UiO : Faculty of Mathematics and Natural Sciences
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Department of Informatics
Networks and Distributed Systems (ND) group

INF 3190
The Network Layer

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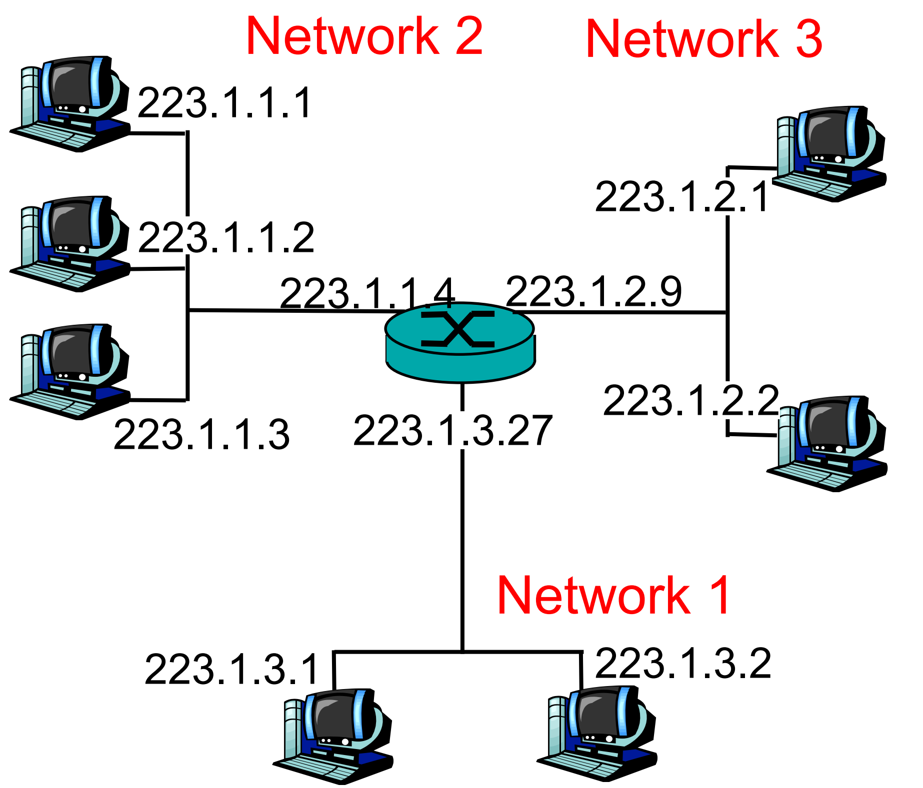
How to contact another Internet host?

- OS knows IP address of DNS server (preconfigured)
  - DNS used to be hosts.txt, now a distributed database of sorts
  - DNS query sent using UDP (User Datagram Protocol)
- UDP entity in the OS
  - adds UDP header, sends packet using IP (Internet Protocol)
- IP entity in the OS
  - adds IP header, sends packet using Ethernet Driver
- Ethernet Driver
  - queries local table for MAC (Medium Access Control) address
  - If not found, broadcast "who has IP address ... (DNS server)?" using ARP (Address Resolution Protocol) on LAN - answer is correct address
- DNS response = dest. IP address, repeat above procedure...

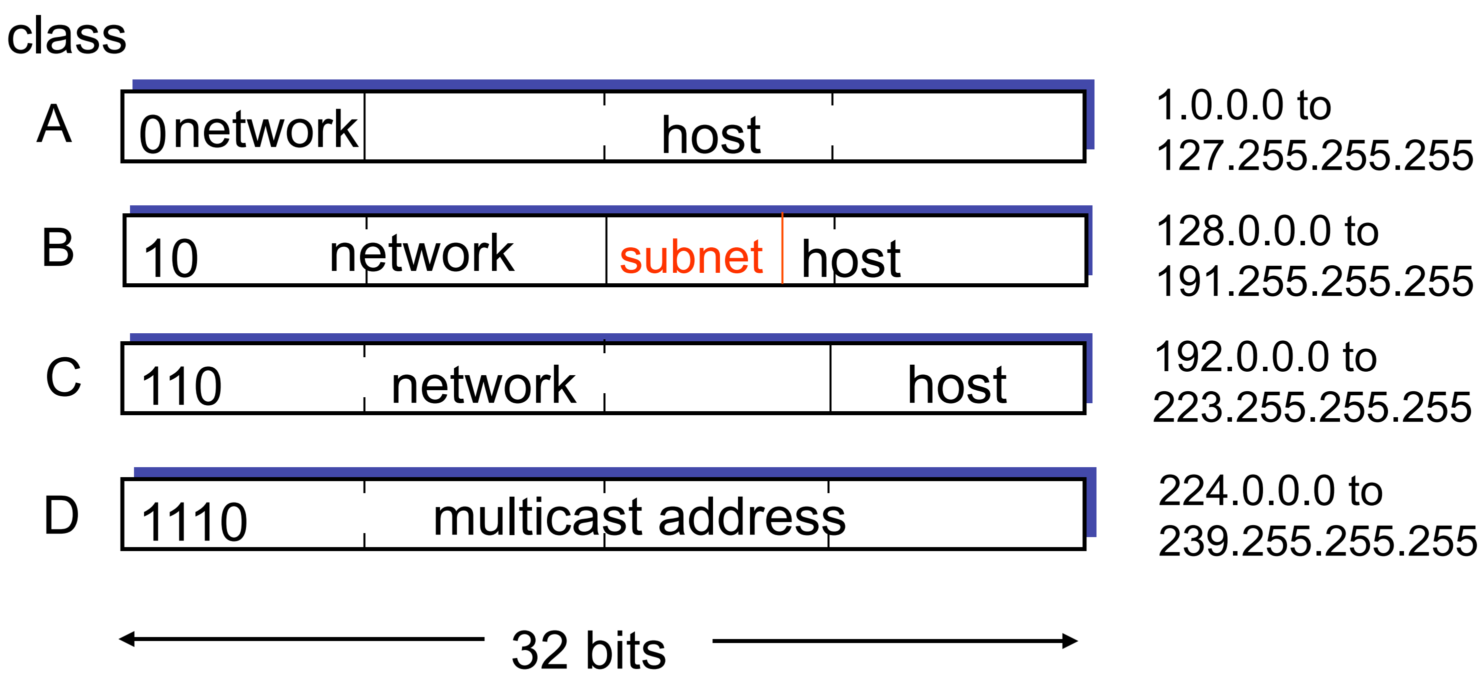
IP Addressing

- IP address: 32-bit identifier for host, router *interface*
  - network part (high order bits)
  - host part (low order bits)
- *interface:* connection between host, router and physical link
  - routers typically have multiple interfaces
  - host may have multiple interfaces
- *What's a network ?*
  - device interfaces with same network part of IP address
  - can physically reach each other without intervening router



network consisting of 3 IP networks (for IP addresses starting with 223, first 24 bits are network address)

Classful (traditional) Addressing



- Inefficient use of address space, address space exhaustion
- e.g., class B net allocated enough addresses for 65K hosts, even if only 2K hosts in that network; also, routing table with 65k entries = inefficient
  - subnetting: take highest bits from host to implement a subnet number
  - split defined via subnet mask (known to local routers but not outside)

Classless InterDomain Routing (CIDR)

network part ⟵ ⟶ host part

11001000 00010111 00010000 00000000

200.23.16.0/23

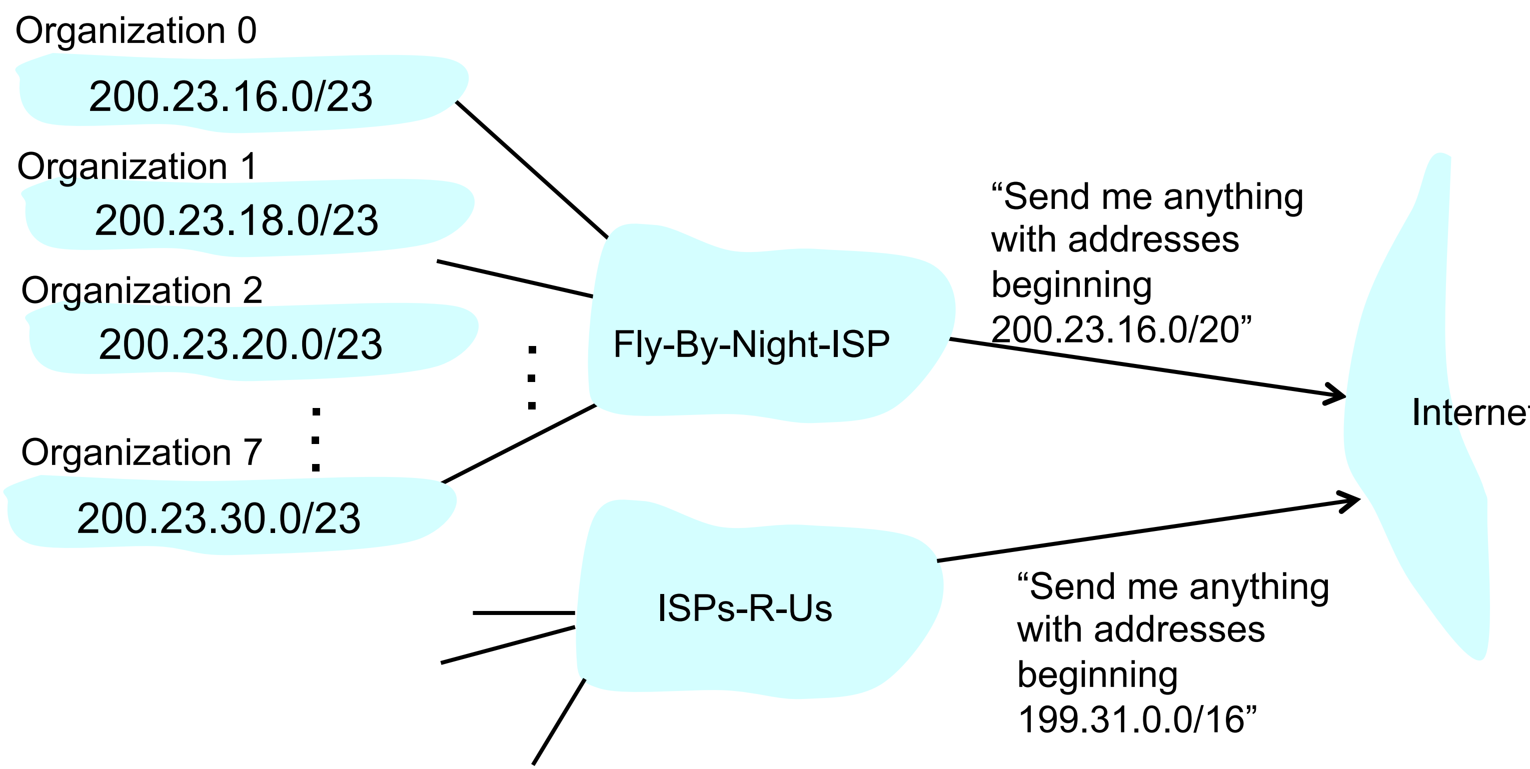
- More efficient use of address space
- Address format: a.b.c.d/x, where x is # bits in network portion
- network portion: arbitrary length
  - get allocated portion of ISP's address space

assigned by ICANN: Internet Corporation for Assigned Names and Numbers

ISP's block	11001000 00010111 00010000	00000000	200.23.16.0/20
Organization 0	11001000 00010111 00010000	00000000	200.23.16.0/23
Organization 1	11001000 00010111 00010010	00000000	200.23.18.0/23
Organization 2	11001000 00010111 00010100	00000000	200.23.20.0/23
...	.....	....	....
Organization 7	11001000 00010111 00011110	00000000	200.23.30.0/23

Hierarchical addressing: route aggregation

Hierarchical addressing allows efficient advertisement of routing information:



Getting a datagram from source to dest.

