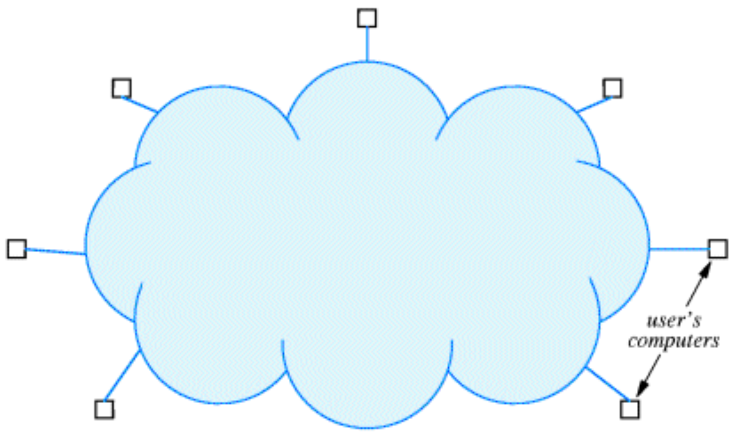
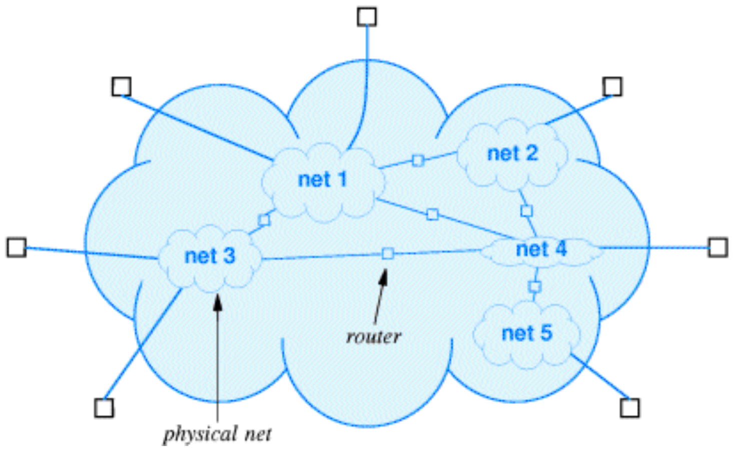
11. Network Layer

11.1. The Internet Concept (1)



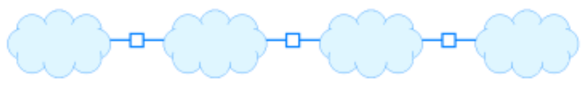
- Internet software provides the *appearance* of a single, seamless communication system (above)
- each computer is assigned an address
- any computer can send a packet to any other computer
- Internet software provides a *virtual network* by hiding the details of
  - physical network connections
  - physical addresses
  - routing information

11.2. The Internet Concept (2)



- neither users nor applications are aware of the underlying physical networks or the routers that connect them
- diagram shows the underlying physical structure in which a computer attaches to one physical network, and routers interconnect the networks

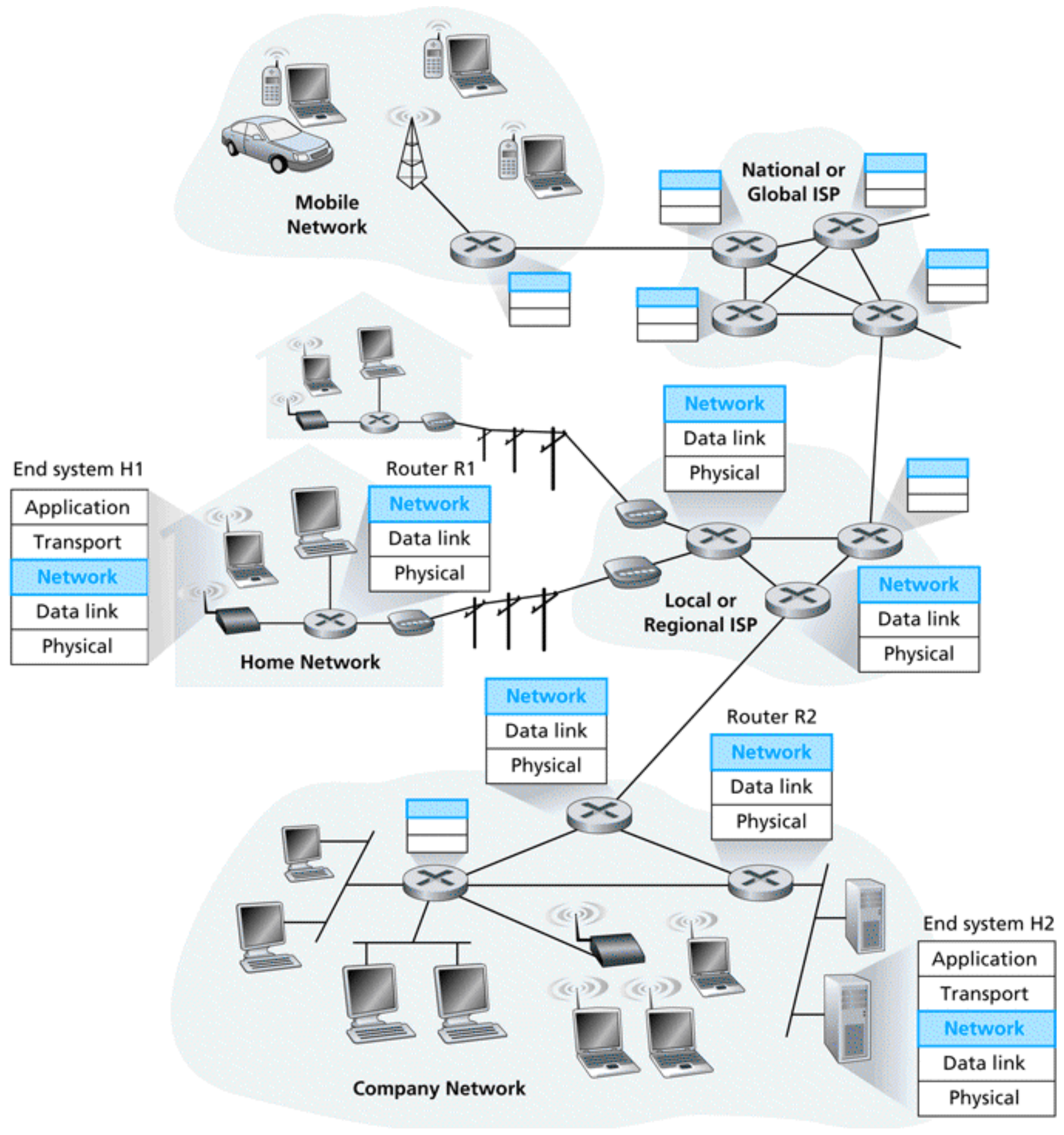
11.3. Routers



- the basic hardware used to connect heterogeneous networks is called a *router*
- network treats a connection to a router the same as a connection to any other computer
- the router has a separate I/O interface for each network it is connected to
- an organisation seldom uses a single router to connect all of its networks:
  - the processor in one router is insufficient to handle all the traffic
  - redundancy improves internet reliability

11.4. Hosts and Routers

- TCP/IP uses the term *host* to refer to any computer connected to an internet
- hosts can be computers running applications or *routers* interconnecting the underlying physical networks
- host computers will need all five layers of the TCP/IP protocol stack
- whereas routers only require the bottom three layers



11.5. Forwarding and Routing

- the role of the network layer is simple: move packets from a sending host to a receiving host
- this requires two network-layer functions:
  - *forwarding*
  - *routing*
- *forwarding* refers to the router's task of deciding which outgoing link an incoming packet should be forwarded on
- *routing* refers to the network-wide process of determining the best paths for packets to follow from a source to a destination
- routers use *forwarding tables* which are determined and distributed using *routing algorithms*

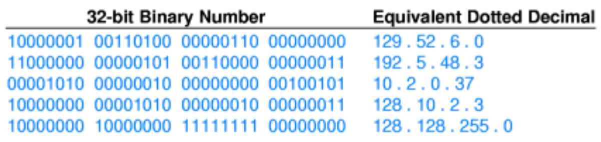
11.6. Data and Control Planes

- the network layer can be decomposed into two interacting parts:

