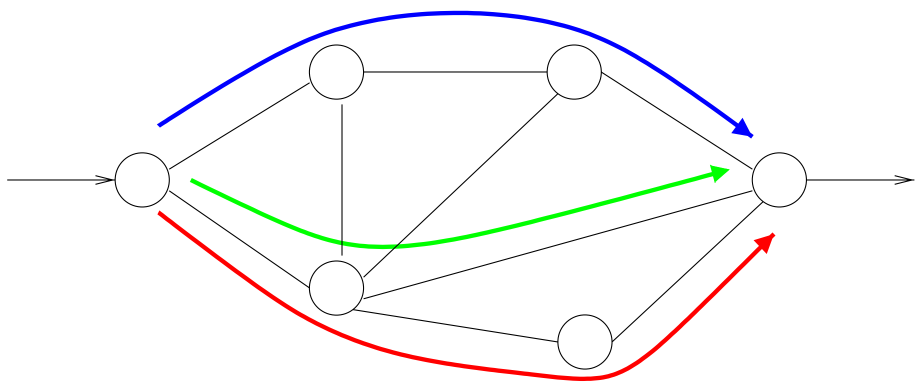
ROUTING

Problem: Given more than one path from source to destination, which one to take?



Features:

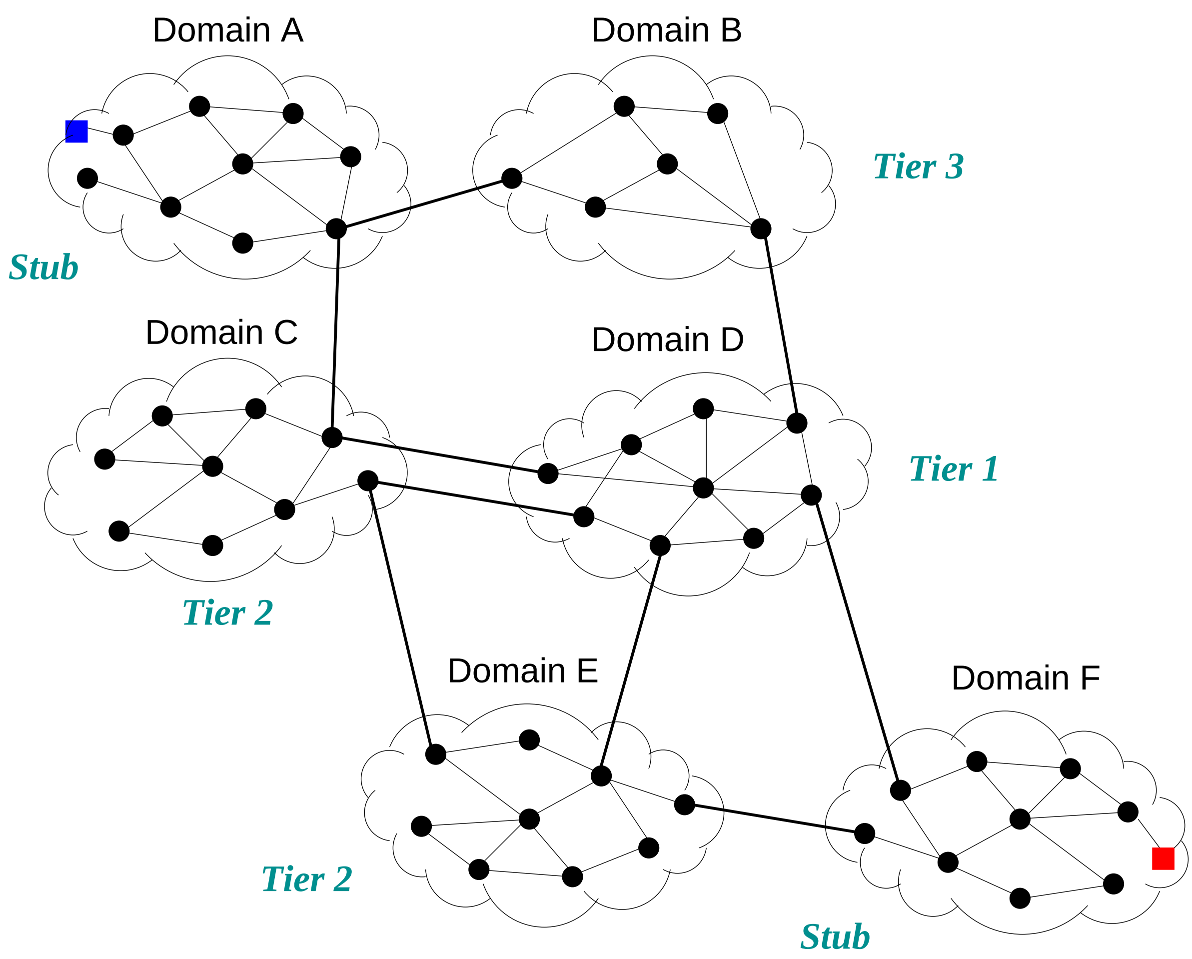
- Architecture
- Algorithms
- Implementation
- Performance

Architecture

Hierarchical routing:

