EEEN20060 Communication Systems

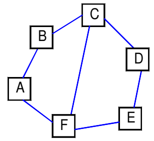
Network Layer

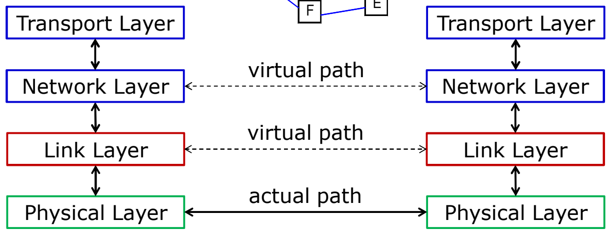
Brian Mulkeen

UCD School of Electrical, Electronic and Communications Engineering

Scoil na hInnealtóireachta Leictrí, Leictreonaí agus Cumarsáide UCD

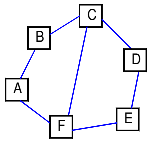
Network Layer





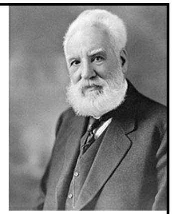
- Summary
  - makes nodes and links work as a network
  - finds routes from source to destination
  - deals with congestion in the network

Services Provided

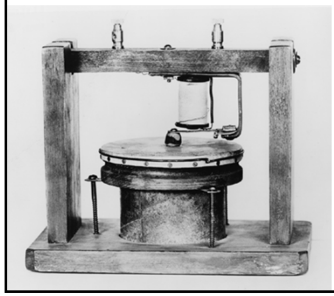


- Basic
  - deliver chunks of data to specified destination
    - best effort, but no guarantees – things can go wrong…
  - transport layer does not need to know how
    - no idea of network topology, protocols used, etc.
  - transport layer needs unique addresses
    - no idea which part of network destination is in…
- Better ? – add idea of connection
  - add concept of stream or flow of data
    - sequence of chunks of data, in order
    - easier to ensure quality of service
  - make reliable – sequence numbers, guarantees…
    - but if not absolute guarantee, transport layer will still have to check everything (if it matters)

Historical Example: Telephone

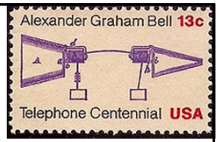


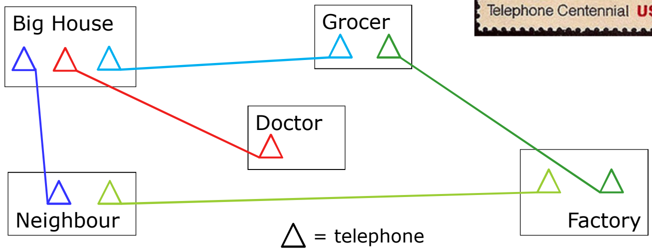
- Patented 1876
  - Alexander Graham Bell (1847-1922)
  - "electrical speech machine"
  - worked with Thomas Watson
  - Elisha Gray developed alternative system



- Basics
  - analogue system
  - convert sound waves to electrical signal
  - send electrical signal along wires
  - convert electrical signal back into sound
  - times two…

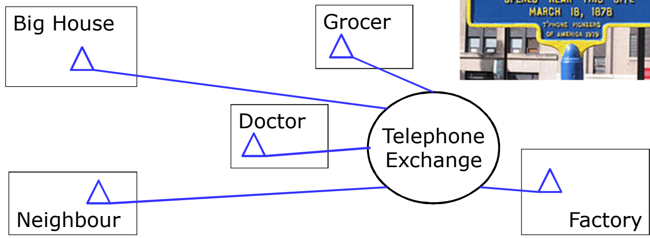
Telephone – Early Days





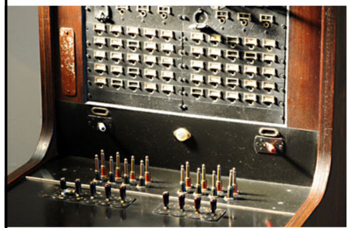
- Telephones leased in pairs
  - contractors installed wires connecting locations
  - repeat for every connection required…
  - soon needed better idea!