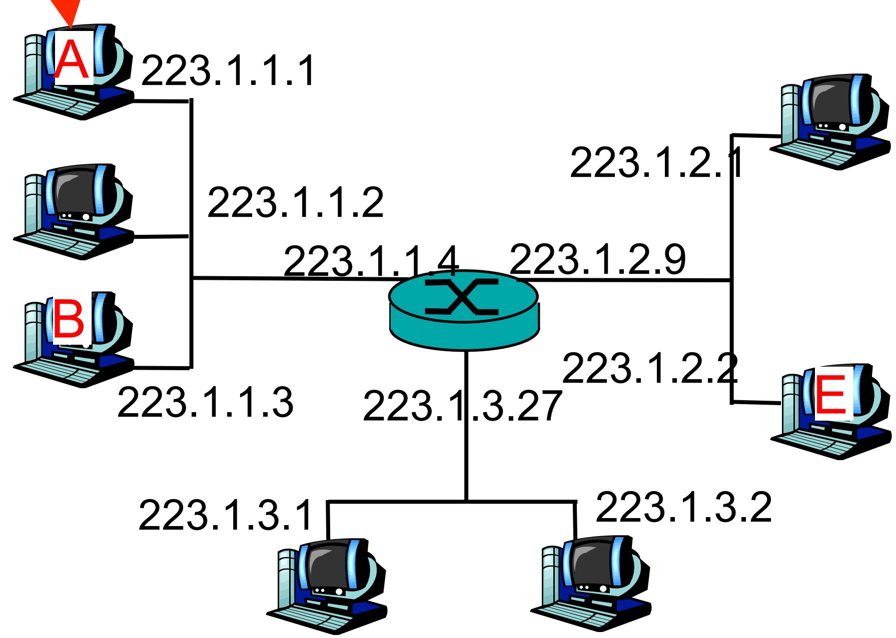
routing table in A

Dest. Net.	next router	Nhops
223.1.1		1
223.1.2	223.1.1.4	2
223.1.3	223.1.1.4	2

IP datagram:

misc fields	source IP addr	dest IP addr	data

- datagram remains unchanged, as it travels source to destination
- addr fields of interest here



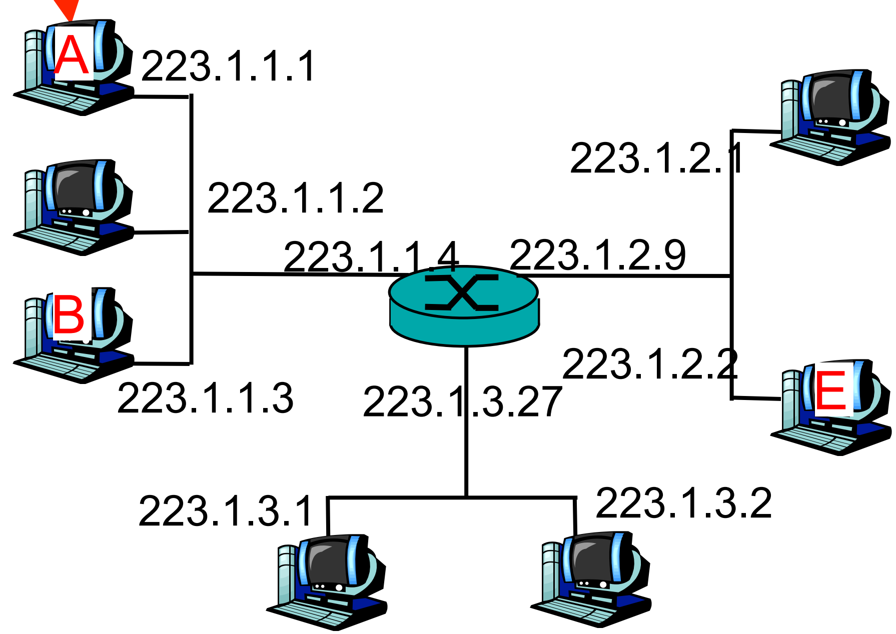
Getting a datagram from source to dest. /2

misc fields	223.1.1.1	223.1.1.3	data

Dest. Net.	next router	Nhops
223.1.1		1
223.1.2	223.1.1.4	2
223.1.3	223.1.1.4	2

Starting at A, given IP datagram addressed to B:

- look up net. address of B
- find B is on same net. as A
- link layer will send datagram directly to B inside link-layer frame
  - B and A are directly connected



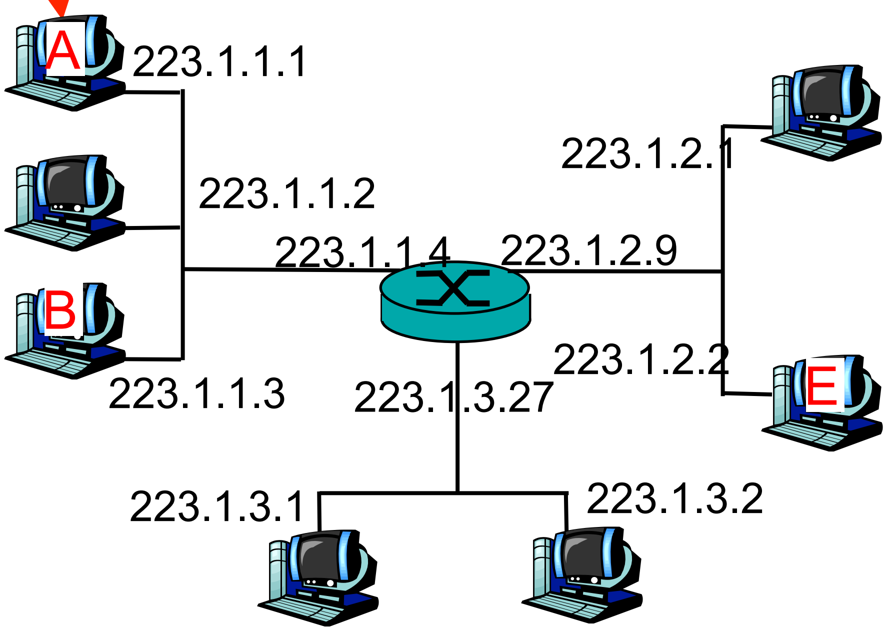
Getting a datagram from source to dest. /3

misc fields	223.1.1.1	223.1.2.2	data

Dest. Net.	next router	Nhops
223.1.1		1
223.1.2	223.1.1.4	2
223.1.3	223.1.1.4	2

Starting at A, dest. E:

- look up network address of E
- E on *different* network
  - A, E not directly attached
- routing table: next hop router to E is 223.1.1.4
- link layer sends datagram to router 223.1.1.4 inside link-layer frame
- datagram arrives at 223.1.1.4
- continued…..



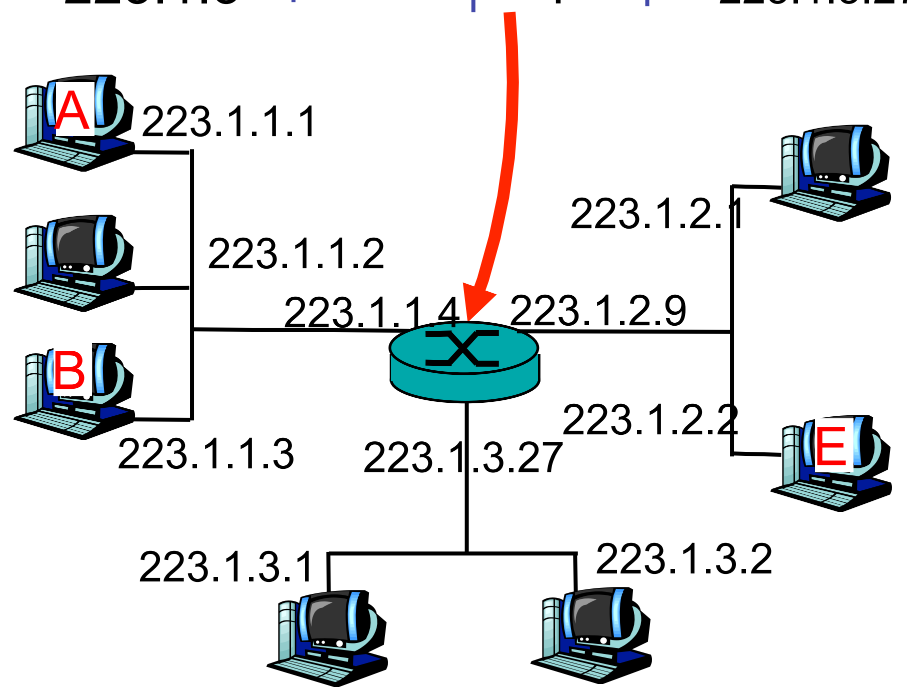
Getting a datagram from source to dest. /3

