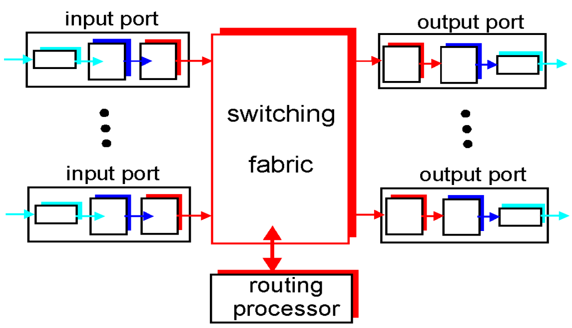
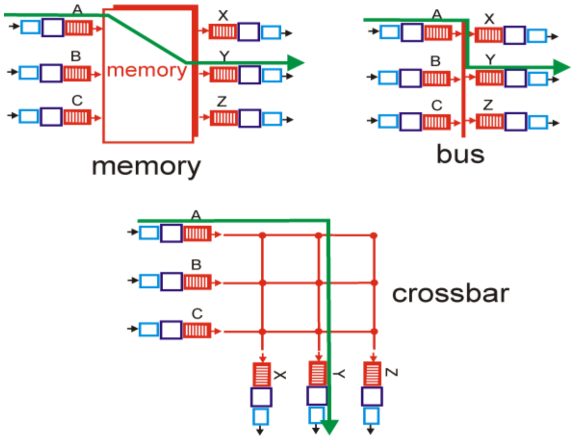
- **Routing** means Determines route from source to destination
- **Forwarding** means Movers packets from input port to proper output port
- **Router**



Run routing process to create and update forwarding table. Forward packets according to forwarding table.

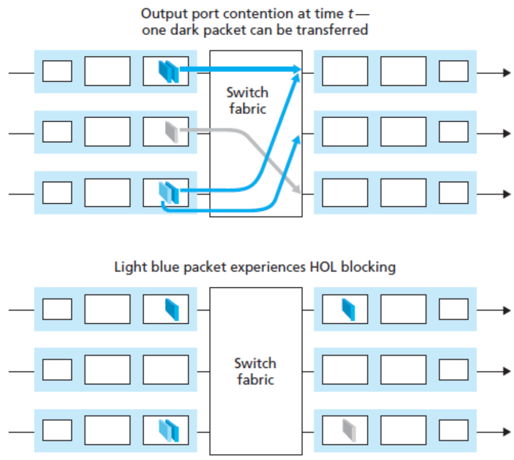


There are various witching fabrics like above.

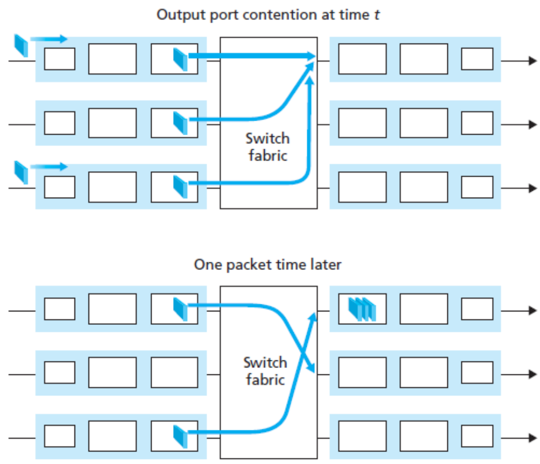
In the memory method, the output port reads packets from the shared memory.

The corssbar method is the fastest because there are several buses.

- **Input Queuing: Head-Of-Line (HOL) Blocking Problem**



- **Output queuing**



- **Switch vs. Router**

	Switch	Router
Network scale	Small	Large
Resource efficiency	Low (Tree-based routing)	High (Shortest path routing)
Operating layer	Layer2	Layer3

- **Routing Algorithms: Link State**

Each node should know network topology and all the link costs. Then finds shortest path to every node. e.g.) Dijkstra algorithm.