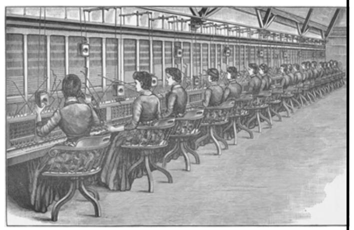
Public Telephone System



- Telephone exchange
  - all telephones in town connect to one place
  - provide temporary connections between users on demand
  - telephone becomes a service…

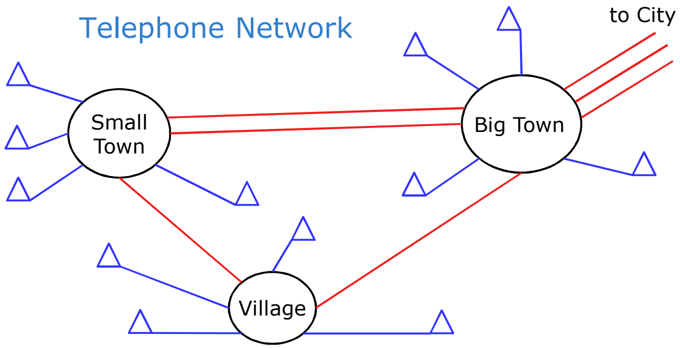
Telephone Exchange





- Manually operated at first
  - human "telephone operator"
  - caller talks to operator,
    - says who he/she wants to talk to
  - operator rings bell of telephone to be called
  - when answered, connects two lines together

Telephone Network

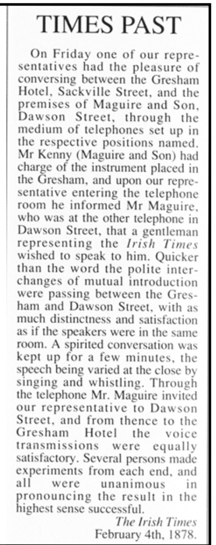


- Add links between exchanges
  - allow communication between users in different towns
  - beginning of a network

Telephone in Ireland

- 1878 – telephone demonstrated
- 1880 – first telephone exchange
  - Dame Street, 5 telephones connected
- 1900 – 56 telephone exchanges
  - 1 link Dublin – Wexford – Waterford
  - 1 link Dublin – Cork, branch to Limerick
  - bare copper wires, on insulators on poles

Overhead line maintenance in the 1930s



TIMES PAST

On Friday one of our representatives had the pleasure of conversing between the Gresham Hotel, Sackville Street, and the premises of Maguire and Son, Dawson Street, through the medium of telephones set up in the respective positions named. Mr Kenny (Maguire and Son) had charge of the instrument placed in the Gresham, and upon our representative entering the telephone room he informed Mr Maguire, who was at the other telephone in Dawson Street, that a gentleman representing the *Irish Times* wished to speak to him. Quicker than the word the polite interchanges of mutual introduction were passing between the Gresham and Dawson Street, with as much distinctness and satisfaction as if the speakers were in the same room. A spirited conversation was kept up for a few minutes, the speech being varied at the close by singing and whistling. Through the telephone Mr. Maguire invited our representative to Dawson Street, and from thence to the Gresham Hotel the voice transmissions were equally satisfactory. Several persons made experiments from each end, and all were unanimous in pronouncing the result in the highest sense successful.

The Irish Times
February 4th, 1878.

