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

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

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

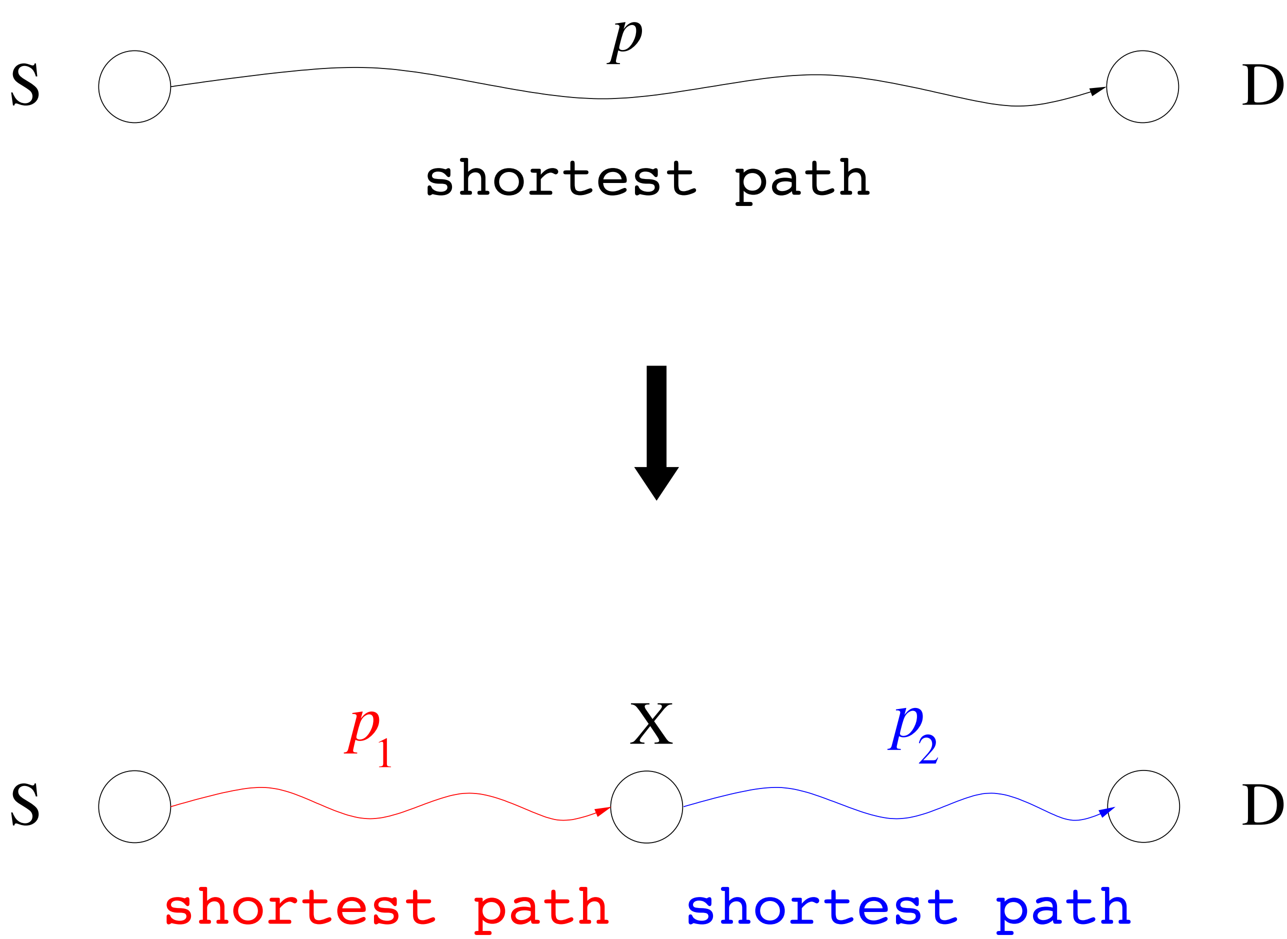
- Pick any intermediate node X on the path
- Consider the two segments p_1 and p_2

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

- 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:



$\rightarrow$ 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:

$\longrightarrow$ 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

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

  $\rightarrow$ 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

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"?

