Network Routing and Network Protocols

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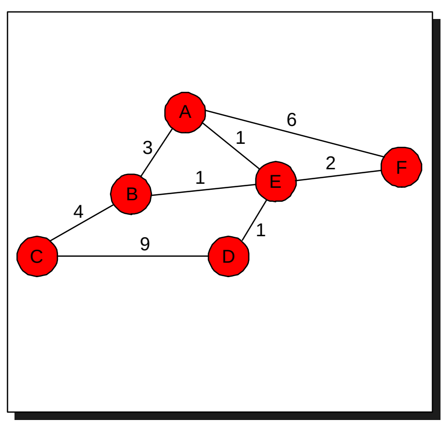
Routing

- Routing algorithms view the network as a graph
- Problem: find lowest cost path between two nodes
- Factors:
  - Static topology
  - Dynamic load
  - Policy
- Two main approaches:
  - Link state protocol
    - Each node builds a local copy of the entire network
  - Distance-vector protocol



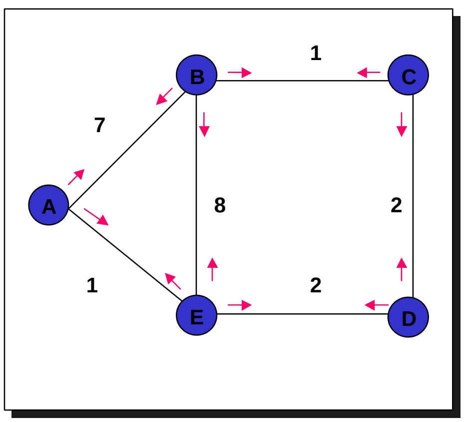
Distributed Bellman-Ford

- Start Conditions:
  - Each router starts with a vector of distances to all directly attached networks

- Send step:
  - Each router advertises its current vector to all neighboring routers

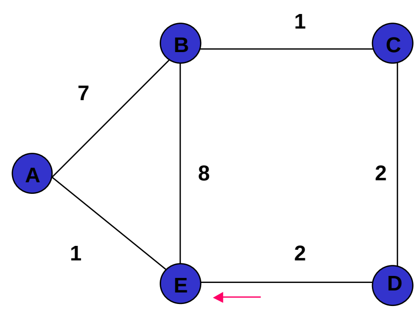
- Receive step:
  - For every network X, router finds shortest distance to X
    - Considers current distance to X
    - Then takes into account distance to X from its neighbors
  - Router updates its cost to X
  - After doing this for all X, router goes to send step

Example - Initial Distances



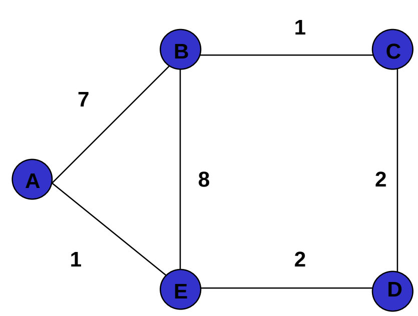
Info at Node	Distance to Node A	B	C	D	E
A	0	7	~	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	~	2	0

E receives D’s routes; Updates Costs



Info at Node	Distance to Node A	B	C	D	E
A	0	7	~	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	4	2	0

Final Distances

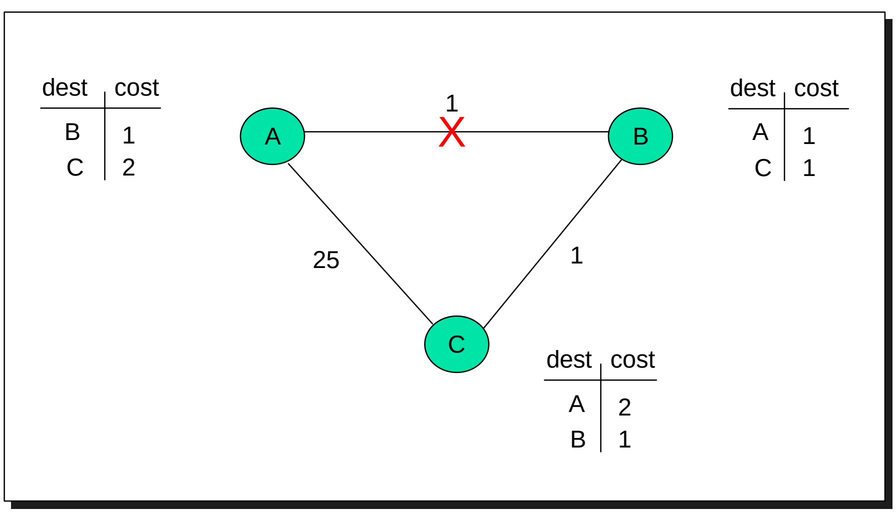


Info at Node	Distance to Node A	B	C	D	E
A	0	6	5	3	1
B	6	0	1	3	5
C	5	1	0	2	4
D	3	3	2	0	2
E	1	5	4	2	0

