Advanced Computer Networking (ACN)

IN2097 – WiSe 2025–2026

Prof. Dr.-Ing. Georg Carle, Sebastian Gallenmüller

Christian Dietze, Marcel Kempf, Lorenz Lehle

Chair of Network Architectures and Services
School of Computation, Information and Technology
Technical University of Munich

Routing and Forwarding

Routing and Forwarding

Autonomous Systems
Internet Architecture

How is the Internet built?

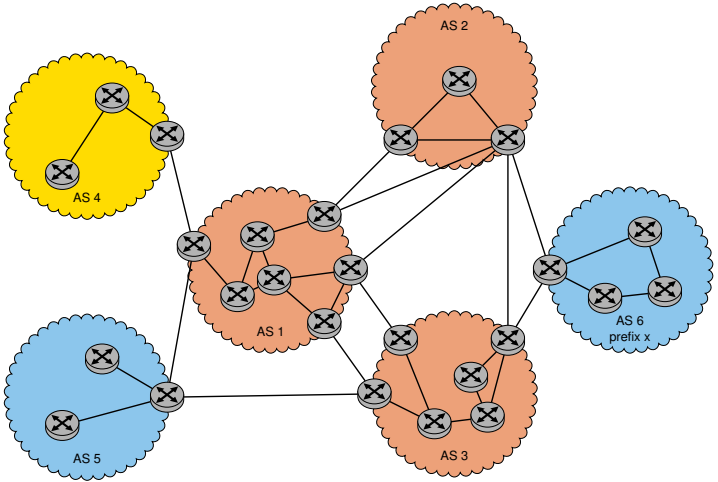
- Comprised of independent networks: Autonomous Systems (ASes), of different types
  - Internet Service Providers (ISPs) offering transit services (e.g. Deutsche Telekom, Vodafone, DFN)
  - Campus Networks: Organisations maintaining networks at one or more locations (e.g. universities, companies)
  - Datacenter Networks: Operated by large IT companies (e.g. Facebook) and Hosting providers, e.g., Amazon AWS
  - Content Delivery Networks (e.g., Akamai, Google, Cloudflare)
- Organisations may manage one or more Autonomous System(s)
- Some ASes distributed world-wide, some regional

Routing protocols find a path towards a destination and allow to create Forwarding tables
Routers use Forwarding tables for per-packet lookup to determine outgoing interface

Autonomous Systems
Example Network

Router Types

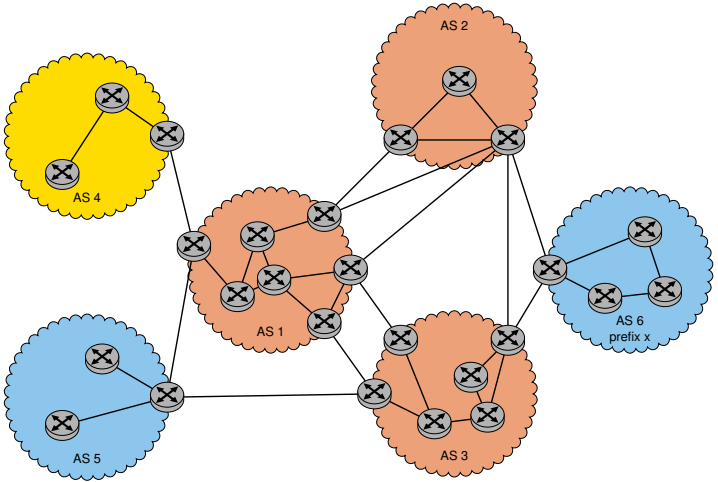
- Border router (Edge router)
- Core router



Autonomous Systems
Example Network

Network Types

- Transit AS:
  - Forwards traffic from one AS to another AS (red)
- Stub AS:
  - AS, which is connected to only one other AS (yellow)
- Multi-homed AS:
  - AS, which is connected to multiple ASes, but doesn't forward traffic on their behalf (blue)



Autonomous Systems
Routing Protocol Types

Inter-Domain Protocols (inter AS routing)

- Exchange routing information between ASes
- Called Exterior Gateway Protocols (EGPs)
- In practice, only the Border Gateway Protocol version 4 (BGPv4) is used

Intra-Domain Protocols (intra AS routing)

- Used to determine path and routing information inside an AS
- Called Interior Gateway Protocols (IGPs)
- Examples: OSPFv2/3, IS-IS, RIP, ...

What is responsibility of EGP, and what of IGP?

