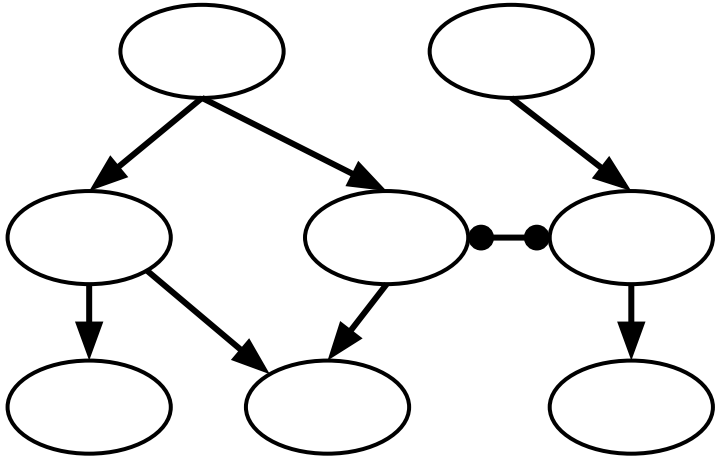


Lecture 9 (Routing 5)

Inter-Domain Routing

CS 168, Spring 2025 @ UC Berkeley

Slides credit: Sylvia Ratnasamy, Rob Shakir, Peyrin Kao

Autonomous Systems

Lecture 9, CS 168, Spring 2025

Autonomous Systems

- **What are ASes?**
- Business Relationships

Goals of Inter-Domain Routing

- Policy-Based Routing
- Gao-Rexford Rules

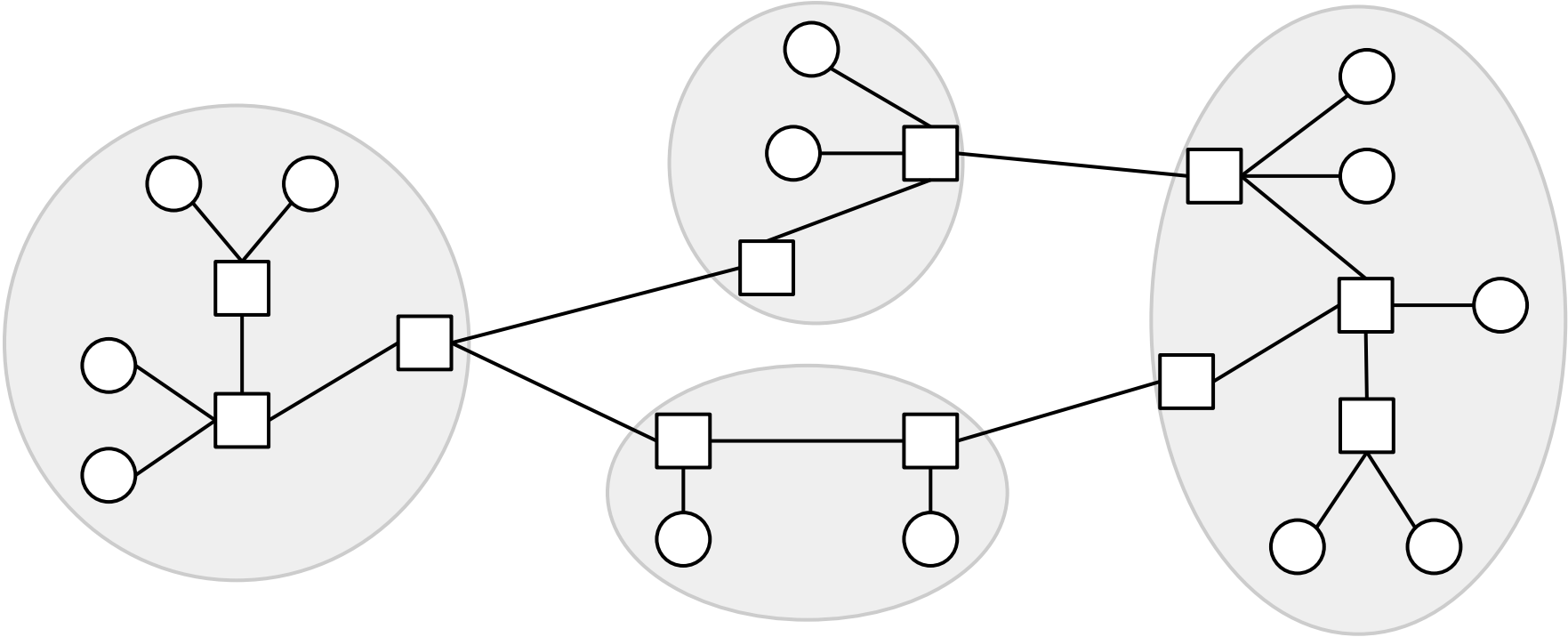
BGP (Border Gateway Protocol)

- Importing and Exporting
- Aggregation and Path-Vector

Intra-Domain vs. Inter-Domain Routing

Recall: The Internet is a network of networks.

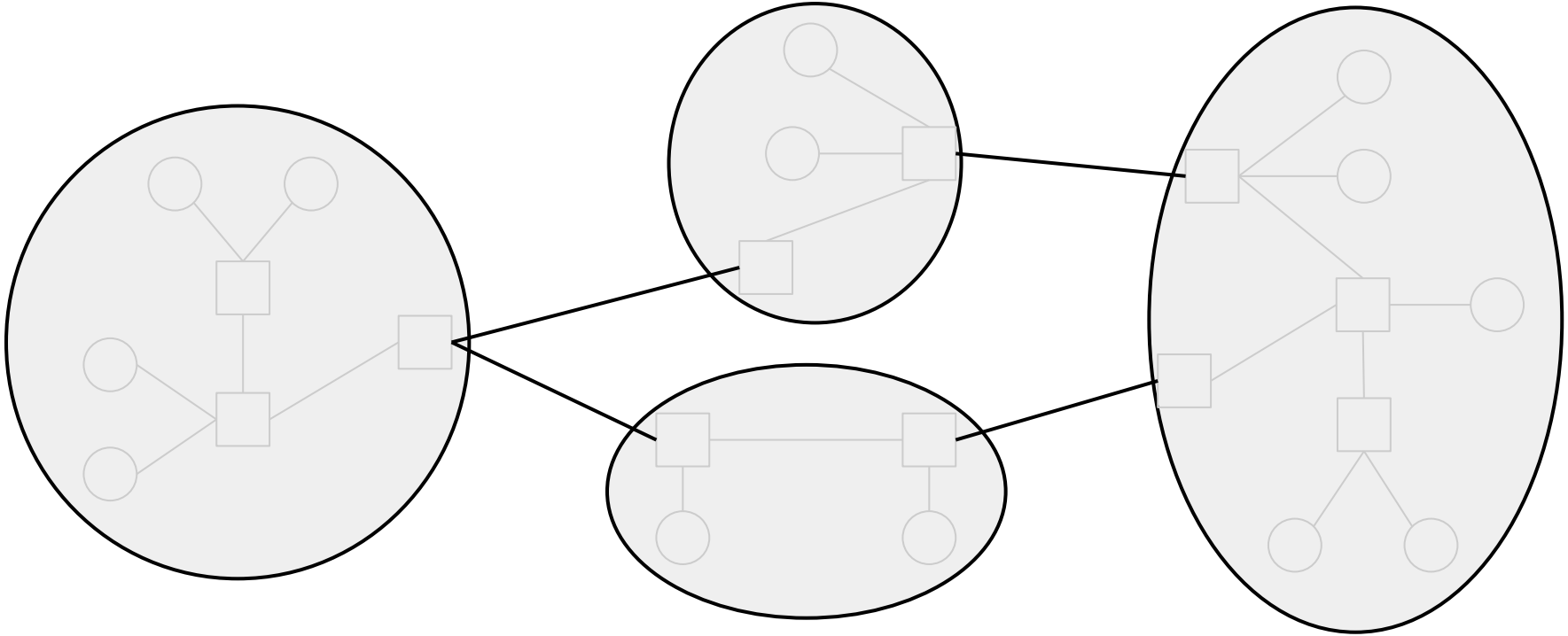
We used intra-domain routing to compute routes inside each network.



Intra-Domain vs. Inter-Domain Routing

Today's focus is inter-domain routing: finding paths between networks.

We'll bring back the individual routers next time.



Autonomous Systems

Autonomous System (AS): One or more local networks, all under a single administrative control.

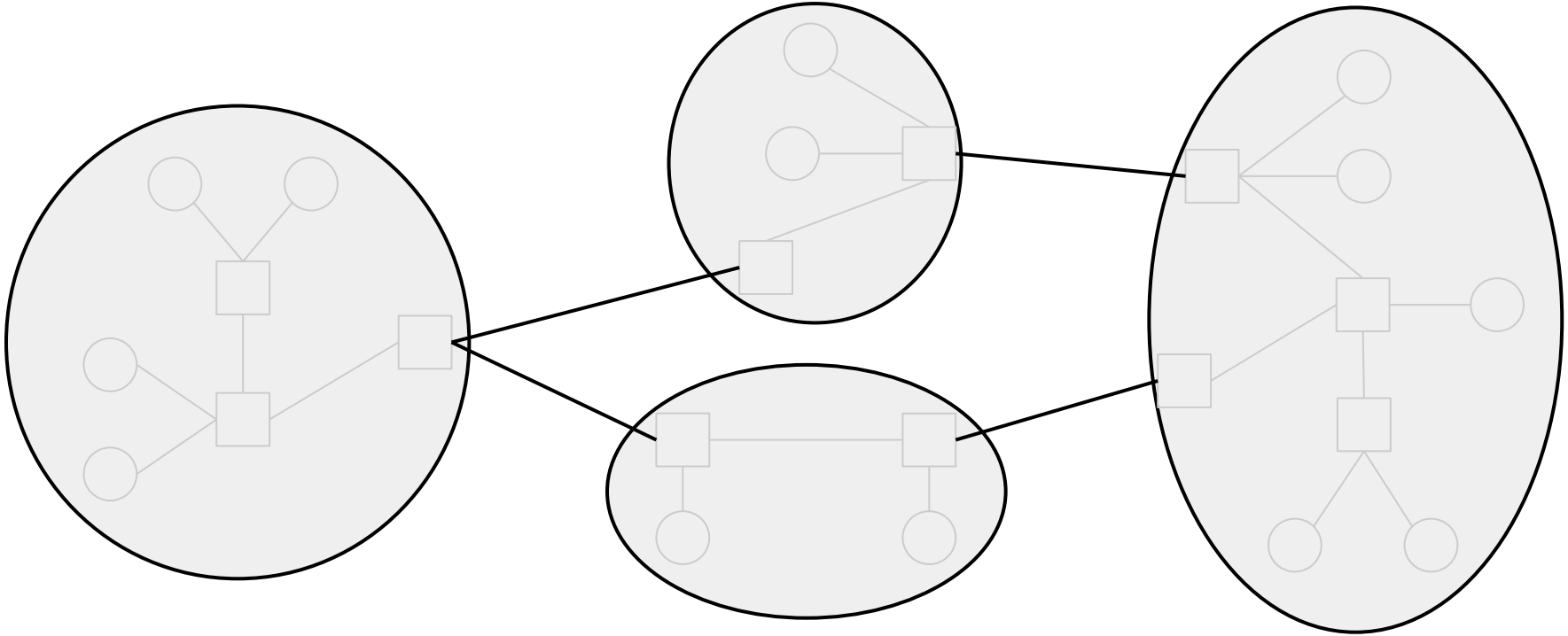
- Example: UC Berkeley's AS might contain both CalVisitor and eduroam.
- Sometimes informally called "domains."

Each AS is assigned a unique AS number (ASN).

- Example: UC Berkeley is ASN 25.

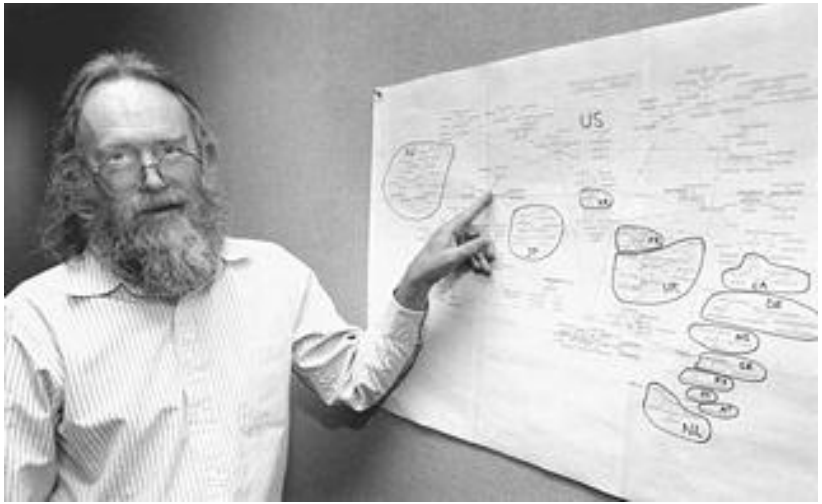
AS Graph

Inter-domain topology (or **AS graph**): A graph of ASes, with the individual routers and hosts abstracted away. Each node is an AS.