    - *data plane*
    - *control plane*
- the *data plane* refers to the function of each router (i.e. forwarding)
- the *control plane* refers to the network-wide logic associated with routing
- the above terminology is used particularly in *software-defined networking* (SDN)

11.7. IP Addresses and Dotted-Decimal Notation

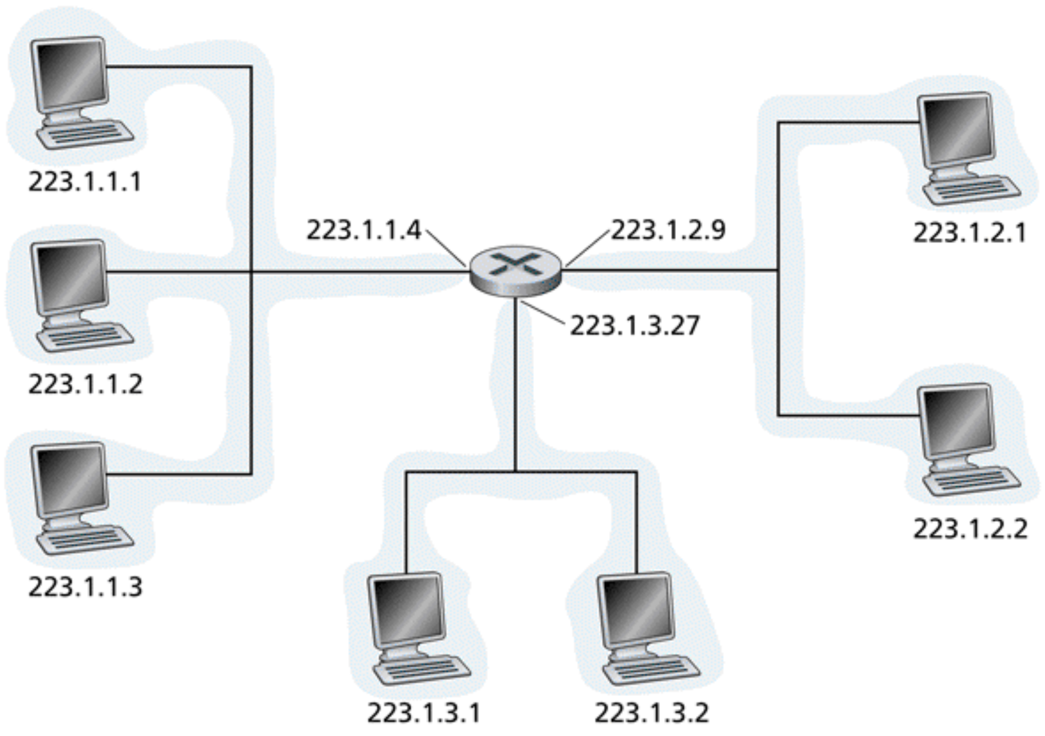
- recall that, in IPv4, each *IP address* is 32 bits long (128 bits in IPv6)
- although IP addresses are 32-bit numbers, humans use *dotted-decimal notation*
- each 8-bit byte is written in decimal and the four values have periods (dots) between them
- the range of possible dotted-decimal addresses goes from `0.0.0.0` through `255.255.255.255`
- here are some example 32-bit addresses and their equivalent dotted-decimal forms:



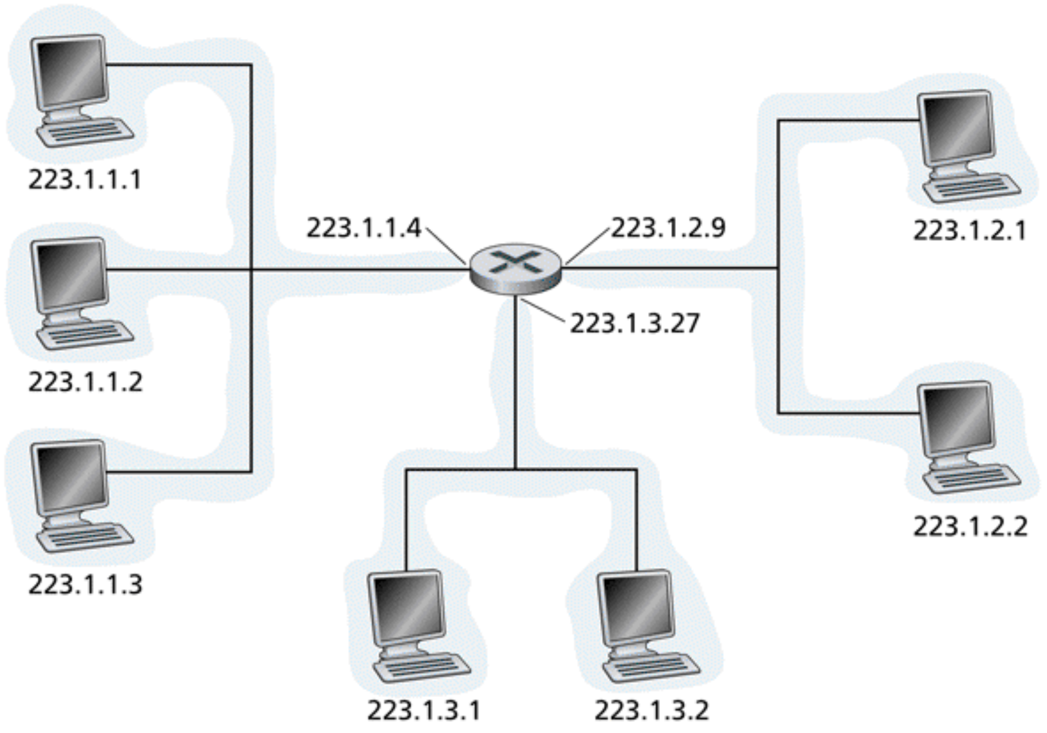
32-bit Binary Number	Equivalent Dotted Decimal
10000001 00110100 00000110 00000000	129 . 52 . 6 . 0
11000000 00000101 00110000 00000011	192 . 5 . 48 . 3
00001010 00000010 00000000 00100101	10 . 2 . 0 . 37
10000000 00001010 00000010 00000011	128 . 10 . 2 . 3
10000000 10000000 11111111 00000000	128 . 128 . 255 . 0

11.8. IP Addressing

- a host computer typically has only one link to the Internet
- the boundary between the host and the physical link is called an *interface*
- a router necessarily has two or more interfaces
- IP addresses are technically associated with *interfaces* rather than hosts or routers



11.9. Subnets



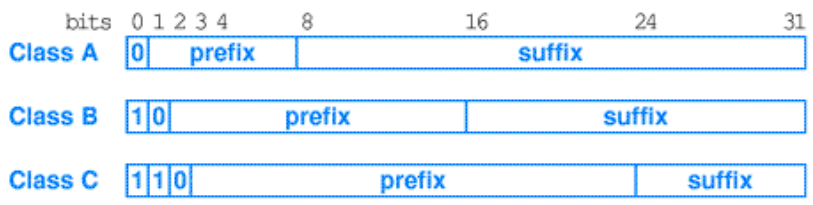
- consider the 4 interfaces whose addresses start with `223.1.1` in the above figure
- they are interconnected without a router and may comprise a local area network
- this network is called a *subnet* (or sometimes just *network*)

11.10. Subnet Addressing

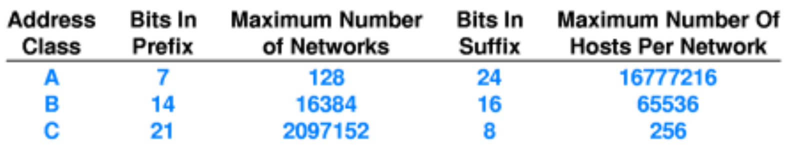
- conceptually, each 32-bit address is divided into two parts: a *network* prefix and a *host* suffix
- this is called *subnet addressing* or *classless addressing*
- addresses are now written in the form `a.b.c.d/n`, where `n` indicates the number of bits in the network prefix
- this notation is called *Classless Inter-Domain Routing* (CIDR) notation
- for example, the top-left subnet in the previous figure would have the subnet address `223.1.1.0/24` to denote a 24-bit network prefix
- any additional host attached to this subnet would be *required* to have an address of the form `223.1.1.xxx`