⟶ Internet: intra-domain vs. inter-domain routing

⟶ separate decision making



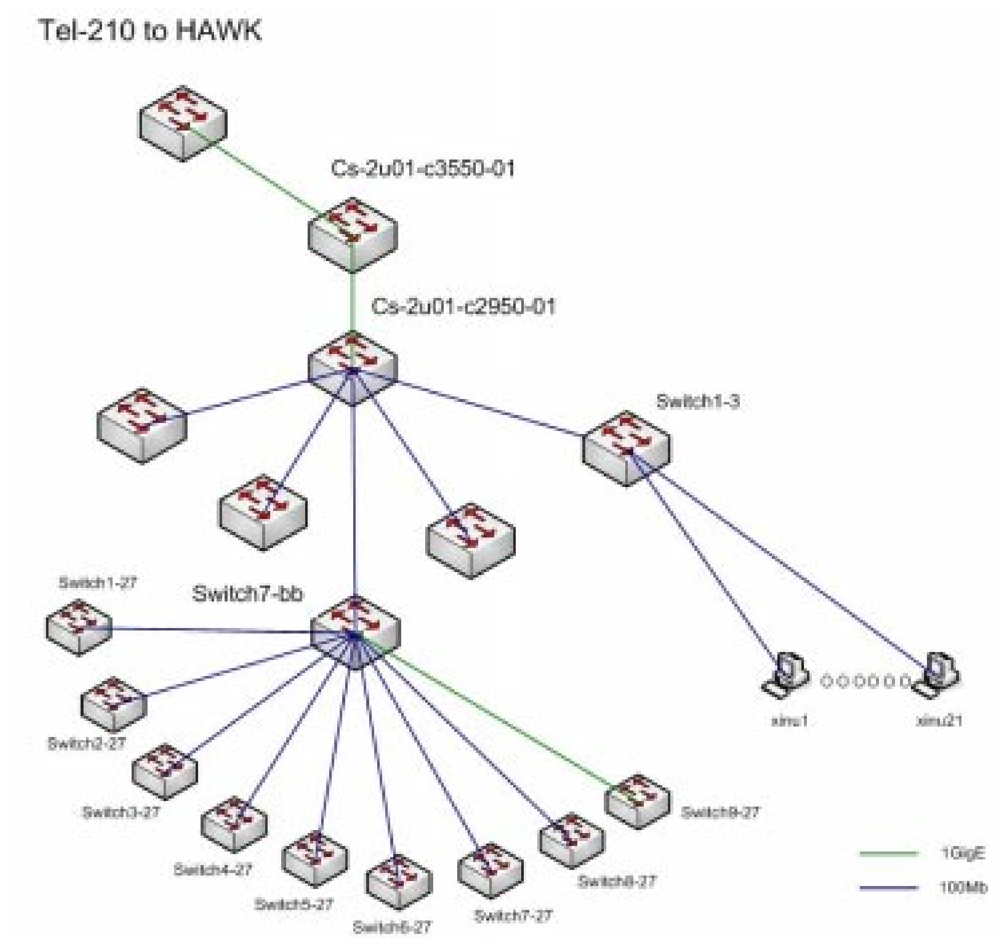
Ex.: Purdue to east coast (BU)

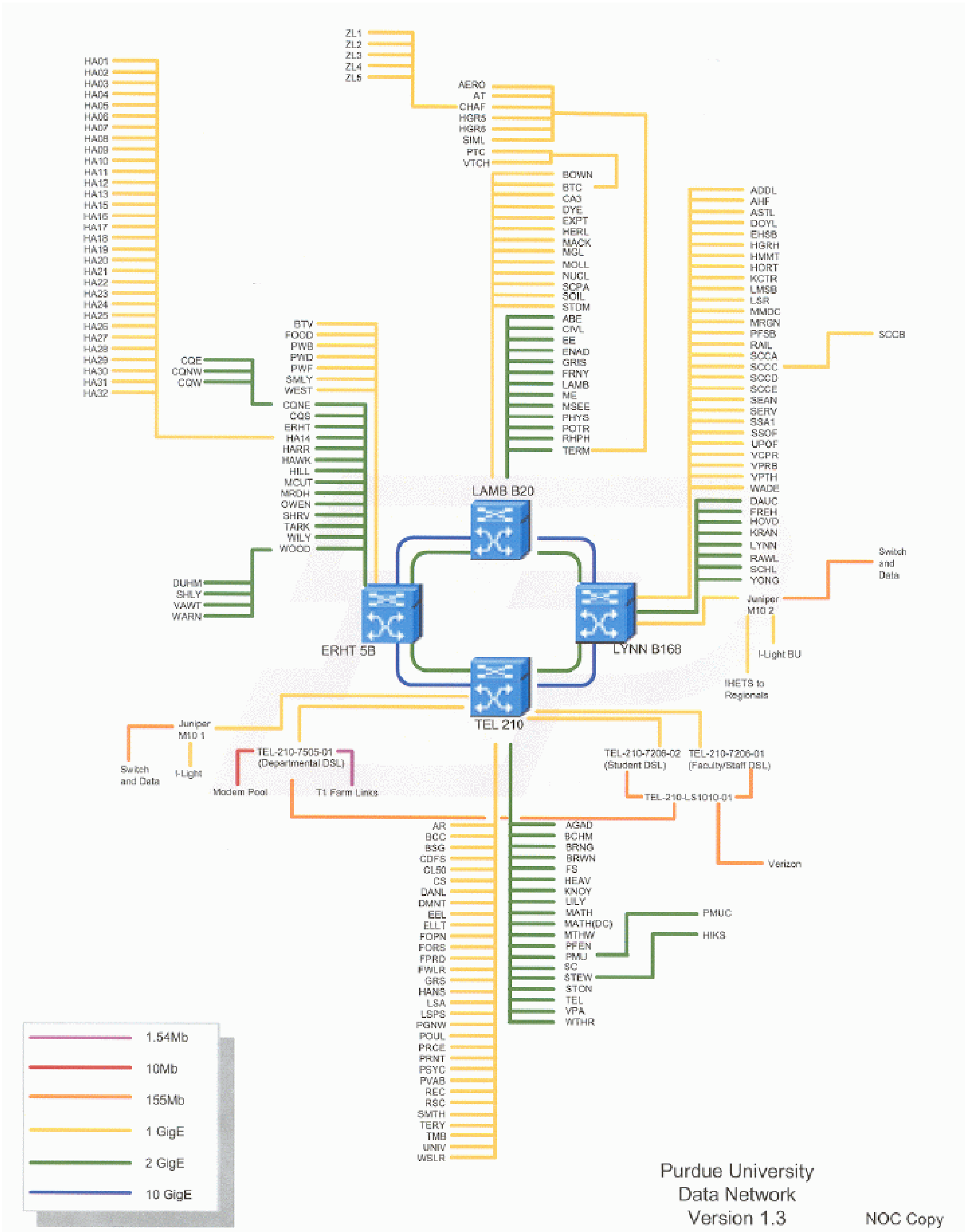
```
[109] infobahn:Routing % traceroute csa.bu.edu
traceroute to csa.bu.edu (128.197.12.3), 30 hops max, 40 byte packets
 1  cisco5 (128.10.27.250)  3.707 ms  0.616 ms  0.590 ms
 2  172.19.60.1 (172.19.60.1)  0.406 ms  0.431 ms  0.520 ms
 3  tel-210-m10-01-campus.tcom.purdue.edu (192.5.40.54)  0.491 ms  0.600 ms  0.510 ms
 4  gigapop.tcom.purdue.edu (192.5.40.134)  9.658 ms  1.966 ms  1.725 ms
 5  192.12.206.249 (192.12.206.249)  1.715 ms  3.381 ms  1.749 ms
 6  chinng-iplsng.abilene.ucaid.edu (198.32.8.76)  5.669 ms  8.319 ms  5.601 ms
 7  nycmng-chinng.abilene.ucaid.edu (198.32.8.83)  25.626 ms  25.664 ms  25.621 ms
 8  noxgs1-PO-6-0-NoX-NOX.nox.org (192.5.89.9)  30.634 ms  30.768 ms  30.722 ms
 9  192.5.89.202 (192.5.89.202)  31.128 ms  31.045 ms  31.082 ms
10  cumm111-cgw-extgw.bu.edu (128.197.254.121)  31.287 ms  31.152 ms  31.146 ms
11  cumm111-dgw-cumm111.bu.edu (128.197.254.162)  31.224 ms  31.192 ms  31.308 ms
12  csa.bu.edu (128.197.12.3)  31.529 ms  31.243 ms  31.367 ms
```