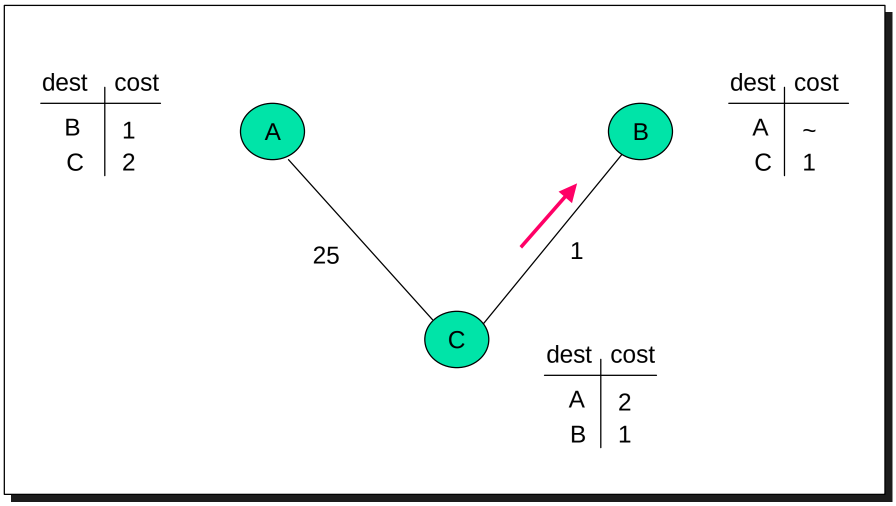
Complexity

- How many steps does it take to converge?
- What is the message complexity of the algorithm?
- How does this compare to link state routing protocol?