Telephone Developments

1913 – electronic amplifiers on long-distance lines

1920s – automatic telephone exchanges
- complex electro-mechanical devices
- controlled by pulses from dial on telephone
- local calls only – long-distance still manual

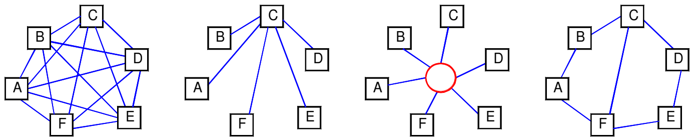
1956 – transatlantic telephone cable
- using many amplifiers powered from land

1958 – 1960s – automation of long-distance calls

1980s – telephone system goes digital
- analogue speech signals converted to digital form
- computer-controlled electronic telephone exchanges

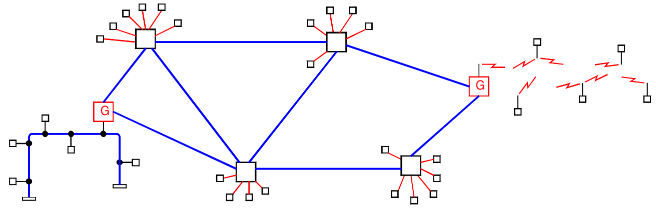
1987 – last manual exchange in Ireland closed

Recall: Network Topology (or Structure)



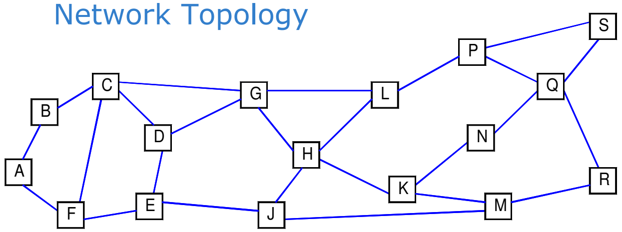
- Large networks use point-to-point links
  - usually bi-directional (two way)
- Mesh network - one extreme possibility
  - direct link from every device to every other
  - for N devices, need $\frac{1}{2}N(N-1)$ two-way links
- Star network – at the other extreme
  - connect every device to one "hub" node
  - need N or $N-1$ two-way links

Network Topology



- Large networks – often mix of topologies
  - special equipment handling messages
    - no user has to pass on messages for others…
  - end-users only at the edges
- Shared medium (e.g. Ethernet, WiFi, …)
  - most MAC protocols restrict to small network
  - typically found at edges of network

Network Topology



- Consider network of *nodes*, joined by *links*
  - nodes are essentially computers
    - usually network equipment, not user devices
  - links are point-to-point – connect 2 nodes
    - assumed bi-directional – normal case
  - links may have different capacities
    - use different protocols (link layer, physical layer)
    - different physical-layer bit rates…

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Network Layer Issues

- Mode of Operation
  - what service does the network provide?
  - how do all the nodes share the resources?
- Addressing
  - how to identify each device in the network?
- Routing
  - how to find a path through the network?
- Internet → interconnected networks
  - many separate networks, interconnected
  - each network managed independently
  - yet must co-operate to provide service

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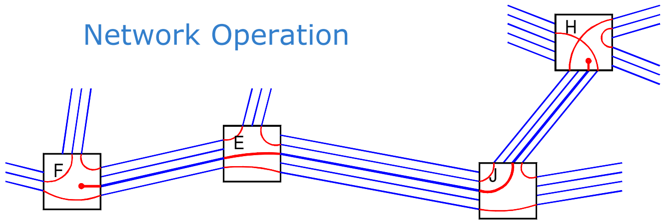
Network Operation



- Circuit Switched Network
  - each link divided into many channels
    - channels equal size across entire network
  - channels connected at intermediate nodes
  - form end-to-end path through network
- Temporary connections
  - set up when requested by a node
    - network must find route to destination…
  - maintained as long as required, then cleared

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Circuit Switching

- Advantages (when connected)
  - no delays, no processing at intermediate nodes
  - private path, throughput guaranteed
    - independent of any other traffic on the network…
- Disadvantages
  - limited throughput – fraction of link capacity
    - even if other channels on link are idle
  - delay in setting up connection
    - find route, wait for free channel on each link
  - resources used while connected, even if no data
    - usually pay for connection time, not data sent
- Good for
  - intermittent long data transfers or exchanges
  - delay-sensitive data…