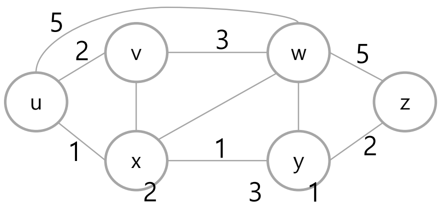
- **Routing Algorithms: Distance Vector**

Each node should know its neighbors and link costs to the neighbors. Then computes the next hop to every node exchanging the information with neighbors. e.g.) Bellman-Ford algorithm

- **Dijkstra Algorithm**

$$O(V^2)$$

where V is number of vertices.



Step	N′	v	w	x	y	z
0	u	2, u	5, u	**1, u**	inf	inf
1	ux	2, u	4, x		**2, x**	imf
2	uxy	**2, u**	3, y			4, y
3	uxyv		**3, y**			4, y
4	uxyvw					**4, y**
5	uxyvwz					

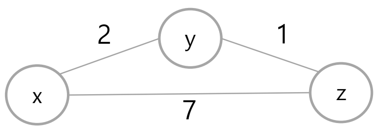
- **Bellman-Ford Algorithm**

$$C_s(d) = \min_x\big(l(s,x) + C_x(d)\big)$$

where $C_s(d)$ denotes cost of shortest path from s to d, $l(s,x)$ denotes link cost from s to x

$$O(V \cdot E)$$

where V, E are number of vertices, and edges

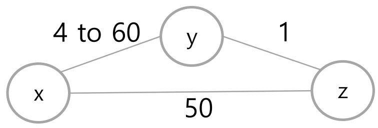


x	dist	out	y	dist	out	z	dist	out
x	0	-		2	x		7	x
y	2	y		0	-		1	-
z	7	z		1	z		0	y

$$C_x(z) = \min\Big(l(x,y) + C_y(z), l(x,z) + C_z(z)\Big) = \min(2+1, 7+0) = 3$$

x	dist	out
	0	-
	2	y
	3	**y**

- **Bellman-Ford Algorithm: Bad News Travels Slow**



time		t0		t1		t2		t3	
from	to	dist	out	dist	out	dist	out	dist	out
x	x	0	-	0	-	0	-	0	-
	y	4	y	60	y	51	z	51	z
	z	5	y	50	z	50	z	50	z
y	x	4	x	**6**	**z**	6	z	**8**	**z**
	y	0	-	0	-	0	-	0	-
	z	1	z	1	z	1	z	1	z
z	x	5	y	5	y	**7**	**y**	7	y
	y	1	y	1	y	1	y	1	y
	z	0	-	0	-	0	-	0	-

44 iterations before algorithm stabilizes

Solution is “Poisoned Reverse”. If routing path is x to y to z, z tells y its distance to x is infinite. So y won’t rout to x via z.

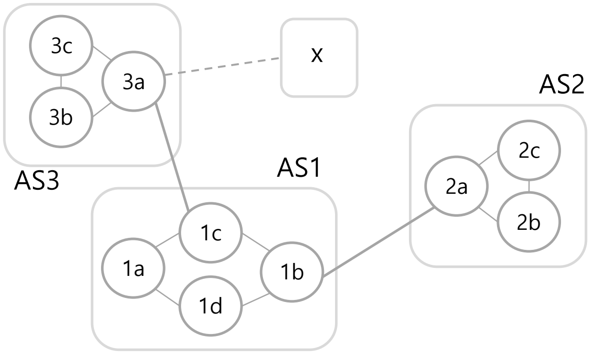
- **Hierarchical Routing: Terminology**

Autonomous System (AS): Group of routers administrated by single organization.

Intra-AS routing: All the routers in a single AS should run the same routing protocol.

Inter-AS routing: Border routers represent the AS to outer world. All the border routers should run the same routing protocol.

- **Hierarchical Routing**



Suppose AS1 learns (via inter-AS protocol) that subnet x reachable via AS3 (gateway 1c) but not via AS2.

Inter-AS protocol propagates reachability info to all internal routers.

Router 1d determines from intra-AS routing info that its interface I is on the least cost path to 1c.