- EGP: Which AS to transfer the packet to?
- IGP:
  - Destination in other AS: Which intra-AS path to reach next AS?
  - Destination inside AS: Which intra-AS path to reach destination?

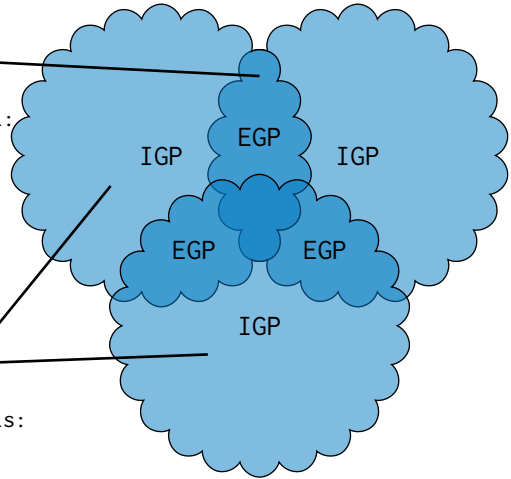
Autonomous Systems

EGP:

Exterior Gateway Protocol

Inter-domain routing protocol:

BGP v4



IGP:

Interior Gateway Protocol

Intra-domain routing protocols:

RIP, OSPF, IS-IS

Autonomous Systems
Terminology

- Routing Information Base (RIB): All routing information a router can gather from updates of neighboring routers
  - May contain multiple routes to the same destination
  - Path selection also depends on business considerations (policy routing)
- Forwarding Information Base (FIB): Mapping from a destination IP network address (prefix) to outgoing interface or next hop router IP address
  - Unique entry for each destination
  - Uses Longest-Prefix-Matching (LPM)
- Forwarding Decision: Algorithm uses the FIB to decide how to forward individual packets

RIB

Prefix	Next Hop	Cost Metric
10.0.2.128/25	A	90
192.168.2.0/24	B	60
192.168.3.0/24	B	30
192.168.0.0/16	C	50
192.168.0.0/16	D	20
10.0.0.0/8	E	70
0.0.0.0/0	F	100
0.0.0.0/0	G	20

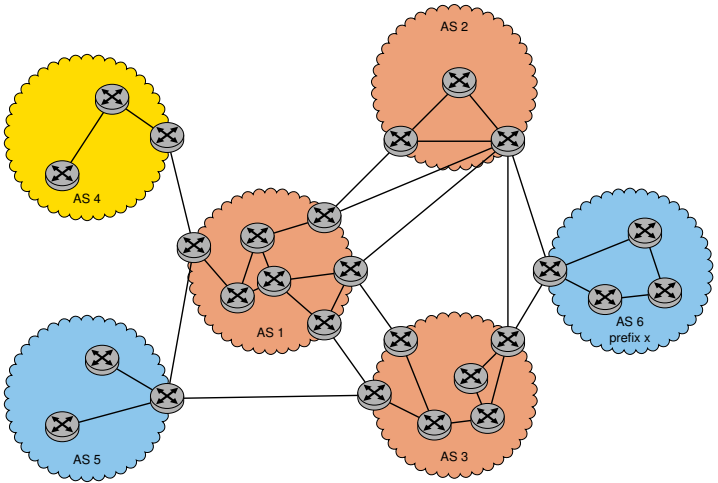
FIB

Prefix	Next Hop
10.0.2.128/25	A
192.168.2.0/23	B
192.168.0.0/16	D
10.0.0.0/8	E
0.0.0.0/0	G

Autonomous Systems
Interconnected ASes

Forwarding table entries

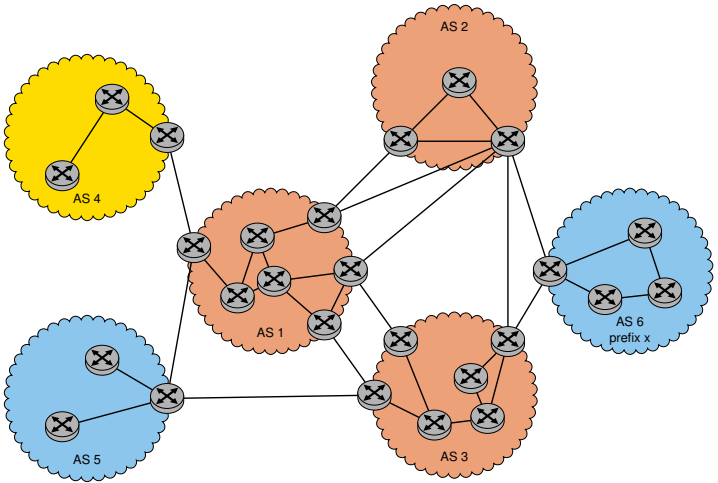
- Intra-AS routing algorithm sets entries for internal destinations
- Inter-AS and intra-AS routing algorithms set entries for external destinations



