Homework #4 Grading

• Default mode: final grading will use 3 homeworks
  – Homework contribution = (hw1+hw2+hw3) / 3

• Extra-credit option A: use hw4 in place of any previous homework
  – Swapping out hw1, we get (hw4+hw2+hw3) / 3

• Extra-credit option B: add 20% of hw4 to other homeworks
  – (hw1 + hw2 + hw3 + 0.2*hw4) / 3

• Example: hw1 = 21, hw2 = 80, hw3 = 70, hw4 = 60
  – Default = 57, option A = 70, option B = 61

• Example: hw1 = 90, hw2 = 102, hw3 = 90, hw4 = 90
  – Default = option A = 94, option B = 100

Curve: 80 A, 70 B, etc.
All datagrams *leaving* local network have the same single source NAT IP address: 138.76.29.7, different source port numbers.

Datagrams with source or destination in this network have 10.0.0/24 address for source, destination (as usual).
NAT: Network Address Translation

• Local network uses just one IP address as far as the outside world is concerned
  - No need to be allocated a range of addresses from ISP – just one IP address is used for all devices
  - Can change addresses of devices in local network without notifying outside world
  - Can change ISP without changing addresses of devices in local network
  - Devices inside local net not explicitly addressable or visible to outside world (a security plus)

• To see your NAT IP and current NAT port, visit http://ipchicken.com/
NAT: Network Address Translation

1: Host 10.0.0.1 sends datagram to 128.194.135.72, 80

2: NAT router changes datagram source addr from 10.0.0.1, 3345 to 138.76.29.7, 5001, updates table

3: Reply arrives dest. address: 138.76.29.7, 5001

4: NAT router changes datagram dest addr from 138.76.29.7, 5001 to 10.0.0.1, 3345

NAT translation table

<table>
<thead>
<tr>
<th>WAN side addr</th>
<th>LAN side addr</th>
</tr>
</thead>
<tbody>
<tr>
<td>138.76.29.7, 5001</td>
<td>10.0.0.1, 3345</td>
</tr>
<tr>
<td>……</td>
<td>……</td>
</tr>
</tbody>
</table>

1: host 10.0.0.1 sends datagram to 128.194.135.72, 80

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3: Reply arrives dest. address: 138.76.29.7, 5001

4: NAT router changes datagram dest addr from 138.76.29.7, 5001 to 10.0.0.1, 3345
NAT: Network Address Translation

• 16-bit port-number field
  – Up to 64K simultaneous connections with a single LAN-side address

• NAT is controversial:
  – Routers should only process up to layer 3
  – Violates the end-to-end argument

• Makes inbound connections difficult
  – Inbound connections needed in P2P and other applications
  – May be overcome by UPnP or manually configuring NAT to route incoming connections to a particular host

• Some believe that address shortage should instead be solved by IPv6
Chapter 4: Roadmap

4.1 Introduction
4.2 Virtual circuit and datagram networks
4.3 What’s inside a router
4.4 IP: Internet Protocol
   - Datagram format
   - IPv4 addressing
   - ICMP
   - IPv6
4.5 Routing algorithms
4.6 Routing in the Internet
4.7 Broadcast and multicast routing
ICMP: Internet Control Message Protocol

- Communicates network-level debug information
  - Error reporting: unreachable host, network, port, protocol
  - Echo request/reply (ping)
- Network-layer above IP
  - ICMP msgs carried in IP datagrams ("layer 3.5")
- ICMP error message
  - Payload contains first 28 bytes of IP pkt causing error

<table>
<thead>
<tr>
<th>Type</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>echo reply (ping)</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>dest network unreachable</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>dest host unreachable</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>dest protocol unreachable</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>dest port unreachable</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>source quench (congestion control - not used)</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>echo request (ping)</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>router advertisement</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>router discovery</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>TTL expired</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>bad IP header</td>
</tr>
</tbody>
</table>
**Traceroute and ICMP**

- Source sends series of **UDP** segments to dest
  - First with TTL = 1
  - Second with TTL = 2
  - Unlikely port number

- When the \( n \)-th datagram arrives to the \( n \)-th router:
  - Router discards datagram
  - Sends to source a TTL Expired (type 11, code 0)
  - Message includes IP hdr from router & first 28 bytes of original packet

- When ICMP message arrives, source calculates RTT
  - Traceroute does this 3 times per hop

**Stopping criterion**

- UDP segment eventually arrives at destination host
  - Destination returns ICMP “port unreachable” packet (type 3, code 3)
  - When source gets this ICMP, it stops
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IPv6

• Initial motivation: 32-bit address space has been completely allocated
• Additional motivation:
  – Simpler header format helps speed up forwarding
  – Header changes to facilitate QoS and extensions

IPv6 datagram format:
  – Fixed-length 40 byte header
  – No fragmentation allowed
  – Priority of packet (QoS)
  – Flow ID (not well defined)
  – Upper-layer protocol (e.g., TCP, ICMP) or IPv6 extension header

16-byte IP, e.g., FEBC:A574:382B:23C1:AA49:4592:4EFE:9982
IPv6 Notes

• **Checksum**: removed entirely to reduce processing time at each hop
  – Recall that IPv4 checksums the header only (TCP/UDP checksum the entire packet)

• **Options**: allowed, but outside of header, indicated by “Next Header” field

• All routers cannot be upgraded simultaneously
  – How will the network operate with mixed IPv4 / IPv6 routers?