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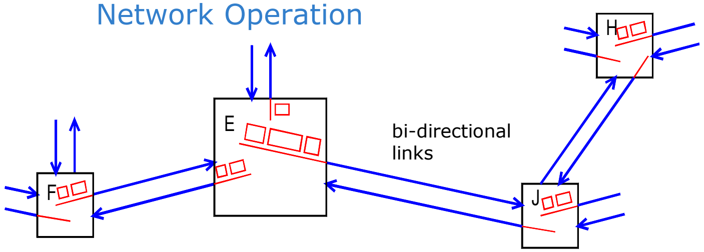
Network Operation



- Message Switched Network
  - link capacity is not divided
  - send entire message into network
    - marked with destination address
  - message must queue at each node
  - transmitted as a unit to next node on route
  - also called "store and forward"

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Message Switching

- Advantages
  - no set-up delay – launch message immediately
  - efficient – full capacity of links available to all
    - no resources reserved and left idle
    - usually pay by volume of data sent
- Disadvantages
  - long, unpredictable delays in queues
    - waiting behind other messages, from other users
  - need large storage capacity at nodes
- Good for
  - transfer of distinct blocks of data
  - data not time-sensitive

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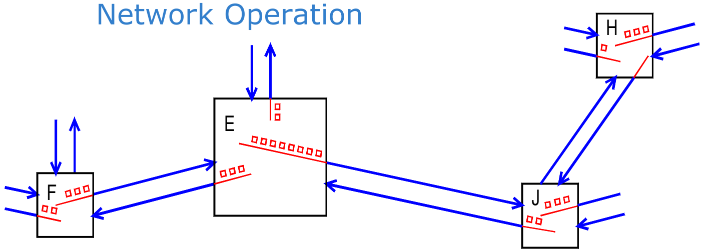
Network Operation



- Packet Switched Network
  - break message into small packets
  - send each into network, with dest. address
  - packets queue at nodes
    - waiting for transmission on link to next node
- Basic operation - independent packets
  - separate routing decision on each

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Packet Switching

- Advantages (like message switching?)
  - no set-up delay – launch packet into network
  - efficient, full link capacity available to all
  - shorter delays than message switching
    - all packets small, can use parallel routes
    - usually less storage capacity needed
  - fairer - packets from various users interleaved
- Disadvantages
  - packets may arrive out of sequence
  - more processing at intermediate nodes
  - still have unpredictable delays
- Good compromise ?
  - one network for everything…

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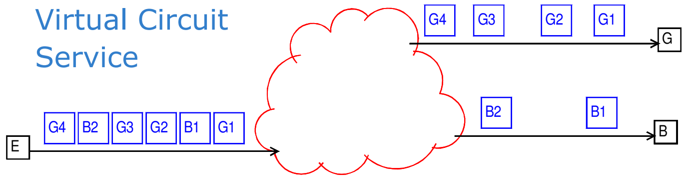
Virtual Circuit Service



- Optional, provided by packet switched network
  - guarantees to deliver packets in sequence
  - can allocate resources to circuit, to control delay…
  - makes network look like circuit switched
- Disadvantages
  - need to set up connection, like circuit switched
    - need to know that packets are part of same flow…
  - extra work for network layer protocol
  - extra information needed in packet header

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How to Implement Virtual Circuits?

1. Packets follow different routes, sort at dest.
   - need sequence number in packet header
   - need tag to identify which connection
     - use in combination with source address…
   - cannot reserve resources, to improve delays…
2. Force all packets to follow same route
   - often use virtual circuit number (VCN)
     - unique on each link, so changed at each node
   - route chosen for connection request packet
     - recorded at every node along the route

Incoming link	VCN	Outgoing link	VCN
J	27	G	45
K	5	L	36
J	36	L	52

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Packet Structure

Header	Payload

- Header contains
  - destination address – final destination
    - needed so network can choose route
  - source address – where packet originated
    - for replies, also used in some routing algorithms
  - packet type – depends on protocol
  - byte count – depends on protocol
  - packet sequence number – if used
    - network may deliver packets in correct sequence
  - virtual circuit number – if used
  - routing information – for some routing methods
- Followed by data - payload