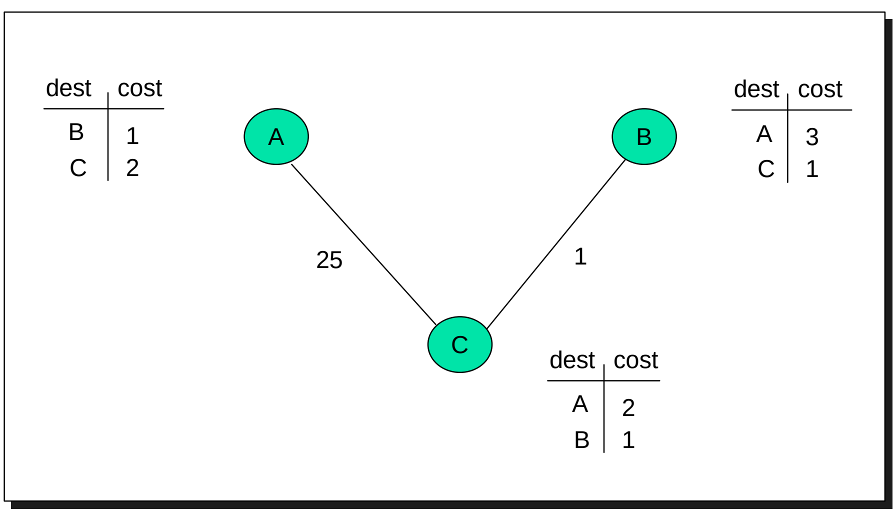
The Bouncing Effect



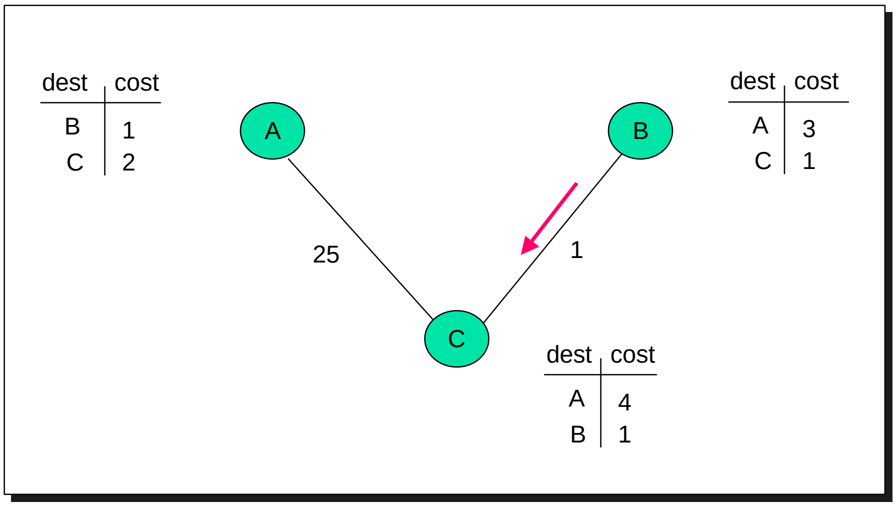
C Sends Routes to B



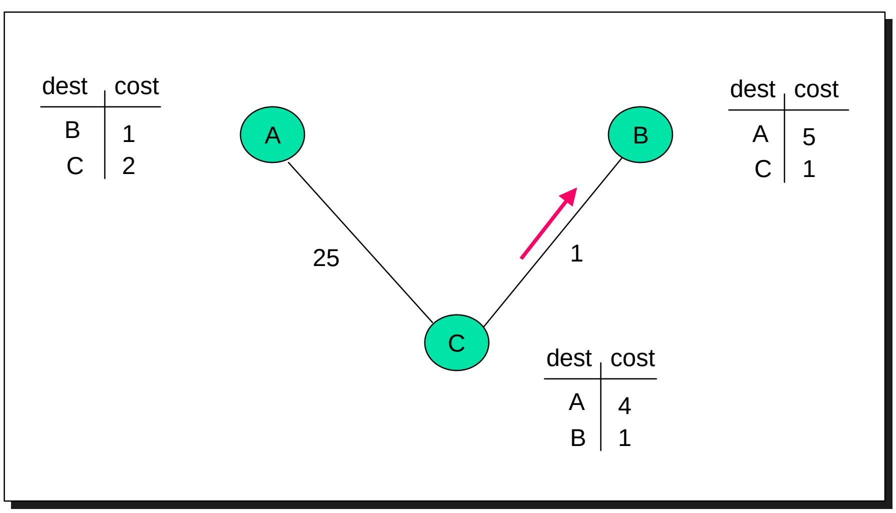
B Updates Distance to A



B Sends Routes to C



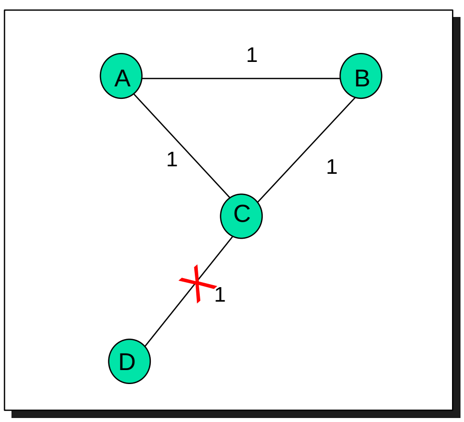
C Sends Routes to B



Solutions

- Problems arise:
  - When metric increases
  - Implicit path has loops
- "Solutions":
  - If metric increases, delay propagating information
    - Adversely affects convergence
  - Split horizon: C does not advertise route to B
  - Poisoned reverse: C advertises route to B with infinite distance
- Works for two node loops
  - Does not work for loops with more nodes

Example Where Split Horizon Fails



- When link breaks, C marks D as unreachable and reports that to A and B
- Suppose A learns it first
  - A now thinks best path to D is through B
  - A reports D unreachable to B and a route of cost=3 to C
- C thinks D is reachable through A at cost 4 and reports that to B
- B reports a cost 5 to A who reports new cost to C
- etc…

Solution: Enhanced Distance Vector

- Each routing update carries the entire path
- Loops are detected as follows:
  - When node gets route check if node is already in path
    - If yes, reject route
    - If no, add self and (possibly) advertise route further
- Advantage:
  - Metrics are local - node chooses path, protocol ensures no loops

Border Gateway Protocol (BGP)

- Designed for scalability
- Granularity is at the level of “autonomous systems” (ASs)
- Usual BGP table has a few thousand entries
- Each entries contains the entire AS-path for getting to a destination
- Uses simple hop-count metric – does not propagate information about bandwidth or congestion in the system
- Some problems:
  - ASes do not necessarily convey packets through shortest paths
    - Some adopt “early exit” strategy – get rid of packet as soon as possible
    - Some send packets only through other ASes with which they have contractual agreements

Networking Software Goals

- Simple
- Scalability
  - Predict what will happen in the future: everything will have a network address
- Heterogeneity (not a goal – but have to support it)
- Robustness: failure, structural changes
  - Something is changing; not a clean reboot
- Performance:
  - Latency: minimum cost (or amount of work to get nothing done!)
    - Measured in time
  - Bandwidth: incremental cost; measured in bytes/second
  - Latency more important than bandwidth
    - Most common mistake in systems is to ignore latency

Issues (Problems to solve)

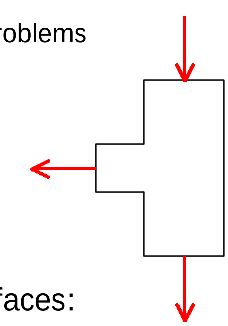
- Link transmission: how do you get a packet of data from one machine to another machine "connected" to it
- Routing
- Naming: mapping names to network addresses
- Multiplexing (how do you share resources, protocols)
- Reliable delivery (cannot guarantee that every packet will be delivered) [ack, timeout, retransmit]
  - Duplicate packets
- Sequencing (process packets in the same order as it was sent; one approach is to have only packet outstanding)

Issues (contd.)