- **Fragmentation and Reassembly**

Link has Maximum Transfer Unit (MTU). If IP packet is larger than MTU, it should be fragmented. Fragmented IP packet should be reassembled at destination.

If exists fragmented IP packet, `fragflag` set 1 and offset calculated by 8-byte boundaries.

	length	ID	fragflag	offset	
	4000	x	0	0	

fragmented to (20-byte for header)

	length	ID	fragflag	offset	
	1500	x	1	0	
	length	ID	fragflag	offset	
	1500	x	1	185	
	length	ID	fragflag	offset	
	1040	x	0	370	

- **IP Address**

I get IP address from Network Administrator.
Network Administrator get IP address from ISP.
ISP get IP address from ICANN

- **IP Classic Allocation**

Class	First Octet Range	Max Hosts	Fromat (Octets)			
			4	3	2	1
A	1-126	2^24-2	0	Host ID		
B	128-191	2^16-2	10			
C	192-223	2^8-2	110	NETID		
D	224-239		1110	Multicast Address		
E	240-255		1111	Experimental		

-2 of 'Max Hosts' for
0x00…00 (Network Identifier)
0xFF…FF (Broadcast Address)

E.g.) YU has IP address block of 165.229.0.0 ~ 165.229.255.255

Class B	**10**100101	11100101	xxxxxxxx	xxxxxxxx
Gateway	165	229		

NETID is 10'0101'1110'0101

- **Classless Inter Domain Routing / Variable Length Subnet Masking (CIDR/VLSM)**

Network id can be arbitrary length. Instead the length of network prefix should be specified.

Before	Network Prefix		output
	165.229.0.0		port4
After	Network Prefix	Subnet Mask	output
	165.229.0.0	255.255.0.0	port4

- **Reserved IP Addresses**

IP address with all 0's in host id part for network prefix.
IP address with all 1's in host id part for broadcast address.

Private IP addresses: Not used in the public Internet

Class	Private IP Address
1xA	10.0.0.0~10.255.255.255
16xB	172.16.0.0.~172.31.255.255
256xC	192.168.0.0 ~ 192.168.255.255

- **Internet Control Message Protocol (ICMP)**

  Used by host and router to communicate network layer information.

- **ICMP and `ping`**

  1. Source sends ICMP "echo request" (type 8, code 0) to destination.
  2. When the echo request arrives to the destination.
  3. Router sends to source an ICMP "echo reply" (type 0, code 0).

- **ICMP and `tracert`**

  1. Source sends series of UDP segments to destination.
     First has Time to Live (TTL) = 1,
     Second has TTL = 2, etc.
     Unlikely port number.
  2. When nth datagram arrives to nth router.
     Router discards datagram.
     And sends to source an ICMP message "TTL expired" (type 11, code 0).
     This includes name of router & IP address.
  3. When ICMP message arrives, source calculates Round Trip Time (RTT).
  4. UDP segment eventually arrives at destination host.
     Destination returns ICMP "host unreachable" packet (type 3, code 3)

- **Address Resolution Protocol (ARP)**

  How to determine MAC address of B knowing B's IP address?

  1. A wants to send datagram to B, and B's MAC address not in A's ARP table.
  2. A broadcasts ARP query packet, containing B's IP address like below.
     [dst MAC address = 0xFFFF'FFFF]
     Then all machines on LAN receive ARP query.
  3. B receives ARP packet, replies to A with its (B's) MAC address like below
     [src MAC address = (B's MAC address)]
     [dst MAC address = (A's MAC address)]
     Frame sent to A's MAC address (unicast)
  4. A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (time out).
     Soft State: Information that times out (goes away) unless refreshed.

- **Multiplexing**

  Packets can be exchanged between hosts. But, usually many processes on single host.

  Each process is assigned unique transport ID in a host. Actually, each socket is assigned an ID. Process can have multiple sockets.

- **Connectionless Multiplexing**

  Anyone can send packets to port #X at any time.