Who assigns new ASNs?

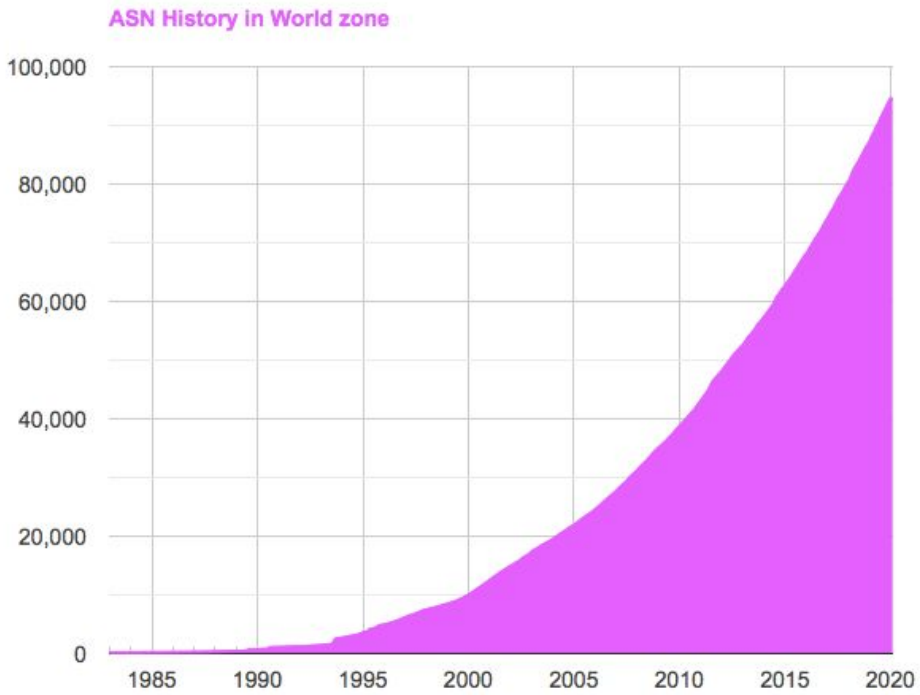
- In the early days: Some guy.
- Today: Internet Assigned Numbers Authority (IANA).



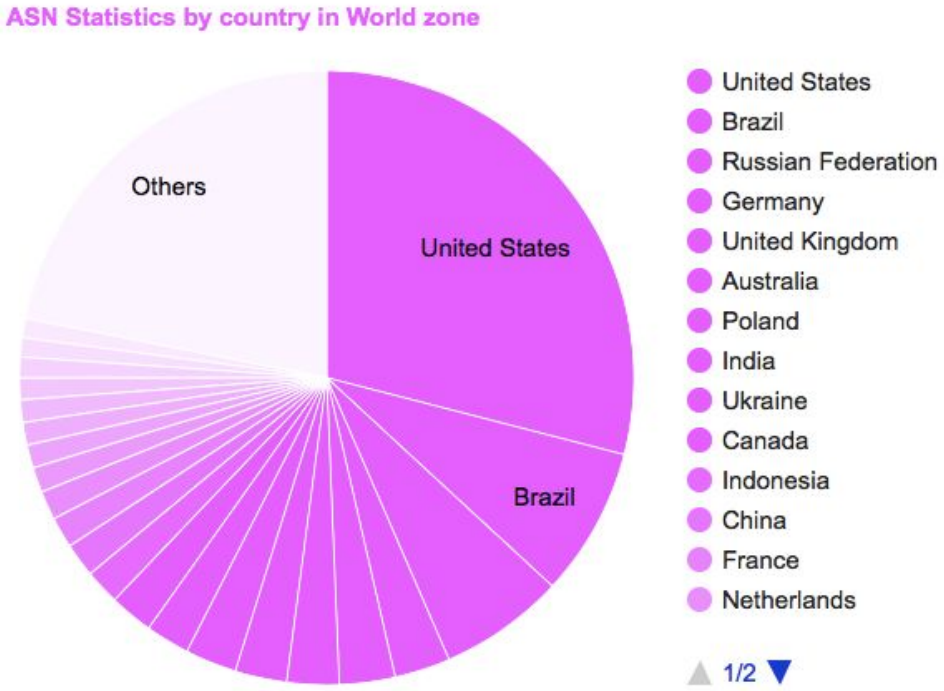
Jon Postel (1943–1998)

Brief History of Autonomous Systems

Number of ASes increases over time: Over 90,000 today!



ASes by country: USA has the most, followed by Brazil.



Types of Autonomous Systems

Stub AS: Only sends/receives packets on behalf of hosts inside the AS.

- Similar to end hosts in intra-domain model.
- Does not forward packets between other ASes.
- Examples: UC Berkeley, local bank.
- Most ASes are this type.

Transit AS: Forwards packets on behalf of other ASes.

- Similar to routers in intra-domain model.
- Can still send/receive packets for hosts inside the AS.
- Examples: AT&T, Verizon.
- Can vary in scale (global, regional).

Note: Some modern ASes (e.g. Google, Amazon) blur the line between stub and transit, but we won't worry about them.

Business Relationships

Lecture 9, CS 168, Spring 2025

Autonomous Systems

- What are ASes?
- **Business Relationships**

Goals of Inter-Domain Routing

- Policy-Based Routing
- Gao-Rexford Rules

BGP (Border Gateway Protocol)

- Importing and Exporting
- Aggregation and Path-Vector

Business Relationships

Inter-domain topology is shaped between business relationships between ASes.

Two different ways for a pair of ASes to be related:

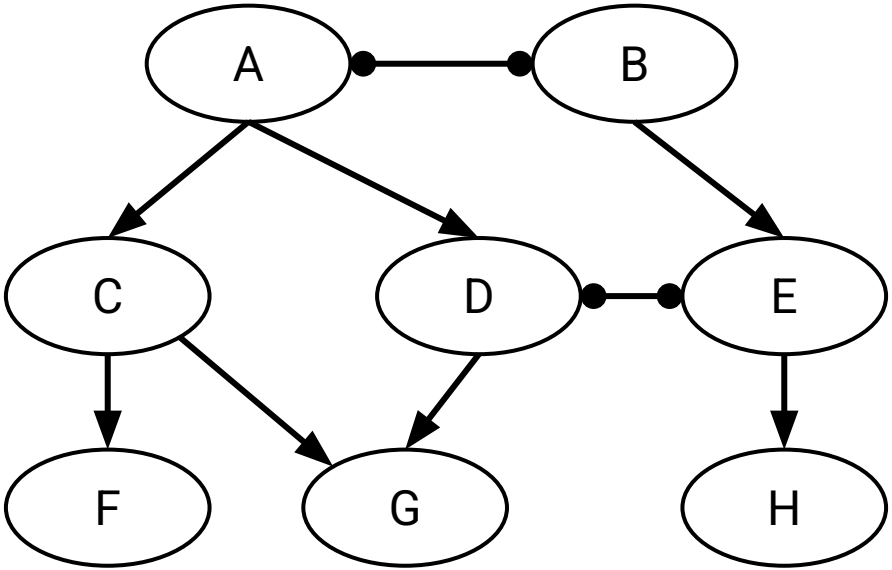
- **Customer-provider** relationship:
  - The customer pays the provider.
  - In exchange, the provider offers to forward traffic to/from the customer.
- **Peering** relationship:
  - Peers don't pay each other.
  - Peers exchange roughly equal traffic.

AS Graph with Business Relationships

Representing business relationships in the AS graph:

- Provider ⟶ Customer
- Peer ●—● Peer

The arrows do not represent direction of packets (e.g. F can send packets to C).

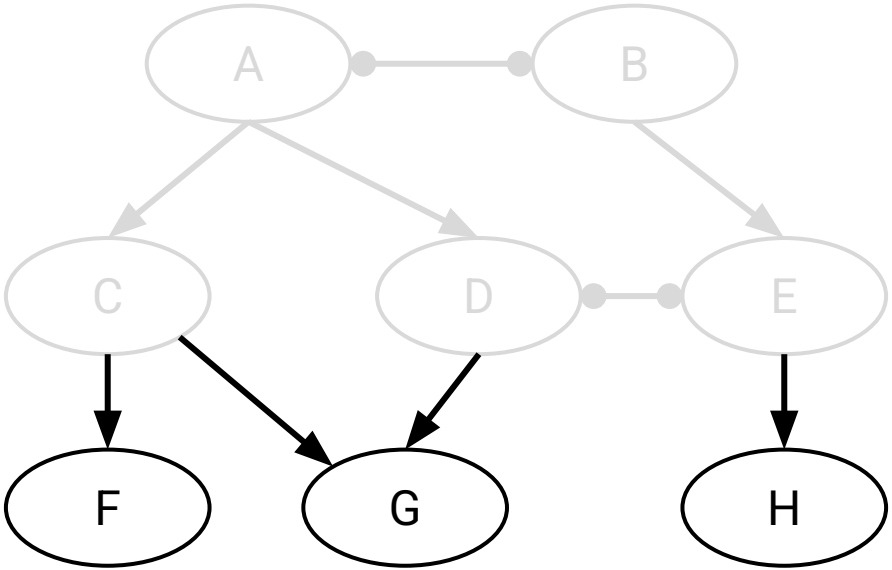


AS Graph with Business Relationships

Stub ASes in this graph: F, G, H.

No outgoing edges: Not providing service to anybody.

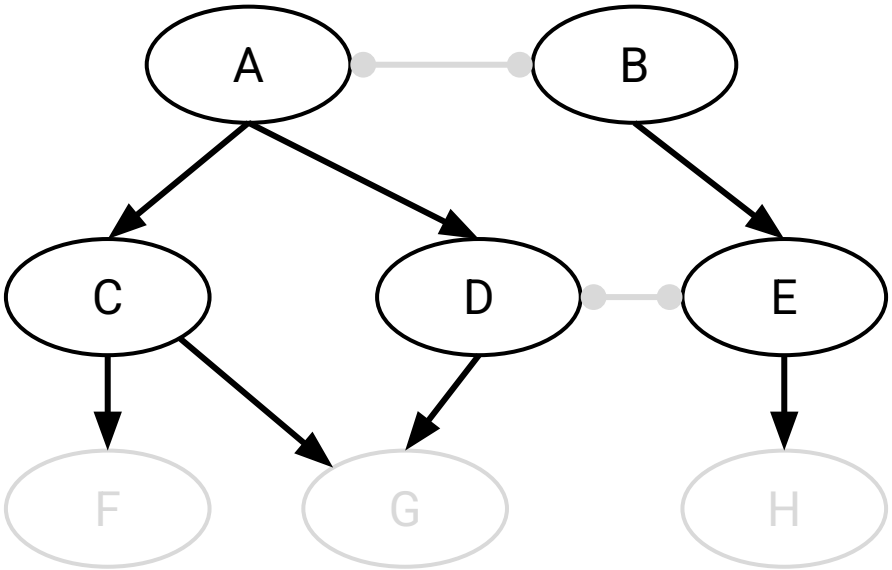
Incoming edge(s) shows who they're buying service from.



AS Graph with Business Relationships

Transit ASes in this graph: A, B, C, D, E.

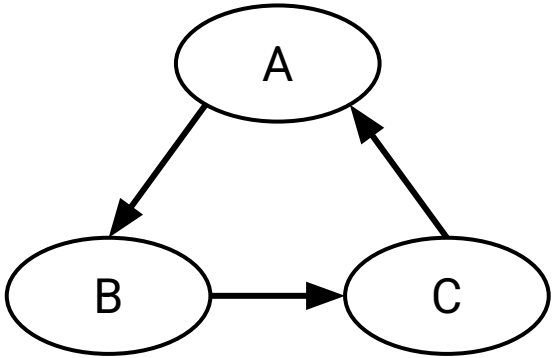
Outgoing edges indicate they're providing service to somebody.



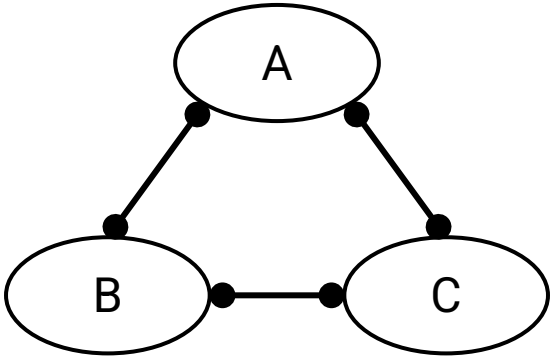
AS Graph is Acyclic

The AS graph has no cycles.

- A cycle means you're paying yourself, which doesn't make sense.
- A cycle of peering relationships is okay.