misc fields	223.1.1.1	223.1.2.2	data

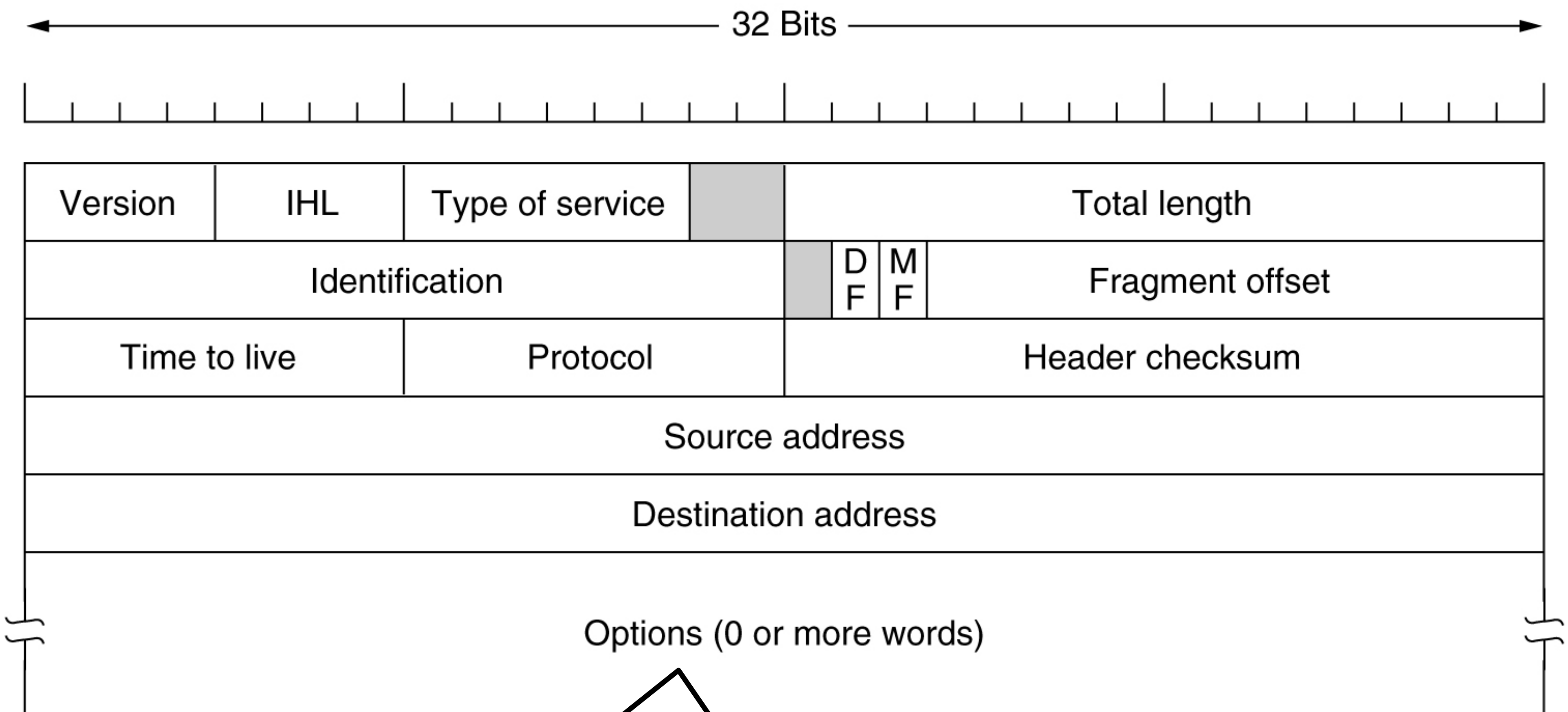
Dest. network	next router	Nhops	interface
223.1.1	-	1	223.1.1.4
223.1.2	-	1	223.1.2.9
223.1.3	-	1	223.1.3.27

Arriving at 223.1.4, destined for 223.1.2.2

- look up network address of E
- E on *same* network as router's interface 223.1.2.9
  - router, E directly attached
- link layer sends datagram to 223.1.2.2 inside link-layer frame via interface 223.1.2.9
- datagram arrives at 223.1.2.2!!! (hooray!)



IPv4 Header



Examples: Loose / Strict Source Routing, Record Route, Timestamp, Router Alert

Internet Protocol Version 6 (IPv6, IPNG)

- Initial motivation: 32-bit address space completely allocated by 2008.
  - Internet growth immense - MANET scenarios etc. etc.
- Additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS
  - new “anycast” address: route to “best” of several replicated servers
- Some header fields changed / removed
  - no checksum → reduce per-hop processing time!
- Multicast - IGMP now part of ICMP
- Mobility - functionality relocated into routers

Transition From IPv4 To IPv6

- Not all routers can be upgraded simultaneous
  - no “flag days”
  - How will the network operate with mixed IPv4 and IPv6 routers?

- Several approaches:
  - Dual Stack: some routers with dual stack (v6, v4) can “translate” between formats (example path: v6 → v6_2_v4 → v4_2_v6 → v6)
  - Tunneling: IPv6 carried as payload in IPv4 datagram among IPv4 routers
  - IPv6/IPv4 network address and protocol translation: serious recent efforts

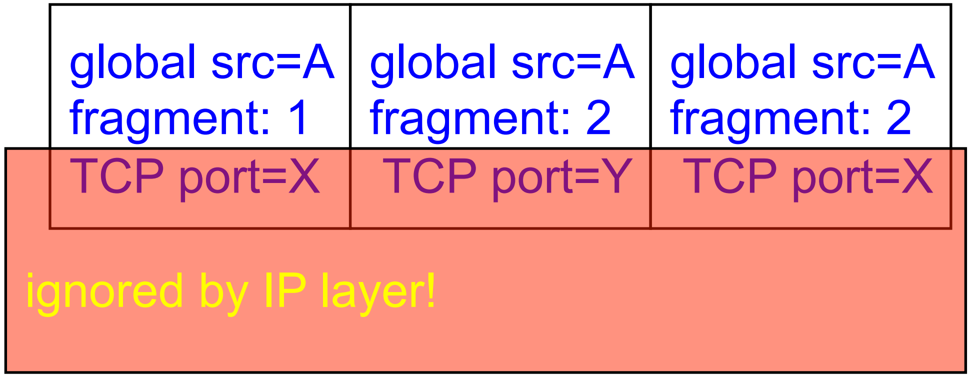
- Short-term solution: Network Address Translator (NAT)
  - assumption: at time t, only x out of y hosts communicate with outside world → use unique translation tables (= state!) to map x local to x global addresses

- NAT extension: NAPT (Network Address / Port Translator)
  - map local ip addr. / (tcp or udp) port no. pair to globally unique ip address / port no.
  - advantage: 1 globally unique ip address can be used by several local hosts at once
  - disadvantage: problems with specific port numbers

Some NAT trouble (there is more!)

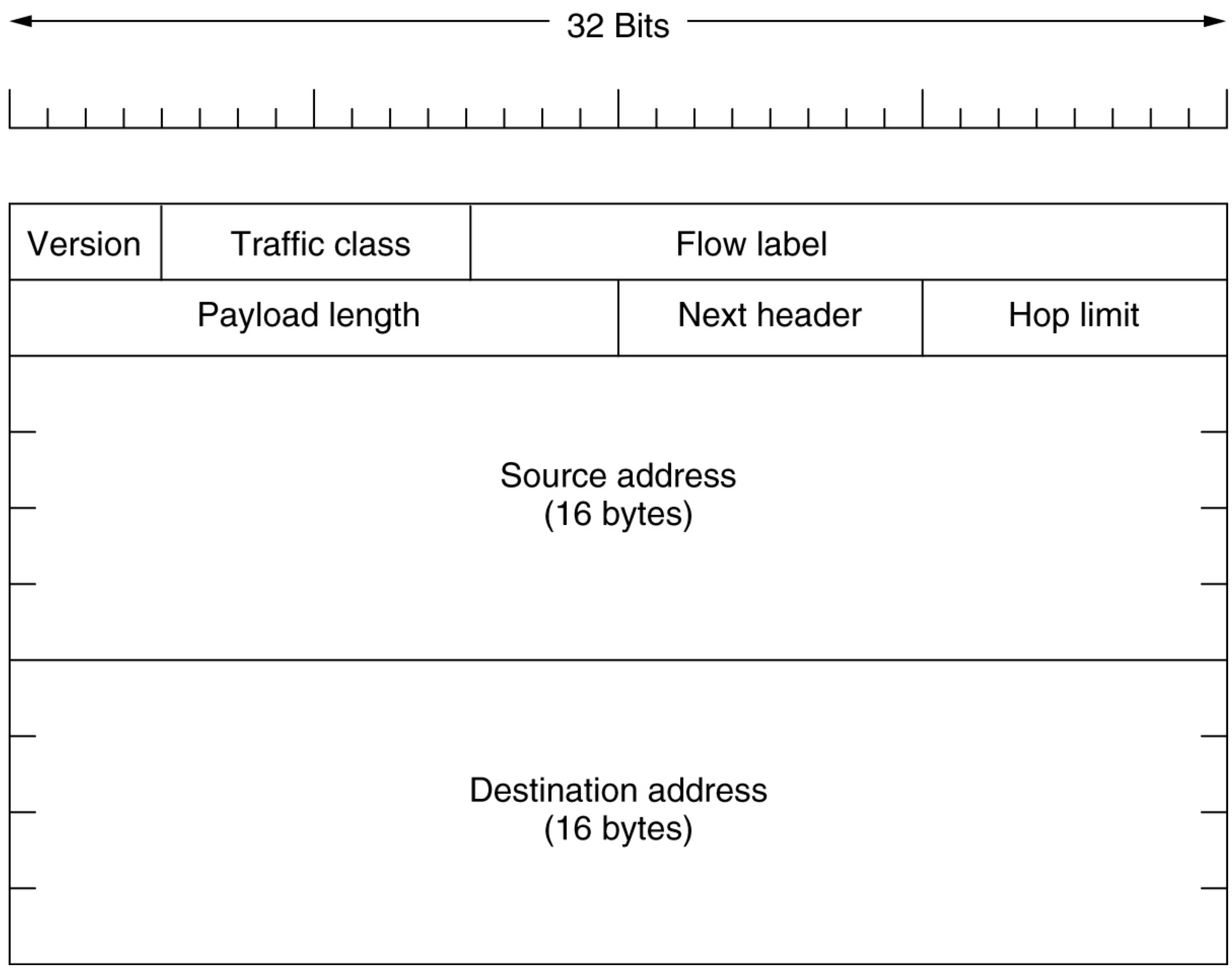
- Problem: realm-specific IP address in payload
  - Solution: per-app treatment by Application Level Gateway (ALG)
    - Problem: [IPsec] encryption at lower layer (transparent to the app)
      - Solution: implement lower-layer decryption + encryption in ALG
        - ...

- IPv4 fragmentation (routers split packets which are too large): semantics of IP address / port number pair lost at IP layer → wrong reassembly!



- NATs break the end-to-end model:
  - complicated functions (state, ..) in the network
  - special per-application functionality at lower layer
  - not possible to contact machines behind NAT directly

Main IPv6 Header



Fragmentation: only in hosts!