- **Connection-oriented Multiplexing**

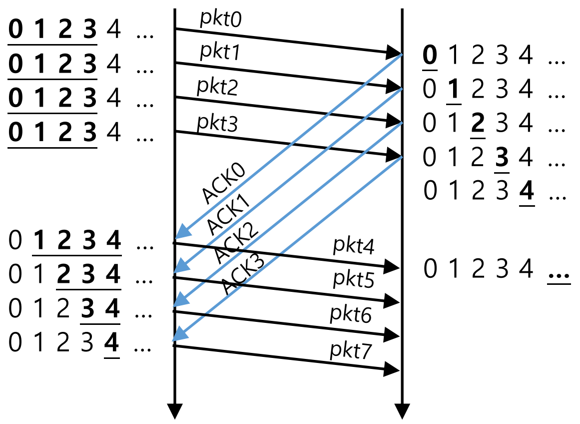
  Only connected sockets can send packets to port #X. There are multiple sockets with port #X not shown outside and distinguished internally by peer.

- **Pipelines Protocols**

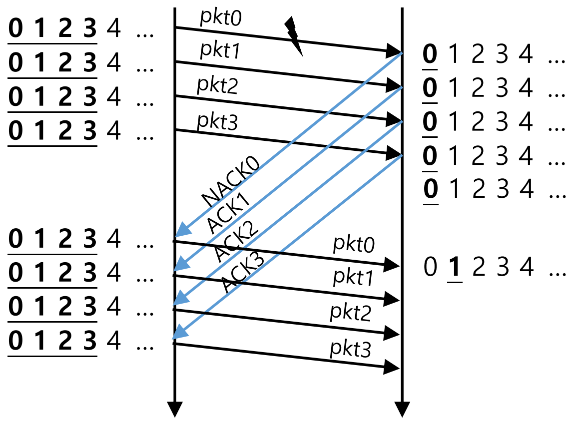
  Sender allows multiple, "in-flight", yet-to-be-acknowledged packets. Two generic forms of pipelined protocols: <u>Go-Back-N</u>, <u>Selective Repeat</u>.

- **Go-Back-N**

Tx window: N, Rx window: 1



[Normal operation]

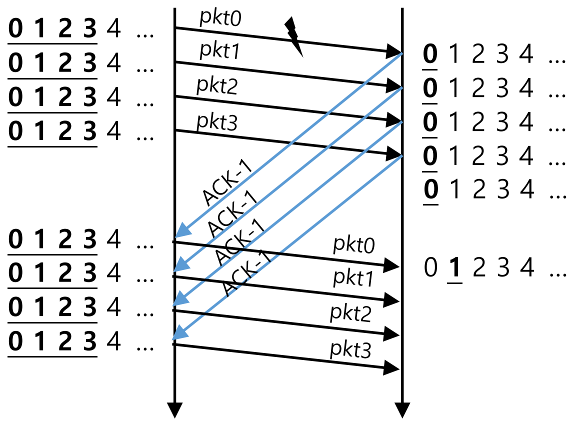


[Corruption of packets]

Sender can transmit N packets at the same time without receiving ACK. If packet is corrupted or lost, retransmit packet stored at buffer.

Receiver should be discard out-of-order packets. If receiver stores out-of-packets, there is no available buffer for the in-order packet.

Also sender should discard the out-of-order ACKs.



[Alternative: Cumulative ACK]

NACK is not required any more. First duplicate ACK acts as a NACK.

- **Go Back to Stop-And-Wait**

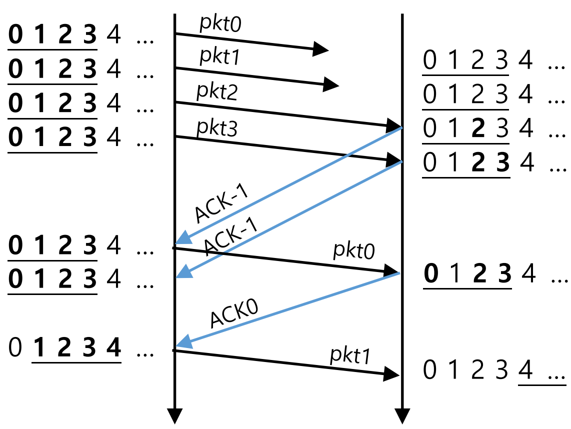
We can develop Stop-And-Wait with Cumulative ACK. Since SAW is a special case of GBN with N=1