- Fragmentation & reassembly
- Flow control
  - Sender generating data faster than the receiver can handle
  - Feedback required from receiver to sender
- Congestion control
  - Related to flow control; similar in many ways
  - There is more than the sender & receiver
  - Problem gets rediscovered every once in a while!
- Presentation
  - Endian-ness, floating point format
- Security (authentication)

Solution: Layered Protocols

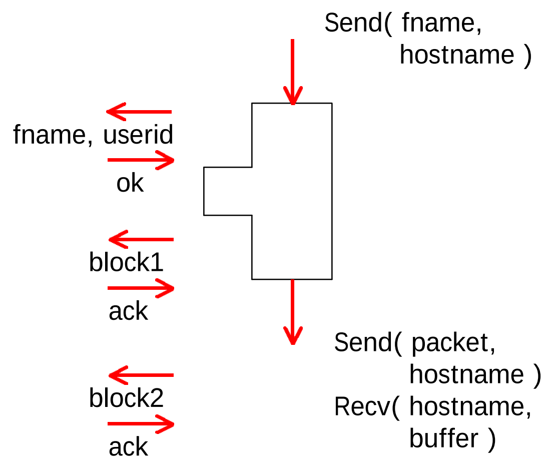
- Collection of protocols
  - Stacked together
  - Each solves one of the problems



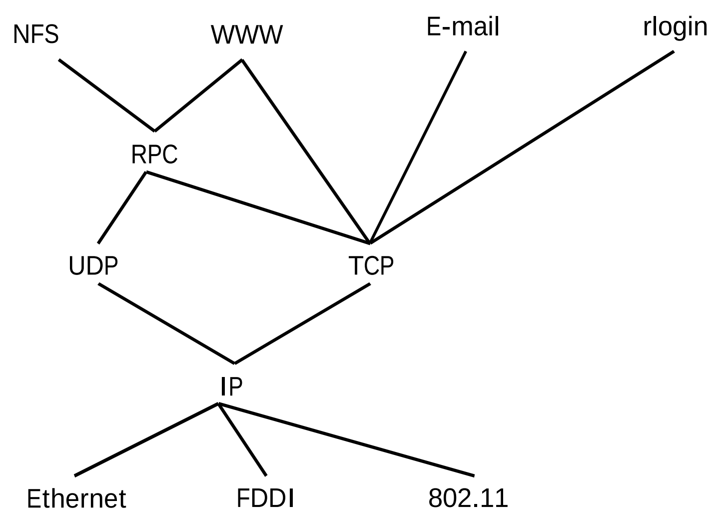
- Protocol has three interfaces:
  - Provides service to higher levels of the protocol stack
  - Depends on some lower transport protocol
  - Has a peer-to-peer interface

Simple File Transfer

- Copy file to remote machine



Protocol Stack



Internet Protocol (IP)

- Datagram protocol (as opposed to stream protocol)
  - No sequencing
  - Stateless
  - Unreliable
  - Host-to-host (not program-to-program)

- IP Functions:
  - Addressing and routing (not naming)
    - Does not know about names
    - Understands addresses
    - Uses route information computed by some other entity
  - Fragmentation (controversial functionality)
    - Other option: let network layer take care of fragmentation

Fragmentation

- If a network has a small packet size, two approaches:
  - Transparent approach at the network level
  - IP fragments:
    - Packet stays fragmented till it reaches destination
    - Reassembled at destination
    - Makes it not stateless!
    - Destination needs to wait for all the fragments to dribble in
      - Keeps track of a partial datagram, and a map of useful parts
      - Packet needs to have a:

    host-id (32 bits), datagram id (16 bits), position (16 bits), length

- IP approach vs. network layer fragmentation/reassembly
  - Question: which is better?

“Time-to-live”

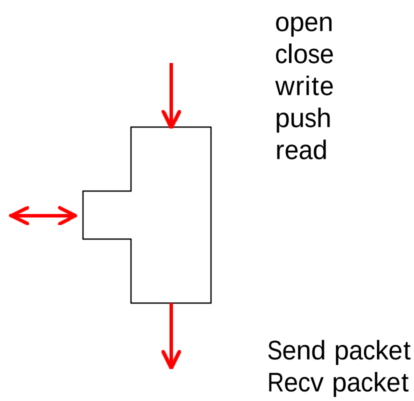
- Field on an IP packet header:
  - 8 bit header (255 secs or ticks)
  - Every router/gateway forwards a packet, it subtracts at least 1 tick
  - When it gets to zero, packet is trashed
  - Prevents packets from roaming around for ever
  - Question: what are the implications of time-to-live?