Optional: extension headers

Routing: CONS vs. CLNS

Pros + Cons of CONS (vs. CLNS):

+ routing decisions at conn. establishment (more sophisticated?)
+ max. packet size: at time of conn. establishment
  (no fragmentation at intermediate routers needed)
+ packets stay in order
+ congestion control by buffer allocation / conn. refusal
- router / link down: connections break
- no dynamic adaption to load (rare for CLNS, too!)
- routers need "memory" per link

Inverse arguments apply for CLNS over CONS

Note: distinguish a) route finding, b) packet forwarding

Virtual circuits

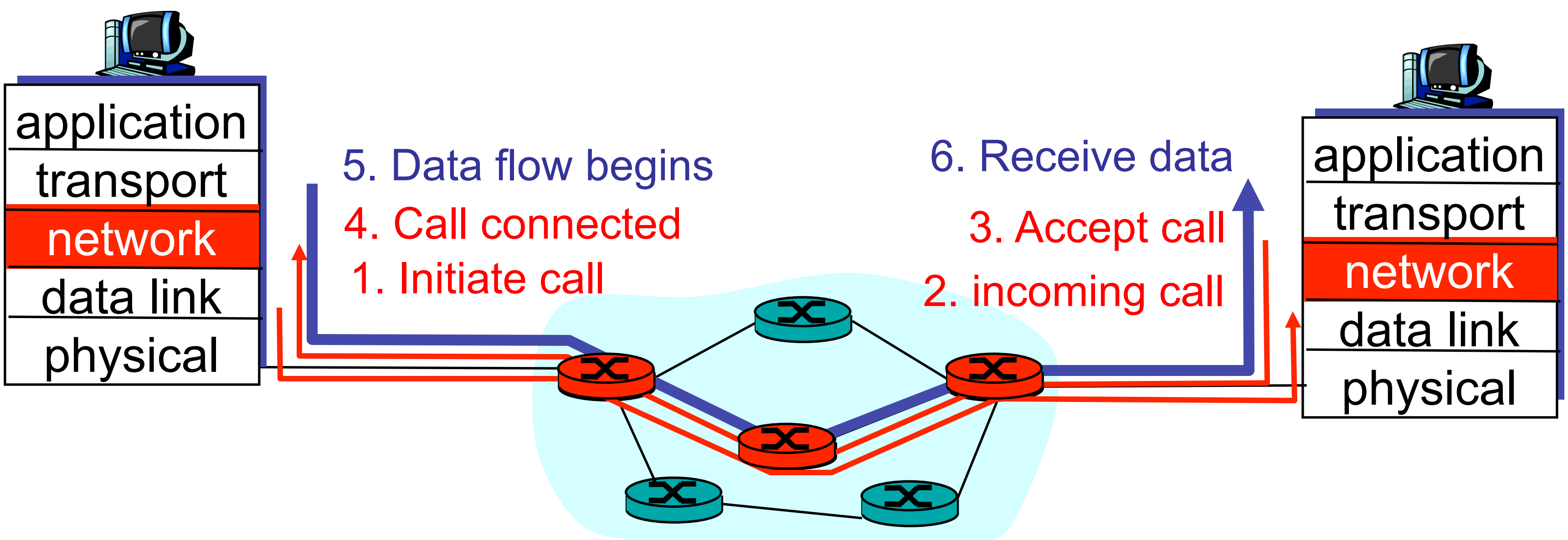
"source-to-dest path behaves much like telephone circuit"

- performance-wise
- network actions along source-to-dest path

- call setup, teardown for each call *before* data can flow
- each packet carries VC identifier (not destination host OD)
- *every* router on source-dest path s maintain "state" for each passing connection
  - transport-layer connection only involved two end systems
- link, router resources (bandwidth, buffers) may be *allocated* to VC
  - to get circuit-like perf.

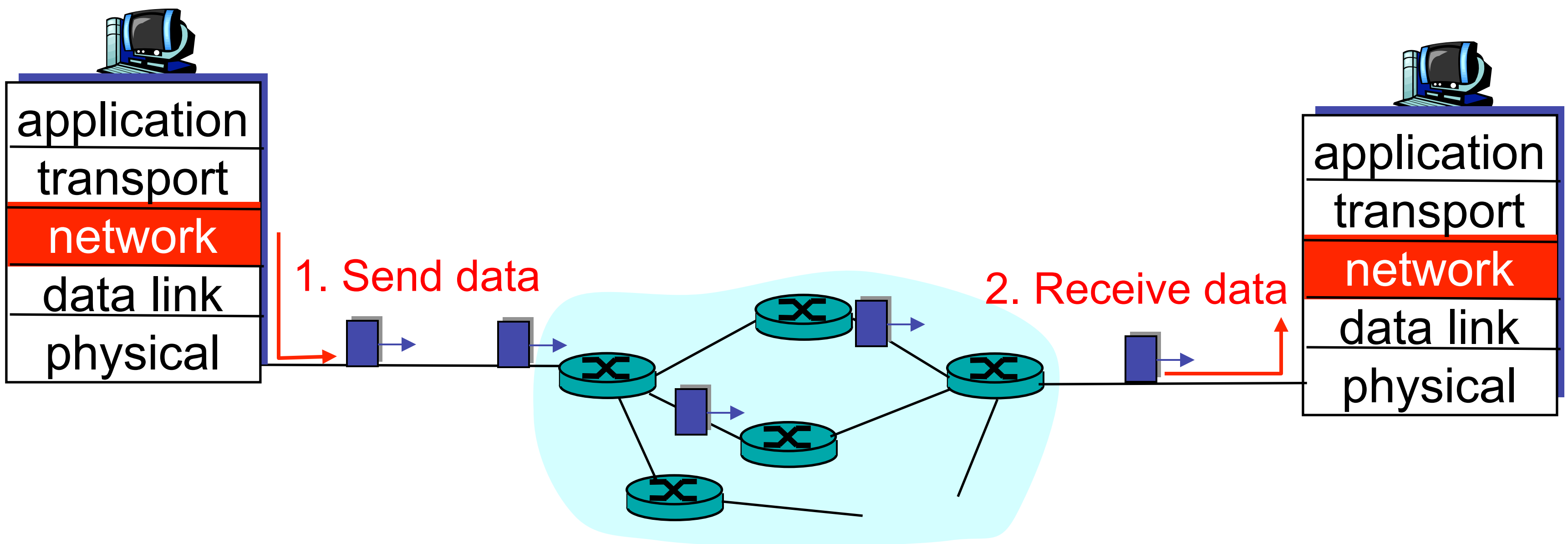
Virtual circuits: signaling protocols

- used to setup, maintain teardown VC
- used in ATM, frame-relay, X.25
- not used in today's Internet

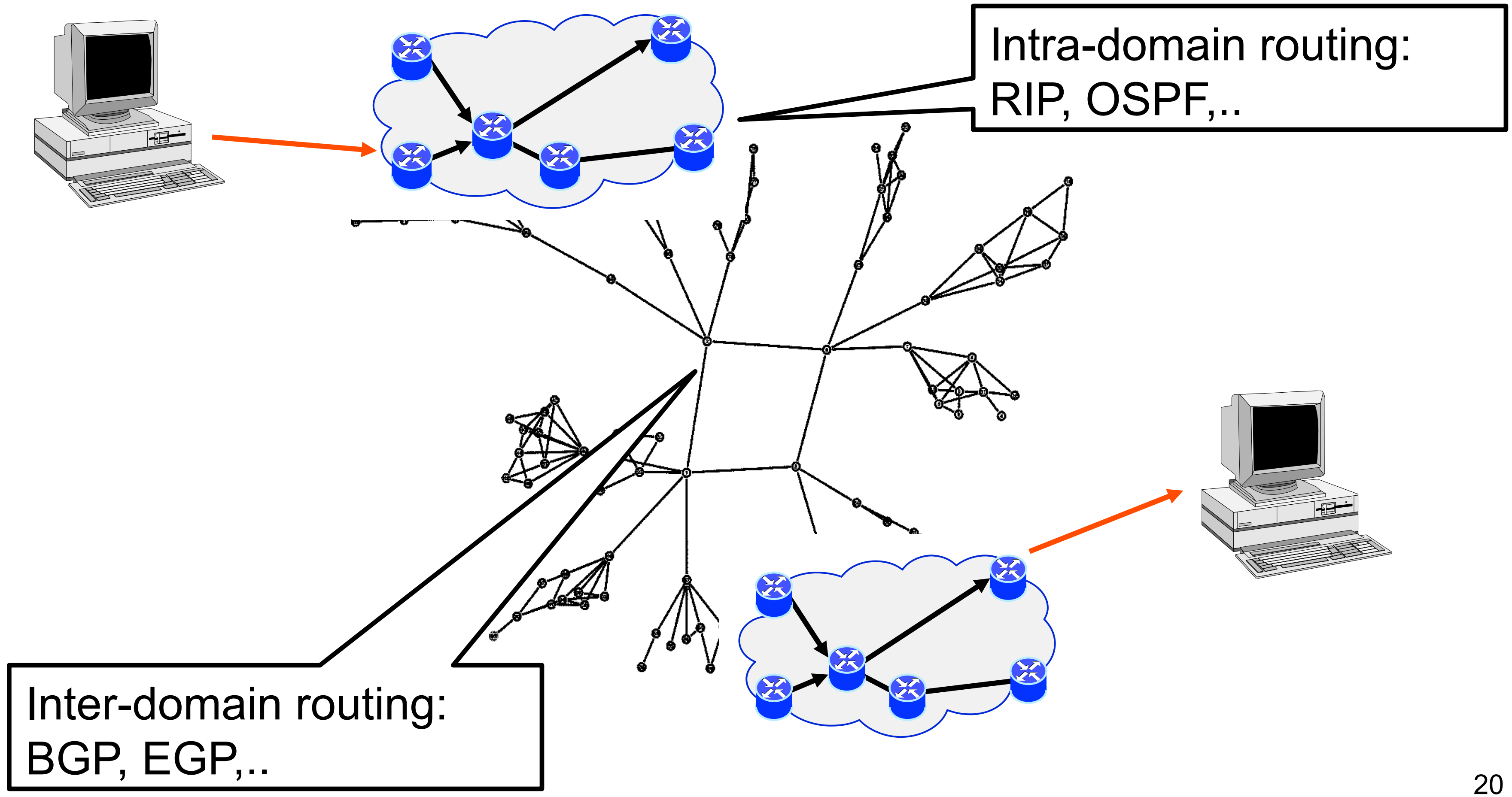


Datagram networks: the Internet model

- no call setup at network layer
- routers: no state about end-to-end connections
  - no network-level concept of "connection"
- packets typically routed using destination host ID
  - packets between same source-dest pair may take different paths



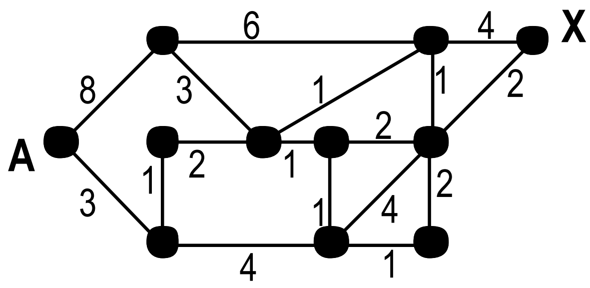
Routing in the Internet



Internet routing is (somewhat) dynamic

- Generated 1998 using “GeoBoy“ from NDG Software
- 10/2003 analysis shows ACONET ⇒ Sprint ⇒ Verio ⇒ wwoz

Routing: L.3 Protocol Function



Optimal Route?