- **Selective Repeat**

Tx window: N, Rx window: N

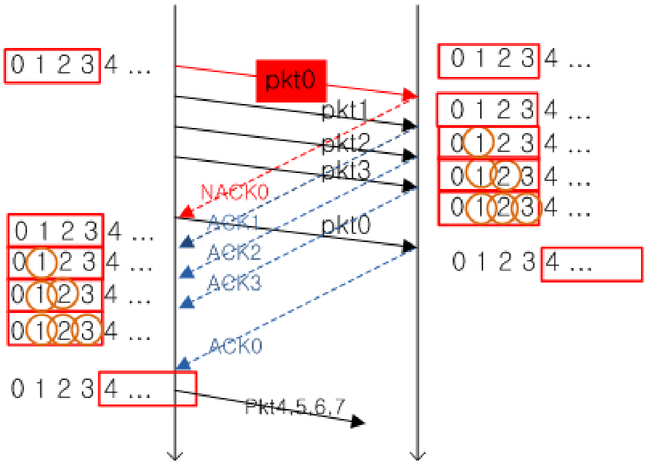
Sender can transmit N packets at the same time without receiving ACK. If packet is corrupted or lost, retransmit packet stored at buffer.

Receiver can store out-of-order packets when there are available buffers.

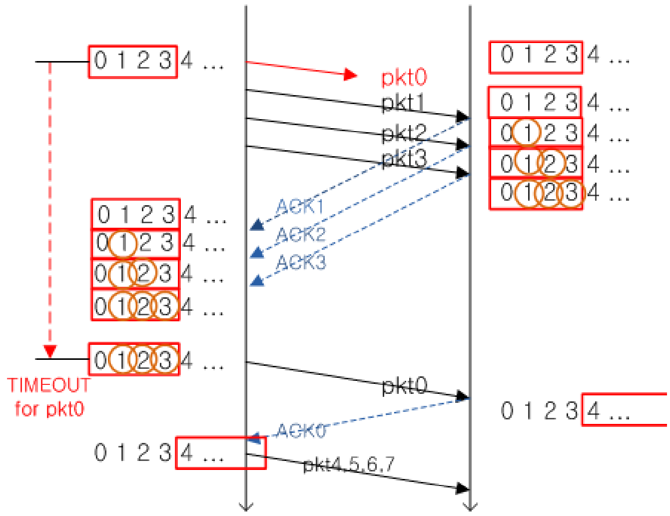


[Cumulative ACK is not good here]

It works, but we could send pkt1 earlier with normal ACK.



[For corruption]



[For loss]

- **Flow Control**

  Sender should not flood receiver buffer.

  There are various methods: Window based methods with TxWnd ≤ RxWnd / Impending overflow notification / Available buffer notification / etc.

  수신자의 버퍼 상태를 고려해서 송신자가 전송속도를 조절하는 것.

- **Congestion Control**

  Informally: “too many sources sending too much data too fast for network to handle”

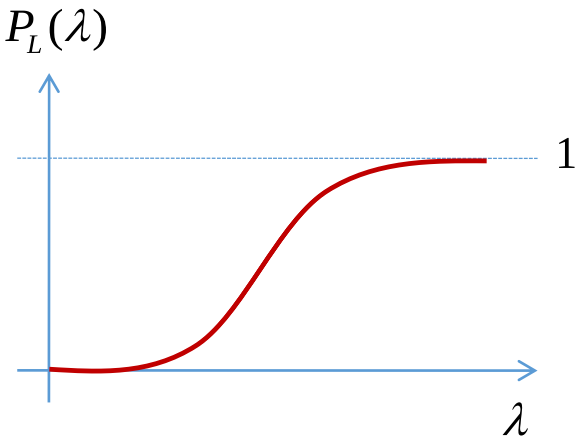
  네트워크를 위해서 송신자가 전송속도를 조절하는 것.