Features and Limitations

- IP packet headers are variable length:
  - Route that a packet takes can be recorded
  - Source routing: specify the route from the source
- What are the IP limits?
  - 32 bits of address
  - Reliability: requires to get to destination in one shot
  - Speed limitations?

Transmission Control Protocol

- Connection oriented
- End-to-end reliable
- Flow controlled
- Congestion controlled



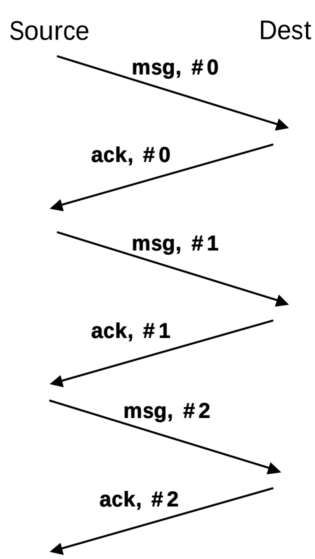
Overall Features

- Reliable
  - Sequence numbers (per byte basis)
  - Acknowledgements
  - Timeout/retransmit
- Flow control
  - “sliding window protocol”
  - Purpose: pipeline communication through overlap
- Multiplexing
  - Several connections to be open (sockets: host, port number)
- Connection-based: state kept at both ends
- Out of band data: “urgent”

Reliable Message Delivery

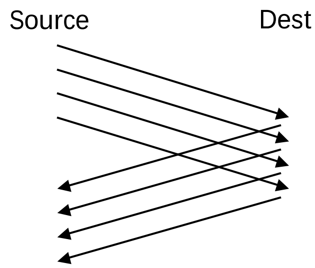
- All of these networks can garble, drop messages
  - Physical media can garble packets or have interference
  - Congestion: too many packets at an intermediate node
  - Destination cannot receive packets as fast as the sender
- What can we do?
  - Detect garbling using checksums
  - Receiver ack's if received properly and timeout at sender
    - If ack gets dropped, sender retransmits
    - Put sequence number in message to identify retransmissions
      - Requires sender to keep copy of all packets sent
      - Receiver must keep track of message ids that could be a duplicate (When can receiver know it's ok to forget?)
  - Destination controls window to indicate its willingness to receive messages
- Solutions:
  - Alternating bit protocol
  - Window based protocol (TCP)

Alternating Bit Protocol



- Send one message at a time
- Don't send next message until ack received
- Receiver keeps track of sequence # of last message received
- Simple
- Small overhead
- Poor performance:
  Bandwidth =
  packet_size/RTT

Window Based Protocol



Peak Bandwidth:
Packets_in_window * packet_size/ RTT
or
packet_size/message_init_overhead

- Send up to N messages at a time without waiting for acks
- "Window" also reflects storage at receiver – sender shouldn't overrun receiver's buffer space
- Each message has sequence number. Receiver can discard state of messages outside the window
- If messages are received out of order:
  - Keep copy until sender fills in the missing pieces

Flow Control Details

Sender messages

sent, acked	sent, not acked	not sent	not sent
		"in window"	not "in window"

Receiver messages

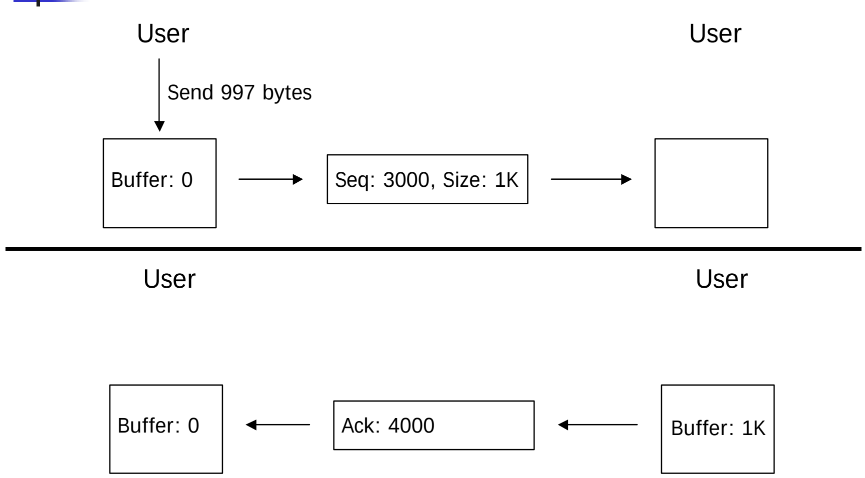
received	received, acked	maybe received	not yet received
given to app	buffered	not acked	

- Receiver acks: "got all messages up to #"
- Duplicate acks implies holes in received message sequence
  - Sender can perform "fast retransmit"

