Designing IP

EE 122: Intro to Communication Networks

Fall 2006 (MW 4-5:30 in Donner 155)

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http://inst.eecs.berkeley.edu/~ee122/

Materials with thanks to Jennifer Rexford, Ion Stoica and colleagues at Princeton and UC Berkeley

1

Announcements

- Homework #2 out Wednesday rather than today
  - And due Oct 11 instead of Oct 4
- We will likely shift the remaining homework dates
- Reminder: Homework #1 due Wednesday

2

Goals of Today's Lecture

- Work through process of designing **IP**, the Internet's (sole) network-layer protocol
- Assess security implications of the design

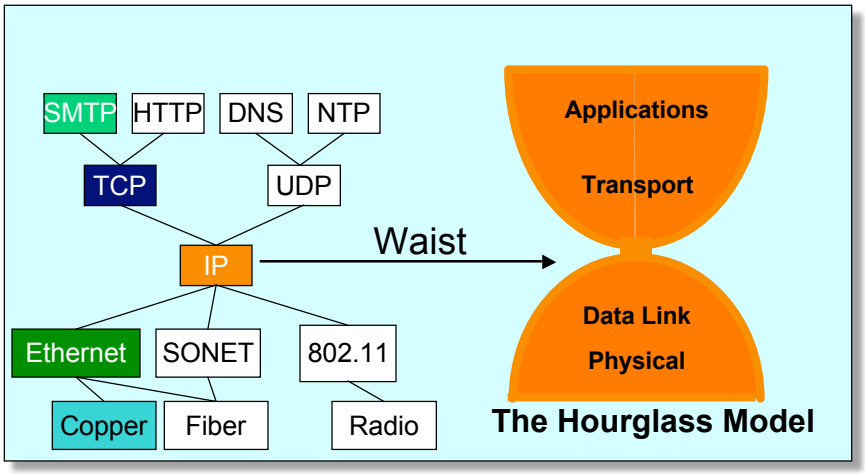
3

Our Story So Far (Context)

- The Internet uses packet-switching rather than circuit-switching in order to
  - Achieve higher levels of utilization (we can use statistical multiplexing to more aggressively share network links)
  - Avoid state inside the network (robust fail-over)
  - Make interconnection between different parties easy (minimal service promises)
- The Internet architecture uses layering to partition functionality into modules
- The "internetworking layer" (or just network layer) forms the waist of the layering hourglass …

4

The Internet *Hourglass*



There is just one network-layer protocol, **IP**.
The "narrow waist" facilitates interoperability.

5

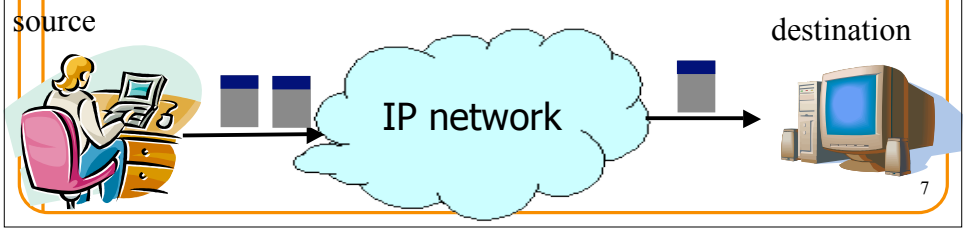
Our Story So Far (Context), Con't

- The End-to-End Principle guides us in where to place functionality
  - If hosts can implement functionality correctly, implement it in a lower layer only as a performance enhancement
  - But do so only if it does not impose burden on applications that do not require that functionality
- The principle of Fate Sharing guides us to keep state with the elements that rely on it, when possible

6

IP Service: Best-Effort Packet Delivery

- Packet switching
  - Divide messages into a sequence of packets
  - Each packet (datagram) is dealt with individually
- "Best-effort" delivery
  - Packets may be lost
  - Packets may be corrupted
  - Packets may be delivered out of order



7

IP Service Model: Why Best-Effort?