Ex.: Purdue to west coast (Cisco)

```
[112] infobahn:Routing % traceroute www.cisco.com
traceroute to www.cisco.com (198.133.219.25), 30 hops max, 40 byte packets
 1  cisco5 (128.10.27.250)  0.865 ms  0.598 ms  1.282 ms
 2  172.19.60.1 (172.19.60.1)  0.518 ms  0.379 ms  0.405 ms
 3  tel-210-m10-01-campus.tcom.purdue.edu (192.5.40.54)  0.687 ms  0.551 ms  0.551 ms
 4  switch-data.tcom.purdue.edu (192.5.40.34)  3.496 ms  3.523 ms  2.750 ms
 5  so-2-3-0-0.gar2.Chicago1.Level3.net (67.72.124.9)  8.114 ms  20.181 ms  8.512 ms
 6  so-3-3-0.bbr1.Chicago1.Level3.net (4.68.96.41)  11.543 ms  9.079 ms  8.239 ms
 7  ae-0-0.bbr1.SanJose1.Level3.net (64.159.1.129)  62.319 ms as-1-0.bbr2.SanJose1.Level3.net
 8  ge-11-0.ipcolo1.SanJose1.Level3.net (4.68.123.41)  68.180 ms ge-7-1.ipcolo1.SanJose1.Level
 9  p1-0.cisco.bbnplanet.net (4.0.26.14)  75.006 ms  72.557 ms  70.377 ms
10  sjce-dmzbb-gw1.cisco.com (128.107.239.53)  66.075 ms  69.223 ms  68.350 ms
11  sjck-dmzdc-gw1.cisco.com (128.107.224.69)  65.650 ms  74.358 ms  69.952 ms
12 ^C
```