TCP Flow Control

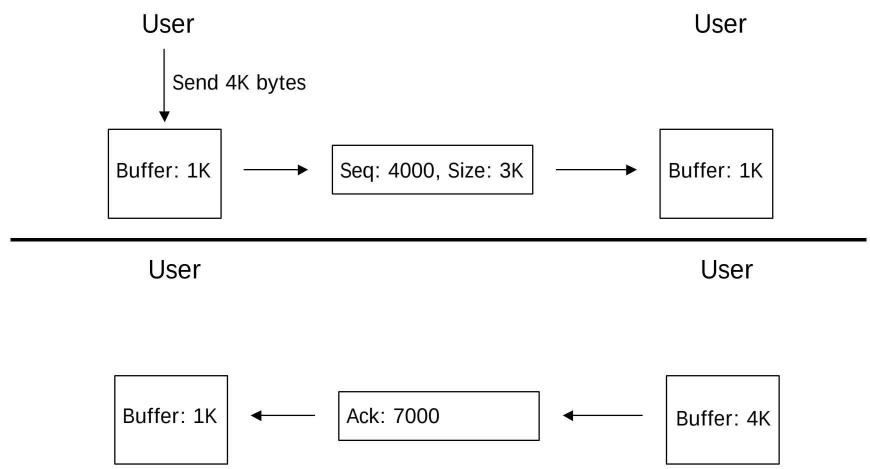
- Assume:
  - Receiver window size = 8K
  - TCP minimum threshold for sending = 1K
  - Initial sequence number = 3000

TCP Flow Control 2



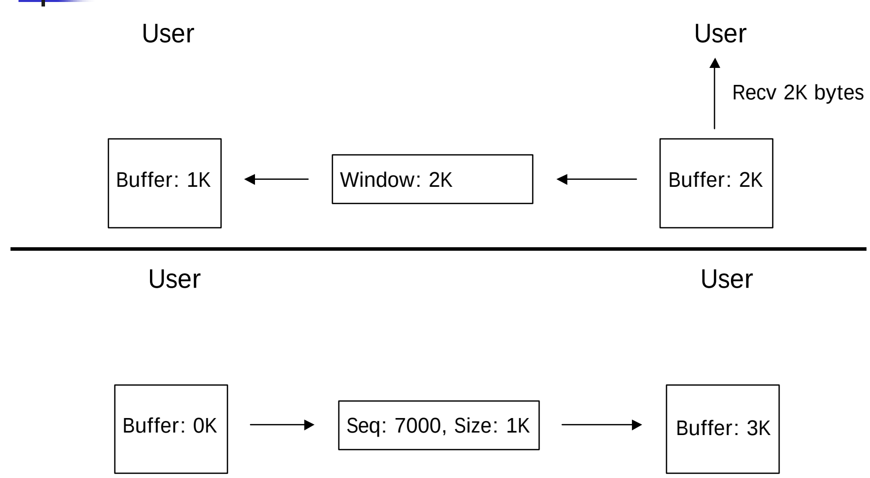
- Acknowledge message: “expecting byte # x”