- IP means never having to say you're sorry…
  - Don't need to reserve bandwidth and memory
  - Don't need to do error detection & correction
  - Don't need to remember from one packet to next
- Easier to survive failures
  - Transient disruptions are okay during failover
- … but, applications *do* want efficient, accurate transfer of data in order, in a timely fashion

8

IP Service: "Best Effort" Suffices

- No error detection or correction
  - Higher-level protocol can provide error checking
- Successive packets may not follow the same path
  - Not a problem as long as packets reach the destination
- Packets can be delivered out-of-order
  - Receiver can put packets back in order (if necessary)
- Packets may be lost or arbitrarily delayed
  - Sender can send the packets again (if desired)
- No network congestion control (beyond "drop")
  - Sender can slow down in response to loss or delay

9

Let's Design IP

- What does it mean to "design" a protocol?
- Answer: specify the syntax of its messages and their meaning (semantics).
  - Syntax = elements in packet header, their types & layout
    - representation
  - Semantics = interpretation of elements
    - information
- For IP, what fields do we need & why?

10

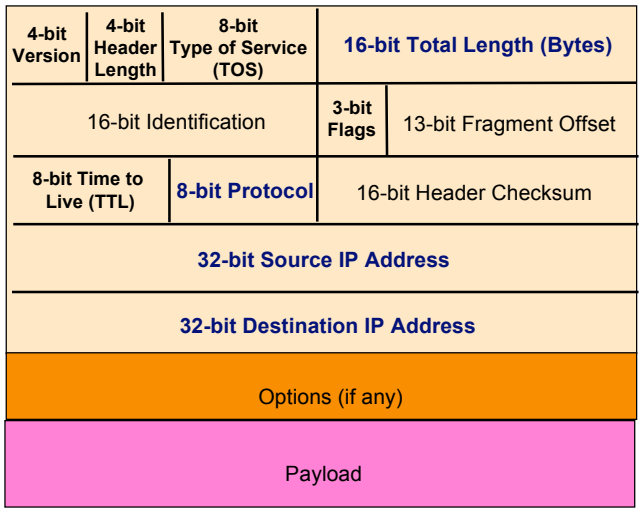
Information to Capture in IP Header

- Addresses: datagram destination & source
- Framing: datagram length, demux information
- Priority: any special forwarding?
- Extensibility: what if we need to tweak/change IP?

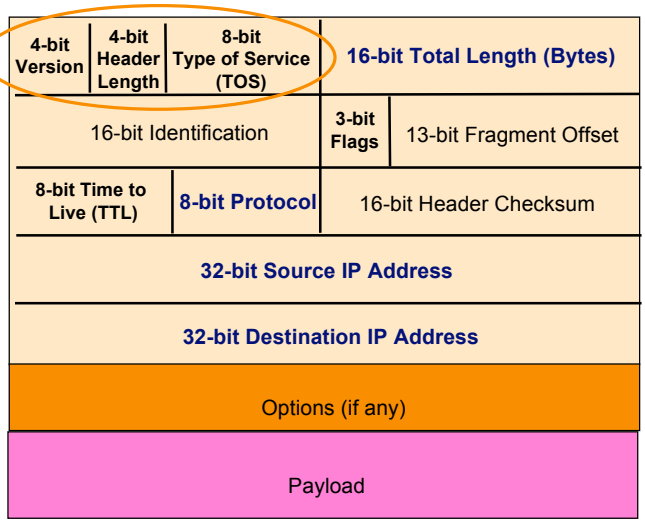
- Dealing with problems:
  - Integrity: is the header what it's supposed to be?
  - Loop avoidance: make sure packets don't endlessly circulate
  - Fragmentation: what if the datagram is too large?

