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

Two approaches:

- system optimal routing

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

  $\rightarrow$ good for the system as a whole

- user optimal routing

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

  $\rightarrow$ selfish route selections by each user

  $\rightarrow$ end result may not be good for system as a whole

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

    → low utilization

    → recall "tragedy of commons" in congestion control

Two pitfalls of user optimal routing:

- fluttering or ping pong effect
- Braess paradox

  → adding more resources can make 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

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

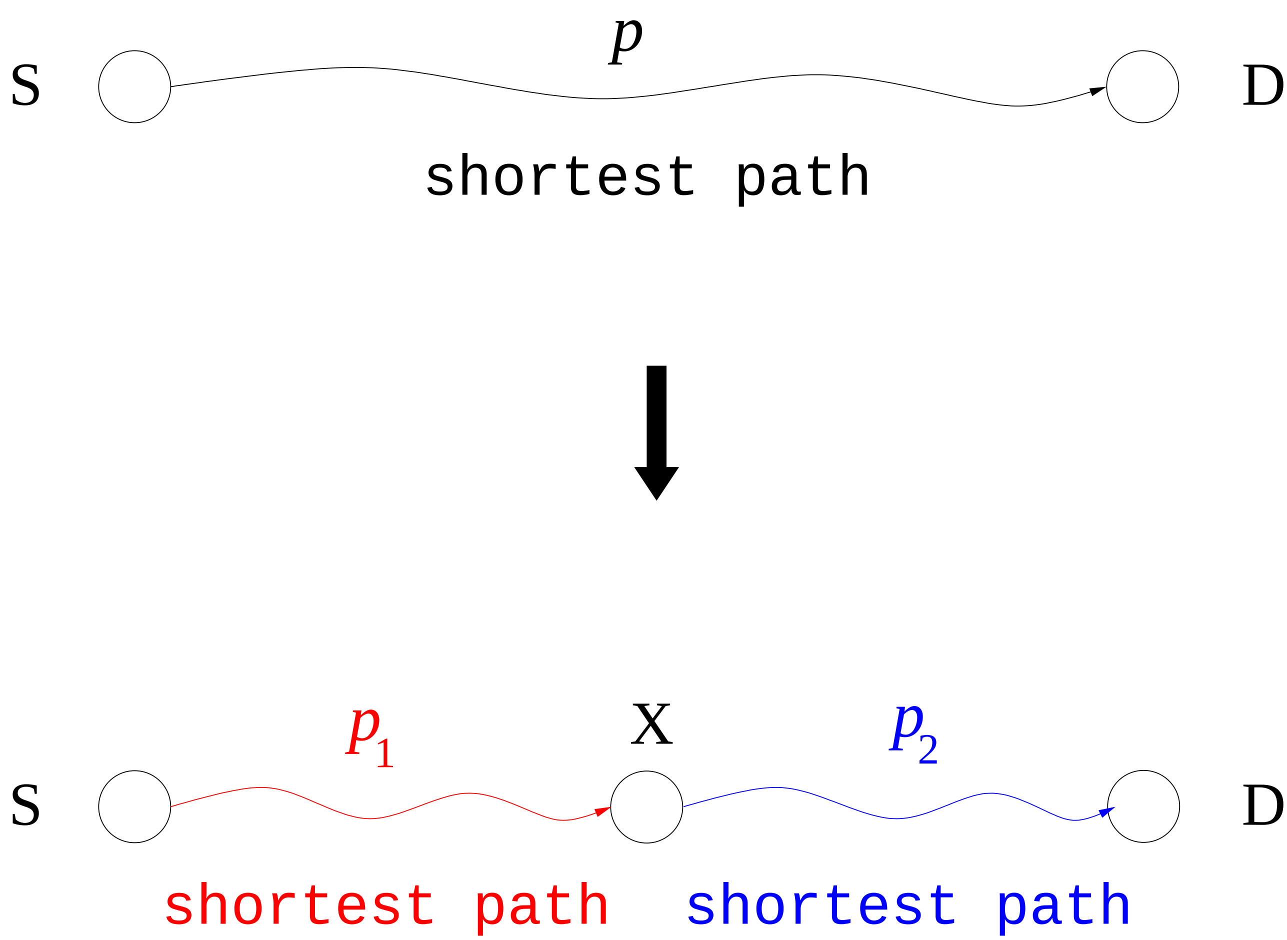
- Pick any intermediate node X on the path
- Consider the two segments p_1 and p_2