- network considered as graph with nodes and links
- links are weighted by "cost":
  e.g.: distance, mean queue length, service time [1/capacity], $$-cost, …)
- optimal route from A to X: the one with minimal cost
- Usually "min. hops": set all cost to 1

Categories:

- stateful (table-based) / stateless (ad-hoc)
- connection-time / forward-time
- centralized / decentralized
- dynamic / static (how much? usually: adaptation to link/node up/down)
- hierarchical (Internet) or not
- unicast / multicast

ad hoc networks!

Routing: Flooding, Hot Potato

Flooding (stateless / ad-hoc, decentralized)

- send all incoming packets on each outgoing line → some copies will make it
- silly? a) useful for „route discovery"; b) can be improved:
  - don't send packet back or in "wrong direction": needs *some* knowledge (e.g., east/west)
  - identify packets (create unique ID or keep entire copy at routers) + add a sequence counter (increased per router): "I have seen *this* packet, with lower seq.no." → discard
    note: this (best) version requires "states", "memory" (scalability problem)
  - stateless enhancement: Time To Live (TTL) counter (decr. per router), 0 → discard

Hot Potato (stateless / ad-hoc, decentralized)

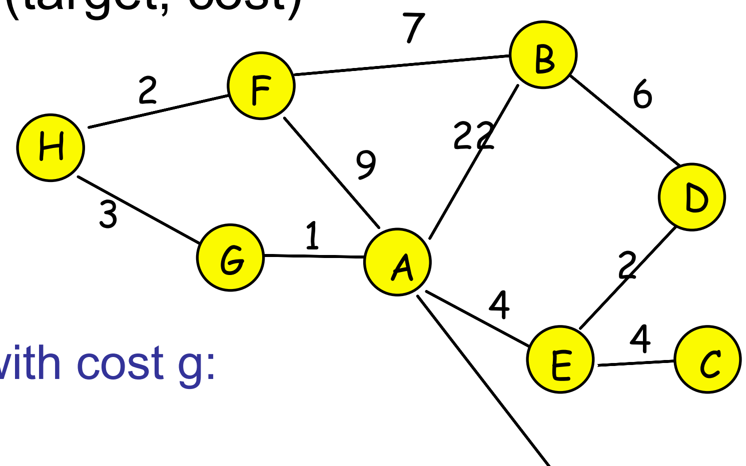
- route packet on link(s) with shortest queue (except incoming)
- good for highly connected net's, today hardly used at all

Centralized Routing (obsolete):

- "Routing Control Center" RCC collects info, computes optimum, broadcasts results
  - dense routing-related traffic "close to" RCC
  - remote routers tend to have older info then those close to RCC
  - single point of failure + scalability problem: frequent changes in large nets!

Distance Vector Routing

- Build local routing table based on info from adjacent routers
- table does not hold entire path, but triples [target, cost, via]
- distance vector = transmitted list of pairs (target, cost)



to	length	via
A	0	-
B	22	B
C	∞	?
D	∞	?
E	4	E
F	9	F
G	1	G
H	∞	?

Bellman-Ford Algorithm:

- each node knows cost for neighbours
- „start“: send table to neighbours

  upon receipt of table from sender s via path with cost g:

  for all rows i in table

  if (msg_table.cost[i]+g < my_table.cost[i]) or (s = my_table.via[i]):

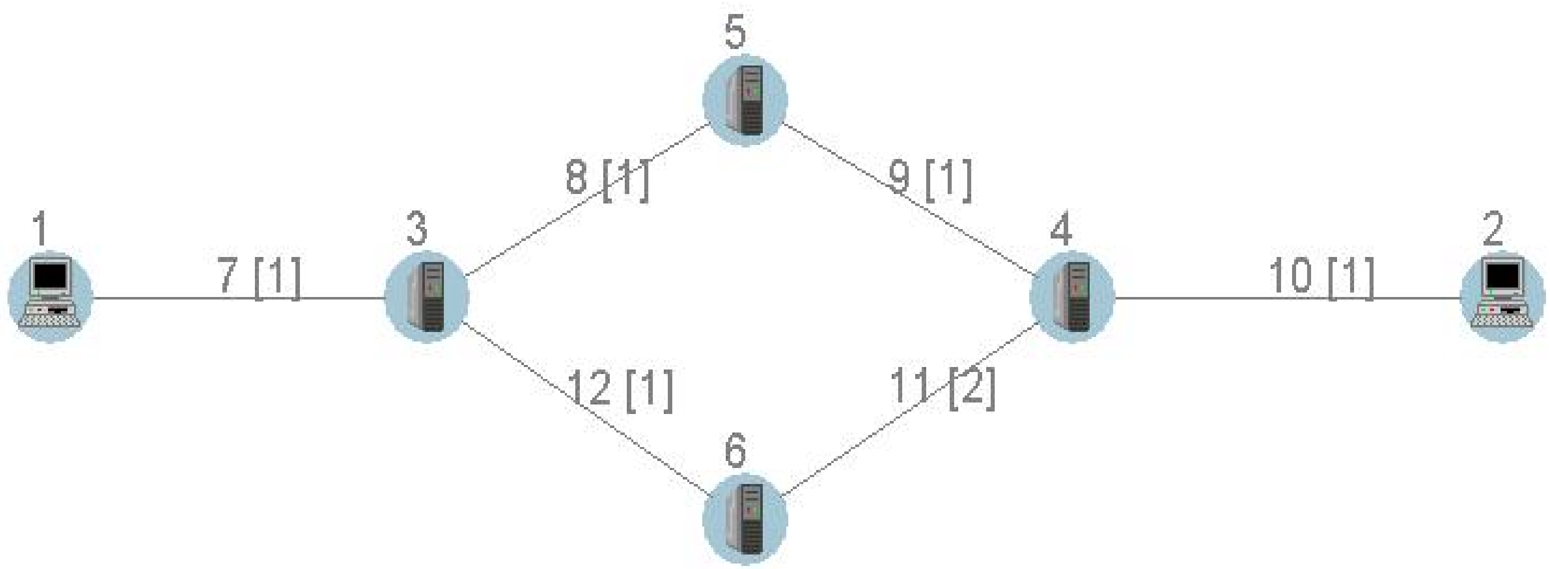
  replace for row i: length := msg_table.cost[i]+g; via := s

  if there was a change:

  send new table to all neighbours except sender

- repeat periodically
- Note: real implementation *discovers* network topology (new entries)

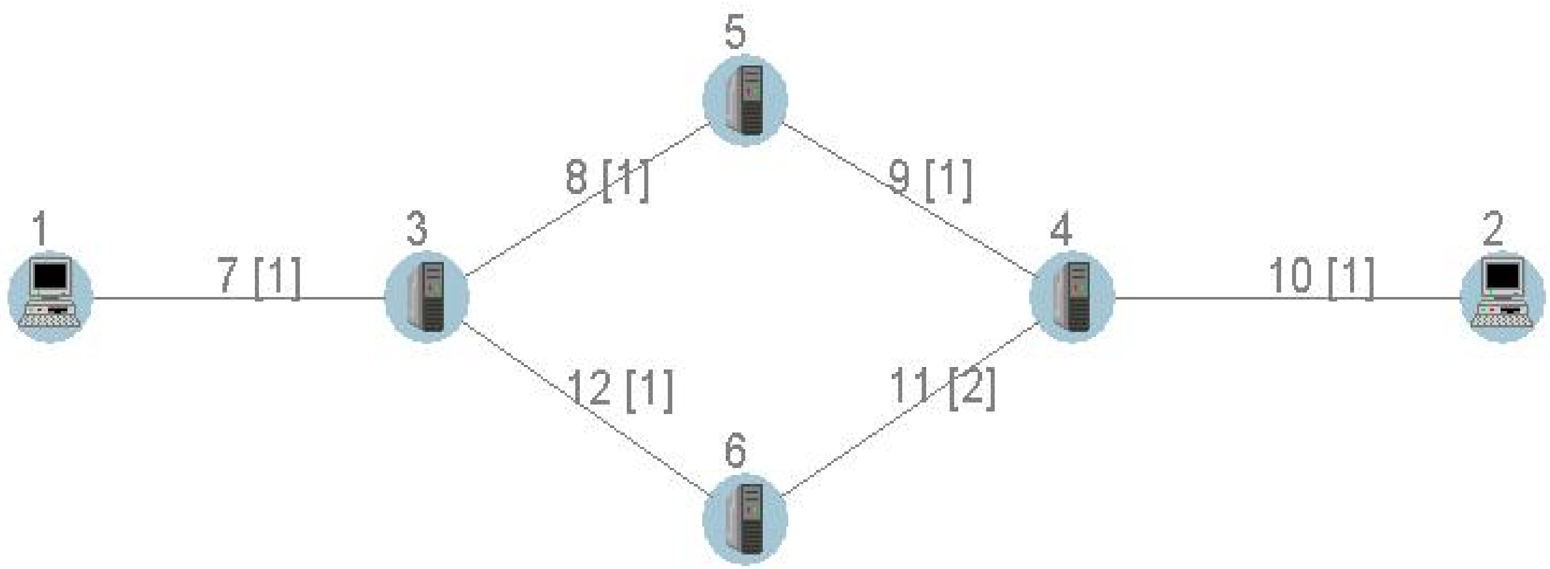
Distance Vector Routing Example: init



Router 3			Router 4			Router 5			Router 6		
dest	cost	gate	Dest	cost	gate	dest	cost	gate	dest	cost	gate
3	0	local	4	0	local	5	0	local	6	0	local
1	1	7	5	1	9	3	1	8	4	2	11
5	1	8	2	1	10	4	1	9	3	1	12
6	1	12	6	2	11	-	-	-	-	-	-