11

IP Packet Structure



IP Packet Structure

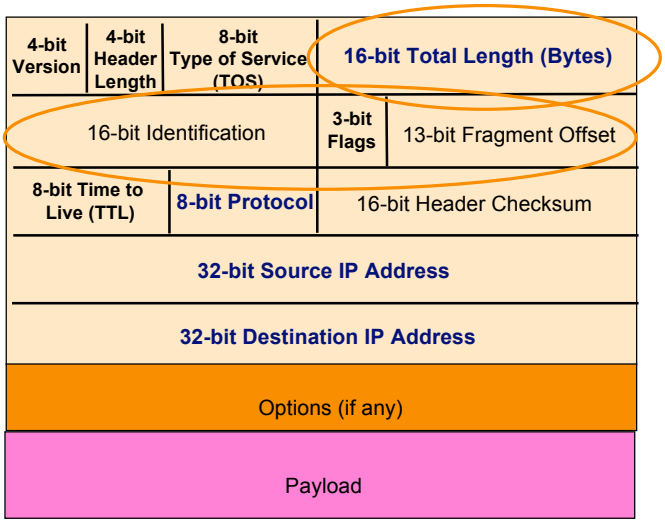


IP Packet Header Fields

- Version number (4 bits)
  - Indicates the version of the IP protocol
  - Necessary to know what other fields to expect
  - Typically “4” (for IPv4), and sometimes “6” (for IPv6)
- Header length (4 bits)
  - Number of 32-bit words in the header
  - Typically “5” (for a 20-byte IPv4 header)
  - Can be more when IP options are used
- Type-of-Service (8 bits)
  - Allow packets to be treated differently based on needs
  - E.g., low delay for audio, high bandwidth for bulk transfer

14

IP Packet Structure

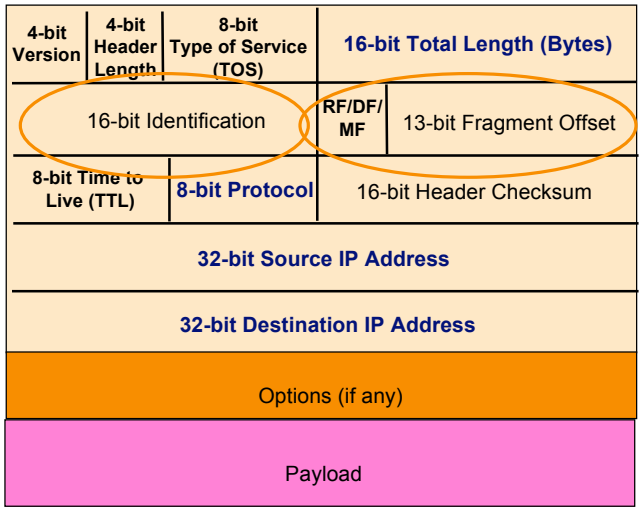


IP Packet Header Fields (Continued)

- Total length (16 bits)
  - Number of bytes in the packet
  - Maximum size is 63,535 bytes (2^{16} -1)
  - … though underlying links may impose smaller limits
- Fragmentation: when forwarding a packet, an Internet router can split it into multiple pieces ("fragments") if too big for next hop link
- End host reassembles to recover original packet
- Fragmentation information (32 bits)
  - Packet identifier, flags, and fragment offset
  - Supports dividing a large IP packet into fragments
  - … in case a link cannot handle a large IP packet

16

IP Packet Structure



Fragmentation, con't

- Identifier (16 bits): used to tell which fragments belong together
- Flags (3 bits):
  - Reserved **(RF):** unused bit (why "reserved"?)
  - Don't Fragment **(DF):** instruct routers to **not** fragment the packet even if it won't fit
    - Instead, they drop the packet and send back a "Too Large" ICMP control message
    - Forms the basis for "Path MTU Discovery", covered later
  - More (**MF**): this fragment is not the last one
- Offset (13 bits): what part of datagram this fragment covers in 8-byte units
- Thus, a fragment has either **MF** set or Offset > 0