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Example: Internet Protocol (IPv4)

- Designed for interconnected networks
  - different capabilities at link layer
- Packet called datagram
  - header min. 20 bytes, optional extensions
    - usually viewed as sequence of 32-bit words
  - max. payload 64 kByte (usually much less)
  - allows *fragmentation* at intermediate node
    - if next network has smaller size limit
- IPv4 address 32 bits
- No guarantees, no virtual circuits
  - datagrams can arrive in any sequence
  - or not at all – left to transport layer to sort out

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IPv4 Header

bits sent left to right, or MSB first

Version	IHL	Type of Service	Total Length (incl. header) in bytes	
Identification (of fragment)			DF MF	Fragment Offset
Time to Live		Protocol	Header Checksum	
Source Address				
Destination Address				
options extend header - more 32-bit words				

– version is 4, IHL = header length, in words
– type of service was for priority & preferences
  • now re-defined for *differentiated services* – same ideas
– all fragments of one packet have same identification
  • offset = where in packet this fragment fits (8-byte multiple)
  • DF = don't fragment, MF = more fragments (0 in last)
– time to live is used as hop counter, decrementing to 0
– protocol identifies transport layer protocol in payload

Addressing

- Q: How to arrange unique addresses?
  – across the world, in networks owned and managed by different organisations
- A: Use a hierarchy
  – assign a range of addresses to an organisation
  – the organisation assigns address to its devices
- Example: telephone network
  – country codes identify which country
    • agreed internationally
  – rest of number can be assigned locally
    • maybe by one regulator, for entire country
    • or subdivided by region, or by telephone company

+353-1-716-1926 +1-858-534-8909

Internet Addressing

- Also hierarchical, but fixed length
  – first part identifies network (organisation?)
  – second part identifies computer on that network
- Originally divided on byte boundaries
  – class A address for large network – 2^{24} devices
  – class B for medium network – 2^{16} devices
  – class C for small network – 2^{8} devices

A	0	network ID	device identification
B	1 0	network identification	device identification
C	1 1 0	network identification	device ID

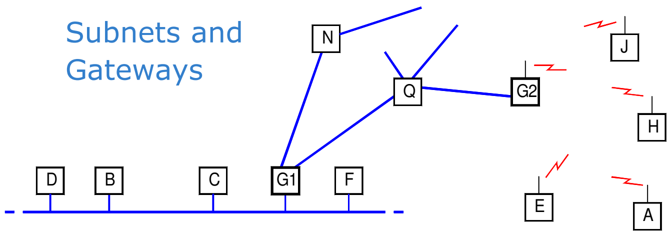
Internet Addressing

Example: ipconfig output

```
Ethernet adapter Local Area Connection:
   Connection-specific DNS Suffix  . : ucd.ie
   IPv4 Address. . . . . . . . . . . : 137.43.148.72
   Subnet Mask . . . . . . . . . . . : 255.255.252.0
   Default Gateway . . . . . . . . . : 137.43.148.1
```

- Now allow boundary anywhere
  – use /N to specify how many bits for network
    • e.g. /24 corresponds to Class C
  – or use *network mask* – 1 bits in network part
    • e.g. 255.255.255.0 corresponds to class C
  – large networks divide into sub-networks…
- Special addresses
  – all 1s at end ⇒ broadcast in that subnet
  – private address ranges – will not be routed
    • e.g. 192.168 range, can be used freely

Subnets and Gateways



- Subnet is usually LAN: Ethernet, WiFi, etc.
  - devices on same subnet communicate directly
    - no intermediate nodes, no routing decisions
- Gateway connects to wider network
  - use to communicate with device outside subnet
  - send packets to gateway – usually router
  - gateway does the routing on wider network…
    - wider network typically uses point-to-point links

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Subnet Mask?