Invalid

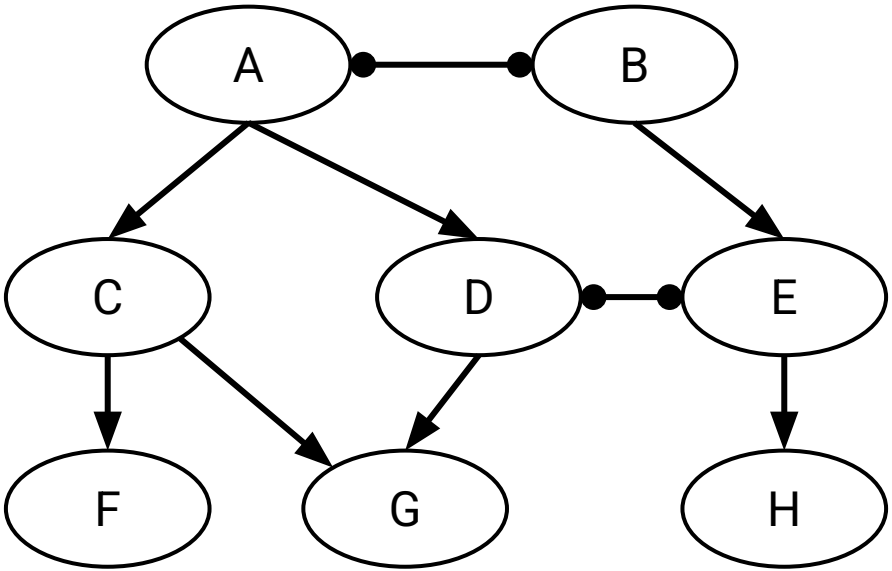


Valid

Provider Hierarchy

The AS graph forms a hierarchy (all arrows point down).

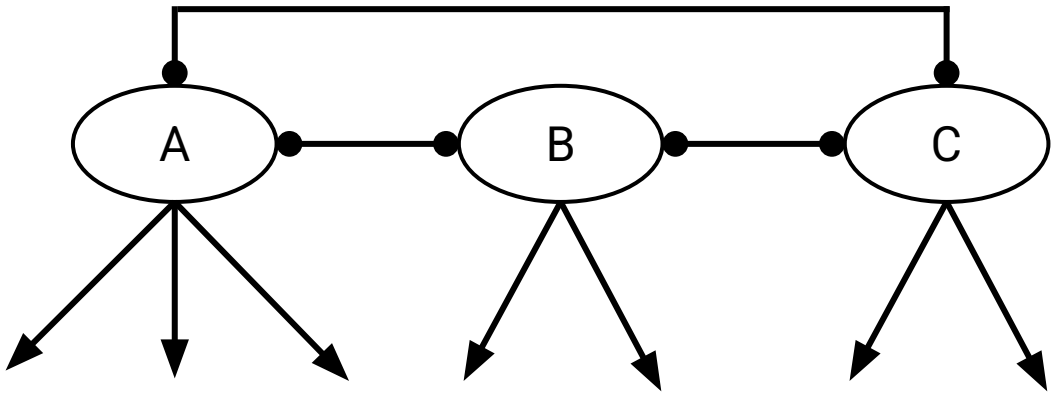
- Service flows down: Higher nodes provide service to lower nodes.
- Money flows up: Lower nodes pay money to higher nodes.



Tier 1 ASes: ASes at the top of the hierarchy.

A Tier 1 AS:

- Has no providers (no incoming edges).
- Has a peering relationship with every other Tier 1 AS.
  - This helps ensure the AS graph is connected (no disconnected components).



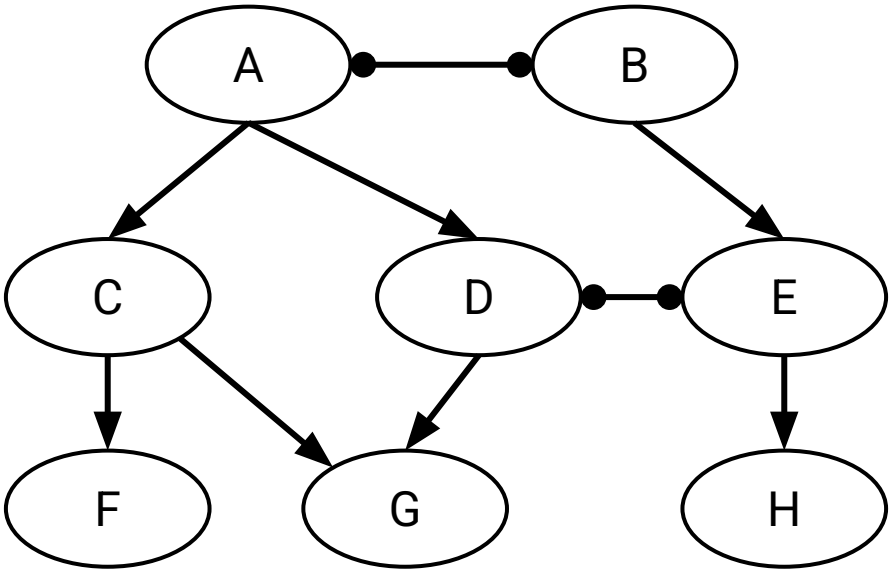
Tier 1 ASes

Tier 1 ASes: ASes at the top of the hierarchy.

- ~20 Tier 1 ASes in real life.
  - USA: AT&T, Verizon
  - Europe: Telecom Italia, France Telecom
  - Asia: NTT Communications (Japan)
- These companies usually own infrastructure spanning the whole world.

Properties of AS Graphs

- Every non-Tier 1 AS has at least one provider (incoming edge).
- Starting at any AS and walking up the graph will eventually lead to a Tier 1 AS.



Goals of Inter-Domain Routing: Policy-Based Routing

Lecture 9, CS 168, Spring 2025

Autonomous Systems

- What are ASes?
- Business Relationships

Goals of Inter-Domain Routing

- **Policy-Based Routing**
- Gao-Rexford Rules

BGP (Border Gateway Protocol)

- Importing and Exporting
- Aggregation and Path-Vector

Goals of Inter-Domain Routing

Scalability: Routing must scale to the entire Internet.

- Solution: Hierarchical IP addressing.

Privacy: ASes don't want to explicitly announce sensitive information.

- I shouldn't have to tell everybody who my provider is.
- Companies might not want to reveal information to rivals.
- "Explicitly" - Some minor leakage is inevitable.

Autonomy: ASes want the freedom to choose their own policies.

- Policy is usually based on business goals.

Policy-Based Routing

Autonomy: ASes want the freedom to choose their own **policies**.

Recall our routing goals:

- Valid paths:
  - Intra-domain definition: No loops, no dead ends.
  - Inter-domain definition: Same.
- Good paths:
  - Intra-domain definition: Least-cost paths.
  - Inter-domain definitions: Paths that respect every AS's policies.

Policy-Based Routing

Autonomy: ASes want the freedom to choose their own **policies**.

Examples of policies:

- Define how I will handle traffic from others:
  - I don't want to carry AS#2046's traffic through my network.
- Defines how others should handle my traffic:
  - I prefer if my traffic was carried by AS#10 instead of AS#4.
  - Don't send my traffic through AS#54 unless absolutely necessary.
- More exotic policies:
  - I prefer AS#12 on weekdays, and AS#13 on weekends.

We have to find paths that respect every AS's policies.

Gao-Rexford Rules

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Autonomous Systems

- What are ASes?
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- **Gao-Rexford Rules**

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Gao-Rexford Rules

In theory, ASes can set any weird policy they want.

In practice, most ASes follow standard conventions: **Gao-Rexford Rules**.

These conventions reflect real-world business practices:

- Making money is good.
- Don't do work for free.

Lixin Gao and Jennifer Rexford surveyed various ASes to come up with these rules.

Gao-Rexford Rules: Choosing Routes

Distance-vector protocol: Prefer the *shortest* path.

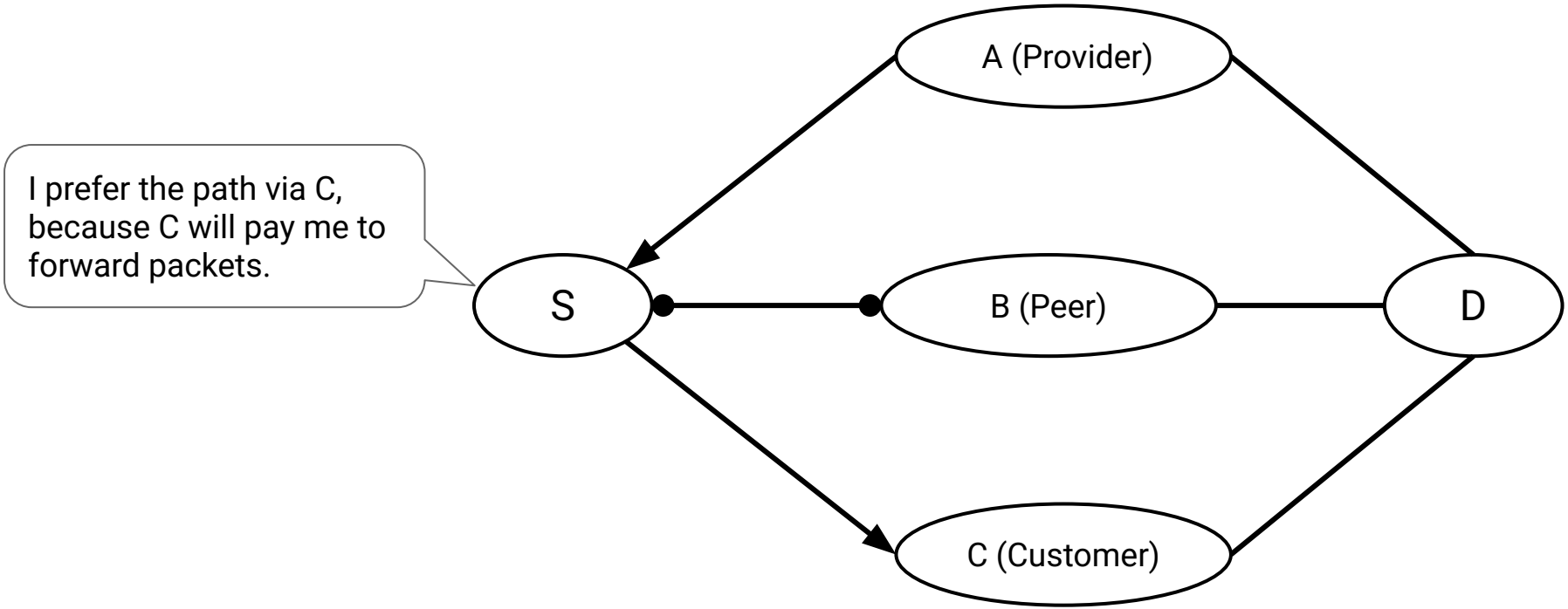
Gao-Rexford rules: Prefer the *most profitable* path.

- Best: Path where the next hop is a customer. (They pay me.)
- Less good: Path where the next hop is a peer. (I don't make money.)
- Worst: Path where the next hop is a provider. (I have to pay.)

Reflects real-world business practice: Making money is good.

Gao-Rexford Rules: Choosing Routes

Gao-Rexford rules: If I'm offered multiple paths, pick the *most profitable* one.



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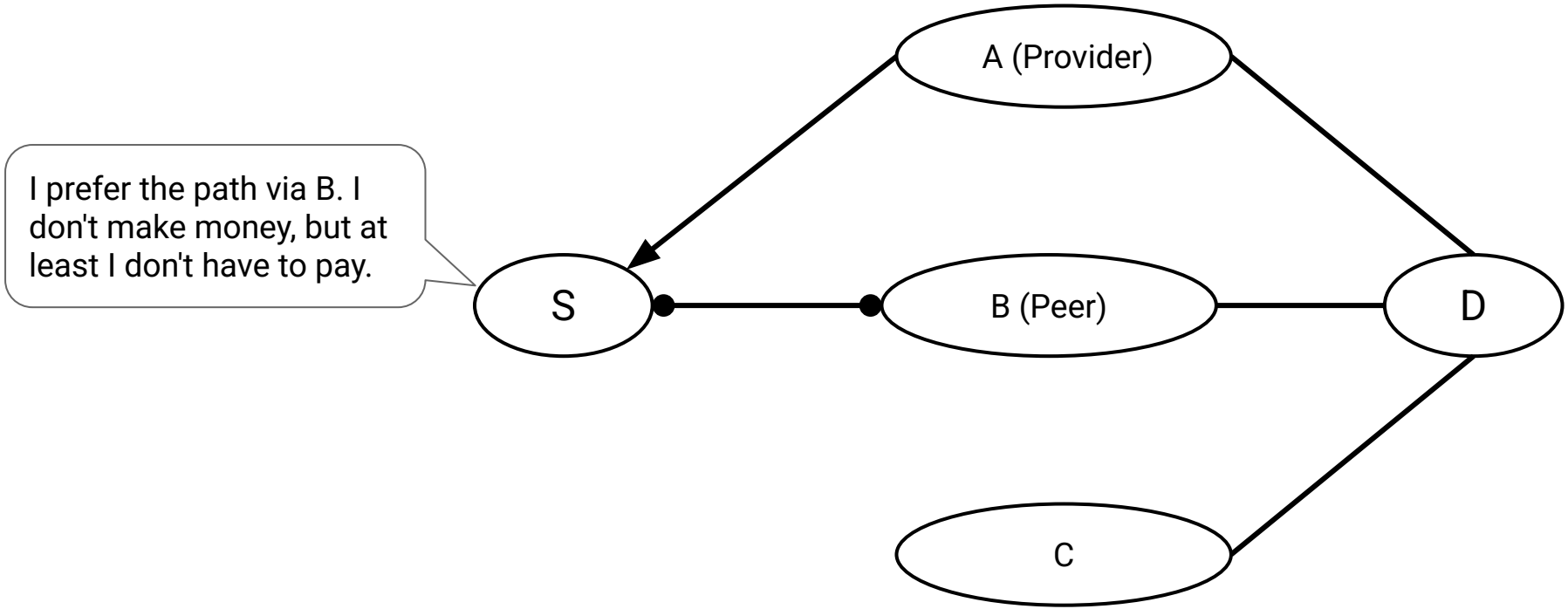


Gao-Rexford Rules: Participating in Routes

Distance-vector protocol: I am okay with participating in any route.