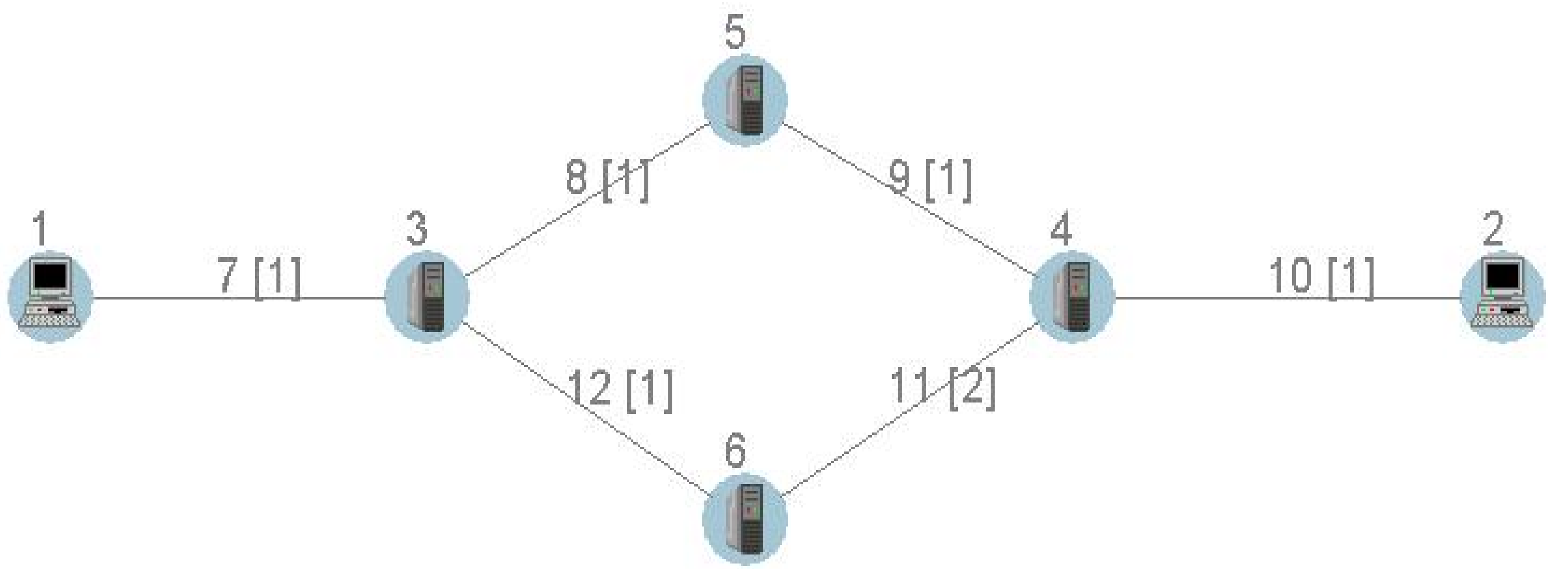
Generated with IRVTool: http://heim.ifi.uio.no/michawe/research/tools/irvtool/

Distance Vector Routing Example: Iteration 1



Router 3			Router 4			Router 5			Router 6		
dest	cost	gate	dest	cost	gate	dest	cost	gate	dest	cost	gate
3	0	local	4	0	local	5	0	local	6	0	local
1	1	7	5	1	9	3	1	8	4	2	11
5	1	8	2	1	10	4	1	9	3	1	12
6	1	12	6	2	11	1	2	8	5	2	12
4	2	8	3	2	9	6	2	8	2	3	11
-	-	-	-	-	-	2	2	9	1	2	12

Distance Vector Routing Example: Iteration 2



Router 3			Router 4			Router 5			Router 6		
dest	cost	gate	dest	cost	gate	dest	cost	gate	dest	cost	gate
3	0	local	4	0	local	5	0	local	6	0	local
1	1	7	5	1	9	3	1	8	4	2	11
5	1	8	2	1	10	4	1	9	3	1	12
6	1	12	6	2	11	1	2	8	5	2	12
4	2	8	3	2	9	6	2	8	2	3	11
2	3	8	1	3	9	2	2	9	1	2	12

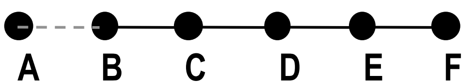
(Distance Vector) Routing Problems

- No globally known point of convergence
  - convergence can take long
- Good news overwrites bad news
  - black hole detection: packets go to /dev/null
  - e.g.: router with wrong table - all destinations cost 0 via local
- Reliance on updates
  - routing messages can be lost!
  - Requirement: timer per entry; typical timer problems again (long = more robust, but takes long to converge in case of link outage)
- Security
  - False updates can lead to trouble! Source must be authenticated

Distance Vector Routing Problems /2

Problem: good news spreads fast, bad news slowly
(count2infinity problem)

Example (cost=1 for all links for simplicity):



1. all tables are correct (e.g., F has cost 5 to A)
2. then, link A-B goes down
3. B recomputes with table initialized to "infinite" for A, receives (A,2) as part of msg. from C (outdated) → table-entry [A,C,3]
   ... but C routes via B! → bouncing effect
4. when C recomputes, it receives (A,3) from B, sets [A,B,4]
5. etc.etc., similar for other routers

course of action may be different (distributed/concurrent algorithm!)
but in any case "infinity" spreads very slowly

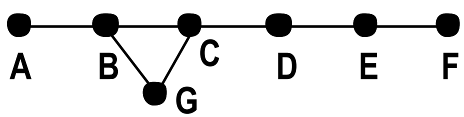
count2infinity occours only in total isolation:

e.g., extra node connected to A and F: high cost, but eventually reroute via F

Split Horizon

Solution: split horizon

- at item 3 above, C omits (A,2) from its message to B
  - More aggressive variant: split horizon with poisoned reverse: instead of omitting (A,2), transmit (A,∞) to B
  - but: problem basically remains if topology is, e.g. as follows:



- why: G tells B about route via G, G tells B about route via C, …
- Note: all these problems are caused by wrong updates
  - enhancement: triggered updates - send updates immediately when table changes
- Many more problems identified / solutions proposed, nothing „perfect“
  → Link state routing has become more common again

Link State Routing

- All routers have "full" information about net (at hierarchy level) [from, to, link, distance]
- each router can compute optimal routes locally
  - typically: Dijkstra's "Shortest Path First" algorithm
- more traffic for spreading out info about net, but no traffic for spreading out "optimum"
- no broadcast of optimum → info more up-to-date, "nearby" changes known/reflected fast: these are most important!
- less scalable than distance vector routing, may generate lots of traffic: hierarchy!

Updating the Distributed Map

- Flooding upon change (link going down, ..) - messages contain:
  - single update line (from, to, link, distance)
  - timestamp or message number N to distinguish between old and new information
  - number: updated slowly (link transition or timer); danger: wraparound!

Algorithm:

```
look for msg_table.line in my_table

if (line not present)
    add line;
    broadcast (everywhere except back to sender);
else if (my_table.N < msg_table.N)
    replace my_table.line by msg_table.line;
    broadcast (everywhere except back to sender);
else if (my_table.N > msg_table.N)
    transmit my_table.line in a new message via incoming interface;

(both numbers equal: do nothing)
```

Dijsktra's Algorithm

```
Initialization:
  N = {A}
  for all nodes v
    if v adjacent to A
      then D(v) = c(A,v)
      else D(v) = infty

Loop
  find w not in N such that D(w) is a minimum
  add w to N
  update D(v) for all v adjacent to w and not in N:
     D(v) = min( D(v), D(w) + c(w,v) )
  /* new cost to v is either old cost to v or known
   shortest path cost to w plus cost from w to v */
until all nodes in N
```

Notation:

c(i,j): link cost from node i to j. cost infinite if not direct neighbors

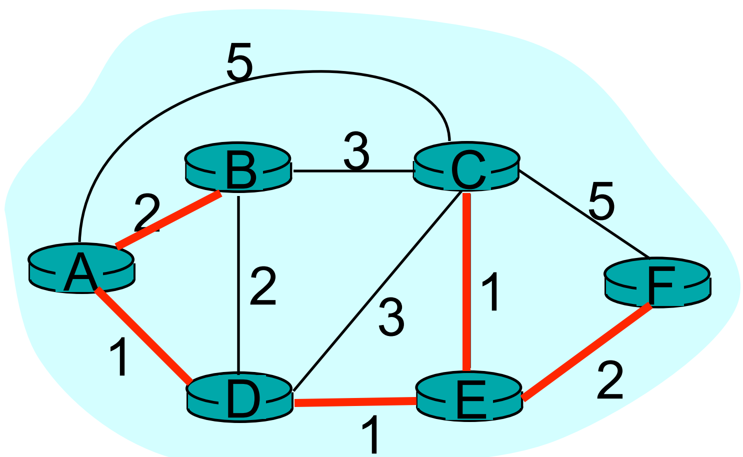
D(v): current value of cost of path from source to dest. V