18

Example of Fragmentation

- Suppose we have a 4,000 byte datagram sent from host 1.2.3.4 to host 3.4.5.6 …

Version 4	Header Length 5	Type of Service 0	Total Length: 4000
Identification: 56273		R/D/M 0/0/0	Fragment Offset: 0
TTL 127	Protocol 6		Checksum: 44019
Source Address: 1.2.3.4			
Destination Address: 3.4.5.6			

(3980 more bytes here)

- … and it traverses a link that limits datagrams to 1,500 bytes

19

Example of Fragmentation, con't

- Datagram split into 3 pieces. Possible first piece:

Version 4	Header Length 5	Type of Service 0	Total Length: 1496
Identification: 56273		R/D/M 0/0/1	Fragment Offset: 0
TTL 127	Protocol 6		Checksum: xxx
Source Address: 1.2.3.4			
Destination Address: 3.4.5.6			

20

Example of Fragmentation, con't

- Possible second piece:

Version 4	Header Length 5	Type of Service 0	Total Length: 1200	
Identification: 56273			R/D/M 0/0/1	Fragment Offset: 187 (187 * 8 = 1496)
TTL 127		Protocol 6	Checksum: yyy	
Source Address: 1.2.3.4				
Destination Address: 3.4.5.6				

21

Example of Fragmentation, con't

- Possible third piece:

Version 4	Header Length 5	Type of Service 0	Total Length: 1304 (4000 - 1496 - 1200 = 1304)	
Identification: 56273			R/D/M 0/0/0	Fragment Offset: 337 (337 * 8 = 2696)
TTL 127		Protocol 6	Checksum: zzz	
Source Address: 1.2.3.4				
Destination Address: 3.4.5.6				

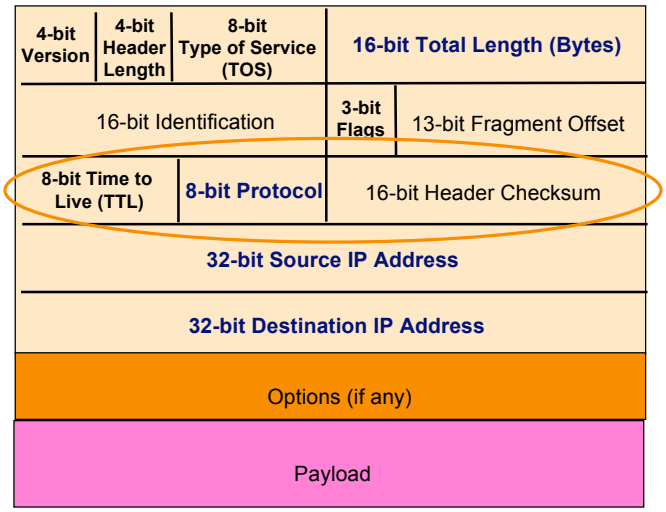
22

5 Minute Break

Questions Before We Proceed?

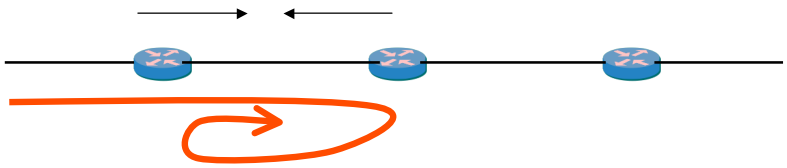
23

IP Packet Structure



Time-to-Live (TTL) Field (8 bits)

- Potentially lethal problem
  - Forwarding loops can cause packets to cycle forever
  - As these accumulate, eventually consume **all** capacity