Three levels: LAN, intra-domain, and inter-domain





ZL1
ZL2
ZL3
ZL4
ZL5
HA01
HA02
HA03
HA04
HA05
HA06
HA07
HA08
HA09
HA10
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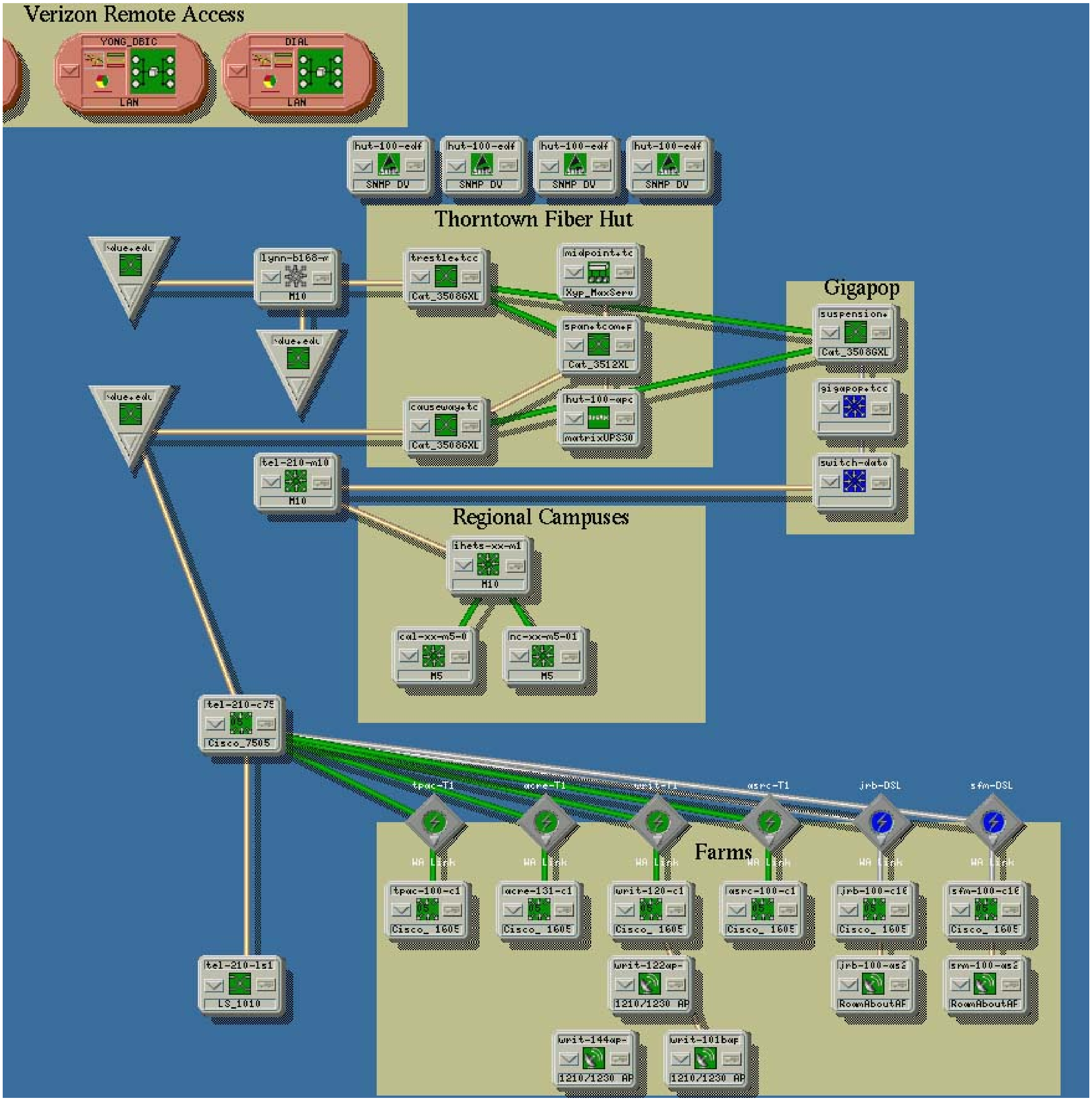
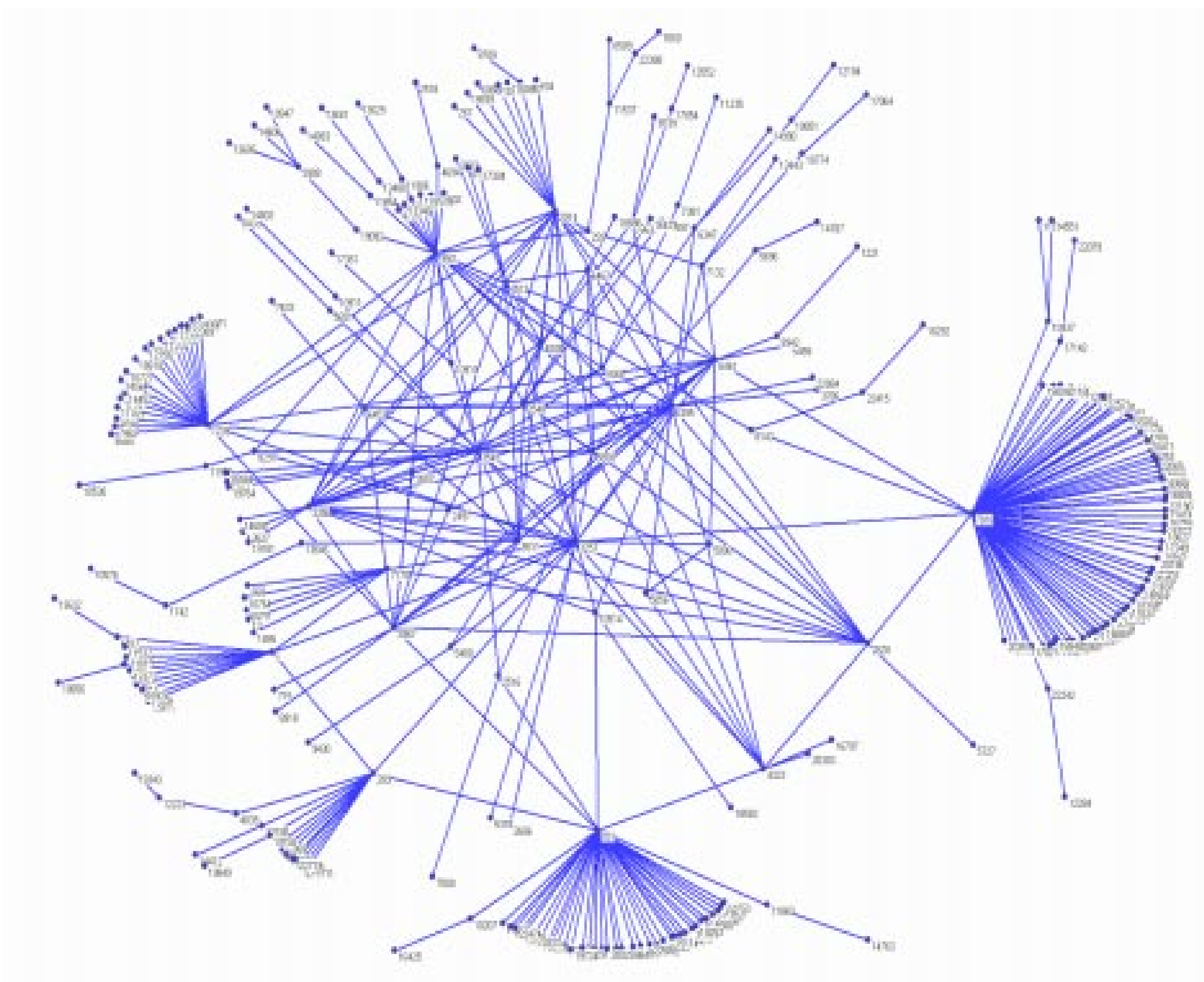
HA32
AERO
AT
CHAF
HGR5
HGR6
SIML
PTC
VTCH
BOWN
BTC
CA3
DYE
EXPT
HERL
MACK
MGL
MOLL
NUCL
SCPA
SOIL
STDM
ABE
CIVL
EE
ENAD
GRIS
FRNY
LAMB
ME
MSEE
PHYS
POTR
RHPH
TERM
ADDL
AHF
ASTL
DOYL
EHSB
HGRH
HMMT
HORT
KCTR
LMSB
LSR
MMDC
MRGN
PFSB
RAIL
SCCA
SCCC
SCCD
SCCE
SEAN
SERV
SSA1
SSOF
UPOF
VCPR
VPRB
VPTH
WADE
SCCB
BTV
FOOD
PWB
PWD
PWF
SMLY
WEST
CQE
CQNW
CQW
CONE
CQS
ERHT
HA14
HARR
HAWK
HILL
MCUT
MRDH
OWEN
SHRV
TARK
WILY
WOOD
LAMB B20
DAUC
FREH
HOVD
KRAN
LYNN
RAWL
SCHL
YONG
Switch and Data
DUHM
SHLY
VAWT
WARN
ERHT 5B
LYNN B168
Juniper M10 2
I-Light BU
IHETS to Regionals
TEL 210
Juniper M10 1
Switch and Data
I-Light
TEL-210-7505-01 (Departmental DSL)
Modem Pool
T1 Farm Links
TEL-210-7206-02 (Student DSL)
TEL-210-7206-01 (Faculty/Staff DSL)
TEL-210-LS1010-01
Verizon
AR
BCC
BSG
CDFS
CL50
CS
DANL
DMNT
EEL
ELLT
FOPN
FORS
FPRD
FWLR
GRS
HANS
LSA
LSPS
PGNW
POUL
PRCE
PRNT
PSYC
PVAB
REC
RSC
SMTH
TERY
TMB
UNIV
WSLR
AGAD
BCHM
BRNG
BRWN
FS
HEAV
KNOY
LILY
MATH
MATH(DC)
MTHW
PFEN
PMU
SC
STEW
STON
TEL
VPA
WTHR
PMUC
HIKS
1.54Mb
10Mb
155Mb
1 GigE
2 GigE
10 GigE
Purdue University
Data Network
Version 1.3
NOC Copy