- "Participating": Being one of the routers forwarding packets along a path.

Gao-Rexford rules: I will only participate in routes where I get paid.

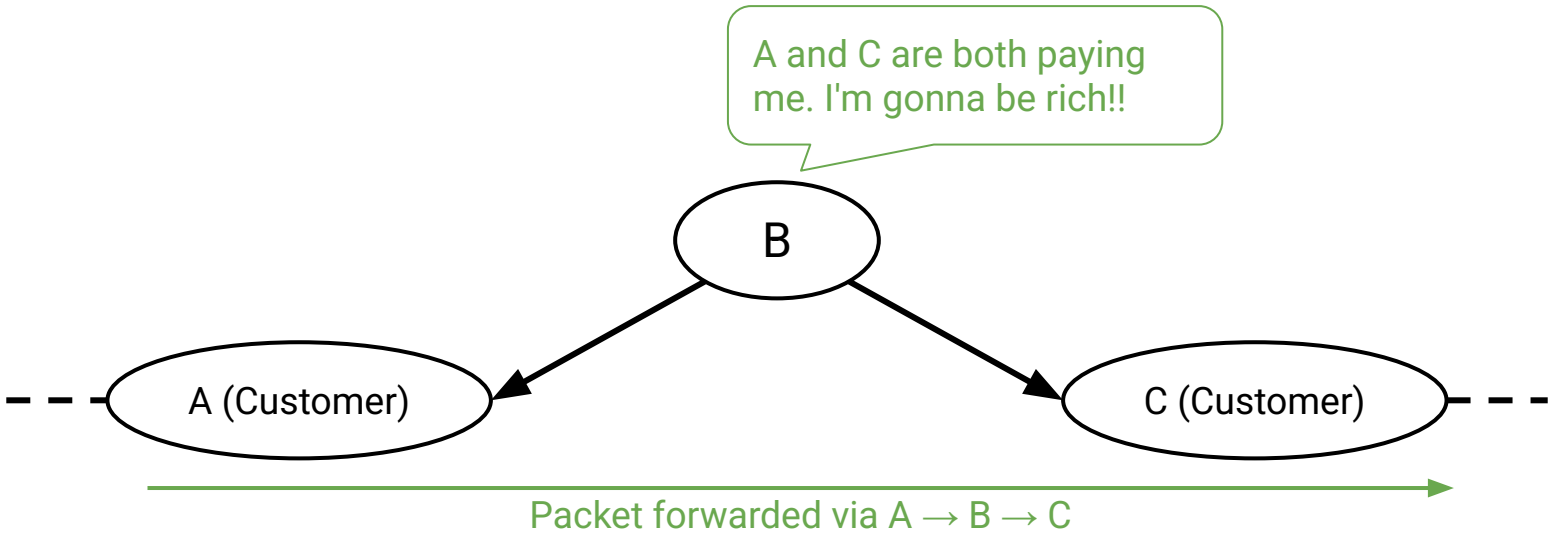
- Reflects real-world business relationship: Don't do work for free.

How to check if I get paid:

- Look at my two neighbors along the path.
- I get paid if and only if one of my neighbors is a customer.

Gao-Rexford Rules: Participating in Routes

I get paid and participate if and only if at least one of my neighbors is a customer.



Gao-Rexford Rules: Participating in Routes

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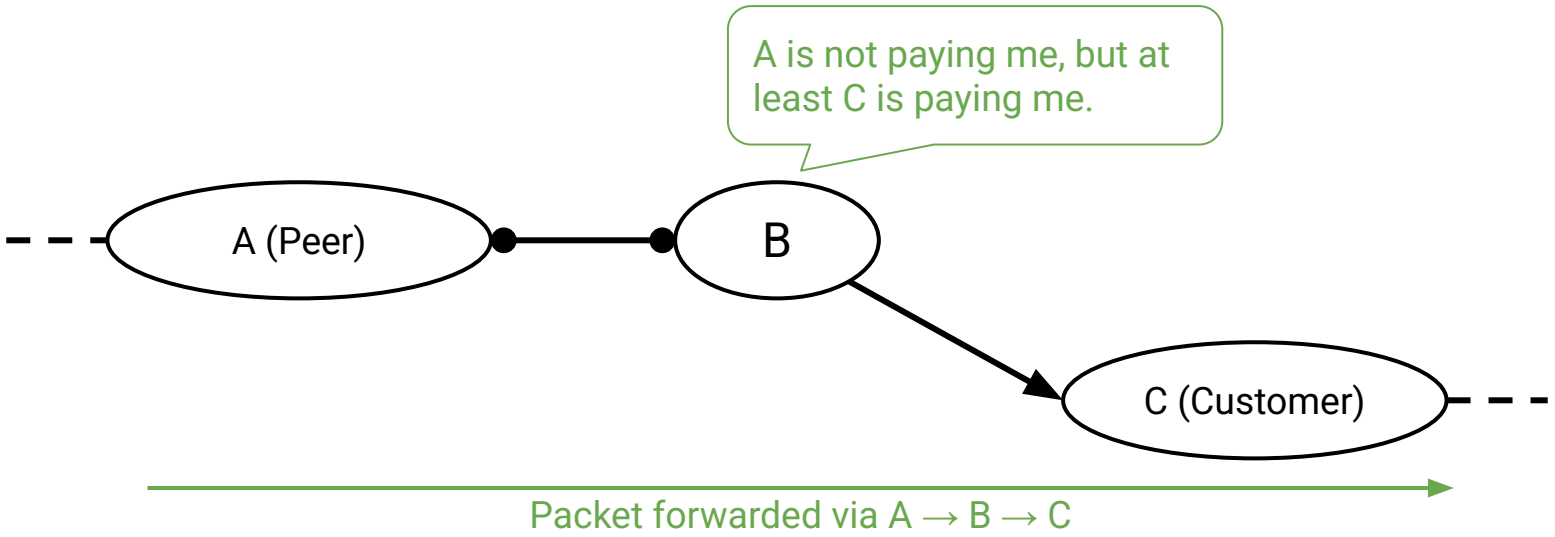
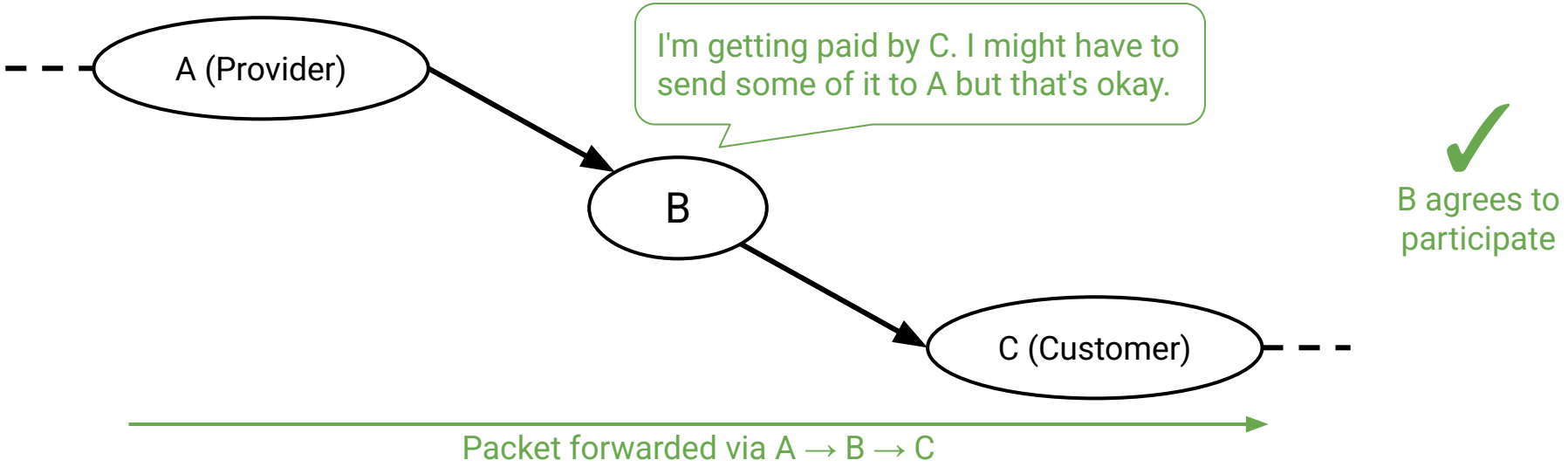


Gao-Rexford Rules: Participating in Routes

I get paid and participate if and only if at least one of my neighbors is a customer.

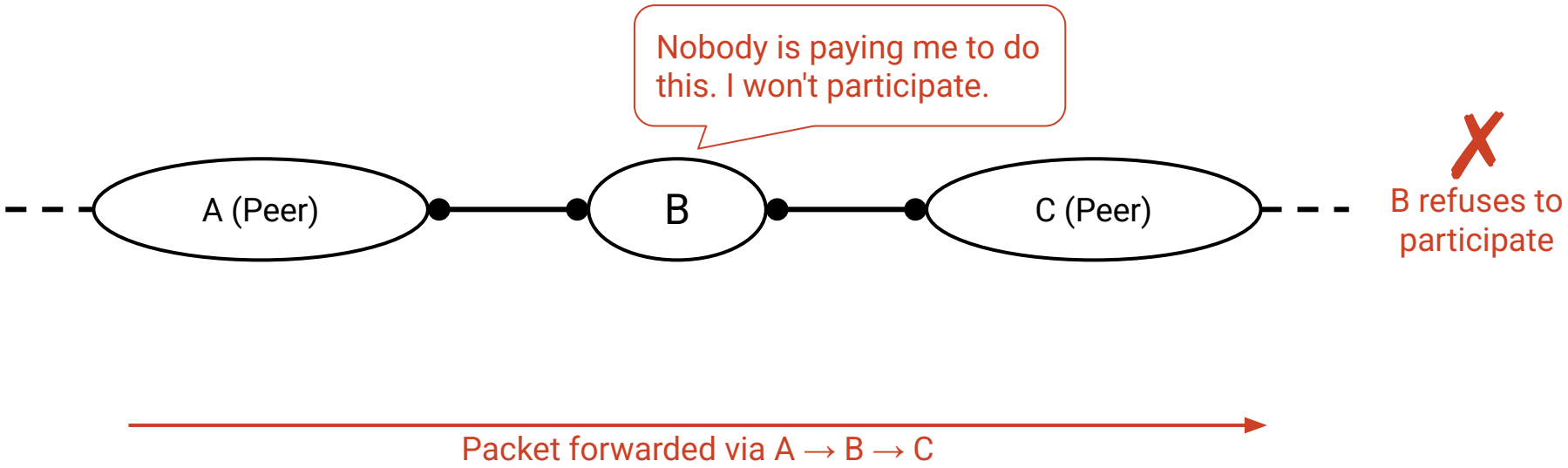
- In this scenario: I get paid by C, but I have to pay A.
- I should still participate because this is how I offer service to my customers.



Gao-Rexford Rules: Participating in Routes

I get paid and participate if and only if at least one of my neighbors is a customer.

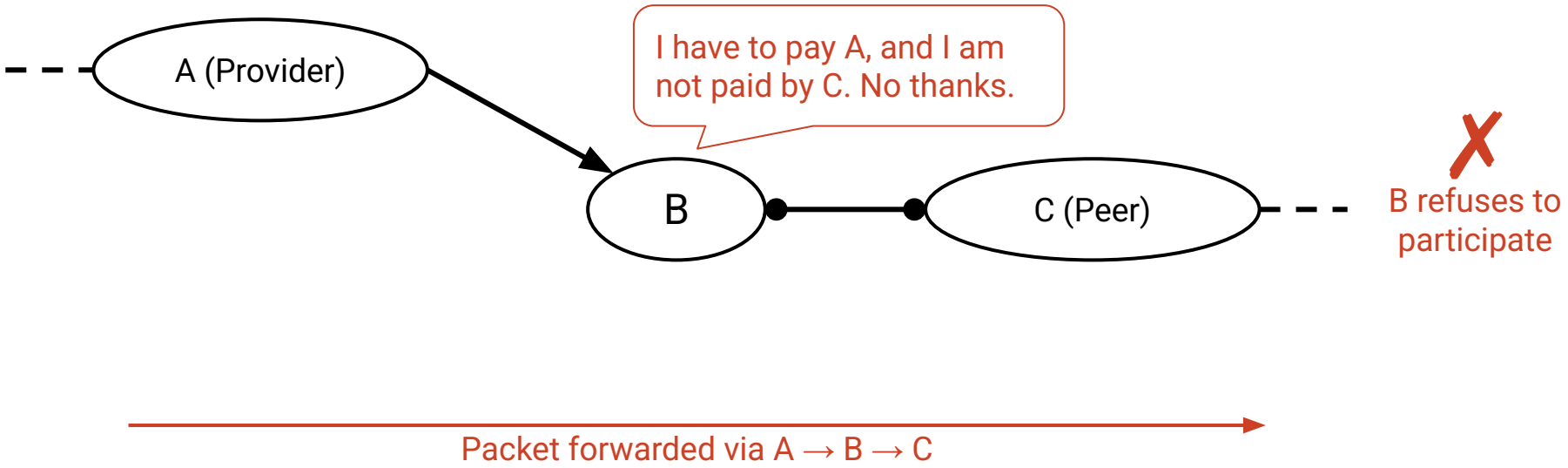
- Peers do not provide transit between other peers.