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

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

  $\longrightarrow$ leads to Dijkstra's algorithm

Illustration:



→ suggests algorithm for finding shortest path

Leads to Dijkstra's shortest-path algorithm:

$\rightarrow$ single-source all-destination

Features:

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

  $\rightarrow$ n: number of nodes
- if heap is used: $O(|E| \log |V|)$

  $\rightarrow$ $O(n \log n)$ if $|E| = O(n)$
- can also be run "backwards"

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

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

  $\rightarrow$ forward version: used in intra-domain routing
- source S requires global link distance knowledge

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

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

  $\rightarrow$ lots of broadcast management packets

- Internet protocol implementation

  → OSPF (Open Shortest Path First)

  → also called link state algorithm

  → broadcast protocol

- builds minimum spanning tree rooted at S:

  → to all destinations

  → if select destination: called multicasting

  → multicast group

  → standardized feature of IETF but not actively utilized on Internet

  → complexity including group membership management

Distributed/decentralized shortest path algorithm:

⟶ Bellman-Ford algorithm

⟶ based on shortest path decomposition property

Key procedure:

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

  → a distance vector

- Each node advertises to neighbors its current best distance estimates

  → i.e., neighbors exchange distance vectors

- Each node updates shortest paths based on neighbors' advertised information

  → same update criterion as Dijkstra's algorithm

Features:

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

  $\rightarrow$ local interaction

  $\rightarrow$ no need to send update if no change

  $\rightarrow$ if change, entire distance vector must be sent
- knows shortest distance, but not path

  $\rightarrow$ just the next hop is known
- elegant but additional issues compared to Dijkstra's algorithm

  $\rightarrow$ e.g., stability
- Internet protocol implementation

  $\rightarrow$ 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

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

→ superexponential

→ too many for brute-force

Is there a more clever or better algorithm?

⟶ as of Nov. 18, 2011: unknown

⟶ specifically: QoS routing is NP-hard

⟶ strong evidence there may not exist good algorithm

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

⟶ e.g., scheduling, crypto, . . .

⟶ "P = NP" problem

⟶ one of the hardest problems in science

In practice: doesn't matter too much for QoS routing

⟶ little demand for very good algorithm

⟶ roughly OK is fine

⟶ intra-domain: short paths

⟶ inter-domain: policy routing

Policy routing:

$\longrightarrow$ meaning of "policy" is not precisely defined

$\longrightarrow$ almost anything goes

Criteria include:

- Performance

  $\rightarrow$ e.g., short paths

- Trust

  $\rightarrow$ what is "trust"?

- Economics

  $\rightarrow$ pricing

- Geo-politics, etc.

Implementation

Major Internet routing protocols:

- RIP (v1 and v2): intra-domain, Bellman-Ford

  → also called distance vector routing

  → metric: hop count

  → UDP

  → nearest neighbor advertisement

  → popular in small intra-domain networks

- OSPF (v1 and v2): intra-domain, Dijkstra

  → also called link state

  → metric: average delay

  → directly over IP: protocol number 89

  → broadcasting via flooding

  → popular in larger intra-domain networks

- IS-IS: intra-domain, Dijkstra

  → directly over link layer (e.g., Ethernet)

