Last Time

• We finished up the Network layer
  – Internetworks (IP)
  – Routing (DV/RIP, LS/OSPF)
  – Scalable addressing/routing (BGP, CIDR)

• It was all about routing: how to provide end-to-end delivery of packets.
This Time

- We begin on the Transport layer

- Focus
  - How do we send information reliably?

- Topics
  - The Transport layer
  - Acknowledgements and retransmissions (ARQ)
  - Sliding windows

The Transport Layer

- Builds on the services of the Network layer

- Communication between processes running on hosts
  - Naming/Addressing

- Stronger guarantees of message delivery
  - Reliability
### Example – Common Properties

<table>
<thead>
<tr>
<th>TCP</th>
<th>IP</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Guaranteed delivery</td>
<td>• Lost packets</td>
</tr>
<tr>
<td>• In-order delivery</td>
<td>• Reordered packets</td>
</tr>
<tr>
<td>• Single delivery</td>
<td>• Duplicate packets</td>
</tr>
<tr>
<td>• Arbitrarily long messages</td>
<td>• Limited size packets</td>
</tr>
<tr>
<td>• Synchronization</td>
<td></td>
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<tr>
<td>• Flow control</td>
<td></td>
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<tr>
<td>• Multiple processes</td>
<td></td>
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</tbody>
</table>

### Internet Transport Protocols

- **UDP**
  - Datagram abstraction between processes
  - With error detection

- **TCP**
  - Bytestream abstraction between processes
  - With reliability
  - Plus congestion control (later!)
Automatic Repeat Request (ARQ)

- Packets can be corrupted or lost. How do we add reliability?
- Acknowledgments (ACKs) and retransmissions after a timeout
- ARQ is generic name for protocols based on this strategy

The Need for Sequence Numbers

- In the case of ACK loss (or poor choice of timeout) the receiver can’t distinguish this message from the next
  - Need to understand how many packets can be outstanding and number the packets; here, a single bit will do
Stop-and-Wait

- Only one outstanding packet at a time
- Also called alternating bit protocol

Limitation of Stop-and-Wait

- Lousy performance if wire time $\ll$ prop. delay
  - How bad? You do the math
- Want to utilize all available bandwidth
  - Need to keep more data “in flight”
  - How much? Remember the bandwidth-delay product?
- Leads to Sliding Window Protocol
Sliding Window – Sender

- Window bounds outstanding data
  - Implies need for buffering at sender
- “Last” ACK applies to in-order data
- Sender maintains timers too
  - Go-Back-N: one timer, send all unacknowledged on timeout
  - Selective Repeat: timer per packet, resend as needed

Sliding Window – Timeline
Sliding Window – Receiver

- Receiver buffers too:
  - data may arrive out-of-order
  - or faster than can be consumed (flow control)
- Receiver ACK choices:
  - Individual, Cumulative (TCP), Selective (newer TCP), Negative

Sliding Window Functions

- Sliding window is a mechanism
- It supports multiple functions:
  - Reliable delivery
  - In-order delivery
  - Flow control
Flow Control

- Sender must transmit data no faster than it can be consumed by the receiver
  - Receiver might be a slow machine
  - App might consume data slowly

- Implement by adjusting the size of the sliding window used at the sender based on receiver feedback about available buffer space
  - This is the purpose of the Advertised Window field

Sender and Receiver Buffering

- Sending application
  - LastByteWritten
  - TCP
  - LastByteAcked
  - LastByteSent

- Receiving application
  - LastByteRead
  - TCP
  - NextByteExpected
  - LastByteRcvd

- Available buffer: yellow
- Buffer in use: orange
Example – Exchange of Packets

SEQ=1
ACK=2; WIN=3
SEQ=2
ACK=3; WIN=2
SEQ=3
SEQ=4
ACK=4; WIN=1
ACK=5; WIN=0

Receiver has buffer of size 4 and application doesn’t read

Example – Buffer at Sender

T=1
1 2 3 4 5 6 7 8 9

T=2
1 2 3 4 5 6 7 8 9

T=3
1 2 3 4 5 6 7 8 9

T=4
1 2 3 4 5 6 7 8 9

T=5
1 2 3 4 5 6 7 8 9

T=6
1 2 3 4 5 6 7 8 9

=acked
=sent
=advertised
Key Concepts

- Transport layer allows processes to communicate with stronger guarantees, e.g., reliability
- Basic reliability is provided by ARQ mechanisms
  - Stop-and-Wait through Sliding Window plus retransmissions