SRC	137.43.148.72	10001001 00101011 10010100 01001000
MASK	255.255.252.0	11111111 11111111 11111100 00000000
ANDed	137.43.148.0	10001001 00101011 10010100 00000000
DEST	137.43.150.159	10001001 00101011 10010110 10011111
MASK	255.255.252.0	11111111 11111111 11111100 00000000
ANDed	137.43.148.0	10001001 00101011 10010100 00000000

- Decide if destination is on same subnet
  - bit-wise AND of my address and subnet mask
    - mask hides or *masks* local part of address…
  - bit-wise AND of destination address and mask
  - if results same, then send directly
    - e.g. find Ethernet address of destination using ARP
    - send Ethernet frame to that address, carrying packet
  - if different, send to gateway…

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Configuring Computers

- Need to know
  - IP address
  - sub-net mask
    - so know which devices are on same network
  - gateway IP address
    - so know where to send packets for other devices
- Can configure manually…
- Usually automatic – DHCP
  - dynamic host configuration protocol
  - broadcast request (e.g. at boot-up)
    - does anyone know who I am?
  - DHCP server (on same subnet) replies
    - giving 3 pieces of information required

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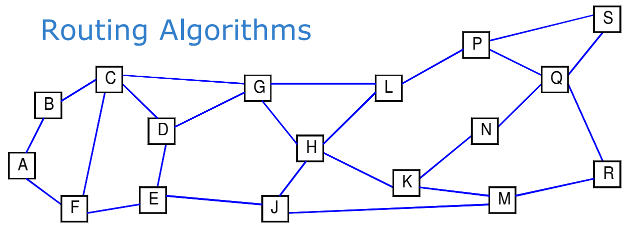
Routing Algorithms



- Find a route through the network
  - from source to destination
- Circuit switched (or virtual circuit internally)
  - route connection request only (rest follow)
- Message switched or simple packet switched
  - route every message or packet
  - algorithm must be efficient!

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Good Routing Algorithm?

- What is the best route?
  - shortest distance? lowest number of hops?
  - highest throughput? shortest delay?
- Who decides?
  - every node along the route, independently?
  - central node, with full picture of network
    - but does not scale to very large network
  - originating node – called source routing
    - source node plans entire route through network
- What information available?
  - none? whatever each node can measure?
  - info from neighbours? full map of network?

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Routing Algorithms

Destination	Next Node	Alternative
A	F	D
C	D	F
P	D	J
- - -	- - -	- - -

- Fixed routing – based on topology only
  - no measurements of traffic or delay
  - routing table at each node
    - specify link to use for any destination
    - only changes if nodes or links change
    - alternatives used in case of problem – link broken
  - need care to avoid loops
    - especially on alternative links…
  - who designs the routing tables?
    - humans? difficult for large network…
    - want some way for node to learn the network

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Routing – No Knowledge

- Flooding – copy packet, send on all links
  - usually exclude link on which it arrived
  - first packet to arrive at destination is used…
  - usually add hop counter
    - decrement at each node, discard at zero
  - will always find quickest route (if exists)
  - needs no prior knowledge of network
  - but very heavy load on network!
- Random routing
  - send packet on random link
    - usually exclude link on which it arrived
  - will eventually find destination
    - but very inefficient, very long delays…

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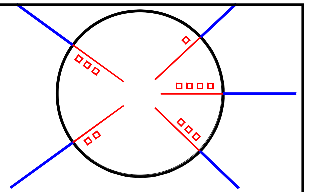
Routing – Local Knowledge



- Isolated routing
  - only information is what node can measure
    - e.g. link throughput, link queue length
  - e.g. send packet on link with shortest queue
    - "hot potato" algorithm – get rid of it as fast as possible
    - only slightly better than random routing
- Backward Learning
  - add hop counter in packet header
  - start as isolated routing
  - monitor incoming packets: source and hops
  - learn "distance" to other nodes in network
  - use this to make better routing decisions…

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Routing – Co-operative

- Nodes send information to neighbours
  - periodically, in special routing message
  - information measured itself
    - capacity of connected links, or delay, or queue length
  - can pass on info received from other neighbours
    - capacity, delay, queue length on neighbours' links
    - or derive number of hops to known destinations
- How often to update all this?
  - faster allows routing to adapt to traffic
  - slower requires less network traffic, less work
- Could centralise – send all info to central node
  - central node consulted on every routing decision?
  - central node issues routing tables?