p(v): predecessor node along path from source to v, that is next v

N: set of nodes whose least cost path definitively known

Dijkstra's algorithm: example

Step	start N	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					



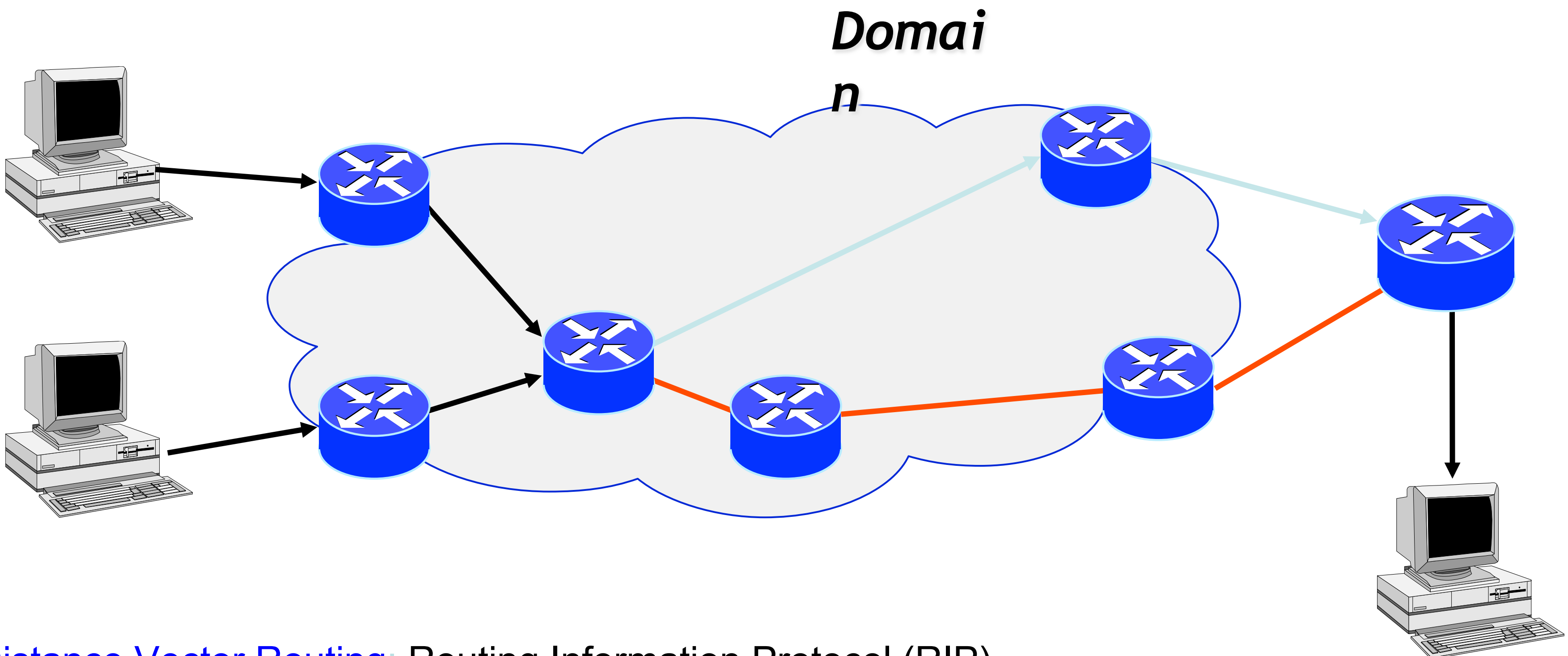
Link State Routing Conclusion

- Internet standard protocol: Open Shortest Path First (OSPF)
  - why? SPF is recommended, but not necessary for compatibility!
    - complexity: check all nodes w not in N → n*(n+1)/2 comparisons (n = number of nodes): $O(n^2)$; more efficient implementations possible: O(n log n)
  - OSPF designed in an open fashion

- Additional advantage of SPF: support of multiple paths
  - minor algorithm change, usually called Equal-Cost Multi-Path (ECMP)
  - idea: send traffic across several paths of equal length (cost)
  - better capacity utilization, less congestion (queuing delay)
  - but: out-of-order delivery, problem with RTT estimation (timeout control)

- Link State Routing also has issues - consider:
  - network split in two parts by link going down
    → two networks with two different maps
  - link up again
    → single link update insufficient, full table update inefficient
    (“bringing up adjacencies“)

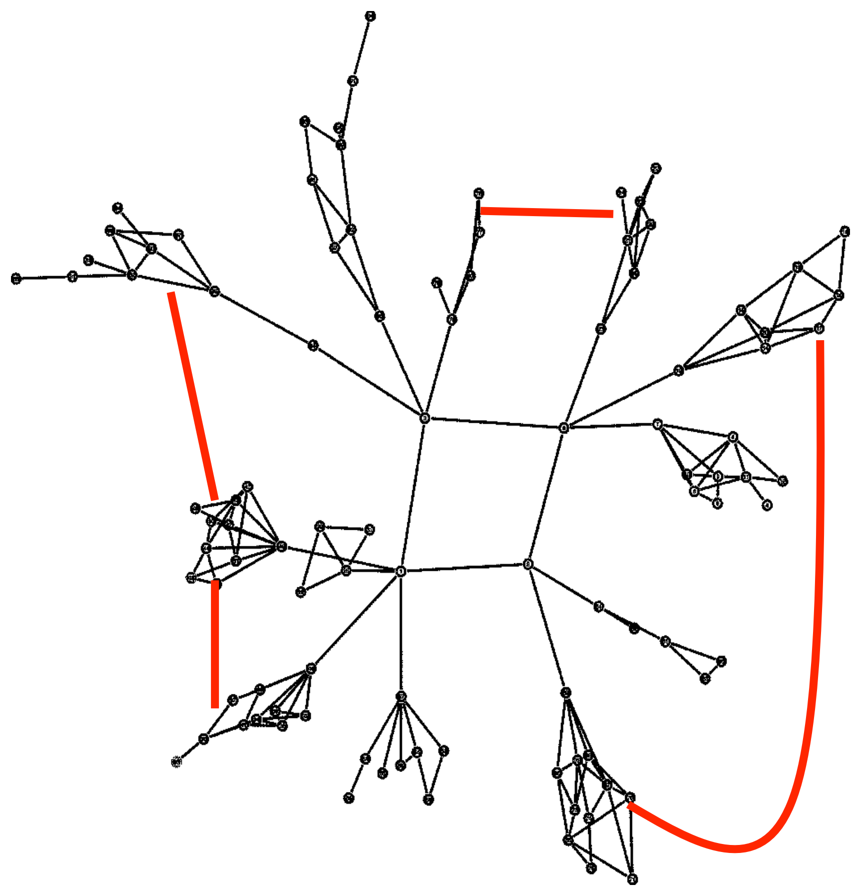
IP Routing: Domain level (IGP's)



- Distance Vector Routing: Routing Information Protocol (RIP), now RIPv2 - several features (authentication, ..), Interior Gateway Routing Protocol (IGRP) - Cisco proprietary, uses TCP instead of UDP
- Link State Routing: Open Shortest Path First (OSPF), consists of 3 subprotocols: Hello, Exchange, Flooding.
- OSI: „Intra-Domain Intermediate System to Intermediate System Routeing Protocol“ (IS-IS) - link state routing protocol similar to OSPF

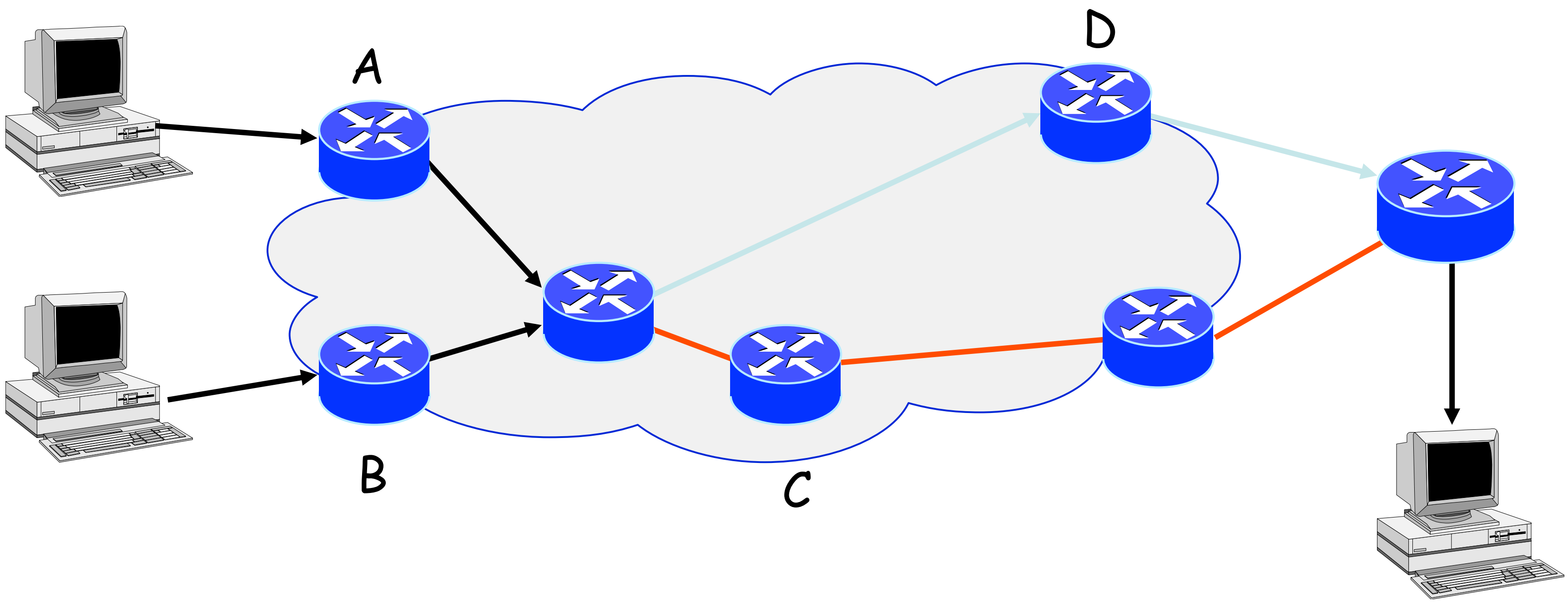
Interdomain routing (EGP's)

- Border Gateway Protocol (BGP):
  Roughly: Distance Vector Routing between "Autonomos Systems" (registered unique AS number)
  - Actually: Path Vector
- Metrics: often configured manually according to costs
- Peering relationships:
  usually cheaper than the backbone
- Implementation: filter
  only accept routes from specific sources



Traffic Engineering

- Static configuration: administrators want to move some traffic
- based on long-term measurements



- IP-in-IP tunneling example:
- B encapsulates packets (new src=B, dst=C), C removes new header

From traffic engineering to MPLS

- Layer violation:
  - If you are tunneling along a fixed path and your network is ATM, you could just as well set up a VC for the path - faster forwarding!
- Automatic variant: Ipsilon IP Switching
  - Switches identify data flow, establish ATM-VC "Short-Cut"
  - Does not scale well - fine granularity
- Better: Multiprotocol Label Switching (MPLS)
  - Not just (but mostly) ATM, even LANs!
  - based upon separation of forwarding and control functionality in routers
  - Label: put short info. (from layer 2) in front of IP (like IP encapsulation)
  - Label Switching Routers (LSR) forward on Label Switched Path (LSP)
  - At destination: remove label, forward IP packet normally

Multi Protocol Label Switching (MPLS)

- Forwarding Equivalence Class (FEC)
  - Group of packets with similar expected treatment (usually: same label)
  - Various forms of classification (choose *which* data flow?) possible

- What if labeled packets are labeled again?
  - Labels are stacked (push, pop, swap [= pop+push, connects two LSPs])

20 bit	Label	Label	Label	IP Header	Data
3 bit	Experi-mental	Experi-mental	Experi-mental		
1 bit	S=0	S=0	S=1		
8 bit	TTL	TTL	TTL		