Gao-Rexford Rules: Participating in Routes

I get paid and participate if and only if at least one of my neighbors is a customer.

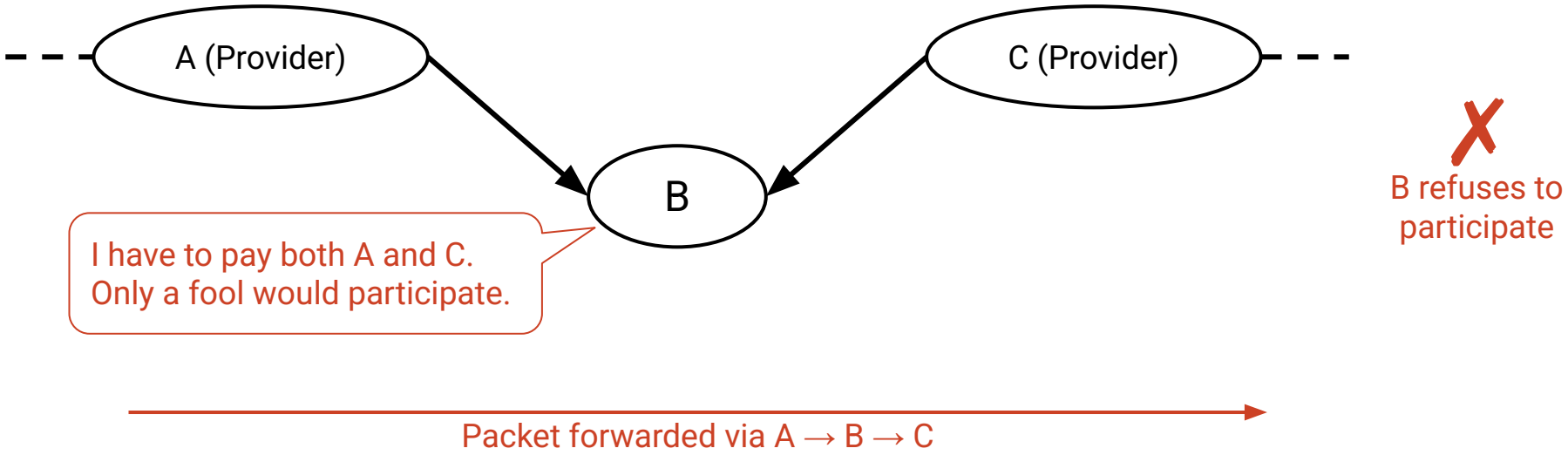
- If one of my neighbors is a peer, the other neighbor must be a customer.
- An AS only carries traffic to/from its own customers over a peering link.



Gao-Rexford Rules: Participating in Routes

I get paid and participate if and only if at least one of my neighbors is a customer.

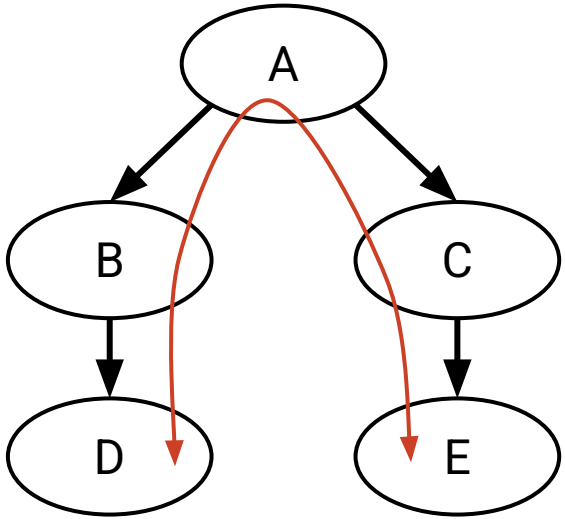
- Routes are **valley-free**.
- Travelling downhill, and turning around and going back uphill is not allowed.



Policy-Based Routing Example

D and E want to exchange traffic along this path.

Will the transit ASes (A, B, C) agree to participate?



Policy-Based Routing Example

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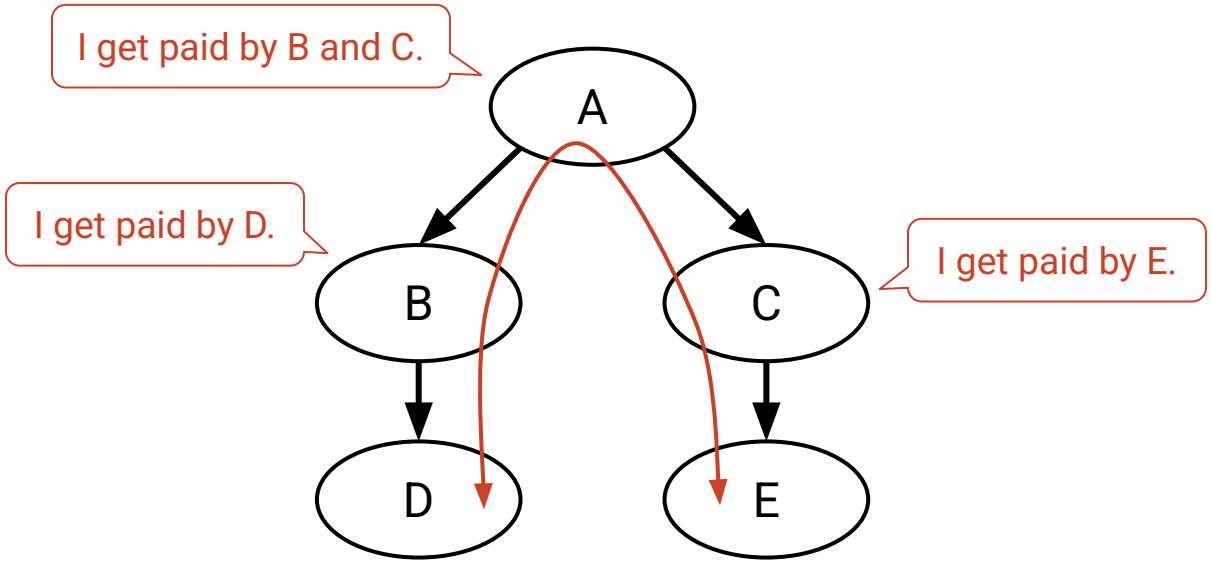
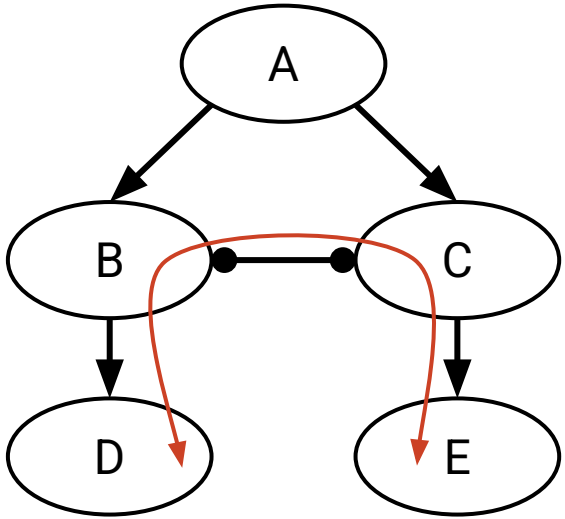
Yes, each transit AS has an adjacent customer.



Policy-Based Routing Example

Suppose we add a new link (B and C establish a peering relationship).

Will the transit ASes (B, C) agree to participate in this new route?



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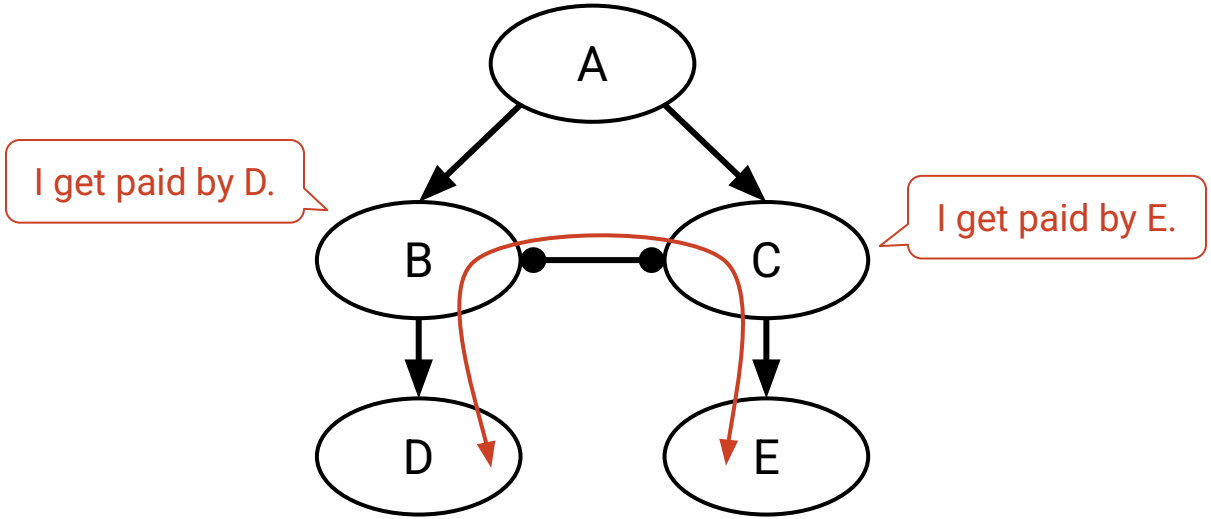
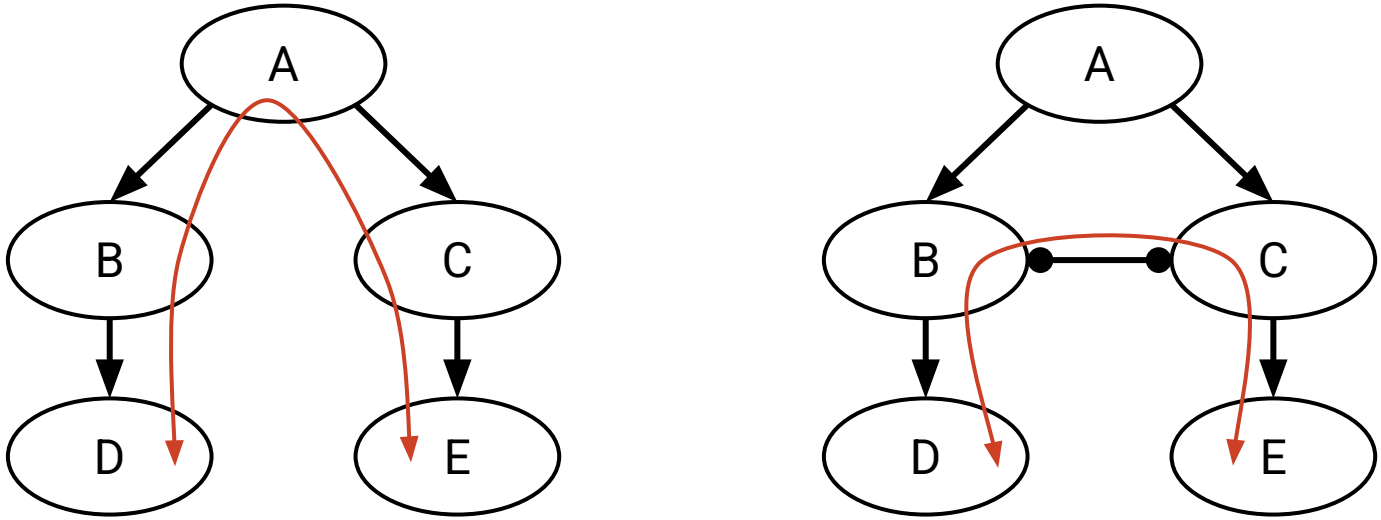


Policy-Based Routing Example

With the new link, B and C save money (they don't have to pay A anymore).