TCP Flow Control 3



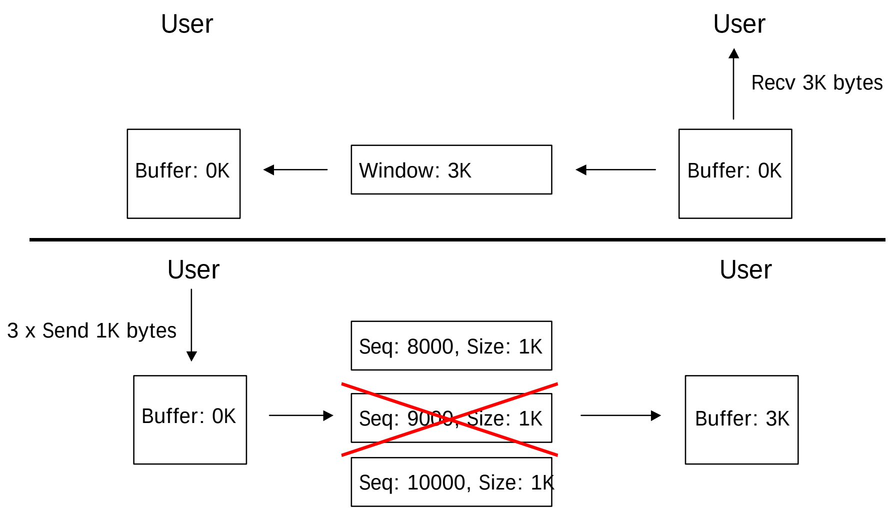
- Send only up to the receiver window

TCP Flow Control 4

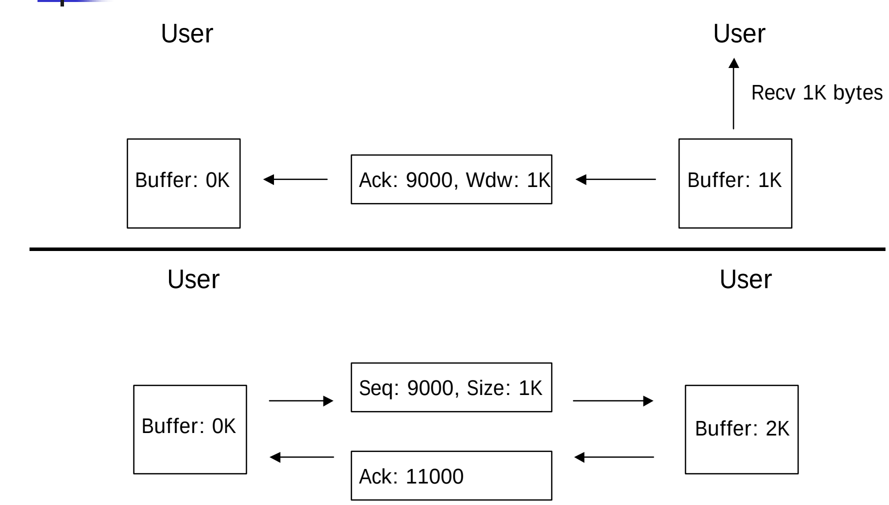


- Receiver sends a window update when user picks up data

TCP Flow Control 5

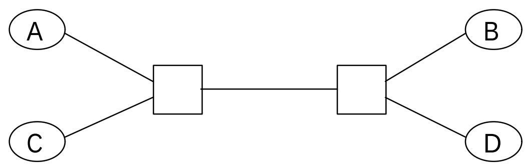


TCP Flow Control 6



Congestion Control

- Window size controls flow and congestion
  - Receiver advertised window is maximum amount of data that can be outstanding
  - Have a smaller window if there is congestion in the system
- Canonical congestion problem:
  - Flow between A-B uses up link capacity
  - Flow between C-D starts, resulting in congestion on the link

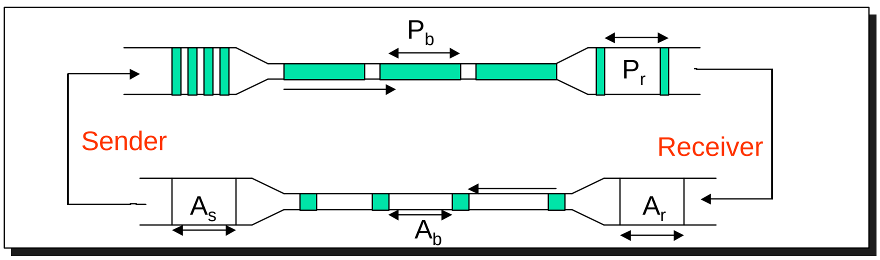


Issues

- Flows need to find a fair use of link resources
  - When a flow starts, it needs to find what is available reasonably fast and under different network capacities
- Flows need to distinguish packet losses from packet delays
  - Spurious detection of packet loss results in more traffic, more congestion, more delays, and so on
- Flows need to adapt to changing network conditions
  - Sometimes increase its utilization, sometimes lower its utilization

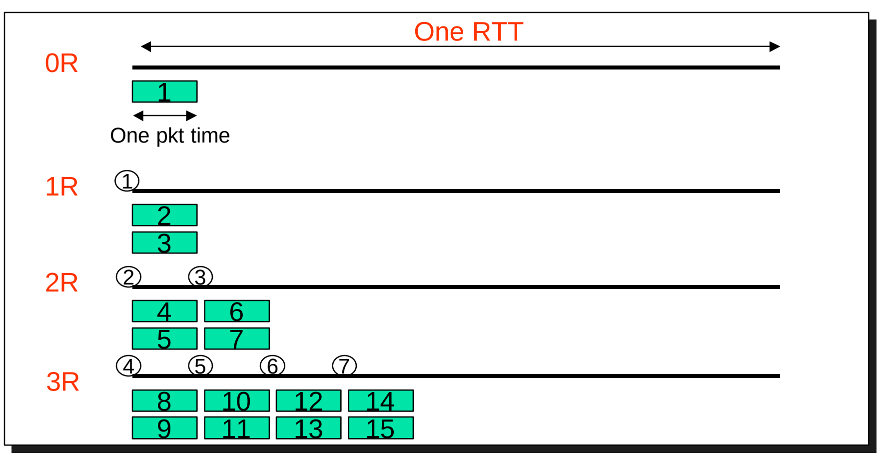
Finding Equilibrium from Startup

- Two features:
  - Self-clocking mechanism
  - “Slow start” mechanism – actually ramps up rather fast!
- Self-clocking:
  - Send a new packet only when a previous packet is acknowledged
  - Soon packets are sent at the rate they are received



Slow Start Mechanism

- Initially set cwnd to be 1
  - Maintain the invariant that cwnd < window given by receiver
  - Increment cwnd by 1 for every acknowledgement