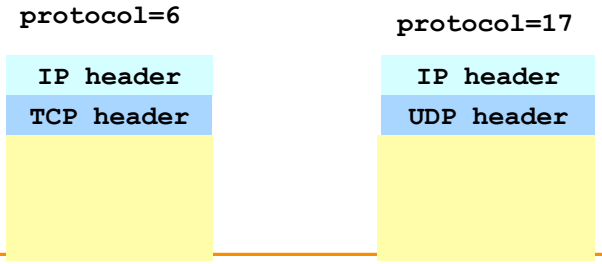


- Time-to-live field in packet header
  - Decremented at each hop, packet discarded if reaches 0
  - …and "time exceeded" message is sent to the source
    - Using "ICMP" control message; basis for **traceroute**

25

IP Packet Header Fields (Continued)

- Protocol (8 bits)
  - Identifies the higher-level protocol
    - E.g., "6" for the Transmission Control Protocol (TCP)
    - E.g., "17" for the User Datagram Protocol (UDP)
  - Important for demultiplexing at receiving host
    - Indicates what kind of header to expect next



26

IP Packet Header Fields (Continued)

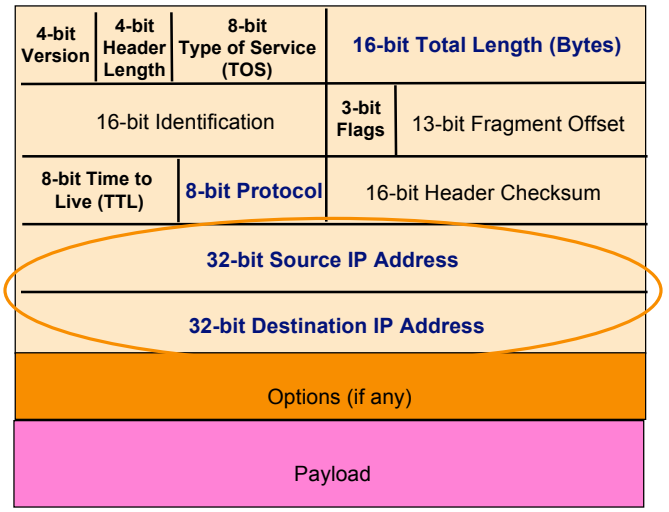
- Checksum (16 bits)
  - Sum of all 16-bit words in the IP **packet header**
  - If any bits of the header are corrupted in transit
  - … the checksum won't match at receiving host

```
   134                134
 + 212              + 216
-----              -----
 = 346              = 350
                    Mismatch!
```

  - Routers discard corrupted packets
    - So they don't act on bogus information

27

IP Packet Structure



IP Packet Header (Continued)

- Two IP addresses
  - Source IP address (32 bits)
  - Destination IP address (32 bits)
- Destination address
  - Unique identifier/locator for the receiving host
  - Allows each node to make forwarding decisions
- Source address
  - Unique identifier/locator for the sending host
  - Recipient can decide whether to accept packet
  - Enables recipient to send a reply back to source

29

IP Address Integrity

- What are the *security implications* of the address fields?
- Source address should be the sending host
  - But, who's checking, anyway?
  - You could send packets with any source you want
  - **Why is checking hard?**