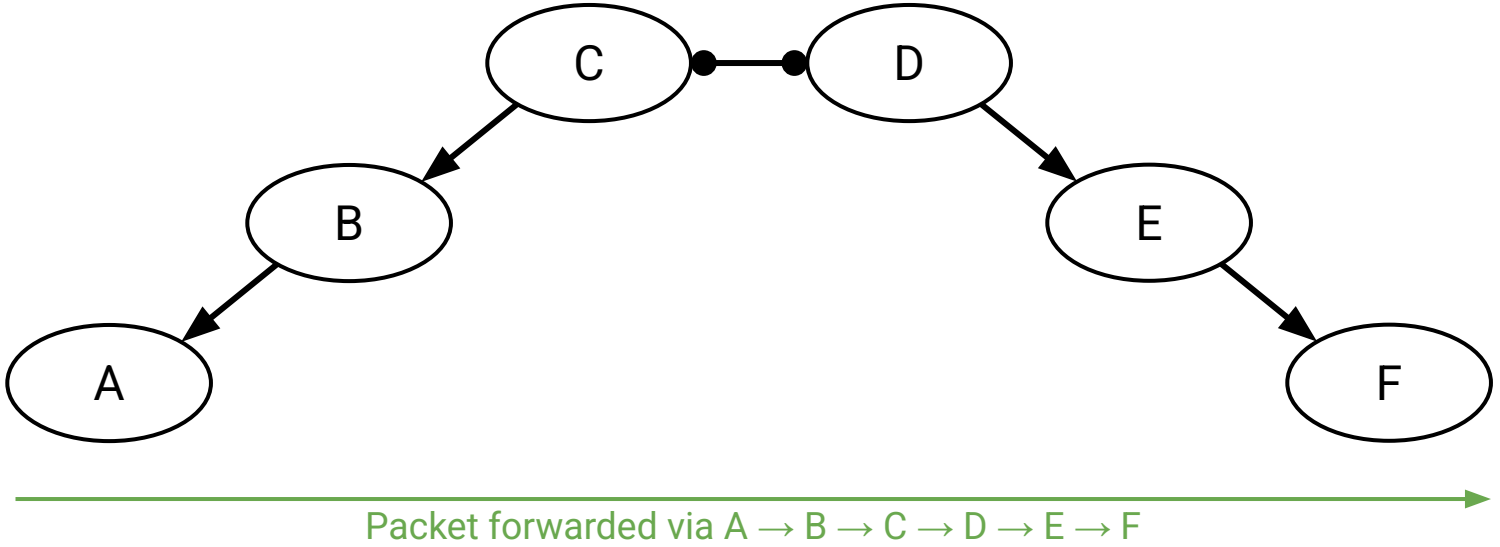
Trade-off: B and C have to pay to build that link.



Properties of Routes with Gao-Rexford Rules

Routes are **single-peaked**.

- We first climb 0 or more uphill links.
- Then, we reach a peak, and traverse 0 or 1 peering links.
- Then, we go strictly downhill all the way to the destination.



Proving Reachability and Convergence with Gao-Rexford

If all of these are true:

- Starting from any AS and moving up the hierarchy will lead to a Tier 1 AS.
- The AS graph has no cycles.
- All ASes follow the Gao-Rexford rules.

Then we can guarantee these two properties:

- **Reachability**: Any two ASes in the graph can communicate.
- **Convergence**: All ASes agree on paths.

These properties hold in steady-state.

- Steady-state: Network topology and policies remain unchanged.
- If something changes, it might take some time for ASes to reconverge.

If ASes pick arbitrary policies (not following Gao-Rexford), we can't guarantee these properties.

Summary: Autonomous Systems, Policy-Based Routing

- AS topology reflects business relationships between ASes.
- Business relationships impact what routes are chosen, and what routes are acceptable.
- Inter-domain routing design must support:
  - Scalability
  - Autonomy (support policy choices)
  - Privacy

BGP: Importing and Exporting

Lecture 9, CS 168, Spring 2025

Autonomous Systems

- What are ASes?
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Goals of Inter-Domain Routing

- Policy-Based Routing
- Gao-Rexford Rules

BGP (Border Gateway Protocol)

- **Importing and Exporting**
- Aggregation and Path-Vector

A Brief History of BGP

- Least-cost routing algorithms are based on old ideas.
  - Shortest-path algorithms predate the Internet:
    Dijkstra's (1956), Bellman-Ford (1958).
- Autonomous systems grew out of necessity.
  - Internet control transferred from the US government to various companies.
  - The Internet grew too big for least-cost routing algorithms.
- Autonomous systems were a new idea to computer science.
  - No precedent for "find paths according to business policy."
  - Ideas behind BGP were developed on the fly (1989–1995).
- It's not perfect, but it's stood the test of time.
- BGP is the one and only inter-domain routing protocol in use.
  - Remember: Everyone must agree on the same one.

Starting Point: Distance-Vector or Link-State?

Distance-vector or link-state: Which would be a better starting point?

Link-state is a bad choice.

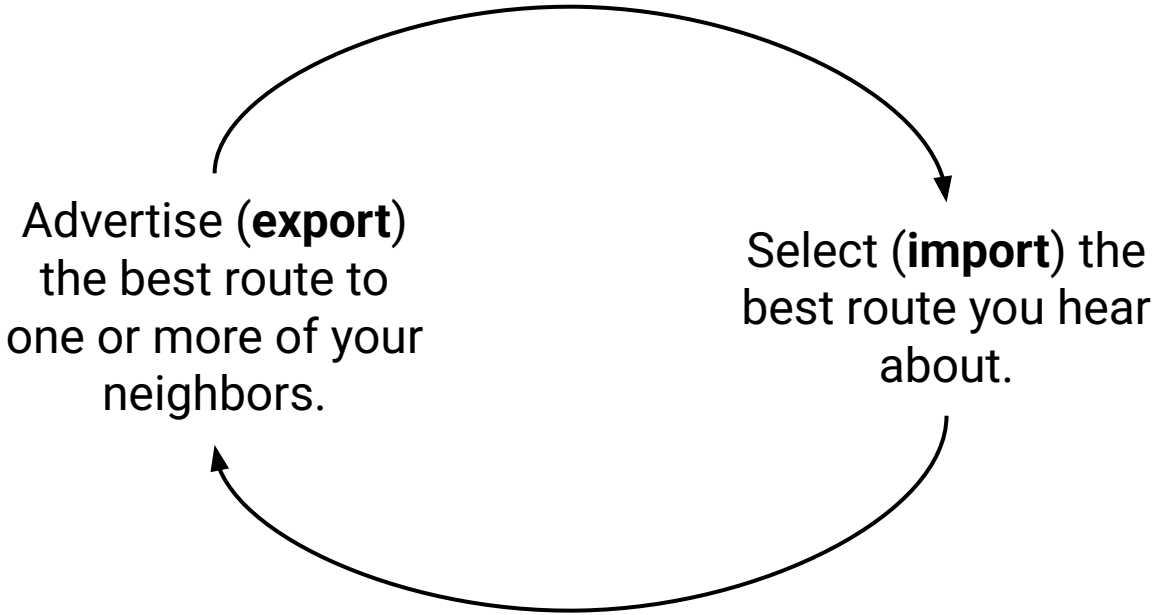
- No privacy: I have to reveal my policies to everybody else.
- No autonomy: Everyone has to agree on a metric (e.g. least-cost) for consistency.

Distance-vector is a better choice.

- BGP extends distance-vector to accommodate policy.
- BGP and distance-vector are similar:
  - Advertisements are specific to one destination (i.e. one prefix).
  - No global sharing of network topology.
  - Iterative and distributed convergence on paths.

Importing and Exporting Paths

New terminology for old ideas:



Use policy to decide which route to import, and who to export routes to.

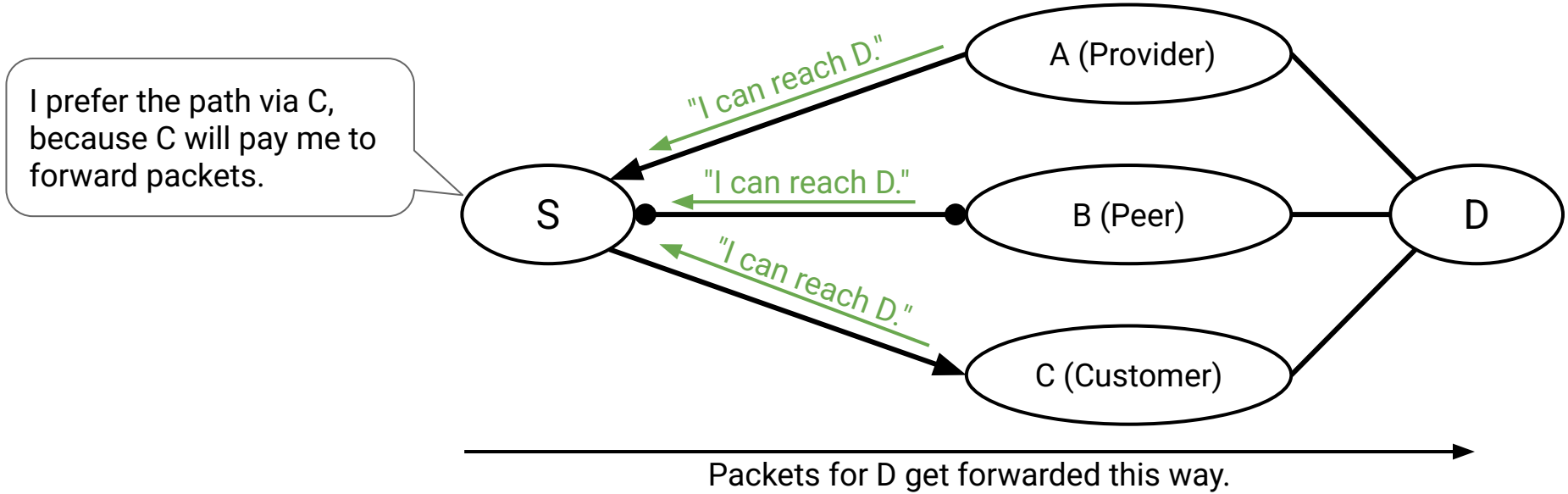
Importing Paths

Gao-Rexford import policy: Pick the route advertised by customer > peer > provider.

- Contrast with distance-vector: Pick the shortest route.

Import decision determines where an AS sends its outbound traffic.

- Why? Because this involves choosing a route.



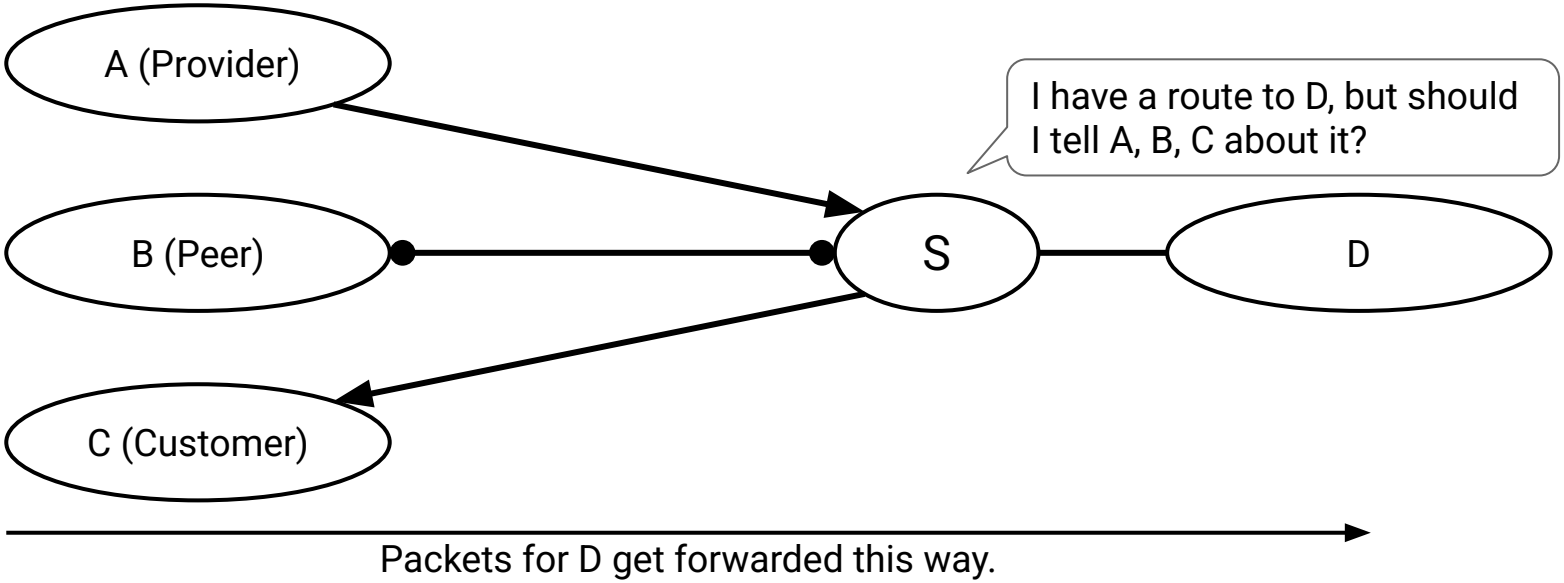
Exporting Paths

Gao-Rexford export policy: I only export a route if participating in it makes me money.

