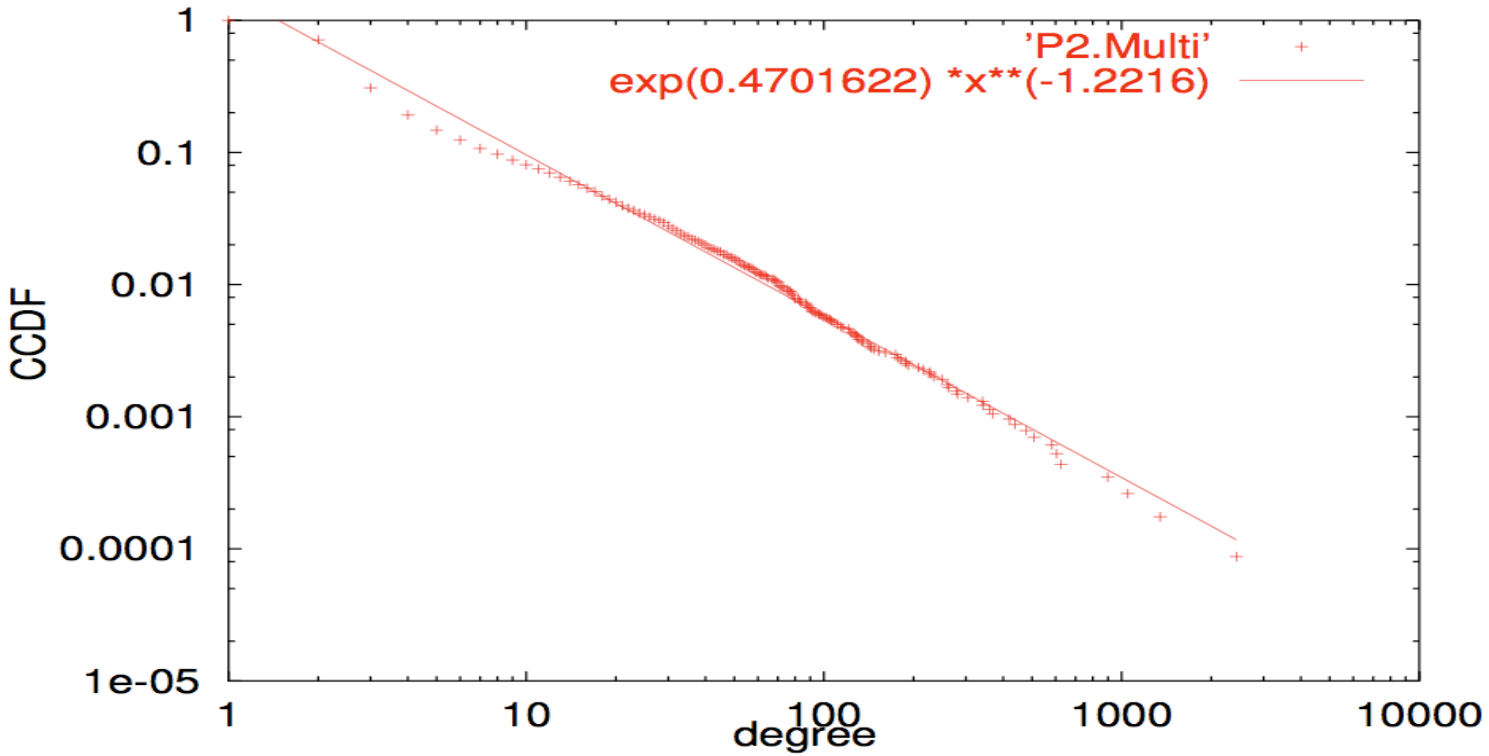
Power Laws

- Some (macroscopic) topological properties can be expressed in the form $y \propto x^a$
  - Faloutsos, Faloutsos, Faloutsos [1999]
  - Changed our view of Internet topology
    - Earlier work assume some random network topologies.
- The power laws hold over time.
- Power laws are common in many large-scale self-organizing systems

Degree Distribution

Power-Law 2 (degree exponent)
Given a graph, the CCDF, D_d, of an degree, d, is proportional to the degree to the power of a constant, $\mathcal{D}$:

$$D_d \propto d^{\mathcal{D}}$$



Degree Rank, Eigenvalue

Power-Law 1 (rank exponent) *Given a graph, the degree, d_v, of a node v, is proportional to the rank of the node, r_v, to the power of a constant, $\mathcal{R}$:*

$$d_v \propto r_v^{\mathcal{R}}$$

Power-Law 3 (eigen exponent) *Given a graph, the eigenvalues, λ_i, are proportional to the order, i, to the power of a constant, $\mathcal{E}$:*