• **Tunneling**: IPv6 carried as payload in IPv4 datagram among IPv4 routers
**Tunneling**

**Logical view:**

A IPv6

B IPv6

---tunnel---

E IPv6

**Physical view:**

A IPv6

B IPv6

C IPv4

D IPv4

E IPv6

F IPv6

**Q:** how does E know the packet has encapsulated IPv6 data?

**A:** protocol field (often 41)
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Interplay Between Routing and Forwarding

Routing algorithm

Local forwarding table

<table>
<thead>
<tr>
<th>header value</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100</td>
<td>3</td>
</tr>
<tr>
<td>0101</td>
<td>2</td>
</tr>
<tr>
<td>0111</td>
<td>2</td>
</tr>
<tr>
<td>1001</td>
<td>1</td>
</tr>
</tbody>
</table>

Value in arriving packet's header

0111
Graph Abstraction

Graph: $G = (V, E)$

$V =$ set of routers $= \{u, v, w, x, y, z\}$

$E =$ set of links $= \{(u,v), (u,x), (u,w), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z)\}$
Graph Abstraction: Costs

- \( c(x,y) = \text{cost of link } (x,y) \)
  - E.g., \( c(w,z) = 5 \)
- Cost options:
  - Could always be 1
  - Could be inversely related to bandwidth or be proportional to congestion
  - Physical distance

Cost of path \((x_1, x_2, x_3, \ldots, x_p) = c(x_1, x_2) + c(x_2, x_3) + \ldots + c(x_{p-1}, x_p)\)

Question: What’s the least-cost path between \(u\) and \(z\)?

Routing algorithms find least-cost paths
Routing Algorithm Classification

Global or local information?
- **Global:**
  - Routers have complete topology, link cost info
  - "Link state" algorithms
- **Local (decentralized):**
  - Router knows physically-connected neighbors, link costs to neighbors
  - Iterative process of computation, exchange of info with neighbors
  - "Distance vector" algorithms

Static or dynamic?
- **Static:**
  - Useful when routes change slowly over time
  - Manual or DHCP-based route creation
- **Dynamic:**
  - Routes change more quickly
  - Periodic update in response to link cost changes
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Simple Link-State Routing Algorithm

Dijkstra’s algorithm
• Entire network topology and link costs known
  – Accomplished via “link state broadcast”
  – Eventually, all nodes have same info
• Computes least cost paths from one node (“source”) to all other nodes
  – Gives forwarding table for that node

• **Iterative**: after $k$ iterations, know least-cost path to $k$ closest destinations

**Notation:**
• $c(x,y)$: link cost from $x$ to $y$
  – Cost is $\infty$ if not direct neighbors
• $D(v)$: current estimate of the cost from source to destination $v$
• $p(v)$: predecessor of $v$ along the least-cost path back to source
• $F$: set of closest nodes whose least-cost path has been finalized (i.e., known for a fact)
**Dijkstra’s Algorithm**

**Initialization:**

\[ F = \{u\}, \quad D(u) = 0 \]

for all nodes \( v \neq u \)

if \( v \) is adjacent to \( u \)

\[ D(v) = c(u,v) \]

else

\[ D(v) = \infty \]

**do {**

find node \( i \) not in \( F \) such that \( D(i) \) is minimum

add \( i \) to \( F \)

for all \( j \) adjacent to \( i \) and not in \( F \):

\[ D(j) = \min(D(j), D(i) + c(i,j)) \]

/* new cost to \( j \) is either old cost to \( j \) or known shortest path cost to \( i \) plus cost from \( i \) to \( j \) */

**} while (not all nodes in \( F \))**
## Dijkstra’s Algorithm: Example

### Step 0
- \( F = u \)
- \( D(u), p(u) = 2, u \)
- \( D(w), p(w) = 5, u \)
- \( D(x), p(x) = 1, u \)
- \( D(y), p(y) = \infty \)
- \( D(z), p(z) = \infty \)

### Step 1
- \( u x \)
- \( D(u), p(u) = 2, u \)
- \( D(w), p(w) = 4, x \)
- \( D(x), p(x) = 2, x \)
- \( D(y), p(y) = 4, y \)
- \( D(z), p(z) = \infty \)

### Step 2
- \( u x y \)
- \( D(u), p(u) = 2, u \)
- \( D(w), p(w) = 3, y \)
- \( D(x), p(x) = \infty \)
- \( D(y), p(y) = 4, y \)
- \( D(z), p(z) = 4, y \)

### Step 3
- \( u x y v \)
- \( D(u), p(u) = \infty \)
- \( D(w), p(w) = 3, y \)
- \( D(x), p(x) = \infty \)
- \( D(y), p(y) = 4, y \)
- \( D(z), p(z) = 4, y \)

### Step 4
- \( u x y v w \)
- \( D(u), p(u) = \infty \)
- \( D(w), p(w) = 3, y \)
- \( D(x), p(x) = \infty \)
- \( D(y), p(y) = 4, y \)
- \( D(z), p(z) = 4, y \)

### Step 5
- \( u x y v w z \)
- \( D(u), p(u) = \infty \)
- \( D(w), p(w) = 3, y \)
- \( D(x), p(x) = \infty \)
- \( D(y), p(y) = 4, y \)
- \( D(z), p(z) = 4, y \)
**Dijkstra’s Algorithm Discussion**

Algorithm complexity: $n$ nodes
- Iteration $k$: need to find min of $(n-k)$ costs, visit $d_i$ neighbors
- Naïve implementation: $O(|E| \cdot |V|)$ complexity
- Heap-based implementation: $O(|E| \cdot \log|V|)$

Oscillations possible, but only for traffic-dependent cost:
- e.g., Link cost = amount of carried traffic