- Contrast with distance-vector: Advertise a route to all neighbors.

Export decision determines what traffic an AS will carry.

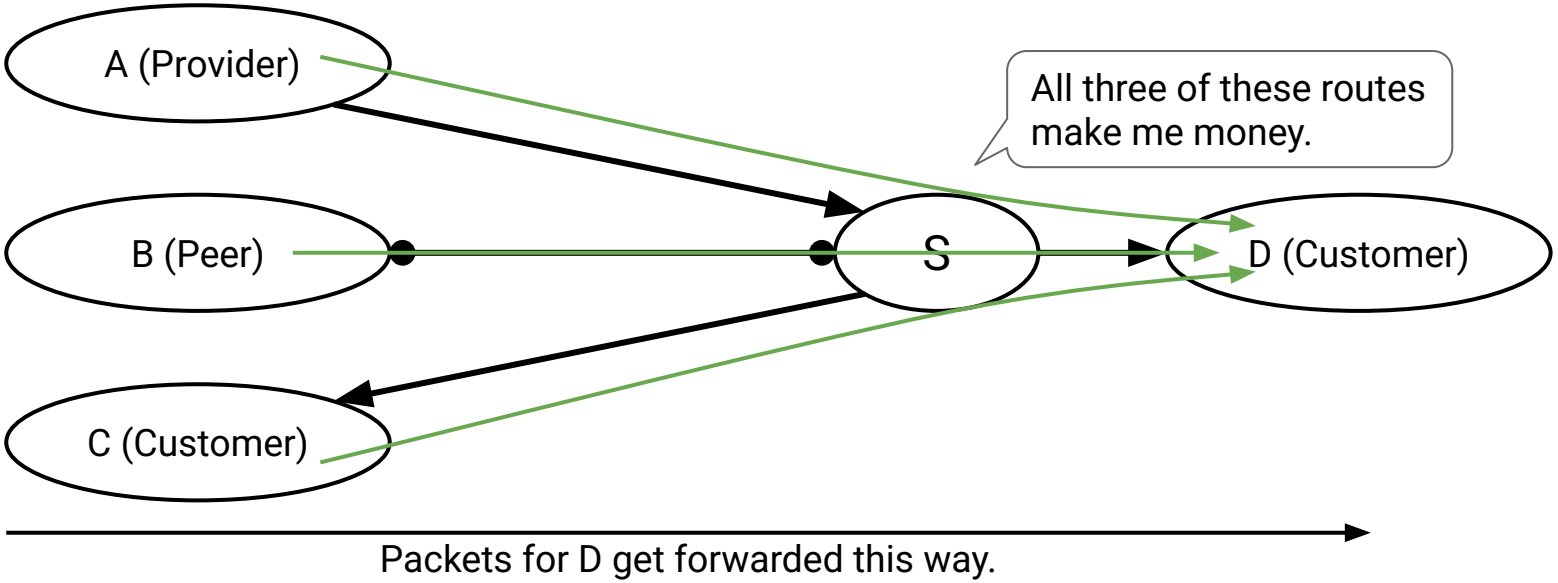
- Why? Advertising a route means I'm letting others forward traffic through me.



Exporting Paths From Customers

Gao-Rexford export policy: I only export a route if participating in it makes me money.

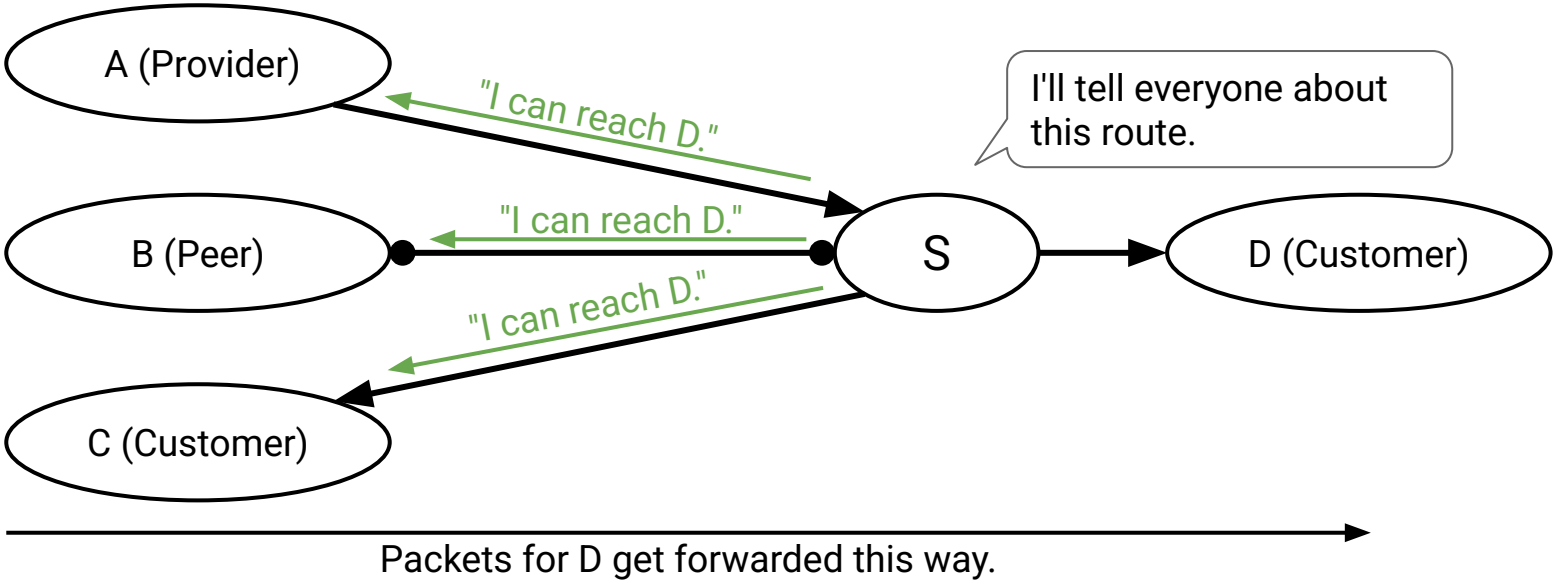
- If I receive a route from a customer, export it to everybody.
- The resulting route will be profitable: There's a customer on one end.



Exporting Paths From Customers

Gao-Rexford export policy: I only export a route if participating in it makes me money.

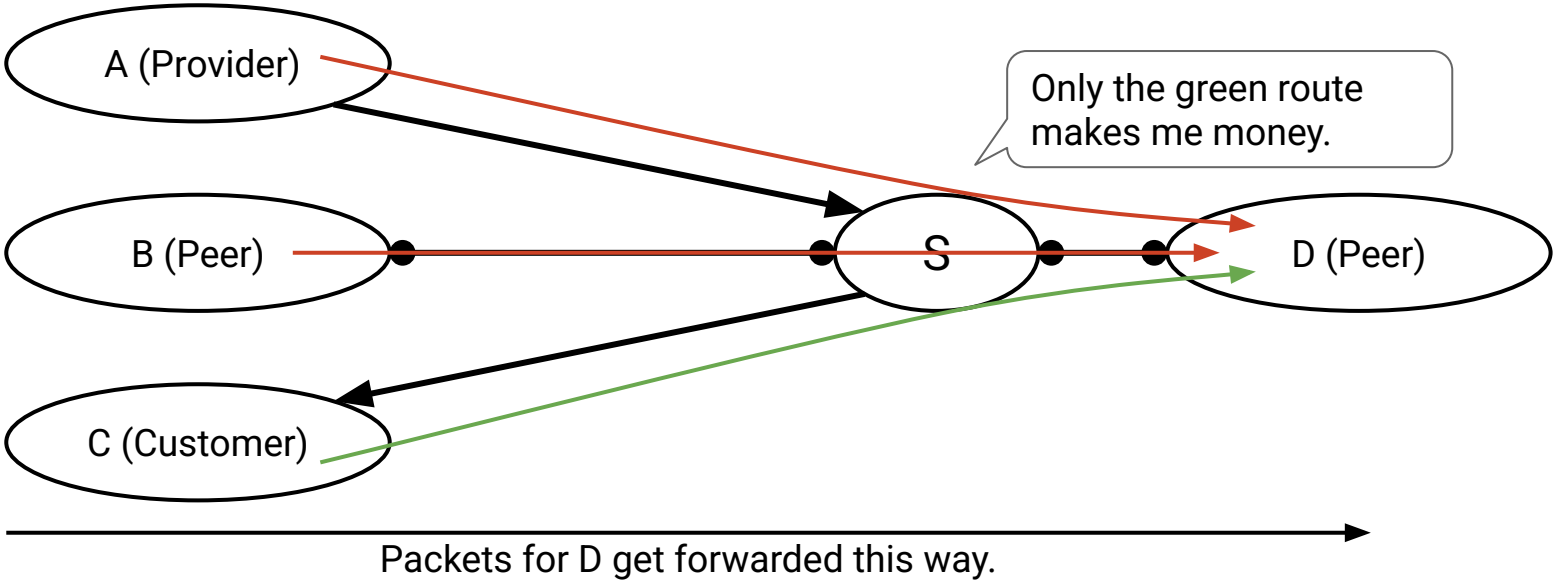
- If I receive a route from a customer, export it to everybody.
- The resulting route will be profitable: There's a customer on one end.



Exporting Paths From Peers

Gao-Rexford export policy: I only export a route if participating in it makes me money.

- If I receive a route from a peer, only export it to a customer.
- The peer isn't paying, so I only profit if the person on the other end is a customer.



Exporting Paths From Peers

Gao-Rexford export policy: I only export a route if participating in it makes me money.

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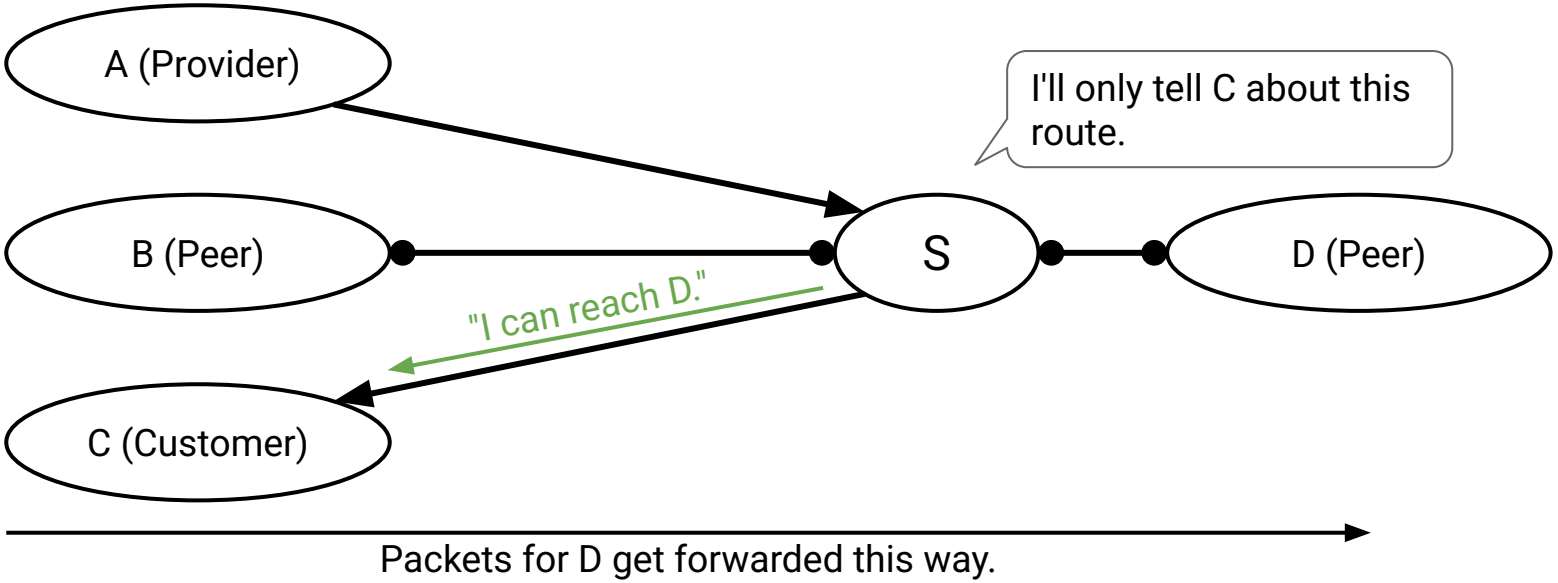
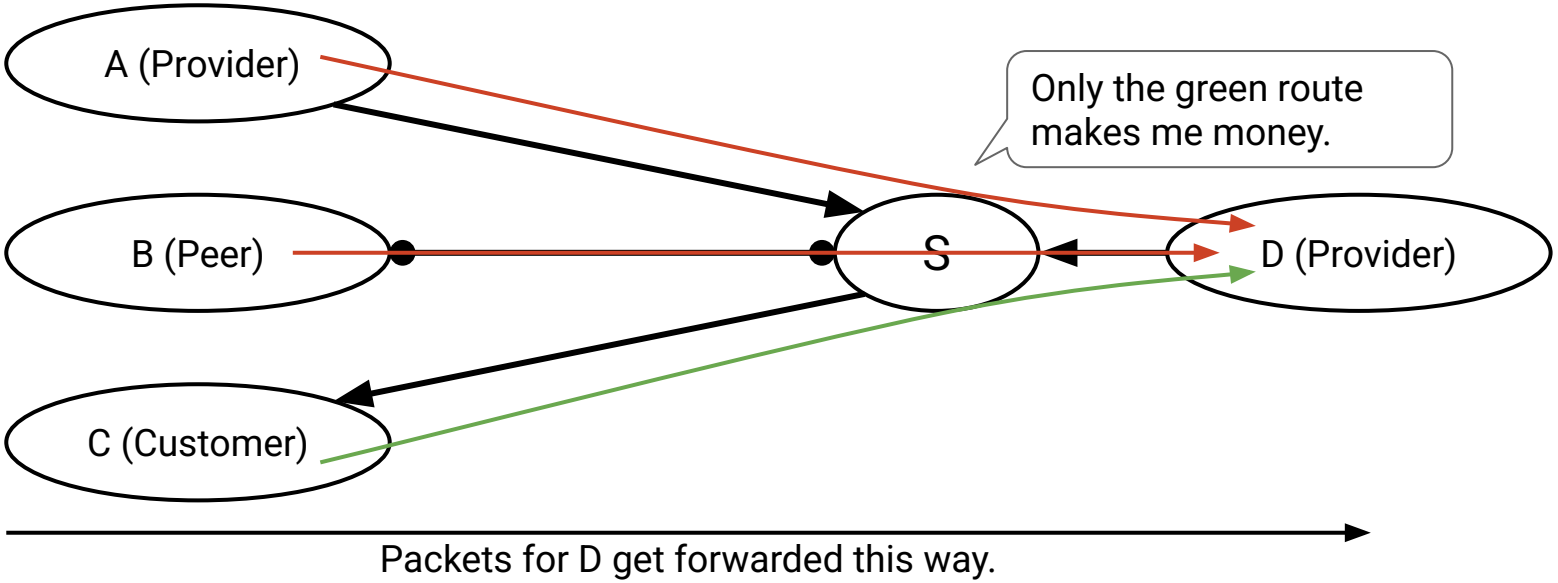