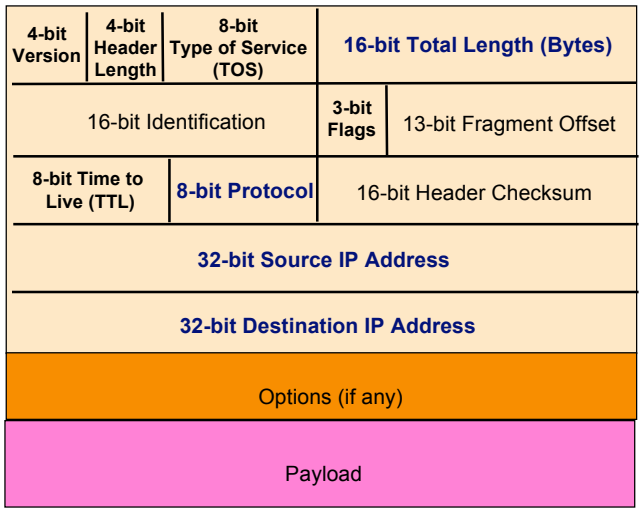
30

IP Address Integrity, con't

- Why would someone use a bogus source address?
- Launch a **denial-of-service** attack
  - Send excessive packets to the destination
  - … to overload the node, or the links leading to the node
  - But: victim can identify/filter you by the source address
- Evade detection by "spoofing"
  - Put **someone else's** source address in the packets
    - **Or**: use a lot of different ones so can't be filtered
- Or: an attack against the spoofed host
  - Spoofed host is wrongly blamed
  - Spoofed host may receive return traffic from the receiver

31

Security Implications of IP's Design

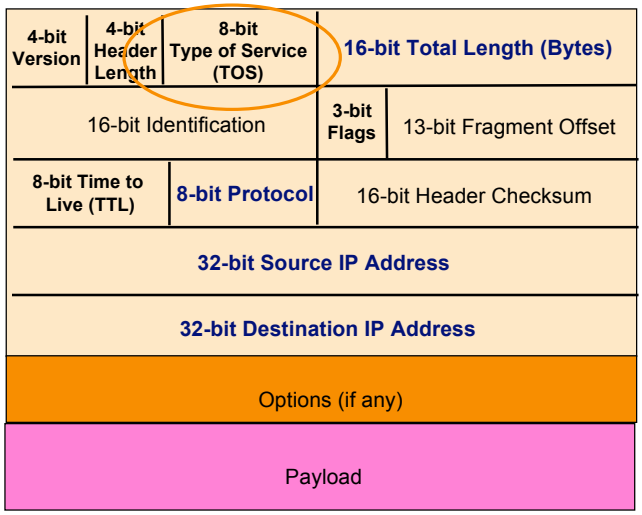


Security Implications, con't

- Version field (4 bits) …. ?
  - Issue: fledgling **IPv6** deployment means sometimes connectivity exceeds security enforcement
    - E.g., firewall rules only set up for **IPv4**
- Header length (4 bits) …. ?
  - Controls presence of IP **options**
    - E.g., **Source Route** lets sender control path taken through network - say, sidestep security monitoring
  - Non-obvious difficulty: IP options often processed in router's slow path
    - Allows attacker to stress router for denial-of-service
  - Often, today's firewalls configured to **drop** packets with options. (So much for extensibility! :-( )

33

IP Packet Structure

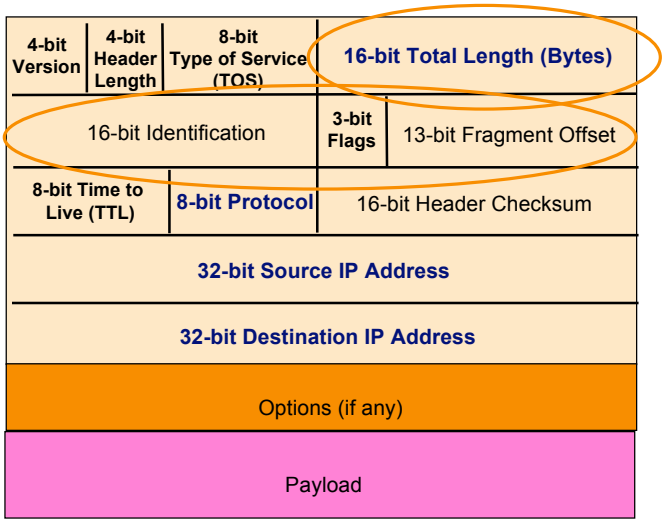


Security Implications of TOS? (8 bits)

- What if attacker sets TOS for their flooding traffic for prioritized delivery?
  - If regular traffic does not set TOS, then network prefers the attack traffic, greatly compounding damage
- What if network charges for TOS traffic …
  - … and attacker spoofs the victim's source address? (denial-of-money)
- In general, in today's network TOS **does not work**
  - Due to very hard problems with billing
  - TOS has now been redefined for *Differential Service*
    - Discussed later in course

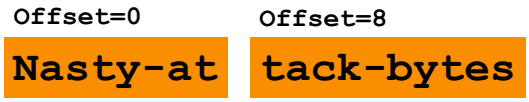
35

IP Packet Structure



Security Implications of Fragmentation?