11.11. Classful Addressing

- IP addresses were originally divided into *classes*, known as *classful IP addressing*, as illustrated below



- the IP class scheme does not divide the 32-bit address space equally:



Address Class	Bits In Prefix	Maximum Number of Networks	Bits In Suffix	Maximum Number Of Hosts Per Network
A	7	128	24	16777216
B	14	16384	16	65536
C	21	2097152	8	256

- the total number of hosts for each class differ because of the number of bits required to identify the class

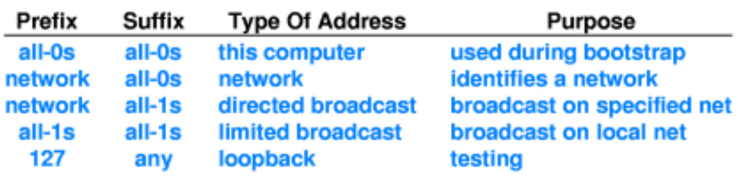
- class *A* can contain 2,147,483,648 hosts, class *B* half of that, and class *C* half again
- classless (subnet) addressing is more flexible

11.12. Obtaining a Block of Addresses

- IP addresses are managed by the *Internet Corporation for Assigned Names and Numbers* (ICANN) to avoid conflicts
- ICANN allocates addresses to regional Internet registries
- ISPs are allocated blocks of addresses by regional registries
- an organisation requests a block of addresses from its ISP
- in this example, an ISP divides its address block among 8 organisations:

ISP:	`200.23.16.0/20`	`11001000 00010111 00010000 00000000`
Org. 0:	`200.23.16.0/23`	`11001000 00010111 00010000 00000000`
Org. 1:	`200.23.18.0/23`	`11001000 00010111 00010010 00000000`
Org. 2:	`200.23.20.0/23`	`11001000 00010111 00010100 00000000`
...	...	...
Org. 7:	`200.23.30.0/23`	`11001000 00010111 00011110 00000000`

11.13. Special IP Addresses



Prefix	Suffix	Type Of Address	Purpose
all-0s	all-0s	this computer	used during bootstrap
network	all-0s	network	identifies a network
network	all-1s	directed broadcast	broadcast on specified net
all-1s	all-1s	limited broadcast	broadcast on local net
127	any	loopback	testing

- IP defines the above set of special addresses that are *reserved* and never assigned to hosts
- the following three blocks of the IP address space are reserved for *private* internets:

`10.0.0.0`	-	`10.255.255.255`	(`10/8` prefix)
`172.16.0.0`	-	`172.31.255.255`	(`172.16/12` prefix)
`192.168.0.0`	-	`192.168.255.255`	(`192.168/16` prefix)

11.14. IP Loopback Address

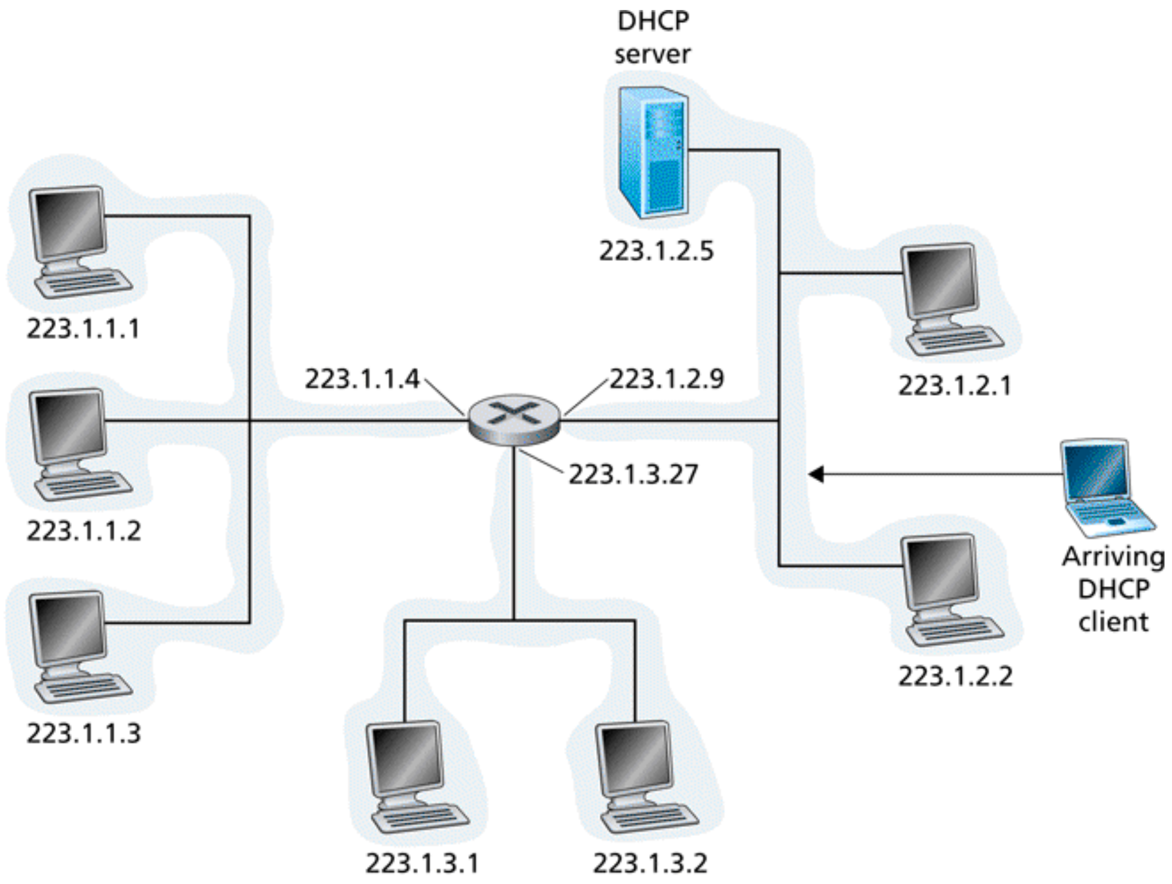
- IP reserves `127/8` for *loopback*
- the host address used with loopback is irrelevant
- programmers often use `127.0.0.1` as the *loopback address*
- it enables a user to run both a client and a server on the same machine
- packets sent to the loopback address never appear on the network

11.15. Obtaining a Host Address

- host IP addresses can be configured manually
- more likely that an IP address will be obtained *automatically* when a computer boots
- this is particularly the case for *mobile* computers
- address allocation is done using the *Dynamic Host Configuration Protocol* (DHCP)
- DHCP also allows a host to learn additional information, such as
    - its network prefix
    - the address of its first-hop router (often called the *default gateway*)
    - its local DNS server