Verizon Remote Access
YONG_DBIC
DIAL
LAN
LAN
hut-100-edf
SNMP DV
Thorntown Fiber Hut
lynn-b168-m
M10
trestle.tcc
Cat_3508GXL
midpoint.tc
Xyp_MaxServ
span.tcom.p
Cat_3512XL
causeway.tc
Cat_3508GXL
hut-100-apc
matrixUPS30
Gigapop
suspension.
Cat_3508GXL
gigapop.tcc
switch-data
tel-210-m10
M10
Regional Campuses
ihets-xx-m1
M10
cal-xx-m5-0
M5
nc-xx-m5-01
M5
tel-210-c75
Cisco_7505
tel-210-ls1
LS_1010
tpac-T1
acre-T1
writ-T1
asrc-T1
jrb-DSL
sfm-DSL
Farms
WA Link
tpac-100-c1
acre-131-c1
writ-120-c1
asrc-100-c1
Cisco_ 1605
writ-122ap-
1210/1230 AP
writ-144ap-
writ-101bap
RoamAboutAP

Inter-domain topology:



⟶ each dot (or node) is a domain (e.g., Purdue)

⟶ called autonomous system (AS): 16-bit ID

Inter-domain connectivity of Purdue:

- Level3 (AS 3356) → INDIANAGIGAPOP (AS 19782) → Purdue (AS 17)
- Internet2/Abilene (AS 11537) → INDIANAGIGAPOP (AS 19782) → Purdue (AS 17)

  ⟶ changes over time (e.g., economic reasons)

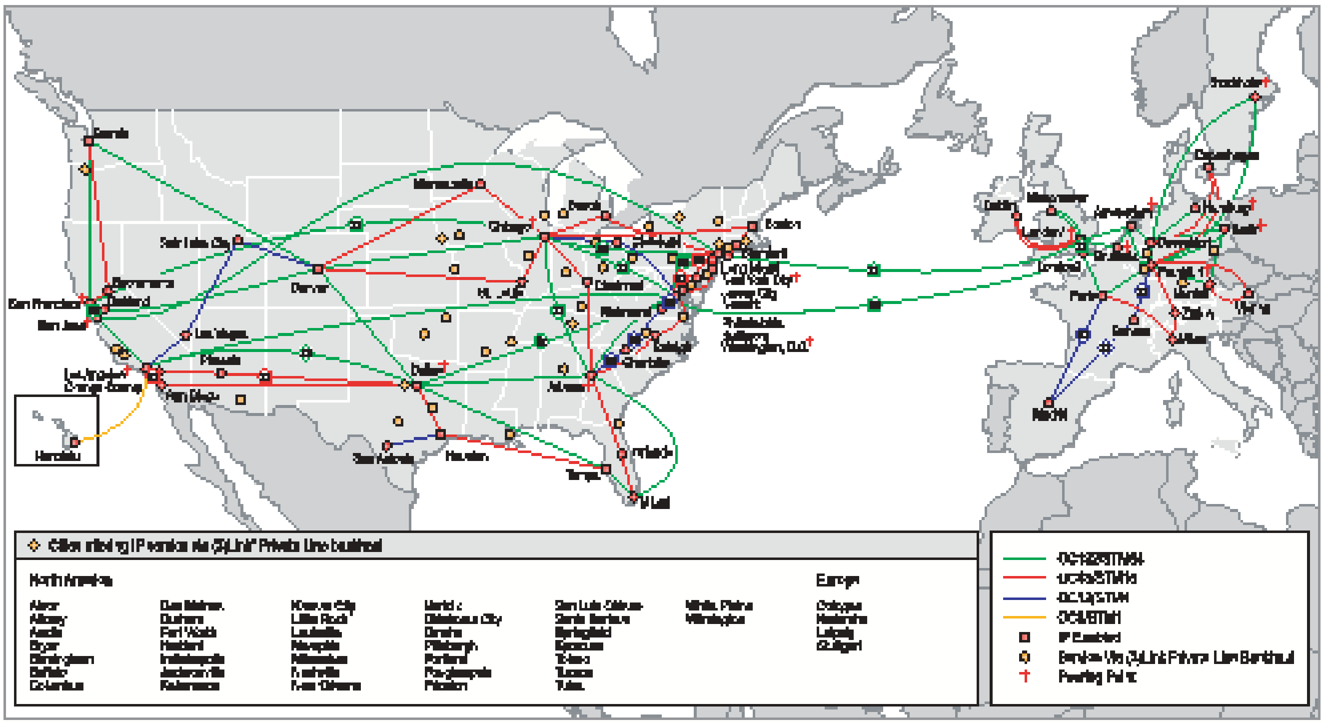
The Indy GigaPoP has its own AS number (19782).