  ➢ Symptoms

    Lost packets (buffer overflow at routers)
    Long delays (queueing in router buffers)

- **Model for Congestion**

  Mathematical mode: Single queue with finite buffer.



$$\lambda P_L(\lambda) = \lambda_r$$

  Where $\lambda = \lambda_n + \lambda_r$.

  λ_n is new (original) data rate. (전송하려는 양)

  λ_r is retransmission data rate. (재전송 해야하는 양)

  $P_L(\ \ )$ is loss probability.

- **User Datagram Protocol (UDP)**

  Connectionless multiplexing / No reliable transfer / No congestion control.

  It’s simple and may not need reliable transfer or congestion control like multimedia application.

- **Transmission Control Protocol (TCP)**

  Connection-oriented multiplexing / Reliable transfer / Congestion control.

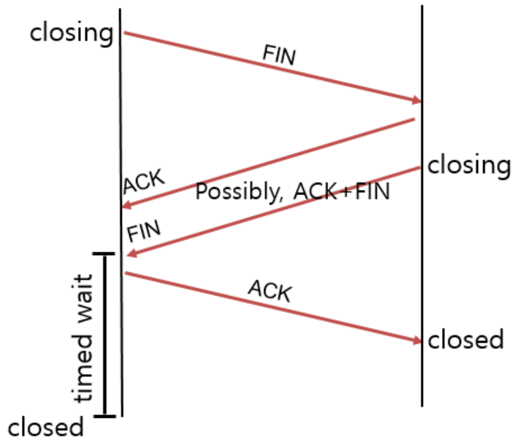
- **Connection Management: Setup**

  1. Client sends SYN to server.
     Specifies initial random seq number #m with no data.

  2. Server replies with SYN/ACK
     ACK for SYN (ack: m+1). Specifies server initial random seq number #n with no data.

  3. Client replies with ACK
     ACK for SYN/ACK (ack: n+1) may with data (seq: m+1).

- **Connection Management: Teardown**



1. Client sends FIN to server.
2. Server replies with ACK.
   Close connection, and sends FIN.
3. Client replies with ACK for FIN
   Enters "timed wait"
4. Server close connection.

- **ARQ in TCP**

Tx window: K, Rx window: M

Sender is window sliding for reception of smallest outstanding segment. Time is maintained.

Receiver stores every received packets, using cumulative ACK and ACK for every successful reception.

- **ARQ in TCP: Delayed ACK**

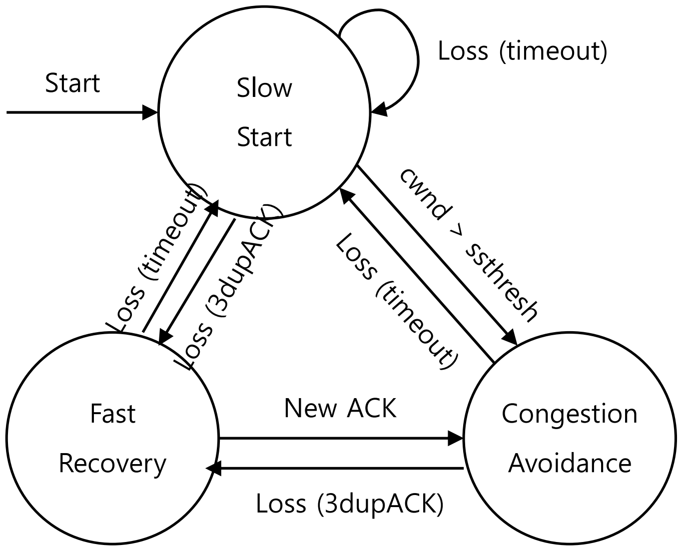
Nagle's algorithm: Reduce TCP segments by aggregating small data.

Reduce ACKs by ACK aggregation. It's mean that under some condition, ACK can be delayed until arrival of next segment.

- **ARQ in TCP: Fast Retransmission**

TCP throughput drops significantly once timeout occurs. Retransmit possibly lost packet by early detection (3 duplicate ACKs).