11.16. Dynamic Host Configuration Protocol

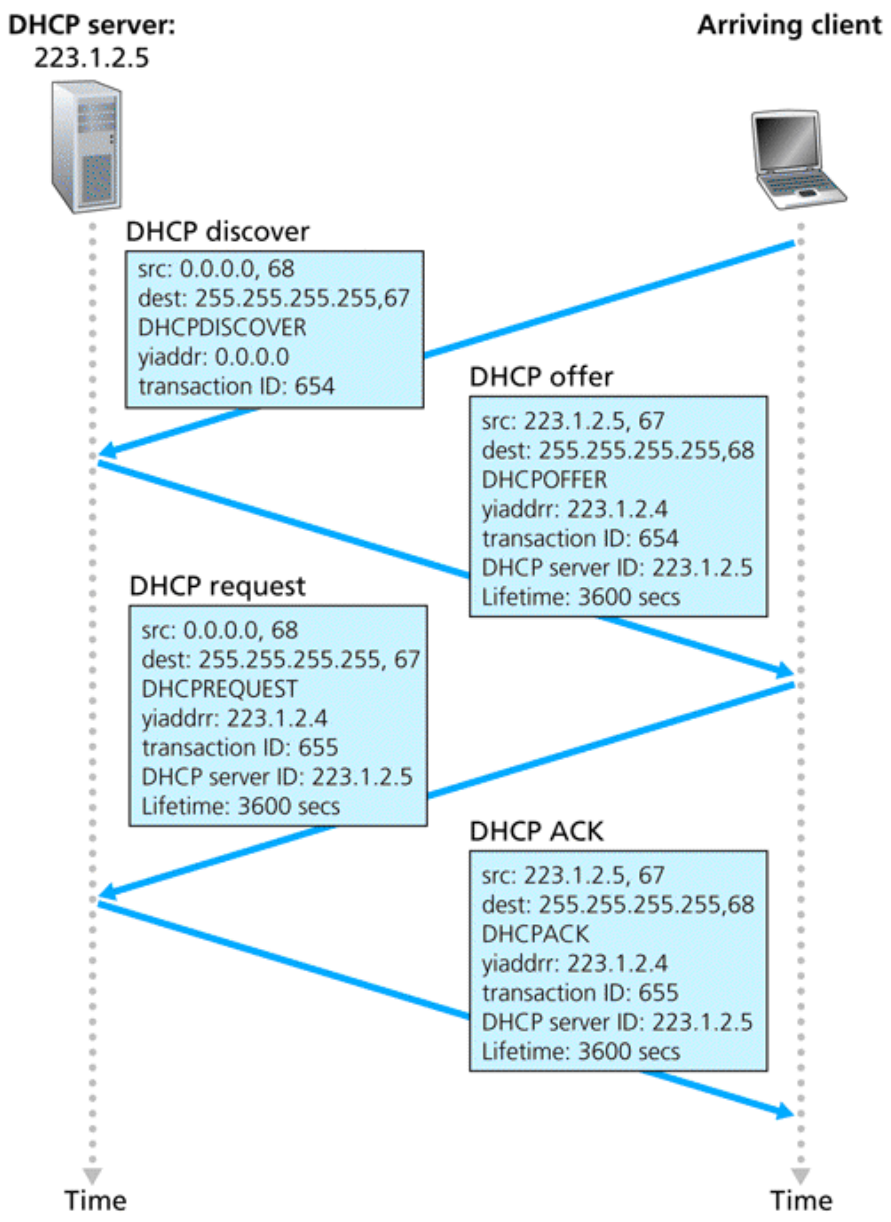
- DHCP is a client-server protocol
- it uses UDP and the server runs on port 67
- in the simplest case, a subnet will have its own DHCP server
- in a home network, the router usually acts as the DHCP server



11.17. DHCP Client-Server Interaction

For a newly arriving host, DHCP is a four-step process:

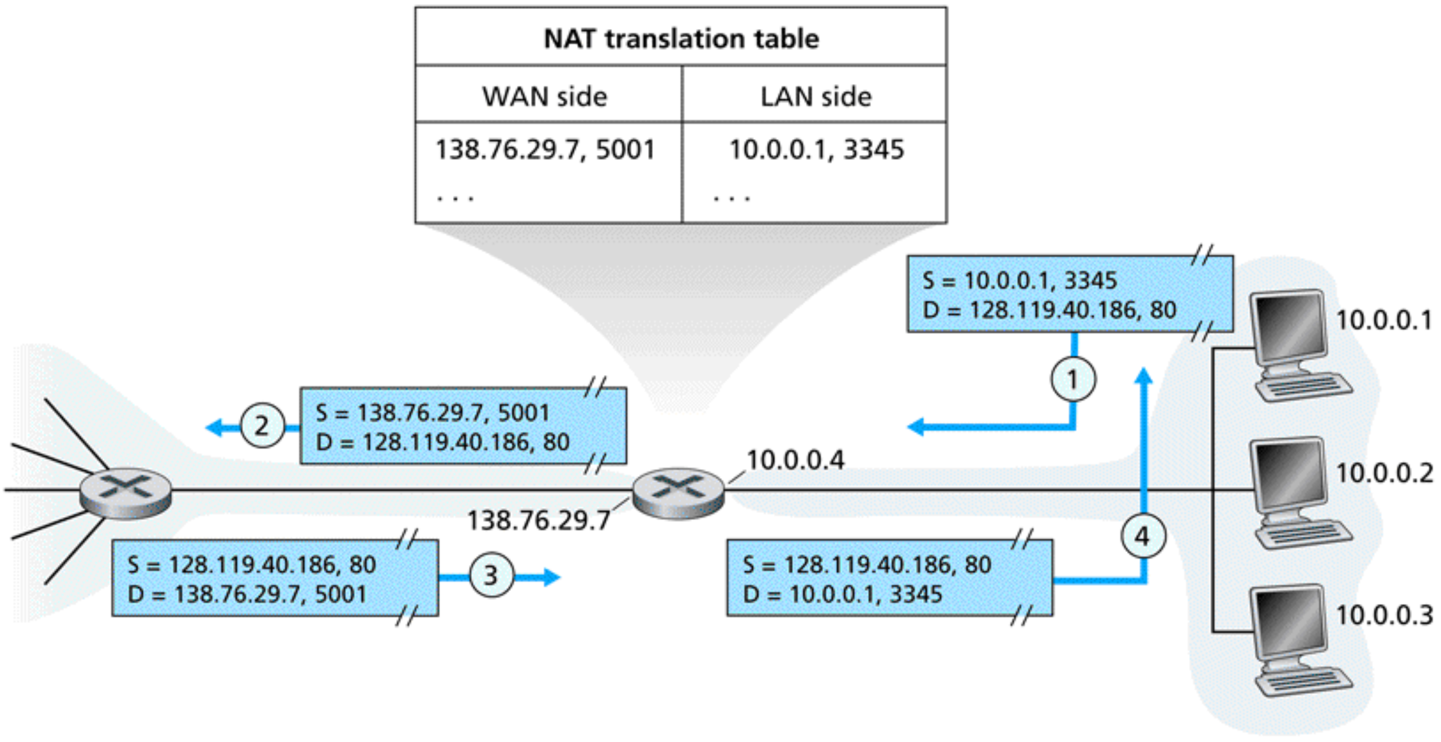
- *DNCP server discovery*: note use of broadcast address (`dest`) and "this host" (`src`) for `yiaddr` ("Your Internet address")
- *DHCP server offer(s)*: note use of broadcast address and IP *address lease time* (`Lifetime`)
- *DHCP request*: used once client has chosen an offer
- *DHCP ACK*: confirmation from server



11.18. Network Address Translation

- every IP-capable device needs an IP address
- implies that every small office, home office (SOHO) subnet needs addresses allocated by ISP
- what if SOHO subnet needs more addresses, but ISP cannot allocate contiguous addresses?
- solution is to use the blocks of IP addresses reserved for private internets
- but these will not be unique, as required for successful communication
- one solution is to use *Network Address Translation* (NAT)
- NAT is usually enabled in home routers

11.19. NAT Example



- NAT-enabled router looks (to the outside world) like a single device with a single IP address
- all traffic leaving the home router has a source IP address of `138.76.29.7`
- all traffic entering the home router has destination address `138.76.29.7`
- how are the hosts within the home network distinguished?
- router uses a *NAT translation table* which includes port numbers
- the NAT router replaces the source IP address and source port number of a LAN datagram with its own IP address and an arbitrary port number (which is recorded in the table)
- the NAT router replaces the destination IP address and destination port number of a WAN datagram with the LAN IP address and port number from the table

11.20. Criticisms of NAT

- port numbers should be used for addressing *processes*, not hosts
- routers are supposed to process packets only up to the network layer
- NAT violates end-to-end principle: hosts should be communicating directly
- IPv6 should be used to solve problem of shortage of addresses
- nevertheless, NAT is widely deployed

11.21. IP Datagrams

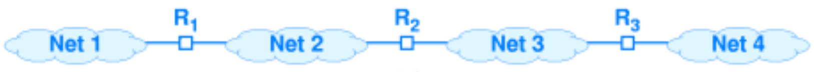
- the network layer is a *connectionless* service
- packets created by a source travel from router to router until they reach a router that can deliver them to the destination
- these packets are called *IP datagrams*, whose format is illustrated below:

Header
Data Area

- the *header* contains information that controls where and how the datagram is sent
- the *data area* is also known as the *payload*
- the size of a datagram is determined by the application that uses it

11.22. Forwarding IP Datagrams

- datagrams follow a path from the source, through routers, to the destination
- each router examines the IP destination address (in the header) and uses a *forwarding table* (also called a *routing table*) to determine the next hop:



(a)

Destination	Next Hop
net 1	R_1
net 2	deliver direct
net 3	deliver direct
net 4	R_3

(b)

- (a) shows an internet with three routers connecting four physical networks
- (b) shows the conceptual forwarding table for router R_2
- each entry in the table lists a destination network and the next hop to that network

11.23. Forwarding Table (1)

- each range of addresses in the table can be represented using CIDR notation
- the next hop can be represented by the interface on which to forward the datagram
- a typical forwarding table would also contain a *default route*
- the router will first scan the table in order to find a matching address range
- failing that, it will use the default route

Destination Address Range	Next Hop Interface
`200.23.16.0/21`	`0`
`200.23.28.0/24`	`1`
`200.23.24.0/21`	`2`
`Default`	`3`

11.24. Forwarding Table (2)

- what if a destination address matches more than one entry in the table?
- e.g., the address `11001000 00010111 00011100 10101010` matches
    - the first 24 bits of the second entry
    - the first 21 bits of the third entry

  in the following table:

Destination Address Range	Next Hop Interface
`200.23.16.0/2111001000 00010111 00010000 00000000`	`0`
`200.23.28.0/2411001000 00010111 00011100 00000000`	`1`
`200.23.24.0/2111001000 00010111 00011000 00000000`	`2`
`Default`	`3`

- the router uses the *longest matching prefix rule*
- so the datagram is forwarded to interface `1`

11.25. Software-Defined Networking (SDN)

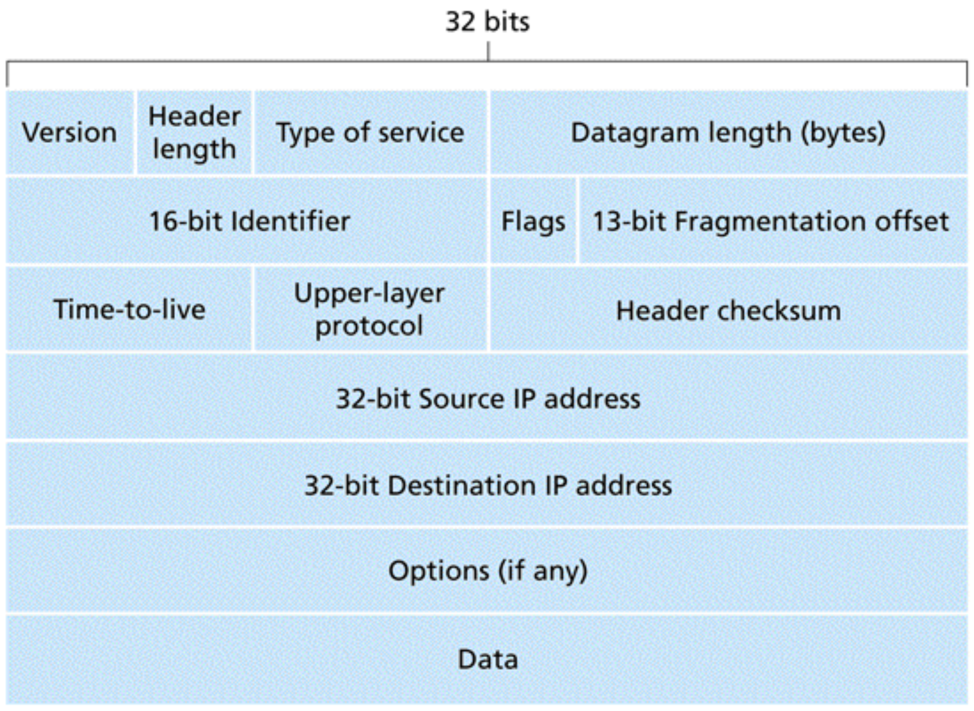
- traditional forwarding is based only on the datagram's destination address

- in SDN, a (software) *controller* (rather than the IP routing algorithms) determines the forwarding tables for the routers under its control
- forwarding tables have more complex "match-plus-action" behaviour
- *match* can be based on multiple header fields, from link, network and transport layers
- *action* can be to forward, drop or copy the datagram, possibly rewriting header fields
- this can be useful in, e.g.:
    - network address translation
    - firewalls
    - load balancing

11.26. IP Best-Effort Delivery

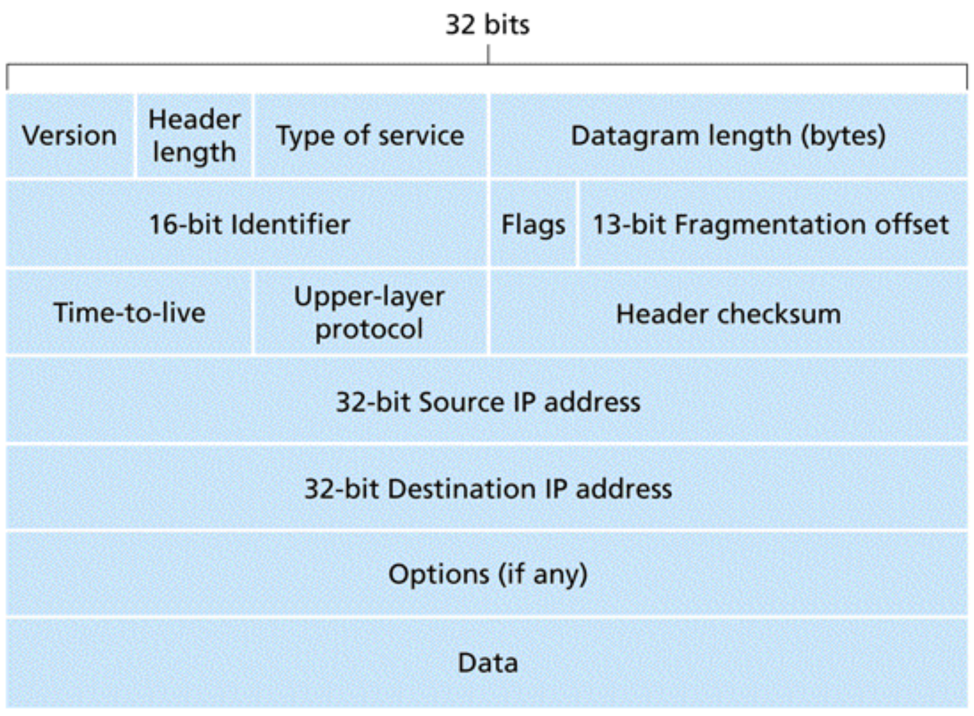
- the standard states that IP will make a *best-effort* attempt to deliver a datagram
- this is because there are a number of problems out of its control:
    - datagram duplication
    - delayed or out-of-order delivery
    - corruption of data
    - datagram loss
- the underlying physical networks can cause such problems
- the higher protocol layers (e.g., TCP) are required to handle these errors

11.27. IP Datagram Format (1)



- *Version*: the IP protocol version number; figure uses version 4 header
- *Header length* (in 32-bit words); required because options may be present in the header
- *Type of service*: 8-bit field for differentiated service (seldom used)
- *Datagram length* (16 bits): number of bytes in header and data
- *Identifier*, *Flags* and *Fragmentation offset* are for IP fragmentation (see later)

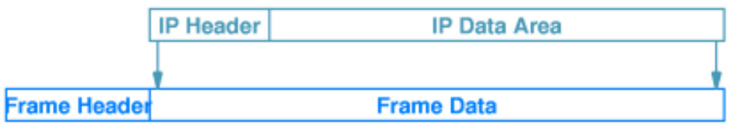
11.28. IP Datagram Format (2)



- *Time-to-live* (TTL)
  - initialised by the sender
  - decremented by one at each router that handles the datagram
  - when it reaches zero, the datagram is discarded and the sender notified with an ICMP message (see later)
- *Protocol* identifies which transport-level protocol should receive the data (e.g. ICMP, TCP or UDP)
- *Header checksum* is calculated over the header only; checked by routers which discard datagram if wrong
- *Source IP address* identifies original sender
- *Destination IP address* identifies final recipient
- a variable-length list of options may also be present
- padding is required to expand the options to a 32-bit word boundary