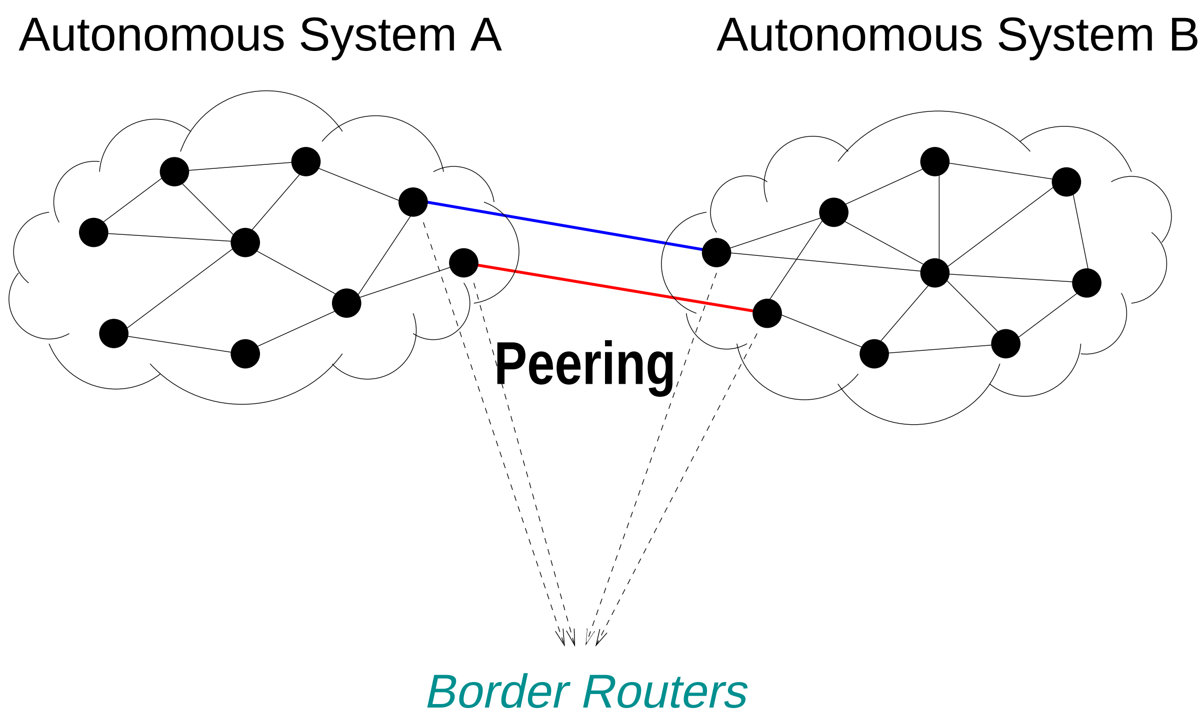
  → also available over IP (more recent)

  → flooding

  → popular in larger intra-domain networks

BGP (Border Gateway Protocol):

⟶ inter-domain routing



⟶ "peering" between two domains

⟶ typical: customer-provider relationship

⟶ in some cases: equals (true peers)

⟶ Internet exchanges: multiple domains meet up

- CIDR addressing

  → i.e., $a.b.c.d/x$

  → Purdue: 128.10.0.0/16, 128.210.0.0/16, 204.52.32.0/20

  → check at `www.iana.org` (e.g., ARIN for US)

- Metric: policy

  → e.g., shortest-path, trust, pricing

  → meaning of "shortest": delay, router hop, AS hop

  → mechanism: path vector routing

  → BPG update message

BGP route update:

$\longrightarrow$ BGP update message propagation

BGP update message format:

$$\text{ASN}A_k \rightarrow \cdots \rightarrow \text{ASN}A_2 \rightarrow \text{ASN}A_1; \text{a.b.c.d/x}$$

Meaning: ASN A_1 (with CIDR address a.b.c.d/x) can be reached through indicated path

$\longrightarrow$ called path vector

$\longrightarrow$ also AS-PATH

Some AS numbers:

- Purdue: 17
- BBN: 1
- UUNET: 701
- Level3: 3356
- Abilene (aka "Internet2"): 11537
- AT&T: 7018

Policy:

- if multiple AS-PATHs to target AS are known, choose one based on policy

  → e.g., shortest AS path length, cheapest, least worrisome

- advertise to neighbors target AS's reachability

  → also subject to policy

  → no obligation to advertise!