- **Congestion Control in TCP**



- **Domain Name Service (DNS)**

Map between IP address and Domain name.

- **DNS Hierarchy**

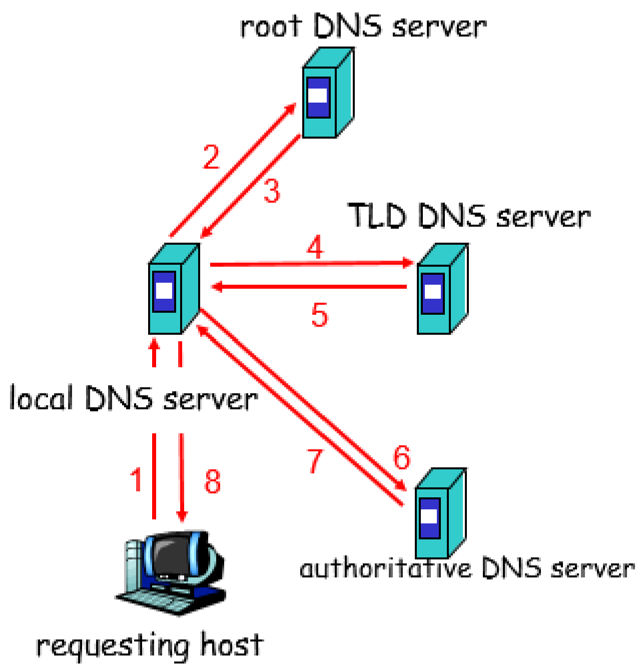
Root DNS Server gives Top Level domain DNS Server's IP.

Top Level Domain (TLD) DNS Server gives Authoritative DNS Server's IP.

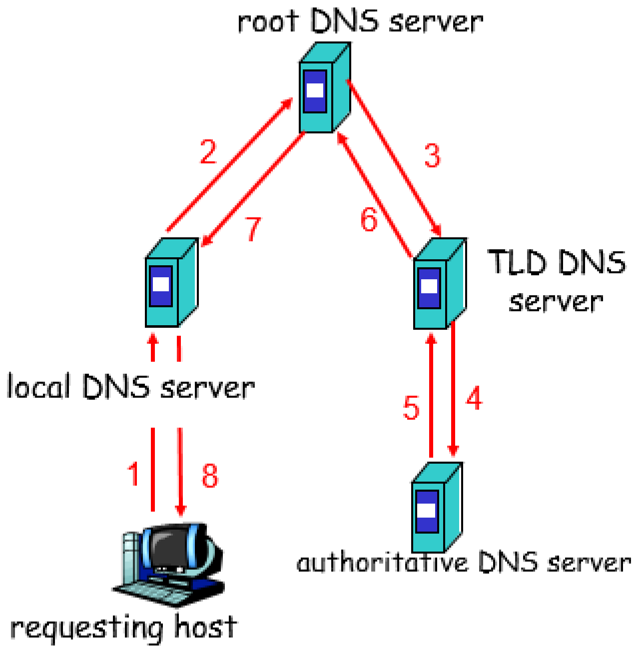
Authoritative DNS Server gives Local DNS Server's IP.

Local DNS Server gives target host's IP.

- **Domain Name Resolution: Iterated Query**



- **Domain Name Resolution: Recursive Query**



- **Dynamic Host Configuration Protocol (DHCP)**

Allow host to dynamically obtain IP address when it joins network.

1. Host broadcasts "DHCP discover"
   src: 0.0.0.0:68
   dst: 255.255.255.255:67
   yiaddr: 0.0.0.0

2. DHCP server responds with "DHCP offer"
   src: 165.229.1.10:67
   dst: 255.255.255.255:68
   yiaddr: 165.229.1.4
   Lifetime: 3600 sec

3. Host requests IP address with "DHCP request"
   src: 0.0.0.0:68
   dst: 255.255.255.255:67
   yiaddr: 165.229.1.4
   Lifetime: 3600 sec

4. DCHP server sends address with "DHCP ACK"
   src: 165.229.1.10:67
   dst: 255.255.255.255:68
   yiaddr: 165.229.1.4
   Lifetime: 3600 sec

- **DHCP Relay**

DHCP server may not be on the same subnet with client. For this, run DHCP relay at each subnet. DHCP relay forwards DHCP messages from Client to DHCP server.