11.29. Encapsulation

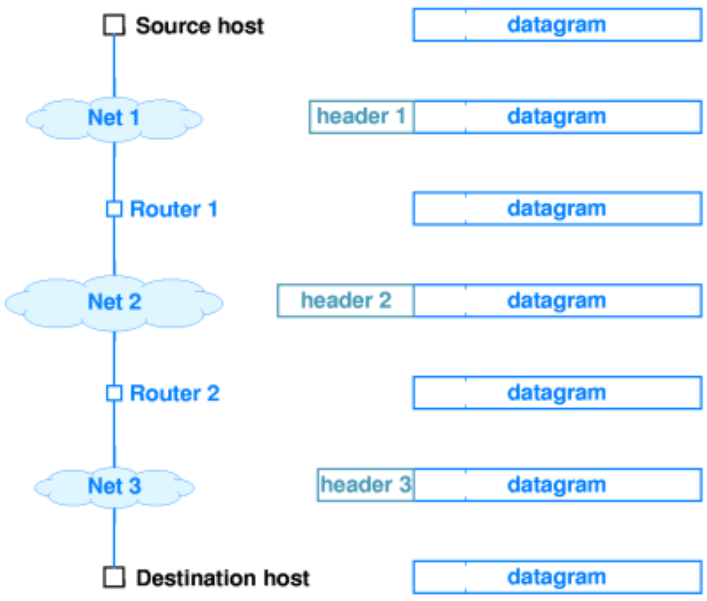
- datagrams are passed down to the link layer in order to be sent over a physical network
- recall that "packets" at the link layer are called *frames*
- so an IP datagram is *encapsulated* in the data area of the frame as illustrated below



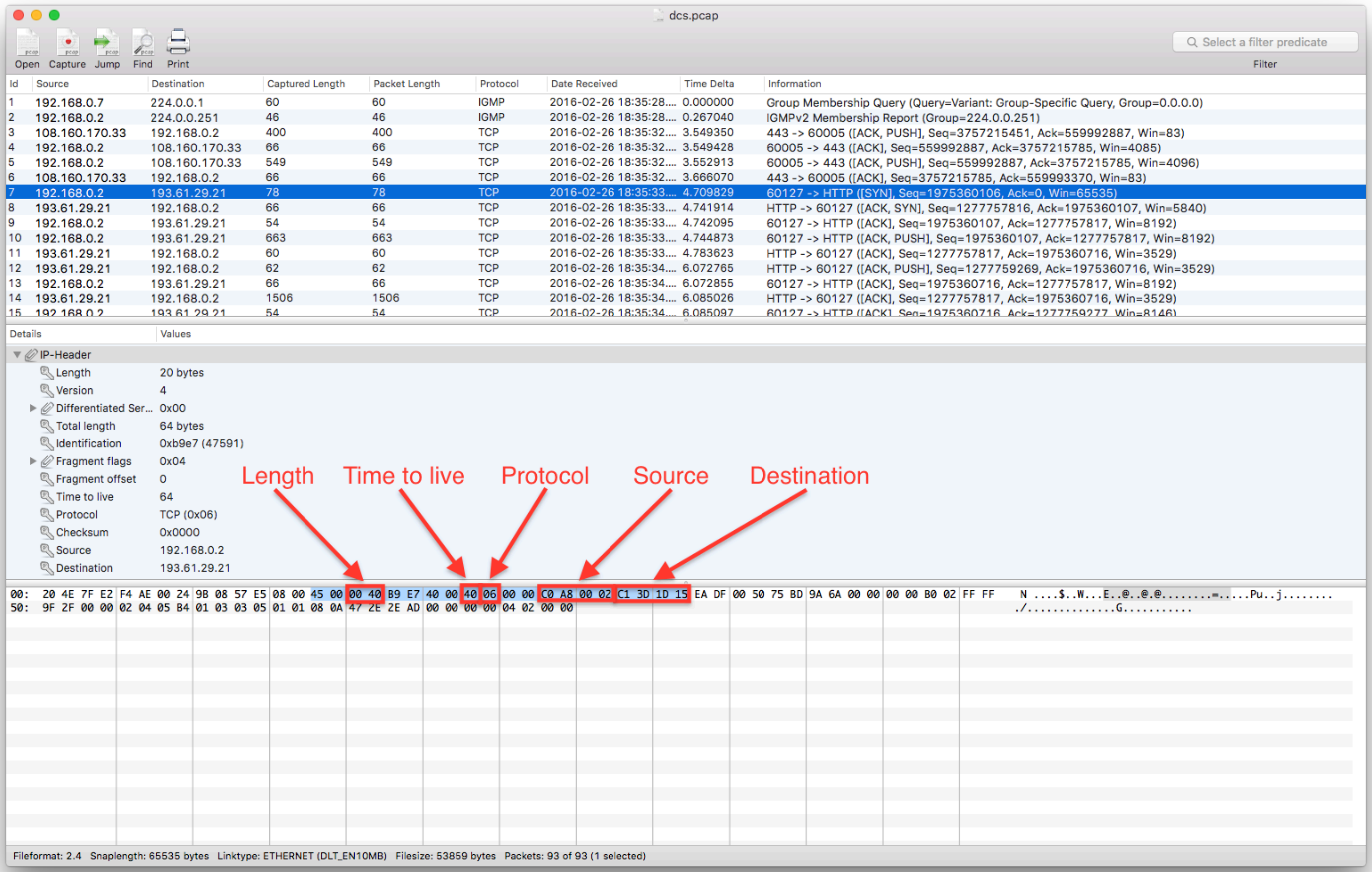
- in practice, some hardware technologies include a frame trailer as well as a frame header
- the receiver of an incoming frame knows that the payload is an IP datagram because of the value of the *frame type* field in the *frame header* (see later)

11.30. Transmission across an Internet

- encapsulation applies to one transmission at a time
- when the frame arrives at the next hop, the IP datagram is removed and the frame discarded
- if the datagram must be forwarded across another network, a new frame is created and the encapsulation is repeated
- each network can use a different hardware technology, so frame formats can differ
- figure below illustrates how a datagram appears as it is encapsulated and unencapsulated from source to destination



11.31. Example of IP Header



Id	Source	Destination	Captured Length	Packet Length	Protocol	Date Received	Time Delta	Information
1	192.168.0.7	224.0.0.1	60	60	IGMP	2016-02-26 18:35:28....	0.000000	Group Membership Query (Query=Variant: Group-Specific Query, Group=0.0.0.0)
2	192.168.0.2	224.0.0.251	46	46	IGMP	2016-02-26 18:35:28....	0.267040	IGMPv2 Membership Report (Group=224.0.0.251)
3	108.160.170.33	192.168.0.2	400	400	TCP	2016-02-26 18:35:32....	3.549350	443 -> 60005 ([ACK, PUSH], Seq=3757215451, Ack=559992887, Win=83)
4	192.168.0.2	108.160.170.33	66	66	TCP	2016-02-26 18:35:32....	3.549428	60005 -> 443 ([ACK], Seq=559992887, Ack=3757215785, Win=4085)
5	192.168.0.2	108.160.170.33	549	549	TCP	2016-02-26 18:35:32....	3.552913	60005 -> 443 ([ACK, PUSH], Seq=559992887, Ack=3757215785, Win=4096)
6	108.160.170.33	192.168.0.2	66	66	TCP	2016-02-26 18:35:32....	3.666070	443 -> 60005 ([ACK], Seq=3757215785, Ack=559993370, Win=83)
7	192.168.0.2	193.61.29.21	78	78	TCP	2016-02-26 18:35:33....	4.709829	60127 -> HTTP ([SYN], Seq=1975360106, Ack=0, Win=65535)
8	193.61.29.21	192.168.0.2	66	66	TCP	2016-02-26 18:35:33....	4.741914	HTTP -> 60127 ([ACK, SYN], Seq=1277757816, Ack=1975360107, Win=5840)
9	192.168.0.2	193.61.29.21	54	54	TCP	2016-02-26 18:35:33....	4.742095	60127 -> HTTP ([ACK], Seq=1975360107, Ack=1277757817, Win=8192)
10	192.168.0.2	193.61.29.21	663	663	TCP	2016-02-26 18:35:33....	4.744873	60127 -> HTTP ([ACK, PUSH], Seq=1975360107, Ack=1277757817, Win=8192)
11	193.61.29.21	192.168.0.2	60	60	TCP	2016-02-26 18:35:33....	4.783623	HTTP -> 60127 ([ACK], Seq=1277757817, Ack=1975360716, Win=3529)
12	193.61.29.21	192.168.0.2	62	62	TCP	2016-02-26 18:35:34....	6.072765	HTTP -> 60127 ([ACK, PUSH], Seq=1277759269, Ack=1975360716, Win=3529)
13	192.168.0.2	193.61.29.21	66	66	TCP	2016-02-26 18:35:34....	6.072855	60127 -> HTTP ([ACK], Seq=1975360716, Ack=1277757817, Win=8192)
14	193.61.29.21	192.168.0.2	1506	1506	TCP	2016-02-26 18:35:34....	6.085026	HTTP -> 60127 ([ACK], Seq=1277757817, Ack=1975360716, Win=3529)
15	192.168.0.2	193.61.29.21	54	54	TCP	2016-02-26 18:35:34....	6.085097	60127 -> HTTP ([ACK], Seq=1975360716, Ack=1277759277, Win=8146)