Accurate Round Trip Time Estimates

- How long should timeout be?
  - Too long? Wastes time
  - Too short? Retransmits even though message is not lost
  - Maintain running estimate of "R"

    $R = (1-\alpha)*R + \alpha * M$

    where M is new measurement, α is decay constant
  - High α makes it unstable
  - Low α makes the system have too much history

- Also measure the error or variance in measurements
- Set timeout to be R + 4*variance

Congestion Avoidance Algorithm

- React to changing network conditions by modifying cwnd
- At loss: (multiplicative decrease)

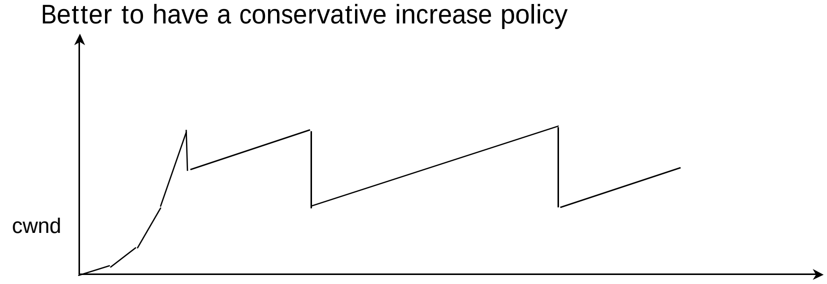
  cwnd = cwnd / 2

  Better to have a drastic decrease when losses occur
- After loss: (additive increase)

  cwnd += 1/cwnd

  Results in slow increase; probes for available bandwidth

  Better to have a conservative increase policy



Announcements

- Assignment 4 has been posted
- Wednesday reading: “Authentication in distributed systems”
- Friday reading: “Andrew File System”
  - Background reading: “Implementing Remote Procedure Calls” and “Sun’s Network File Systems”

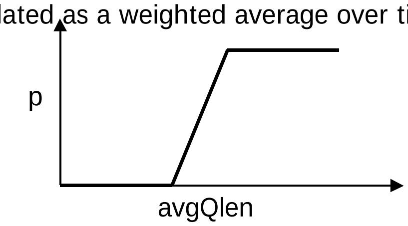
Congestion Control at Routers

- Router queues can fill up
- When they fill up?
  - What to drop?
  - When to drop?
- Random Early Detection (RED) algorithm: use randomization
- Router can be in one of three states:
  - Few packets in the queues: do not drop any packets (normal operating phase)
  - Lots of packets in the queues: drop for sure (congestion phase)
  - Intermediate number of packets: calculate probability for dropping based on queue length and number of packets since last drop (congestion avoidance phase)

RED Drop Probability

- Voodoo constants: minqThresh, maxqThresh, maxp
- Step 1:

  p = maxp * (avgQlen – minqThresh)/(maxqThresh – minqThresh)
  p <= maxp
  avgQlen is calculated as a weighted average over time

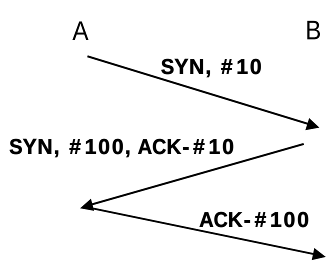


- Step 2:

  Drop probability = p / (1 – count*p)
  count is number of packets since last drop
  Try to avoid cascading drops

Connections

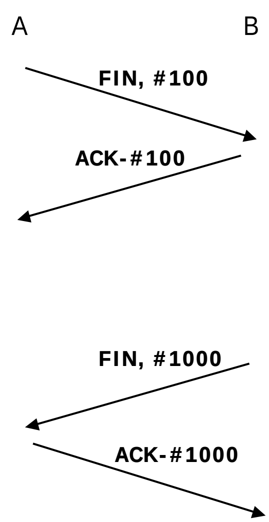
- Requires three-way handshakes
- Setup:
  - Open request packet (SYN, initial sequence number)
  - Acknowledgement (SYN, own sequence number, ack number)
  - Acknowledgement of the acknowledgement
- SYN occupies 1 byte of sequence space



Failure Scenarios

- Cannot reuse sequence number if there are some old live data
  - Keep track of previous recent connections
- What if machines go up and down?
  - Wait for a while when machine reboots
  - Let old packets die
- What if connection packets get lost?
  - Timeout and retransmit
  - But initially very conservative estimate of RTT

Connection Tear Down



- Keep connection state around for some more time
  - FIN occupies 1 byte in sequence space
  - Connection state is last byte received in sequence
- Typically kept for 2*RTT duration
- No clean solution as to when state can be forgotten
- A distributed consensus problem

General's Problem

- Two generals on separate mountains
- Can communicate only via messengers
  - Messengers can be captured
- Need to coordinate an attack
  - If they attack at the same time, they win
  - Else they will all die
- Devise a protocol to coordinate the two generals