Exporting Paths From Providers

Gao-Rexford export policy: I only export a route if participating in it makes me money.

- If I receive a route from a provider, only export it to a customer.
- I pay the provider, so I only profit if the person on the other end is a customer.



Exporting Paths From Providers

Gao-Rexford export policy: I only export a route if participating in it makes me money.

- If I receive a route from a provider, only export it to a customer.
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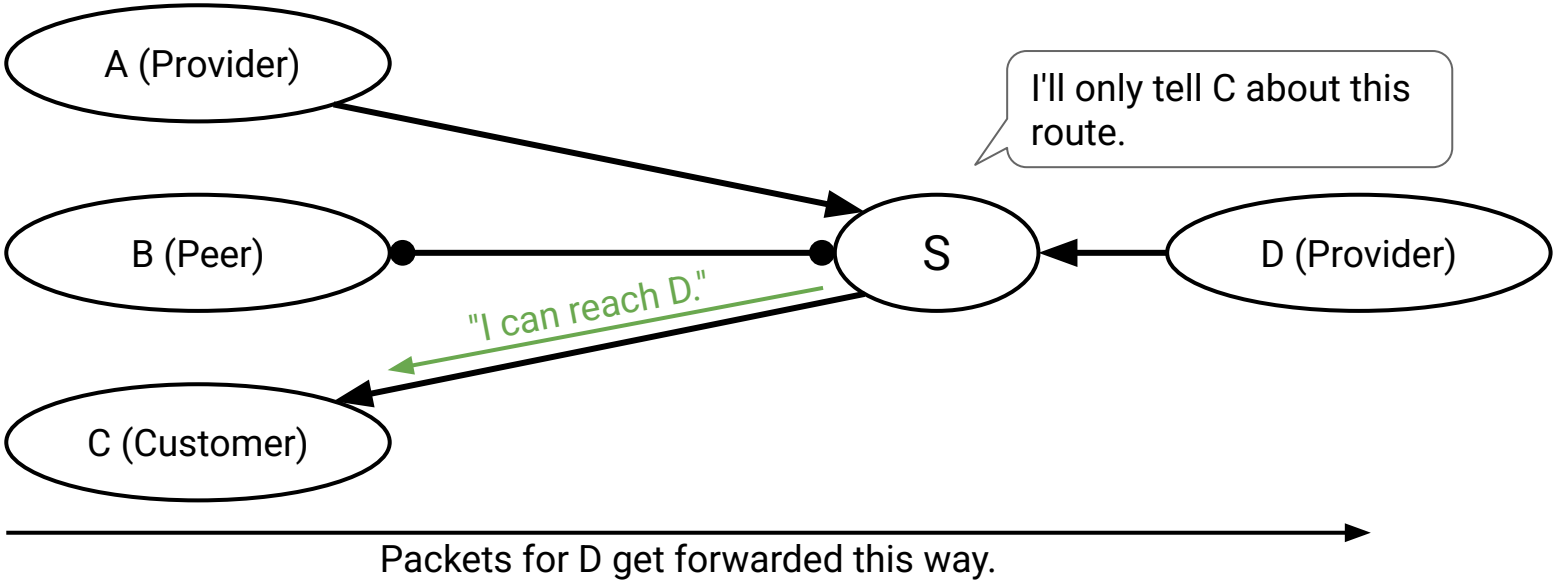


Exporting Paths From Providers

Gao-Rexford export policy: I only export a route if participating in it makes me money.

Key idea: The route needs a customer on at least one side.

- If a customer advertised the route, we already have a customer on one side. The other side can be anybody.
- If a peer/provider advertised the route, we're still missing a customer. The other side must be a customer.

Route advertised by...	Export route to...
Customer	Everyone (providers, peers, customers)
Peer	Customers only
Provider	Customers only

BGP: Aggregation and Path-Vector

Lecture 9, CS 168, Spring 2025

Autonomous Systems

- What are ASes?
- Business Relationships

Goals of Inter-Domain Routing

- Policy-Based Routing
- Gao-Rexford Rules

BGP (Border Gateway Protocol)

- Importing and Exporting
- **Aggregation and Path-Vector**

Modifications from Distance-Vector to BGP

Changes we've made so far:

- Import paths based on policy (e.g. prefer customer > peer > provider), instead of based on least-cost.
- Export paths based on policy (e.g. only advertise profitable routes), instead of advertising all routes.

We need to make two more changes:

- Aggregating prefixes for scalability.
- Changing from distance-vector to path-vector.

Modification #1: Aggregating Prefixes

Recall: For scalability, each forwarding table entry maps a range of IPs to a next hop.

Each AS is addressed by a prefix (all machines inside the AS share the same prefix).

BGP can **aggregate** multiple entries into one, combining ranges into one larger range.

Destination Prefix	Next hop
12.1.0.0/16	Physical port #1
12.2.0.0/16	Physical port #1
12.3.0.0/16	Physical port #1

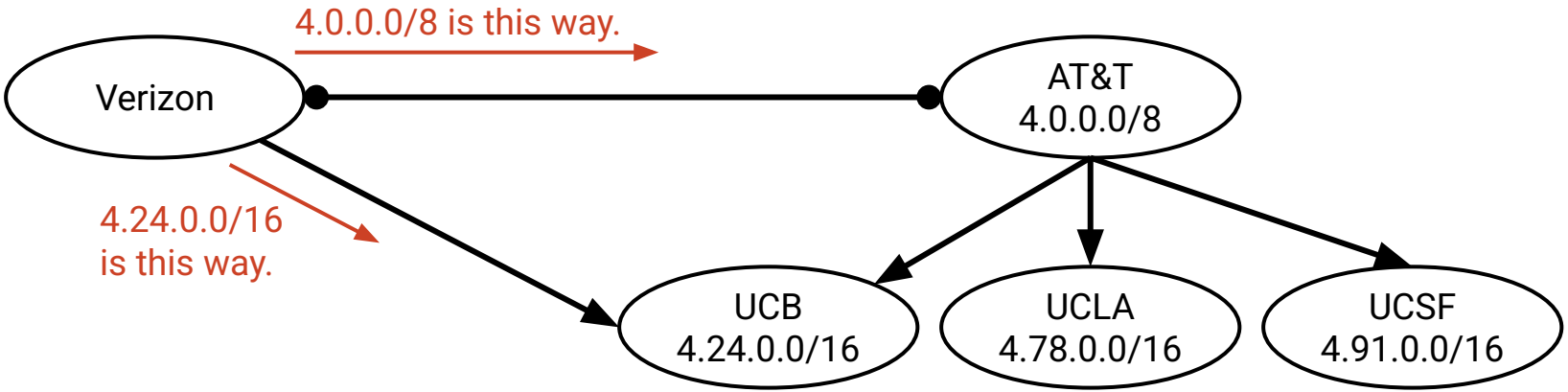
Destination Prefix	Next hop
12.0.0.0/8	Physical port #1

Modification #1: Aggregating Prefixes

Recall: Aggregation scales because addresses are hierarchical.

Multi-homing: An AS having multiple providers.

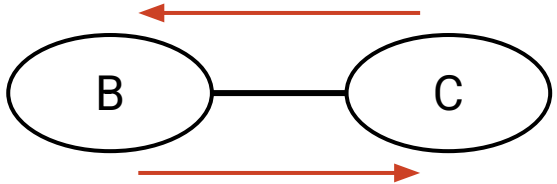
- Multi-homing limits aggregation.



Modification #2: Distance-Vector → Path-Vector

Problems with distance-vector-based BGP:

- There might be loops.
  - Least-cost routing guaranteed no loops.
  - Switching to policy-based routing caused us to lose that guarantee.



B's policy: "I like sending packets via C."
C's policy: "I like sending packets via B."

- We can support Gao-Rexford rules, but not arbitrary policies.
  - Suppose my policy is: "My traffic should never pass through AS#2019.
  - I get an announcement: "I am AS#20 and I can reach D with cost 10.
  - How do I know if this route satisfies my policy?

Modification #2: Distance-Vector → Path-Vector

Solution: Change from distance-vector to **path-vector**.

- Instead of advertising distance to destination, advertise the whole AS path.
- Example: "I am A, and I have a path to D via A → B → C → D."

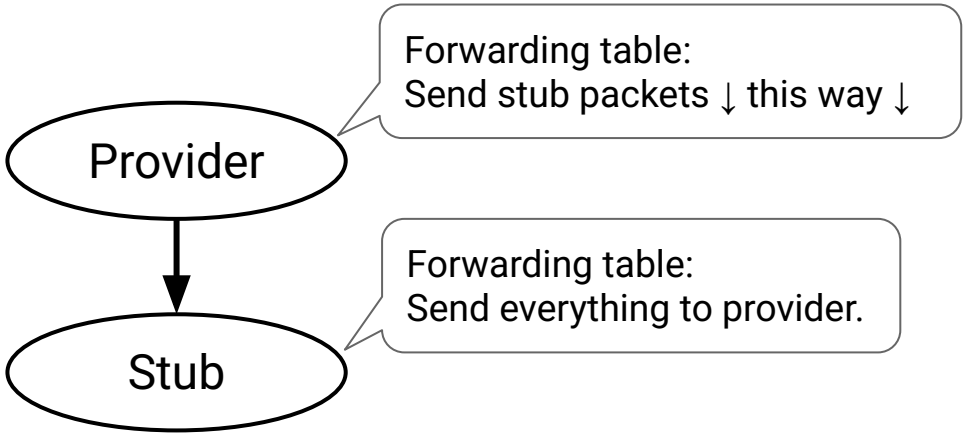
This solves both of our problems.

- Loop detection: Check if adding myself to the path creates a loop.
  - If I'm C, adding myself to the path creates a cycle: C → A → B → C → D.
  - If the path has a cycle (after adding myself), reject the advertisement.
- Arbitrary policies: The entire path is available for checking against policy.
  - If my policy is "don't send my packets through B," I can check the path and reject the advertisement.

Stub ASes Use Default Routes

If a stub AS is connected to a single provider, it doesn't need to run BGP.

- The stub AS default-routes everything to the provider.
- The provider advertises that they can reach the stub AS's prefix.
  - The provider is advertising on behalf of the stub.



Summary: Inter-Domain Routing

- In the AS graph, edges reflect physical connections and business relationships.
  - Customers pay providers.
  - Peres don't pay each other.
- Paths are selected based on policy.
- Policy (e.g. Gao-Rexford rules) reflects business goals.
  - Making money is good.
  - Don't do work for free.
  - Good stuff (reachability, converge) happens if you follow Gao-Rexford rules.
- BGP extends distance-vector to implement inter-domain routing.
  - Destinations are IP prefixes that can be aggregated.
  - Each AS advertises its path to a prefix.
  - Policy dictates which paths an AS selects (import policy), and which paths it advertises (export policy).