  ⟶ part of I-Light (Indiana state-wide project)

  ⟶ located at IUPUI, connects Purdue & IU

Level3 backbone network: www.level3.com

LEVEL 3 IP BACKBONE



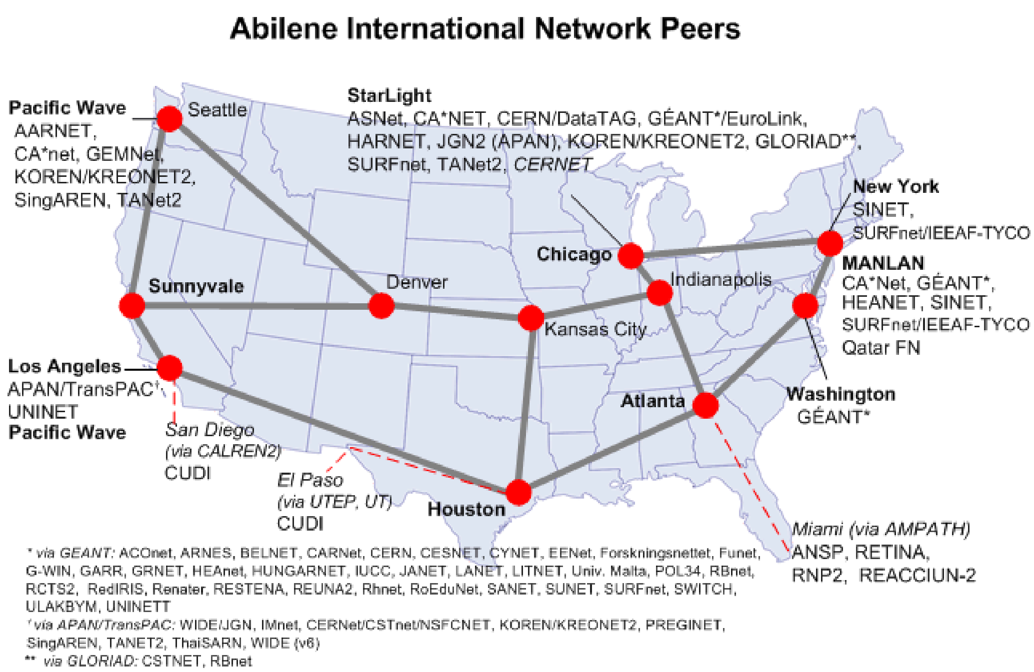
⟶ 10 Gbps (or slower) backbone (same as Purdue)

⟶ same as Purdue CS!

⟶ next step: 100 Gbps backbone (a few years away)

⟶ in the meantime: LAG (link aggregation group)

Abilene/Internet2 backbone: www.internet2.edu



Granularity of routing network:

- Router
- Domain: autonomous system

  → 16 bit identifier ASN

  → assigned by IANA along with IP prefix block (CIDR)

Network topology (i.e., map/connectivity):

- Router graph

  → node: router

  → edge: physical link between two routers

- AS graph

  → node: AS

  → edge: physical link between 2 or more border routers

  → sometimes at exchange point or network

Router type:

- access router
- border router
- backbone router

AS type:

- stub AS

  → no forwarding

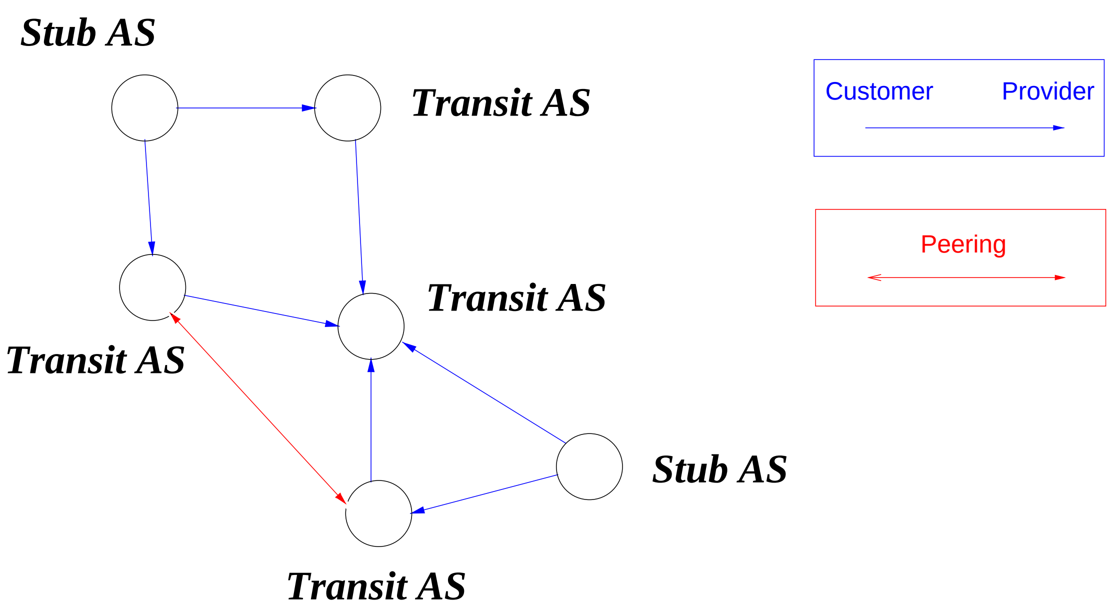
  → may be multi-homed (more than one provider)