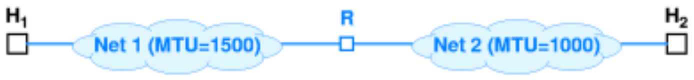
Details	Values
IP-Header	
Length	20 bytes
Version	4
Differentiated Ser...	0x00
Total length	64 bytes
Identification	0xb9e7 (47591)
Fragment flags	0x04
Fragment offset	0
Time to live	64
Protocol	TCP (0x06)
Checksum	0x0000
Source	192.168.0.2
Destination	193.61.29.21

```
00:  20 4E 7F E2 F4 AE 00 24 9B 08 57 E5 08 00 45 00 00 40 B9 E7 40 00 40 06 00 00 C0 A8 00 02 C1 3D 1D 15 EA DF 00 50 75 BD 9A 6A 00 00 00 00 B0 02 FF FF    N ....$..W...E..@..@.@........=.....Pu..j........
50:  9F 2F 00 00 02 04 05 B4 01 03 03 05 01 01 08 0A 47 2E 2E AD 00 00 00 00 04 02 00 00                                                                   ./.............G..........
```

Fileformat: 2.4   Snaplength: 65535 bytes   Linktype: ETHERNET (DLT_EN10MB)   Filesize: 53859 bytes   Packets: 93 of 93 (1 selected)

11.32. Maximum Transmission Unit (MTU)

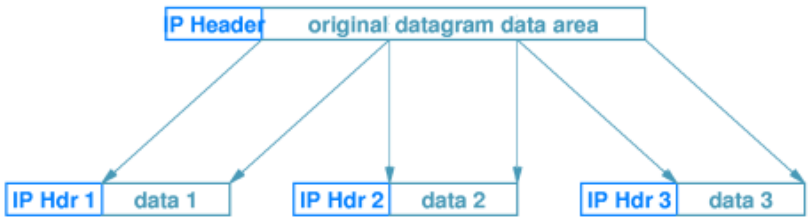
- each hardware technology specifies the maximum amount of data that a frame can carry
- this is called the *Maximum Transmission Unit* (MTU)
- figure below illustrates a router connecting two networks with different MTUs



- host H_2 can only transmit datagrams containing 1,000 bytes or less, which router *R* can forward across network *1*
- however, if host H_1 transmits a 1,500-byte datagram, router *R* cannot send it across network *2*

11.33. Datagram Fragmentation (1)

- IP uses a technique called *fragmentation* to solve the problem of differing MTUs
- if a datagram is larger than the network MTU, it is divided into smaller *fragments* which are each sent separately
- this process is illustrated below



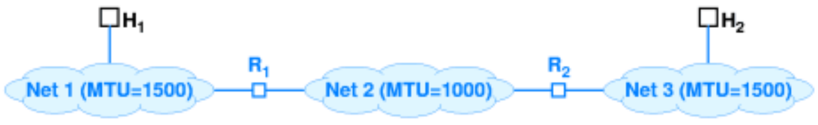
11.34. Datagram Fragmentation (2)

- a host or router uses the MTU and the datagram header size to calculate how many fragments are required (they must be in multiples of 8 bytes)
- then the header of the original datagram is copied into the headers of each of the fragments
- the following fields change
  - *Datagram length* to reflect the smaller size
  - *Flags* to indicate this is a fragment
  - *Fragmentation offset* to reflect the position of the fragment within the *original* datagram
  - *Header checksum*

  crucially, the *Identification* field does not change
- each fragment becomes its own datagram and is routed independently of any other datagrams
- this makes it possible for the fragments of the original datagram to arrive at the final destination out of order

11.35. Datagram Reassembly

- at the final destination, the process of re-constructing the original datagram is called *reassembly*
- the unique *Identification* field groups fragments together
- the *Fragmentation offset* field tells the receiver how to order the fragments
- a bit in *Flags* signals the last fragment
- an example is illustrated below



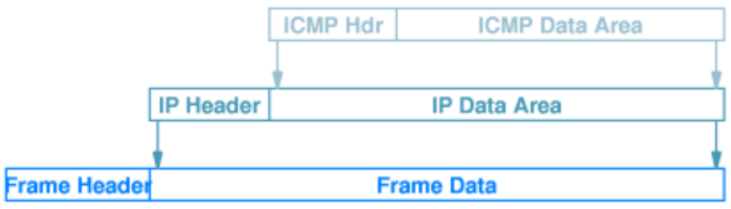
- assume host H_1 sends a 1,500 byte datagram (20-byte header and 1,480 bytes of data) to host H_2
- so router R_1 will fragment the datagram into two fragments
    - the first fragment will contain a 20-byte header (*Fragmentation offset* is zero) and 976 bytes of data (four bytes are wasted)
    - the second fragment will contain a 20-byte header (*Fragmentation offset* is 976/8 = 122) and the remaining 504 bytes of data

11.36. Fragment Loss

- with IP's best-effort delivery, it is possible for one or more fragments to be lost
- when the first fragment arrives, the receiver starts a timer
- if this timer expires before all the fragments have been received, the receiver *discards* those fragments it has received
- TCP can recover from the loss of the corresponding datagram
- there is no mechanism for a receiver to tell a sender which fragments arrived
- this makes sense because
    - the sender does not know about fragmentation
    - if it retransmits, the route and hence fragmentation may be different
- it is possible for a fragment to be fragmented
- the information in the fragments always refers to the *original* datagram

11.37. Internet Control Message Protocol (ICMP)

- if the IP software detects a transmission error, via an invalid header checksum, there is nothing that can be done - datagram is discarded
- however, less drastic errors can be reported back to the sender
- one example is a router decrementing the TTL field in the IP header to zero
- it discards the datagram, but reports the fact to the original source
- this is done using the *Internet Control Message Protocol* (ICMP)
- note that ICMP messages are carried in the payload area of an IP datagram, as illustrated below



11.38. Some ICMP Message Types

- the first two fields in the ICMP header are Type and Code

Type	Code	Description
0	0	echo reply (to ping)
3	0	destination network unreachable
3	1	destination host unreachable
3	2	destination protocol unreachable
3	3	destination port unreachable
3	6	destination network unknown
3	7	destination host unknown
4	0	source quench (congestion control)
8	0	echo request
9	0	router advertisement

10	0	router discovery
11	0	TTL expired
12	0	bad IP header

11.39. Some ICMP Message Descriptions

- *Destination Unreachable*
    - a router sends this error back to the source if it is unable to forward a datagram
- *Source Quench*
    - when a router runs out of buffer space, it starts discarding datagrams
    - when it discards a datagram, it sends a source quench to the sender requiring it to reduce the rate at which it is transmitting datagrams
    - in fact, this is seldom used because TCP performs congestion control
- *TTL Expired*
    - a router has decremented the TTL field in the IP header to zero
    - this error message is used by the `traceroute` application to construct a list of routers to a given destination
- *Bad IP Header*
    - one of the values in the IP header is wrong
- ICMP also includes message types for passing information between hosts, in particular between routers
    - e.g., *Echo Request*/*Echo Reply*, is used by the `ping` application