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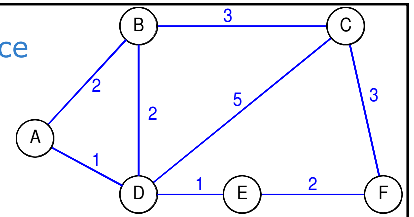
Example: Distance Vector Routing



- "Distance" relates to "cost" of using a route
  - must be sum of "distances" on links of route
  - could be geographical distance
  - more often related to delay, queue length…
  - or could be just number of hops
- Each node must know distance to neighbours
  - or be able to measure it – look at queues?
    - or send special packet, note time to get reply
    - if hops, distance to every neighbour is 1

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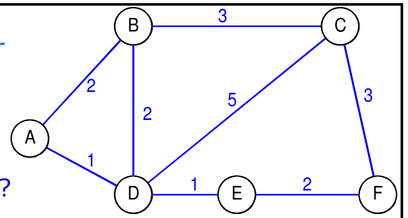
Distance Vector Routing



- Distance vector?
  - for one node
  - list of known nodes, with lowest distance to each
- Example: initial distance vector at A
  - B:2, D:1 just what it knows itself
- Nodes send distance vectors to neighbours
  - receive distance vectors from neighbours
  - update routing table with new information
- Example: A receives distance vector from D
  - A:1, B:2, C:5, E:1 (initially)

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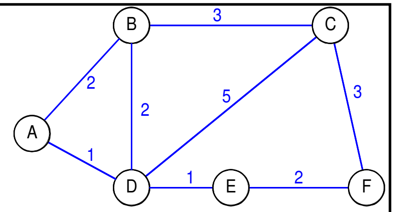
Distance Table

Destination	Via B	Via D
B	2	3
C	5	6
D	4	1
E	∞	2



- Each node maintains table of distances
  - to each other node (that it knows about)
  - via each neighbour (or link)
  - updates as new distance vectors arrive
  - best distances used to create distance vector
- Example: table at A, early in process
  - received from B: A:2, C:3, D:2
  - received from D: A:1, B:2, C:5, E:1

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Table Updates

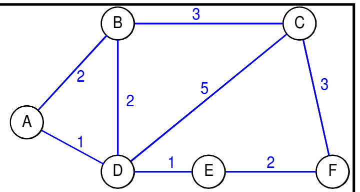


Table at A		
Destination	Via B	Via D
B	2	3
C	5	6
D	4	1
E	5	2
F	7	4

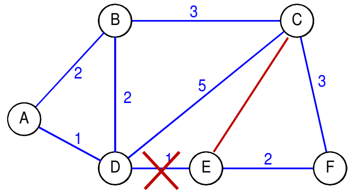
Tables shown after some time, nothing changing…

Table at D				
Dest.	Via A	Via B	Via C	Via E
A	1	4	10	3
B	3	2	8	4
C	6	5	5	6
E	3	5	10	1
F	5	7	8	3

- Nodes gradually hear about other nodes
  - update their own tables
  - send new distance vectors if values change

Network Changes

Table at D				
Dest.	Via A	Via B	Via C	Via E
A	1	4	10	3
B	3	2	8	4
C	6	5	5	6
E	3	5	10	1
F	5	7	8	3



- New link – example C to E, distance 1
  - nodes connected announce new distances
  - other nodes update tables, send new vectors
  - news travels quickly around network
- Link failure – example D to E fails
  - how does D route traffic for E ?
  - what does D announce in distance vector ?