- transit AS

  → tier-1: global reachability & no provider above

  → tier-2 or tier-3: providers above

AS graph:



Inter-AS relationship: bilateral

- customer-provider: customer subscribes BW from provider

  $\longrightarrow$ most common

  $\longrightarrow$ customer can reach provider's reachable IP space

- peering:

  $\longrightarrow$ only the peer's IP address and below

  $\longrightarrow$ the peer's provider's address space: invisible

Common peering:

- among tier-1 providers

  → ensures global reachability

  → socio-economic self-organization

  → less regulated than telephony

- among tier-2 providers

  → regional providers

  → economic factors

- among stubs

  → economic factors

  → e.g., content provider & access ("eyeball") provider

  → e.g., Time Warner & AOL

Route or path: criteria of goodness

- Hop count
- Delay
- Bandwidth
- Loss rate

Composition of goodness metric:

$\longrightarrow$ quality of end-to-end path

- Additive: hop count, delay
- Min: bandwidth
- Multiplicative: loss rate

Goodness of routing:

$\longrightarrow$ assume N users or sessions

$\longrightarrow$ suppose path metric is delay

- System optimal routing

  $\rightarrow$ choose paths to minimize $\frac{1}{N}\sum_{i=1}^{N} D_i$

- User optimal routing

  $\rightarrow$ each user i chooses path to minimize D_i

  $\rightarrow$ selfish actions

Pros/cons:

- System optimal routing:
  - Good: minimizes delay for the system as a whole
  - Bad: complex and difficult to scale up
- User optimal routing:
  - Good: simple
  - Bad: may not make efficient use of resources

    → utilization

Some pitfalls of user optimal routing:

⟶ stemming from selfishness

- Fluttering or ping pong effect
- Braess paradox

→ adding more resources makes things worse

Algorithms

Find short, in particular, shortest paths from source to destination.

Key observation on shortest paths:

- Assume p is a shortest path from S to D

  $\rightarrow S \overset{p}{\rightsquigarrow} D$

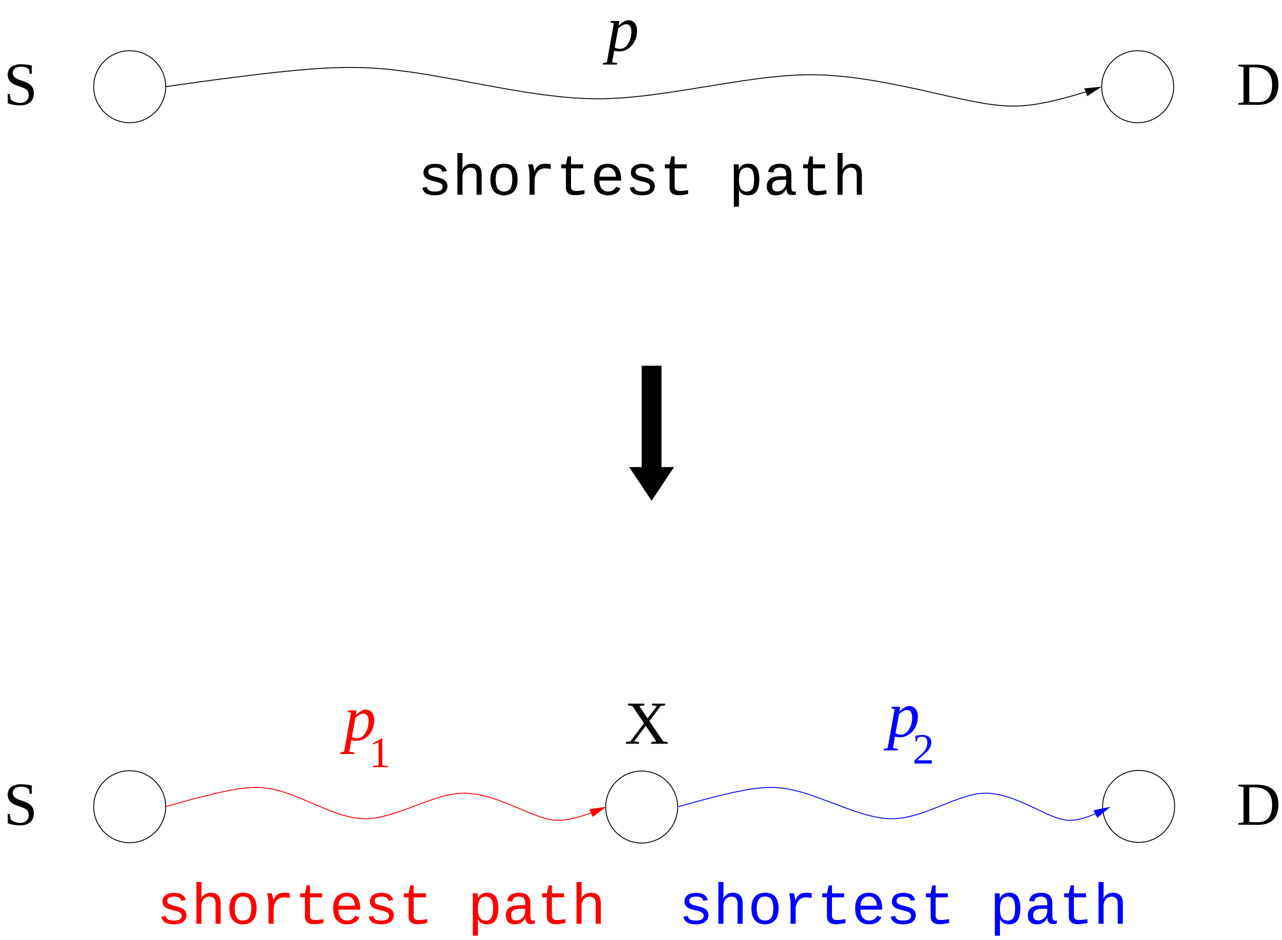
- Pick any intermediate node X on the path