Stack top — Stack bottom

MPLS details

- Label designed for speed:
  - 32 bit
  - S=1: “this is the last label“
  - TTL is the only IP header field that MUST be treated at each hop
- Labels distributed via Label Distribution Protocol (LDP)
- MPLS applications:
  - Traffic engineering (like IP-in-IP tunneling)
  - Split load by establishing more LSPs for one FEC
  - Virtual Private Networks (VPNs)
  - First aid if links go down (switch to different LSP)
  - QoS support

Multi Protocol Lambda Switching (MPλS)

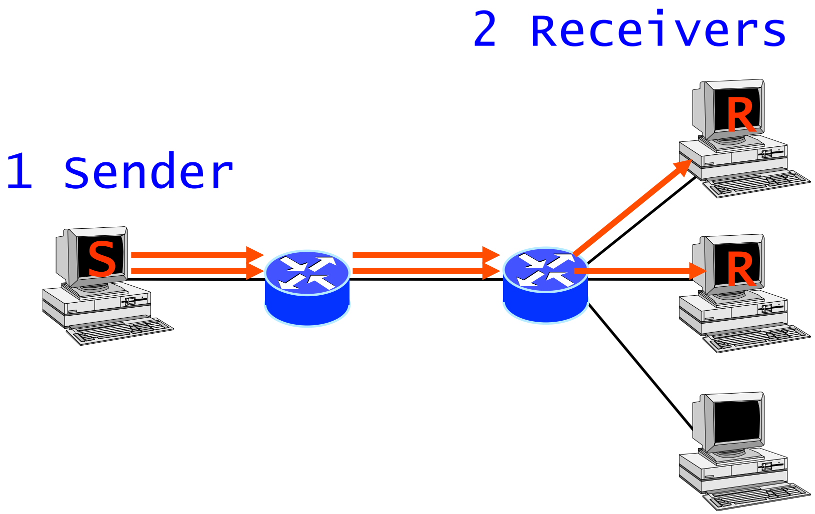
- Wavelength Division Multiplexing (WDM)
  - frequency multiplexing for optical tranmission media
  - optical packet switches - switches based on colours
  - problems: contention (signals with same colour overlap), ...

- IP over WDM: difficult to realize
  easier if connection oriented

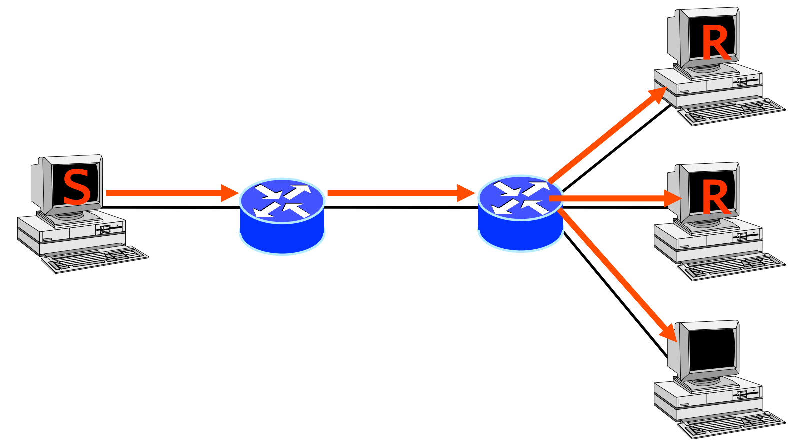
- Achieved via MPLS (Wavelength = label) -> MPλS

- MPλS switches can be connected via λ's for default-routing and signaling (similar to MPLS <=> ATM VC)

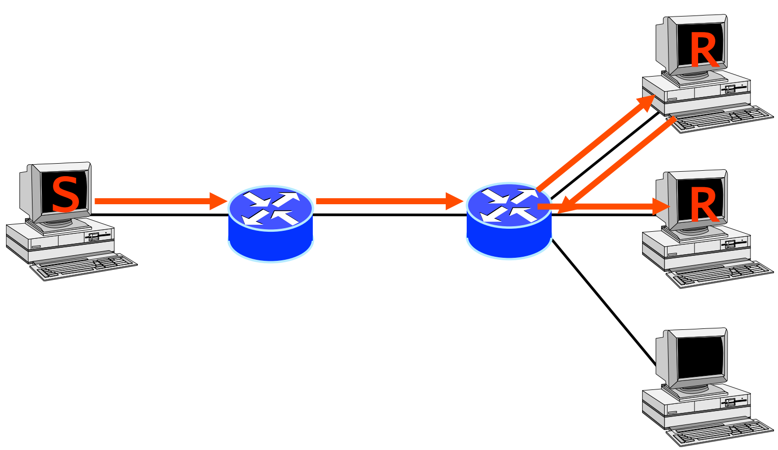
Unicast / Broadcast / (overlay) Multicast



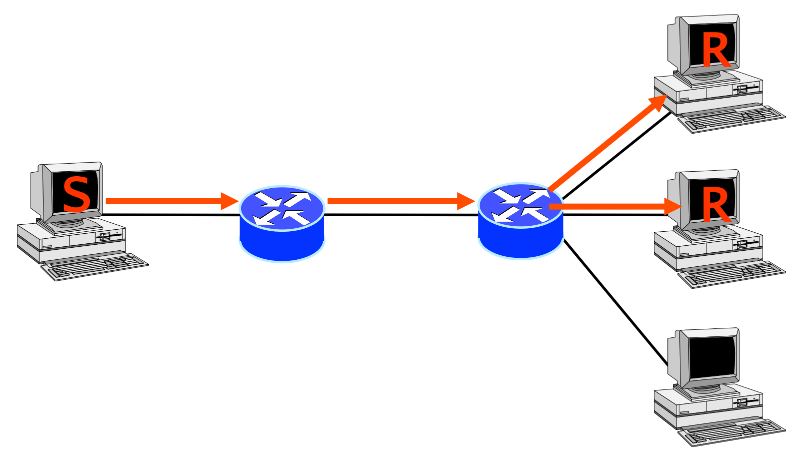
Unicast



Broadcast



MBone



IP Multicast

IP Multicast

- Required for applications with multiple receivers only
  - video conferences, real-time data stream transmission, ..

- Interested receivers + relevant routers regarded as a spanning tree
  - packet distribution algorithm called multicast routing

- Issues:
  - group management
    - protocol required to join / leave group dynamically: Internet Group Management Protocol (IGMP)
    - state in routers: hard / soft (lost unless refreshed)?
    - who initiates / controls group membership?
  - error control (congestion control, flow control) problematic: ACK implosion!
  - Internet: inter-domain and intra-domain protocols necessary
  - address allocation, requirement of router support, modest business motivation (customer / provider / ISP roles): deployment cumbersome

Mobility

- Vision: anywhere, anytime (Internet) access

- Possibility: obtain address dynamically (“plug-and-play“)
  - addresses hard-coded by system admin in a file
  - obtained via Dynamic Host Configuration Protocol (DHCP):
    - host broadcasts “DHCP discover” msg, DHCP server responds with “DHCP offer” msg, host requests IP address: “DHCP request” msg, DHCP server sends address: “DHCP ack” msg

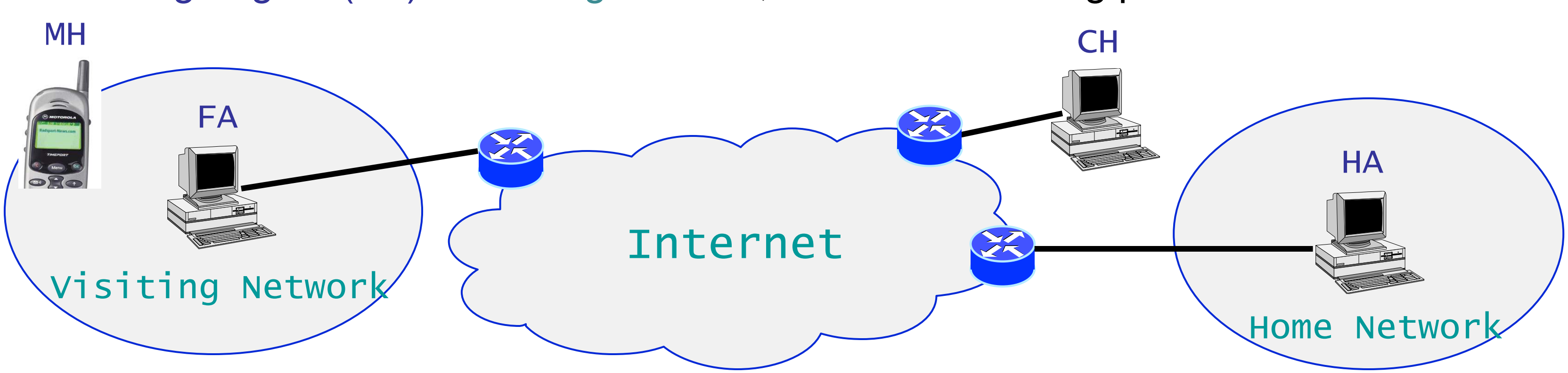
  - DHCP, DNS etc. perhaps still too troublesome for emerging IP based networks: home, automobile and airplane areas, ubicomp
    → alternative: IETF ZEROCONF effort - goals:
    - Allocate addresses without a DHCP server (use MAC address, ser.no., ..)
    - Translate between names and IP addresses without a DNS server
    - Find services, like printers, without a directory server
    - Allocate IP Multicast addresses without a MADCAP server

Mobility /2

- IP address = host identifier AND location
  - address changes: identifier changes => e.g. TCP connections are interrupted
  - connections should persist when users move
    ...no problem within (W)LAN, but what if user moves from LAN 1 to LAN 2 ?
  - what if a user wants to run a server?

- Solution: Mobile IP
  - mobile host (MH): address does not change
  - corresponding host (CH): wants to contact MH
  - home agent (HA): represents MH when MH not in home network
  - foreign agent (FA): in visiting network, forwards incoming packets to MH

always knows location of HA !



Mobility /3

- Two relevant addresses per MH:
  - Home address: permanent MH address, belongs to home subnet
  - Care-of-address: used by MH in visiting network - two types:
    - Foreign-Agent-Care-of-Address: FA forwards incoming packets to MH; several MH's can share the same address (not used in IPv6)
    - Collocated-Care-of-Address: assigned to MH in visiting network - no FA! address must be different for each MH in visiting network

- Operation:
  - Agent Discovery: passive (agent advertisement msgs from HA / FA) or active (agent solicitations query for advertisements) detection of HA or FA
  - Registration: MH sends care-of-address to HA + registers (request-reply); HA keeps table of home address - care-of-address entries → can reach MH
  - Tunneling: data flow: CA → HA → FA → MH → CA

tunnel (HA → FA)

source = home address! (MH → CA)