  → specifics depend on bilateral contract (SLA)

SLA (service level agreement):

⟶ bandwidth (e.g., 1 Gbps)

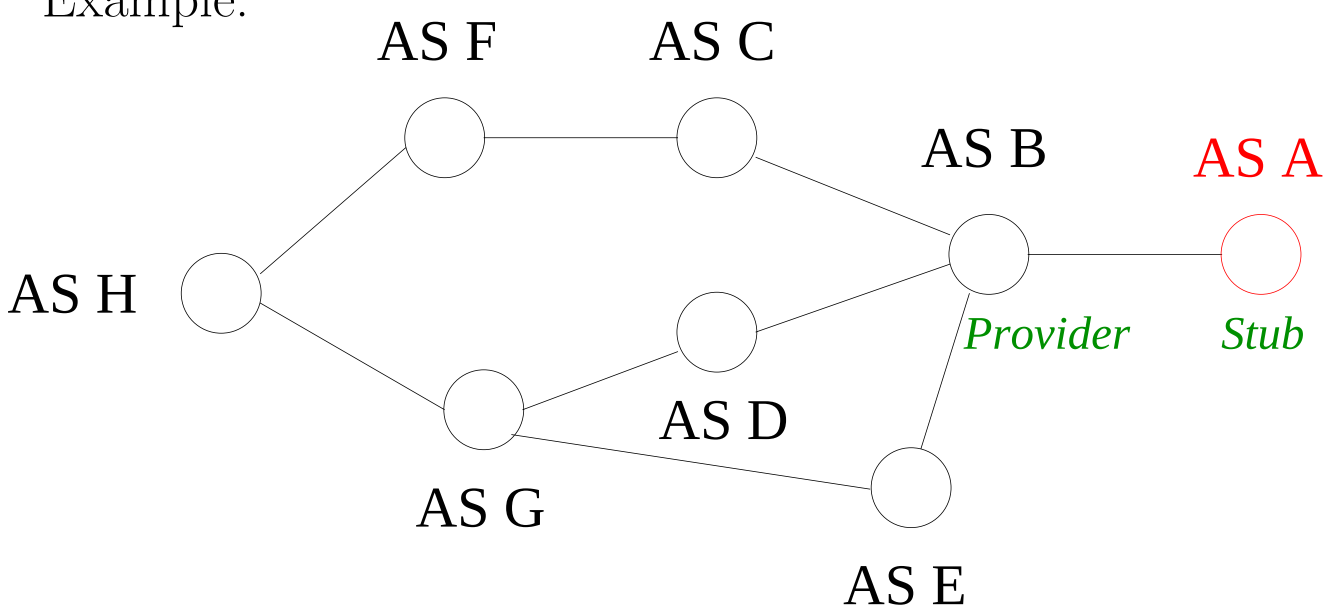
⟶ delay (e.g., avrg. 25ms US), loss (e.g., 0.05%)