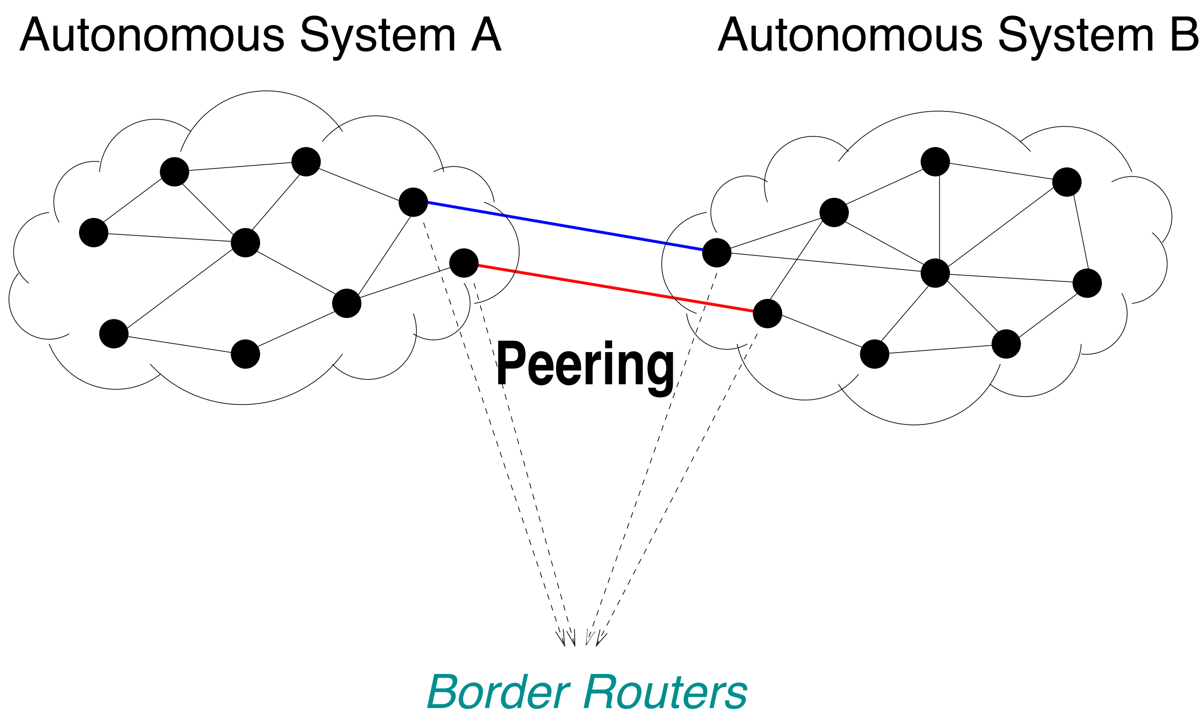
- Economics

  $\rightarrow$ pricing

- Politics, etc.

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:

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

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

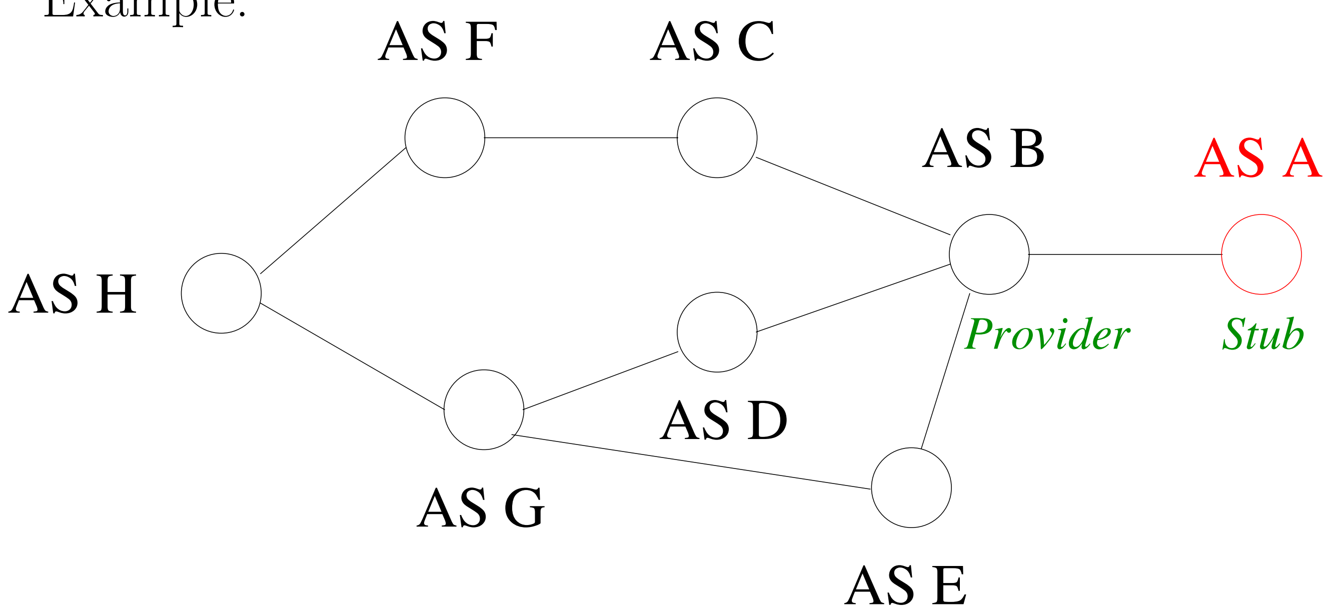
$\longrightarrow$ called path vector

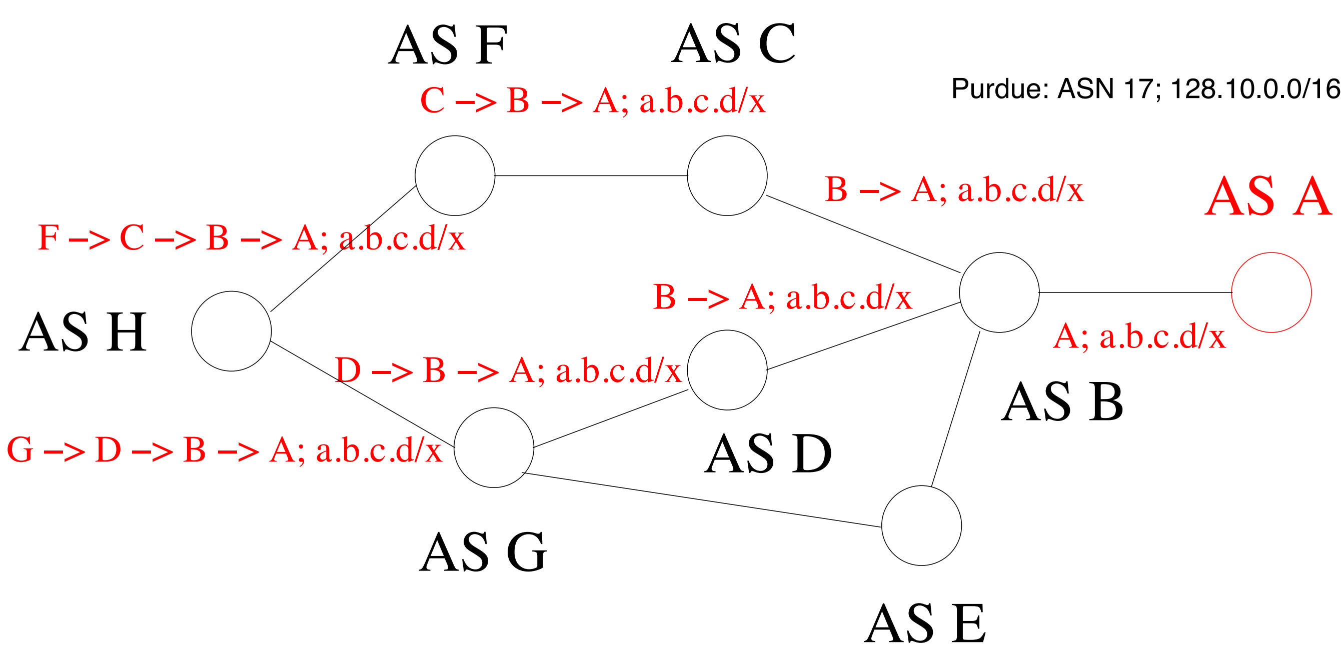
$\longrightarrow$ also AS-PATH

Some AS numbers:

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

Example:


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


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

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

Other factors for route instability:

- ⟶ selfishness (e.g., fluttering)
- ⟶ BGP's vector path routing: inherently unstable
- ⟶ more common: slow convergence
- ⟶ 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