Link Failure

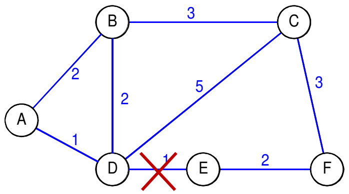
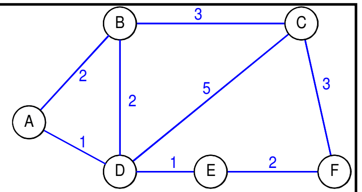


Table at D			
Dest.	Via A	Via B	Via C
A	1	4	10
B	3	2	8
C	6	5	5
E	3	5	10
F	5	7	8

- New distance vector from D:
  - A:1, B:2, C:5, E:3, F:5 - last 2 are problem!
  - but A updates in response: E:4, F:6
  - D responds: E:5, F:7 - etc., etc.
- Very slow reaction to removal of link
  - when does sensible routing resume ?
  - what is the basic problem here ?

Improvements

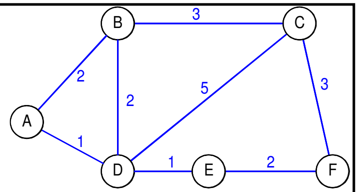


- Basic problem:
  - relying on decisions made by neighbours
  - only told result of decision – best distance
  - not told detail of route – could be back to you!
- Improvement – "poisoned reverse"
  - A recognises that route to E is via D
  - in distance vector sent to D, give dist. to E as ∞
    - or give distance on best route via another link…
  - solves simple problems, but not larger loops…
- Used in Internet at first
  - replaced by Link State Routing

Link State Routing

Sender B	
Seq. No.	
Age	
A	2
C	3
D	2

Sender A	
Seq. No.	
Age	
B	2
D	1



- Nodes measure "cost" on links to neighbours
  - just as in distance vector routing
  - but send this to all nodes – flooding
    - special routing packet, as in example
    - sequence number allows duplicates to be discarded
    - hop counter (age) ensures packets killed eventually
- Each node gets full topology of network
  - can make its own routing decisions
    - not relying on decisions made by other nodes

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IP version 6

- Aimed to provide
  - more addresses – now 128-bit, so 3.4×10^{38}
    - as more devices connected to Internet
  - faster operation, less load on routers
    - to get benefit of faster links
    - e.g. no header checksum – saves time
    - e.g. no fragmentation of datagram en route
  - better options for quality of service
    - differentiated services, had been added to IPv4
    - flow labels allow something like virtual circuit…
  - better security facilities
- Header 40 bytes, with optional extensions
  - extension headers provide extra features
    - not always wanted…

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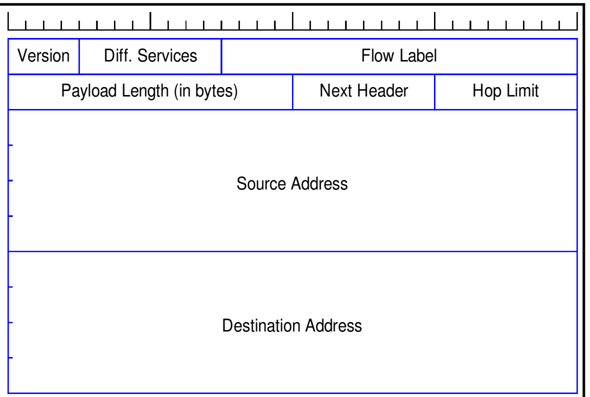
Basic IPv6 Header



- Fixed header length
  - next header specifies type of extension header
    - each extension header also has next header field…
  - if last header, specifies higher-level protocol

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IPv6 Adoption

- Slow!
- Standard published 1998
  - IPv6 traffic to Google services only 6% March 2015
  - other techniques being used to make more efficient use of IPv4 addresses…
- IPv6 traffic?
  - can be carried through IPv4 networks
  - using technique called *tunnelling*
    - IPv6 packet is carried as payload of IPv4 packet
    - using IPv4 like link layer…

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