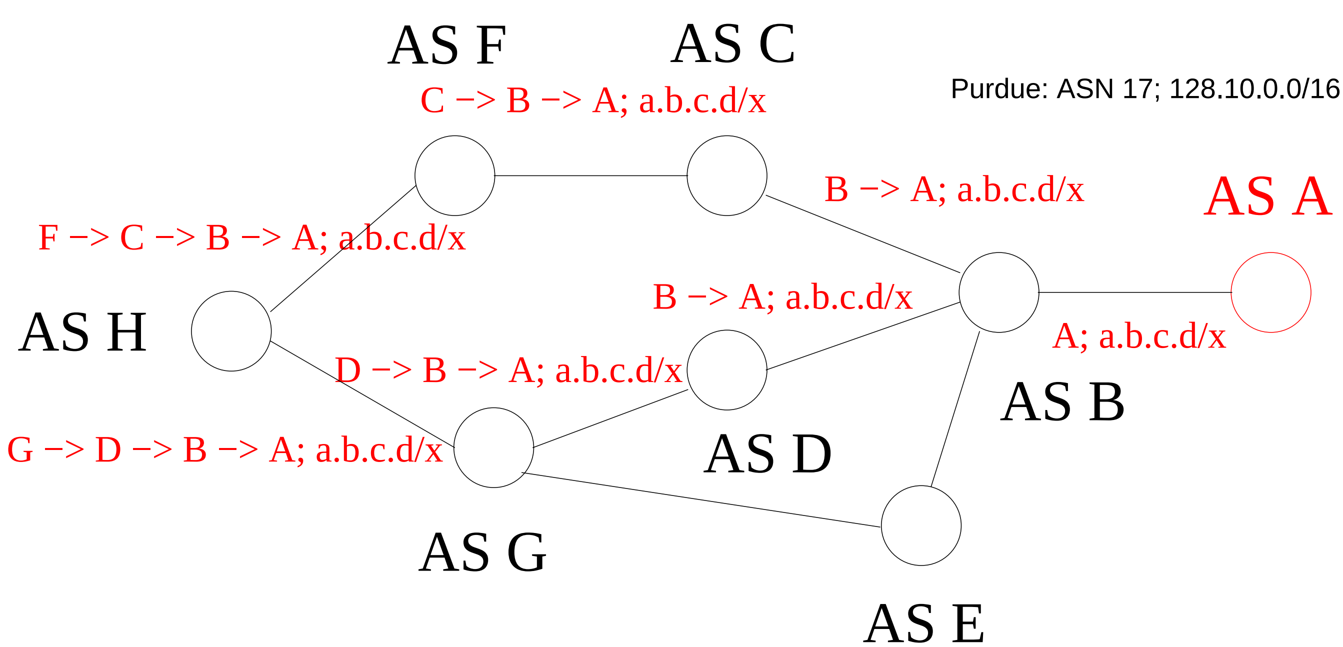
⟶ also peak vs. average

⟶ pricing (e.g., 1 Mbps: below $100)

⟶ availability, etc.

Example:


AS F
AS C
AS B
AS A
AS H
Provider
Stub
AS D
AS G
AS E


AS F
AS C
C –> B –> A; a.b.c.d/x
Purdue: ASN 17; 128.10.0.0/16
B –> A; a.b.c.d/x
AS A
F –> C –> B –> A; a.b.c.d/x
B –> A; a.b.c.d/x
AS H
A; a.b.c.d/x
D –> B –> A; a.b.c.d/x
AS B
G –> D –> B –> A; a.b.c.d/x
AS D
AS G
AS E

Performance

Route update frequency:

- $\longrightarrow$ routing table stability vs. responsiveness
- $\longrightarrow$ rule: not too frequently
- $\longrightarrow$ 30 seconds
- $\longrightarrow$ stability wins
- $\longrightarrow$ hard lesson learned from the past (sub-second)
- $\longrightarrow$ legacy: TTL

Other factors for route instability:

- $\longrightarrow$ selfishness (e.g., fluttering)
- $\longrightarrow$ BGP's vector path routing: inherently unstable
- $\longrightarrow$ more common: slow convergence
- $\longrightarrow$ target of denial-of-service (DoS) attack

Route amplification:

$\longrightarrow$ shortest AS path $\neq$ shortest router path

$\longrightarrow$ e.g., may be several router hops longer

$\longrightarrow$ AS graph vs. router graph

$\longrightarrow$ policy: company in Denmark

Route asymmetry:

$\longrightarrow$ routes are not symmetric

$\longrightarrow$ estimate: $> 50\%$

$\longrightarrow$ mainly artifact of inter-domain policy routing

$\longrightarrow$ various performance implications

$\longrightarrow$ source traceback

Black holes:

- $\longrightarrow$ persistent unreachable destination prefixes
- $\longrightarrow$ BGP routing problems
- $\longrightarrow$ further aggrevated by DNS