$$\lambda_i \propto i^{\mathcal{E}}$$

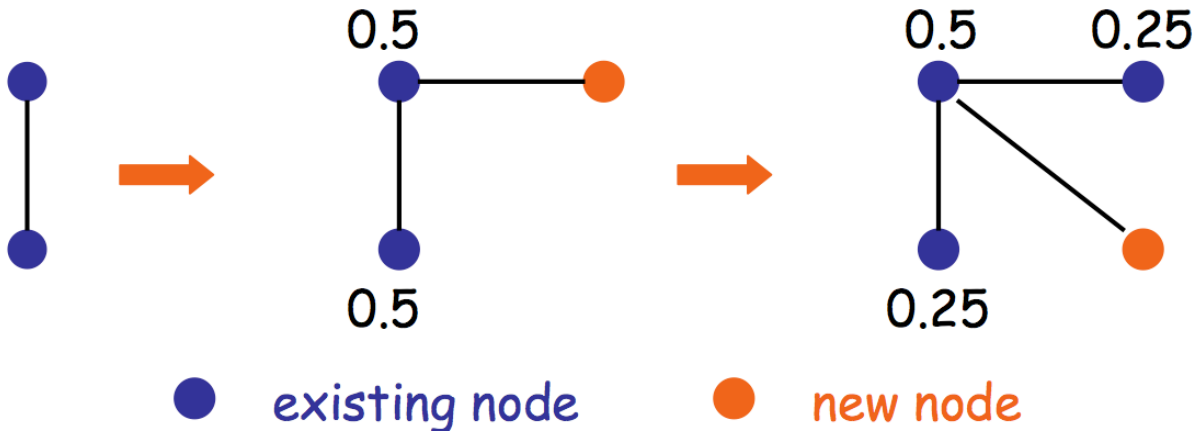
Implications

- The majority of nodes have small degrees.
- A non-trivial number of nodes has very large degrees.

- Very resilient against random failures/attacks.
- Vulnerable to targeted attacks.
  - Really?

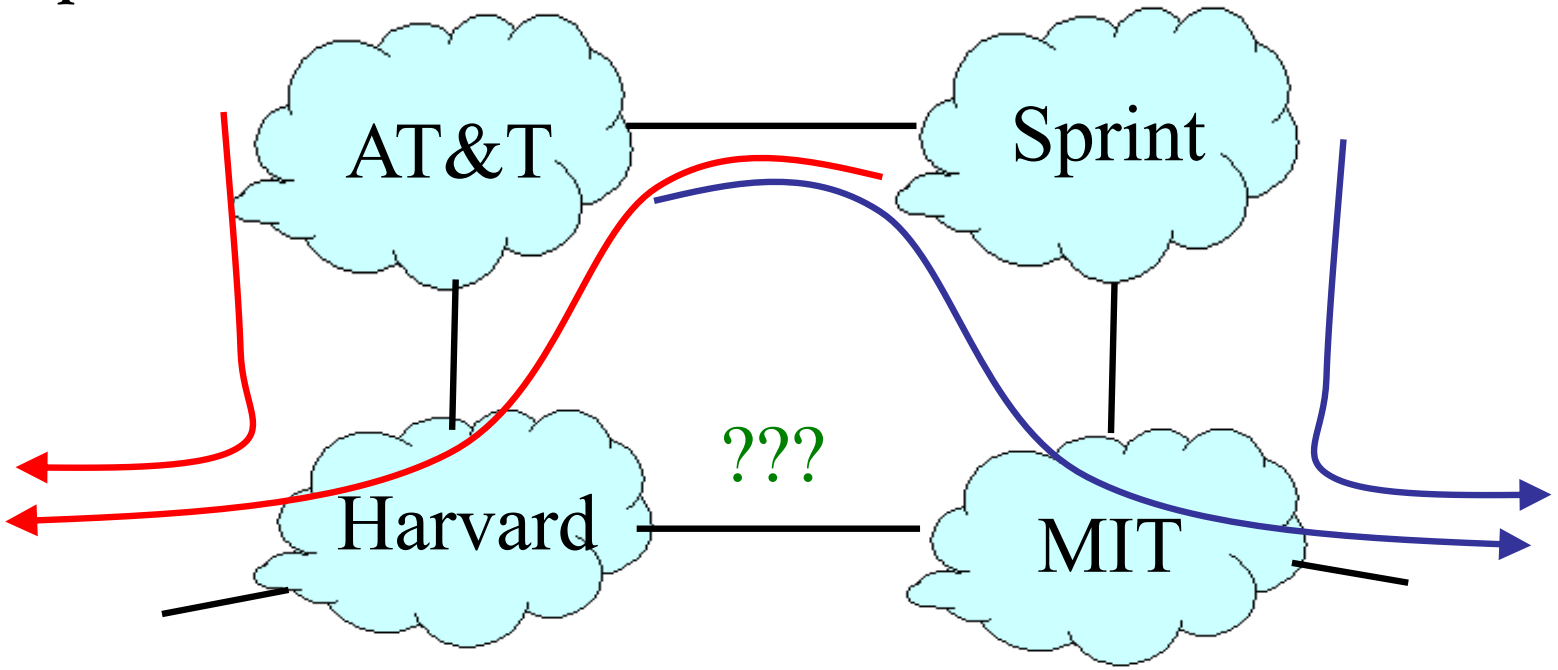
The B-A model

- How did the power-law emerge?
  - Modelling the micro behavior => macro properties.
- Incremental growth
  - Starts with m_0 nodes, each step adds one new node with m links.
- Preferential Attachment
  - Attach to node i with probability $\Pi(k_i) = k_i / \Sigma_j k_j$
- Result in power law topology $P(k) = \frac{2m^2}{k^3}$



No Topology is Complete

- Limited collection of paths
  - Some links might never be traversed
  - Especially links low in the AS hierarchy
  - … and backup links
- Example: paths observed from two tier-1 ISPs miss a lower-tier peer link



Research Questions

- Collecting Topology
  - Where to put additional monitors?
  - How (in)complete the observed topology is?
  - How much does the missing part affect research results?
- Characterizing Topology
  - Static properties
    - Degree, tier hierarchy, graphic properties, etc.
  - Dynamic properties
    - How fast the topology changes, and what's the trend?
- Modeling Topology Evolution
  - Economic, technological, and operational factors behind the topology evolution.