Autonomous Systems
Interconnected ASes

Inter-AS tasks

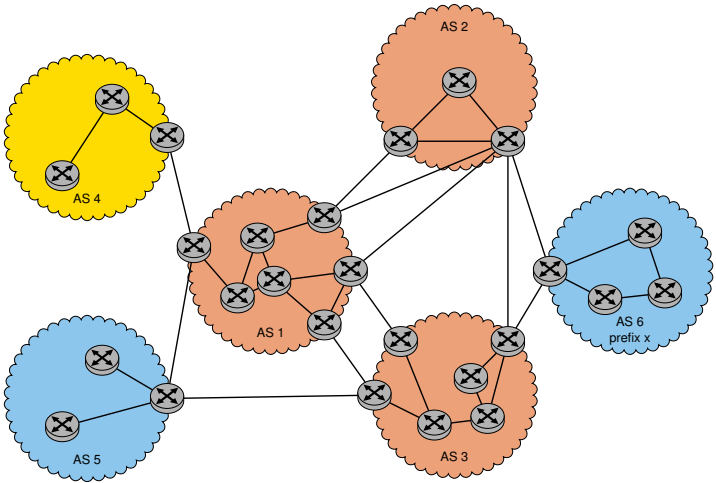
- Suppose core router in a red AS receives datagram destined outside of AS
- Core router should forward packet to border router, but which one?
- Red ASes must learn which destinations are reachable through which neighboring AS
- Red ASes must propagate this reachability info to all routers within AS (i.e., not just the border routers)
- This is job of inter-AS routing protocol BGP



Autonomous Systems
Interconnected ASes

Setting forwarding table in a router

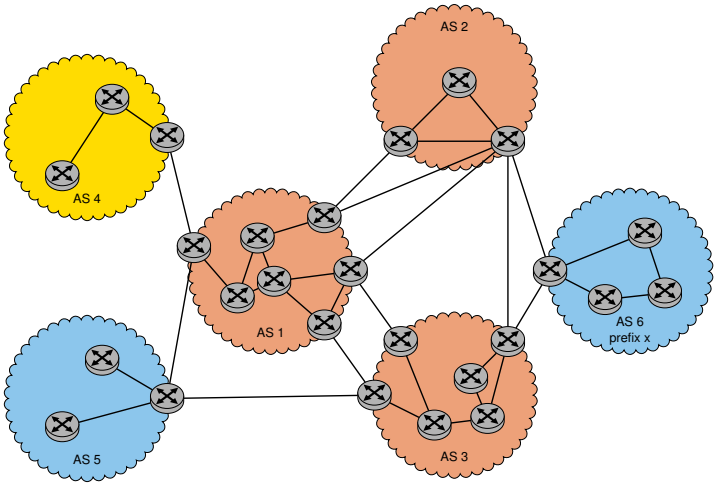
- Suppose AS1 learns (via inter-AS protocol - BGP) that subnet x is reachable via one neighbor AS2 but not via another neighbor AS3.
- Inter-AS protocol propagates reachability information to all internal routers.
- Core router determines from intra-AS routing information which interface is on the least cost path to border router towards AS2.
- Core router installs forwarding table entry for that subnet x



Autonomous Systems
Interconnected ASes

Choosing among multiple ASes

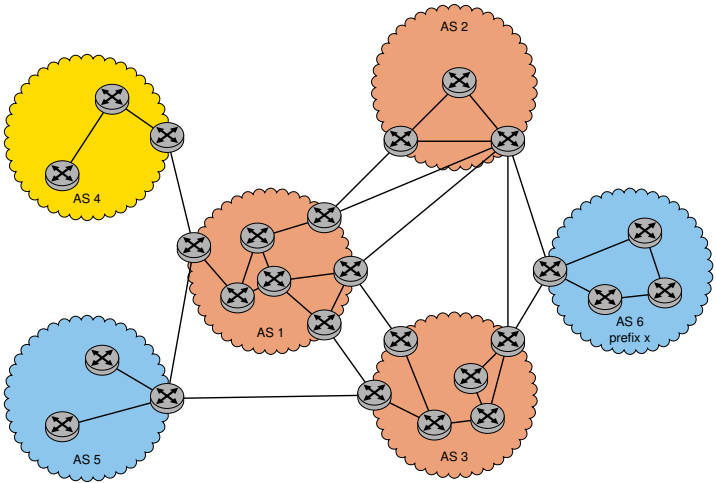
- Now suppose AS1 learns from inter-AS protocol that subnet x is reachable from AS3 and from AS2.
- To configure forwarding table, core router must determine towards which border router it should forward packets for destination x.
- This is also job of inter-AS routing protocol BGP