- Consider the two segments p_1 and p_2

  $\rightarrow S \overset{p_1}{\rightsquigarrow} X \overset{p_2}{\rightsquigarrow} D$

- The path p_1 from S to X is a shortest path, and so is the path p_2 from X to D

Illustration:



$\longrightarrow$ reverse implication need not hold

$\longrightarrow$ suggests algorithm for finding shortest path

Procedure: Grow a routing tree $\mathcal{T}$ rooted at source S

$\longrightarrow$ initially $\mathcal{T}$ only contains S

1. Find a node X with shortest path from S

   $\rightarrow$ there may be more than one such node

   $\rightarrow$ add X (and path $S \stackrel{p}{\rightsquigarrow} X$) to routing tree $\mathcal{T}$

2. Find node $Y \notin \mathcal{T}$ with shortest path from S

   $\rightarrow$ update existing paths if going through Y is shorter

   $\rightarrow$ i.e., $\min\{d(S,Z), d(S,Y) + \ell(Y,Z)\}$

   $\rightarrow$ need only check for $Z \notin \mathcal{T}$

3. Repeat step two until no more nodes left to add

Observations:

$\longrightarrow$ once node is added, it's final (no backtracking)

$\longrightarrow$ builds minimum spanning tree routed at S

$\longrightarrow$ Dijkstra's algorithm

Remarks:

- Running time: $O(n^2)$ time complexity

  $\longrightarrow$ n: number of nodes

- If heap is used: $O(|E| \log |V|)$

  $\longrightarrow$ good for sparse graphs: $|E| \ll n^2$

  $\longrightarrow$ e.g., if linear: $O(n \log n)$

- Can also be run "backwards"

  $\longrightarrow$ start from destination D and go to all sources

  $\longrightarrow$ a variant used in inter-domain routing

  $\longrightarrow$ forward version: used in intra-domain routing

- Source S requires global link distance knowledge

  $\longrightarrow$ centralized algorithm (center: source S)

  $\longrightarrow$ every router runs Dijkstra with itself as source

- Internet protocol implementation

  → OSPF (Open Shortest Path First)

  → link state algorithm

  → broadcast protocol

- Minimum spanning tree routed at S:

  → multicasting: multicast tree

  → standardized but not implemented on Internet

Distributed/decentralized shortest path algorithm:

$\longrightarrow$ Bellman-Ford algorithm

$\longrightarrow$ based on shortest path decomposition property

Key procedure:

- Each node X maintains current shortest distance to all other nodes

  $\rightarrow$ a distance vector

- Each node advertises to neighbors its current best distance estimates

  $\rightarrow$ i.e., neighbors exchange distance vectors

- Node X, upon receiving an update from neighbor Y, performs update: for all Z

$$d(X, Z) \leftarrow \min\{\, d(X, Z),\; d(Y, Z) + \ell(X, Y)\,\}$$

... same criterion as Dijkstra's algorithm

Remarks:

- Running time: $O(n^3)$
- Each source or router only talks to neighbors

  → local interaction

  → no need to send update if no change

  → if change, entire distance vector must be sent
- Knows shortest distance, but not path

  → just the next hop is known
- Elegant but additional issues compared to Dijkstra's algorithm

  → e.g., stability
- Internet protocol implementation

  → RIP (Routing Information Protocol)

QoS routing:

Given two or more performance metrics—e.g., delay and bandwidth—find path with delay less than target delay D (e.g., 100 ms) and bandwidth greater than target bandwidth B (e.g., 1.5 Mbps)

$\longrightarrow$ from shortest path to best QoS path

$\longrightarrow$ multi-dimensional QoS metric

$\longrightarrow$ other: jitter, hop count, etc.

How to find best QoS path that satisfies all requirements?

Brute-force

- Enumerate all possible paths
- Rank them

How many paths are there:

- If there are n nodes, there can be up to

  $$\frac{n(n-1)}{2}$$

  undirected links

- Hence, from source S there can be up to

  $$(n-1)\,(n-2)\cdots 3\,2\,1 \;=\; (n-1)!$$

  paths

- By Stirling's formula

  $$n! \approx \sqrt{2\pi n}\left(\frac{n}{e}\right)^n$$

  $\longrightarrow$ superexponential

  $\longrightarrow$ too many for brute-force

Is there a more clever or better algorithm?

⟶ as of Apr. 12, 2006: unknown

⟶ specifically: QoS routing is NP-complete

⟶ strong evidence there may not exist good algorithm

In networking: several problems turn out to be NP-complete

⟶ e.g., scheduling, control, . . .

⟶ "P = NP" problem

⟶ one of the hardest problems in science ever

Doesn't matter too much for QoS routing

⟶ little demand for very good algorithm

⟶ roughly ok is fine

⟶ intra-domain: short paths

⟶ inter-domain: other factors ("policy")

Policy routing:

$\longrightarrow$ policy is not precisely defined

$\longrightarrow$ almost anything goes

Routing criteria include

- Performance

  $\rightarrow$ e.g., short paths

- Trust

  $\rightarrow$ what in the world is "trust"?

- Economics

  $\rightarrow$ pricing

  $\rightarrow$ flexibility through multiple providers

- Politics, social issues, etc.

$\longrightarrow$ no good understanding of "policy" to date

$\longrightarrow$ anecdotal