11.40. Routing Algorithms

- recall that routers use forwarding tables to determine the next hop for a datagram
- how are the forwarding tables calculated?
- typically a host is directly connected (e.g. on a LAN) to a single (*default*) router
- communication with this default router is done by the link layer (see later)
- so the problem is finding a route (or *path*) from a source router to a destination router
- this is done by *routing algorithms* executing in the routers and exchanging information
- or by SDN (software-defined networking) controllers

11.41. Autonomous Sytems

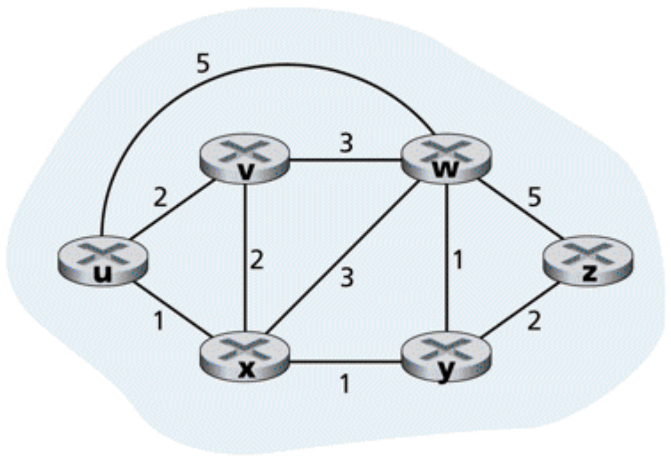
- in fact, Internet routers are grouped into *autonomous systems* (ASs)
- each autonomous system is assigned an Autonomous System Number (ASN)
- there are 5 Regional Internet Registries (RIRs) worldwide
- each RIR assigns ASNs to network operators
- the routers within each AS are under the same administrative control and run the same (*intra-AS*) routing algorithm
- ASs are connected by *gateway routers* running an (*inter-AS*) routing algorithm

11.42. Internet Routing Protocols

- there are a number of Internet routing protocols, e.g.:
    - *Routing Information Protocol* (RIP)
    - *Open Shortest Path First* (OSPF)
    - *Border Gateway Protocol* (BGP)
- RIP and OSPF are intra-AS protocols
- BGP is an inter-AS protocol
- we will consider only OSPF

11.43. Abstract Graph Model

- the routers and the connections between them can be represented as a *graph*
- a graph *G = (N,E)* consists of a set *N* of *nodes* and a set *E* of *edges*
- each edge in *E* is a pair of nodes *(x,y)*
- so the nodes represent routers and the edges represent connections:



- each edge *(x,y)* also has a *cost c(x,y)* associated with it
- the cost might reflect physical length, link speed or monetary cost
- a *path* from x_1 to x_n is a sequence of nodes $(x_1, x_2, \ldots, x_n)$ such that each (x_i, x_{i+1}) is an edge in E
- the *cost* of a path is the sum of the costs of the edges in it
- routing is concerned with finding *least-cost paths* between pairs of nodes
- what is the least-cost path between *u* and *w*?

11.44. Open Shortest Path First

- OSPF assumes that all link costs are known
- this is accomplished by nodes broadcasting packets to all other nodes
- the routing algorithm uses Dijkstra's algorithm for computing "shortest" paths in a graph
- Dijkstra's algorithm computes the least-cost path from a source node (*u* below) to all other nodes
- the following notation is used in the algorithm:
  - *D(v)*: the current cost of the least-cost path from *u* to *v*
  - *p(v)*: previous node on current least-cost path to *v*
  - *N'*: subset of nodes to which least-cost path is known

11.45. OSPF Algorithm

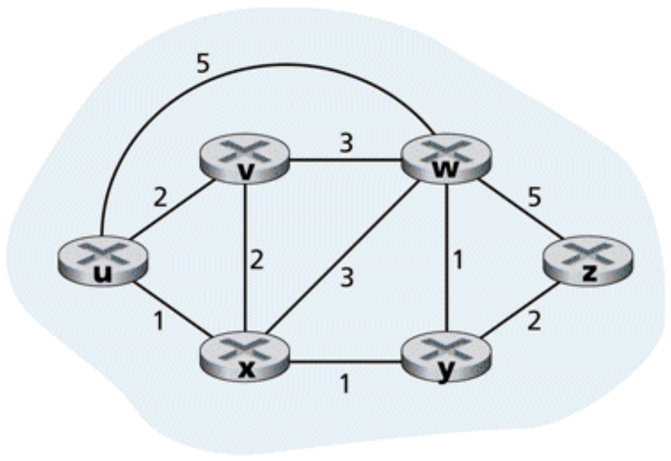
```
  Initialisation:
 1.   N' = {u}
 2.   for all nodes v
 3.     if v is a neighbour of u
 4.        then D(v) = c(u,v)
 5.        else D(v) = infinity

 6.   Loop
 7.     find w not in N' such that D(w) is a minimum
 8.     add w to N'
 9.     update D(v) for each neighbour v of w not in N':
10.       D(v) = min( D(v), D(w) + c(w,v) )
11.   until N' = N
```

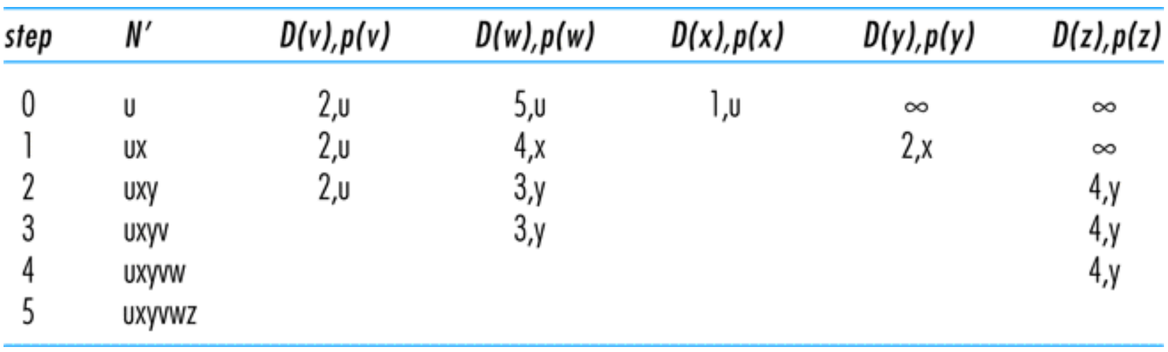
- in line 10, the new cost to `v` is either the old cost to `v` or the cost of the known least-cost path to `w` plus the cost from `w` to `v`

11.46. Example of OSPF Algorithm

- running the OSPF algorithm on the graph

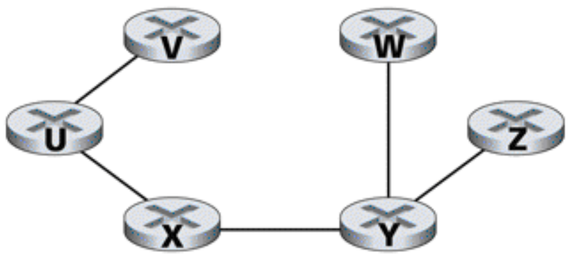


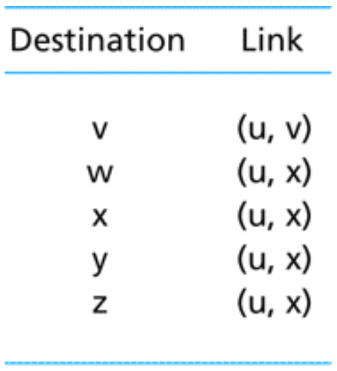
- gives rise to the following values:



step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					

- and the following least-cost paths and forwarding table for *u*:





Destination	Link
v	(u, v)
w	(u, x)
x	(u, x)
y	(u, x)
z	(u, x)

11.47. Links to more information

- The companion web site for Tanenbaum's book, Chapter 5.
- IANA IPv4 Address Space Registry
- Network Address Translation is specified in RFC3022 (2001)
- Address allocation for private Internets is specified in RFC1918 (1996)
- Internet Control Message Protocol is specified in RFC792 (1981)

See Chapters 4 and 5 of [Kurose and Ross], Chapters 20, 21, 22 and parts of 23 of [Comer] and parts of Chapter 5 of [Tanenbaum].