Autonomous Systems
Interconnected ASes

Inter-AS and intra-AS routing

- Inter-AS routing
  - Only for destinations outside of own AS
  - Used to determine gateway router
  - Also: steers transit traffic (from AS i to AS j via our own AS)
- Intra-AS routing
  - Used for destinations within own AS
  - Used to reach gateway router for outside destinations



Routing and Forwarding

Border Gateway Protocol [1]

Basics

- Each AS has a unique AS Number (ASN)
  - e.g., Vodafone UK (AS6847), Vodafone DE (AS6751), LRZ (AS12816), I8 net.in.tum (AS56357)
- BGP is based on the Path-Vector model
- BGP router exchange information derived from their routing table entries
- Which next AS (and as a consequence which next router) to choose is a policy (business) decision
- Path-Vector: UPDATE Messages contain all ASes on the path towards a destination network (prefix)
- AS-level Loops can be noticed if an ASN is contained multiple times in a path

There are two BGP variants:

- Internal BGP (iBGP): BGP exchanges information with routers in the same AS
- External BGP (eBGP): BGP exchanges information with routers of neighboring ASes

Hierarchical prefix announcement using BGP

How does an organization get a subnet?

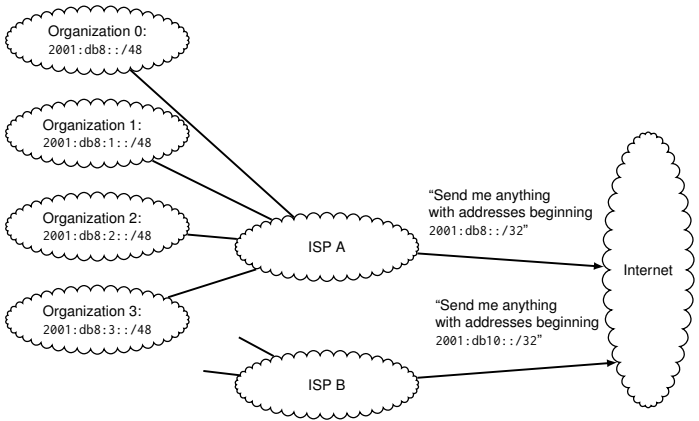
- Gets allocated portion of its provider ISP's address space

Example:

- ISP: `2001:db8::/32`
- Organization 0: `2001:db8::/48`
- Organization 1: `2001:db8:1::/48`
- Organization 2: `2001:db8:2::/48`
- Organization 3: `2001:db8:3::/48`
- ...
- Organization 7: `2001:db8:7::/48`

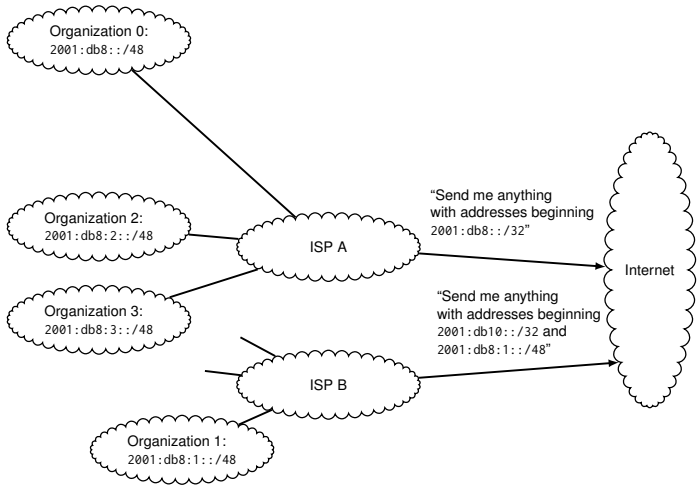
Hierarchical prefix announcement using BGP

Hierarchical addressing allows for efficient advertisement of routing information:



Hierarchical prefix announcement using BGP

ISP B has a more specific route to Organization 1:



iBGP

Difference between iBGP and eBGP

- iBGP: Both routers have the same ASN
- eBGP: Routers have different ASNs
- iBGP: Propagates information on externally reachable prefixes to routers within AS

Message Types

BGP uses different message types, transmitted over TCP (see RFC 4271)

- OPEN: Opens a connection between two routers
- TEARDOWN: Close the connection
- NOTIFICATION: Send error codes
- UPDATE: Announce a new route, or un-reachability of an old one

Update Messages

Message contains:

- Destination prefix (a.b.c.d/x)
- AS path - list of ASes
- Next Hop - IP address of the router sending the update
- Origin - Learned via IGP/EGP/other

More attributes can be added:

- LOCAL_PREF “Local preference”: Used to prefer one gateway over another
- MULTI_EXIT_DISC “Multiple exit discriminator”: If multiple entries (i.e., border routers) into an AS exists, says which is preferred

Local information is used on top of the information provided in the update messages, in order to make a routing decision.

Each AS writes its own ASN at the beginning of the AS path. This is important for the loop detection.

BGP is an “information hiding protocol” (quote from Randy Bush)

Example Update Message

Information

Prefix: 185.86.232.0/22

AS Path: 202109 33891 48918 56357

Next Hop: 5.101.111.2

Origin: EGP

Explanation:

- This update concerns itself with the destination subnet 185.86.232.0/22
- Packets will be routed through 4 ASes
- The next hop is 5.101.111.2
- The next hop learned this route through the EGP

BGP route selection

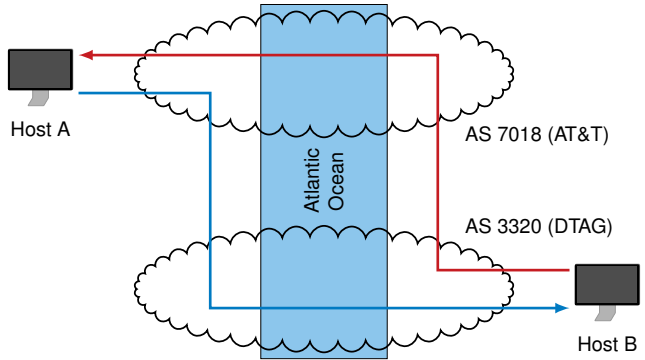
Router has to select which route to choose (multiple may be available)

1. Local preference value attribute: policy decision
2. Shortest AS-PATH
3. Closest NEXT-HOP router outside AS: hot potato routing
4. Additional criteria (e.g., lowest Multi-Exit Discriminator MED when different border routers to same neighboring AS exist)

Hot potato routing

Large ASes connect at different sites

- Where to hand over traffic destined for the other AS?
- Always hand it over as fast as possible
- The longer a packet is transferred inside an AS, the more is costs
- Choosing the “nearest” connection site minimizes the cost
- Leads to asymmetric routing



Peering Types

There are different types of peering relationships

- Private: Direct connection to (frequently large) AS
- Public: Exchanging traffic with other ASes at an Internet Exchange Point (IXP)

Peering is preceded by a peering agreement, which may be made by two sysadmins talking to each other, or using lengthy contracts.

There exist multiple definitions of peering. In this course, the primary meaning (technical viewpoint: *protocol viewpoint) of peering is defined as follows:*

- *Two ASes peer with each other, if they have some kind of BGP relationship, i.e., two ASes are directly connected*
- *This reflects the* protocol viewpoint: It is irrelevant if one party pays the other party
- Alternative viewpoint - the *policy viewpoint: It is very relevant if one party pays the other party. Here, more narrowly peering implies that there is no financial compensation.*

Private Peering

Private peering can be accomplished in a variety of ways:

- Install a cable from the server room of AS 1 to the server room of AS 2
- Peering possible at colocation center operated by a carrier-neutral data center provider
  - Examples: Interxion (pronounced “interaction”), e-shelter
- Peering possible at colocation center operated by a carrier
  - Example: AT&T, Verizon, Level 3 Communications

Keep in mind: Different rules exist regarding connections between customers, ranging from no charge to significant monthly fee

Private peering use cases:

- Exchange a large amount of traffic with a single AS
- Attractive setup for upstream providers
- Interconnection of, within, and inbetween data centers

Routing and Forwarding

[1] Y. Rekhter, T. Li, and S. Hares, A Border Gateway Protocol 4 (BGP-4), https://tools.ietf.org/html/rfc4271, 2006.