- **Hyper Text Transfer Protocol (HTTP)**

Web page consists of objects and base HTML-file which includes several referenced objects. Each object is addressable by a URL.

<u>www.wikipedia.org</u>/<u>static/images/logo.png</u>
host name path name

Client initiates TCP connection to server, port usually 80. Server accepts TCP connection from client. HTTP messages exchanged between browser and Web server

HTTP is stateless. Server maintains no information about past client requests.

- **HTTP Request Message**

```
GET /somedir/page.html HTTP/1.1
Hist: www.someurl.com
User-agent: Mozilla/4.0
Connection: close
Accept-language:fr
```

- **HTTP Request Methods**

GET for downloading files from Server.
POST for input from Client to Server.
PUT for uploading files to Server.
DLELTE for deleting files in Server.
…

- **HTTP Response Message**

```
HTTP/1.1 200 OK
Connection close
Date: Thu, 06 Aug 1998 12:00:15 GMT
Server: Apache/1.3.0 (Unix)
Last-Modified: Mon, 22 Jun 1998 ...
Content-Length: 6821
Content-Type: text/html
datas...
```

- **File Distribution: Client-Server**

Server sequentially sends N copies: NF/u_S time.

Client i takes F/d_i time to download.

Time to distribute file F to N clients.

$$d_{CS} = \max\left\{N\frac{F}{u_S}, \frac{F}{\min_i d_i}\right\}$$

Where

u_s is server upload bandwidth.
u_i is peer i upload bandwidth.
d_i is peer i download bandwidth.

Increases linearly in N (for large N).

- **File Distribution: P2P**

Server must send one copy: F/u_S time.

Client i takes F/d_i time to download.

Client i uploads F_i and Server uploads F_S

$F_i/u_i = F_S/u_S$ and $\sum F_i + F_S = NF$

Upload time = $NF/(u_S + \sum u_i)$

$$d_{P2P} = \max\left\{\frac{F}{u_S}, \frac{F}{\min_i d_i}, \frac{NF}{u_s + \sum u_i}\right\}$$

- **Network Address Translation (NAT)**

Private address not used in public Internet. So multiple devices in local network use only one public address. NAT allows them to share public addresses well.

1. Host 10.0.0.1 sends datagram to 165.229.11.5:80

2. NAT router changes datagram source address from 10.0.0.1:3345 to 165.229.11.5:5001, updates table.

3. Reply arrives dest. address 165.229.11.5:5001

4. NAT router changes datagram destination address from 165.229.11.5:6001 to 10.0.0.1:3345

- **NAT Traversal Problem**

Client wants to connect to server which address is 10.0.0.1:50000 on the network using NAT. But client cannot use 10.0.0.1 to destination address. Since only one externally visible address such as public IP of the NAT network that contains the server

➢ Manually configure NAT table

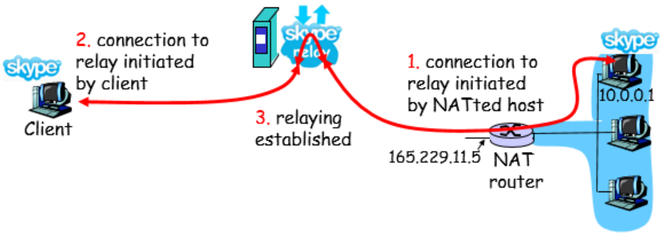
Modify table 165.229.11.5:x passes to 10.0.0.1:50000 manually.

➢ Automatically configure NAT table

By Internet Gateway Device (IGD) Protocol. Host learns NAT IP address. Add/Remove NAT table dynamically

➢ Relaying

Clients establish connections to relay. Relay bridges packets between connections.



1. Connection to relay initiated by NATted host.

2. Connection to relay initiated by client.

3. Relaying established.

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