- Allows evasion of network monitoring/enforcement
- E.g., split an attack across multiple fragments
  - Packet inspection won't match a "signature"

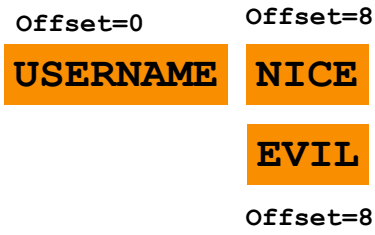


- E.g., split TCP header across multiple fragments
  - Firewall can't tell anything about connection associated with traffic
- Both of these can be addressed by monitor remembering previous fragments
  - But that costs state

37

Fragmentation Attacks, con't

- What if 2 overlapping fragments are inconsistent?



- How does network monitor know whether receiver sees `USERNAME NICE` or `USERNAME EVIL`?

38

Fragmentation Attacks, con't

- What if fragments exceed IP datagram limit?

```
Offset=65528
NineBytes
```

  - Maximum size of 13-bit field: 0x1FFF = 8191
    Byte offset into final datagram = 8191*8 = 65528
    Length of final datagram = 65528 + 9 = **65537**
- Result: kernel crash
  - Denial-of-service using just a few packets
  - Fixed in modern OS's

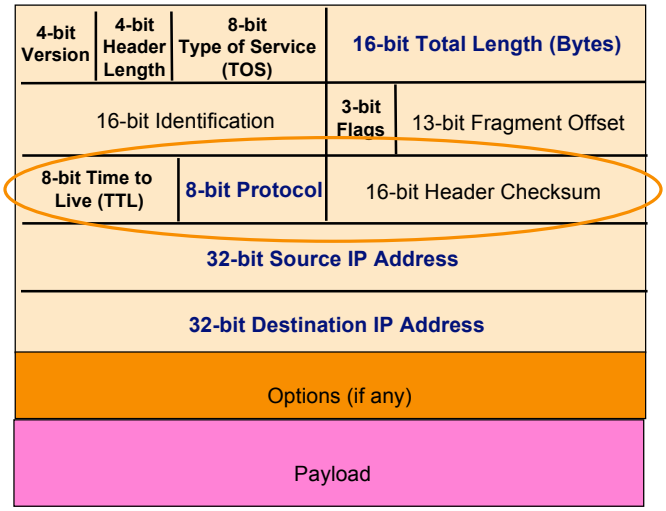
39

Fragmentation Attacks, con't

- What happens if attacker doesn't send all of the fragments in a datagram?
- Receiver winds up holding the ones they receive for a long time
  - State-holding attack

40

IP Packet Structure



Security Implications of TTL? (8 bits)

- Allows discovery of topology (ala' traceroute)
- Can provide a hint that a packet is spoofed
  - It arrives at a router w/ a TTL different than packets from that address usually do
    - Because path from attacker to router has different # hops
  - Though this is *brittle* in the presence of routing changes
- Initial value that's picked is somewhat distinctive to sender's operating system. This plus other such initializations allow OS fingerprinting …
  - Which in turn can allow attacker to infer its likely vulnerabilities

42

Security Implications of Remainder?

- No apparent problems with protocol field (8 bits)
  - It's just a demux'ing handle
  - If value set incorrectly, next higher layer will find packet ill-formed
- Similarly, bad IP checksum field (16 bits) will very quickly cause packet to be discarded by the network

43

Next Lecture

- IP Addressing & Forwarding
- Read P&D: 4.1.3, 4.1.4, 4.3.1, 4.3.2
- Homework #1 due Wednesday

44