CS4450

Computer Networks:
Architecture and Protocols

Lecture 13
THE Internet Protocol

Spring 2018
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Reflection

- **The events in last few days have left me sad!**

- **Such events must be condemned**
  - They have no place in our society

- **Please do not lose faith**
  - If you are feeling overwhelmed
    - Please express your thoughts
    - Talk to friends, family, me, professionals

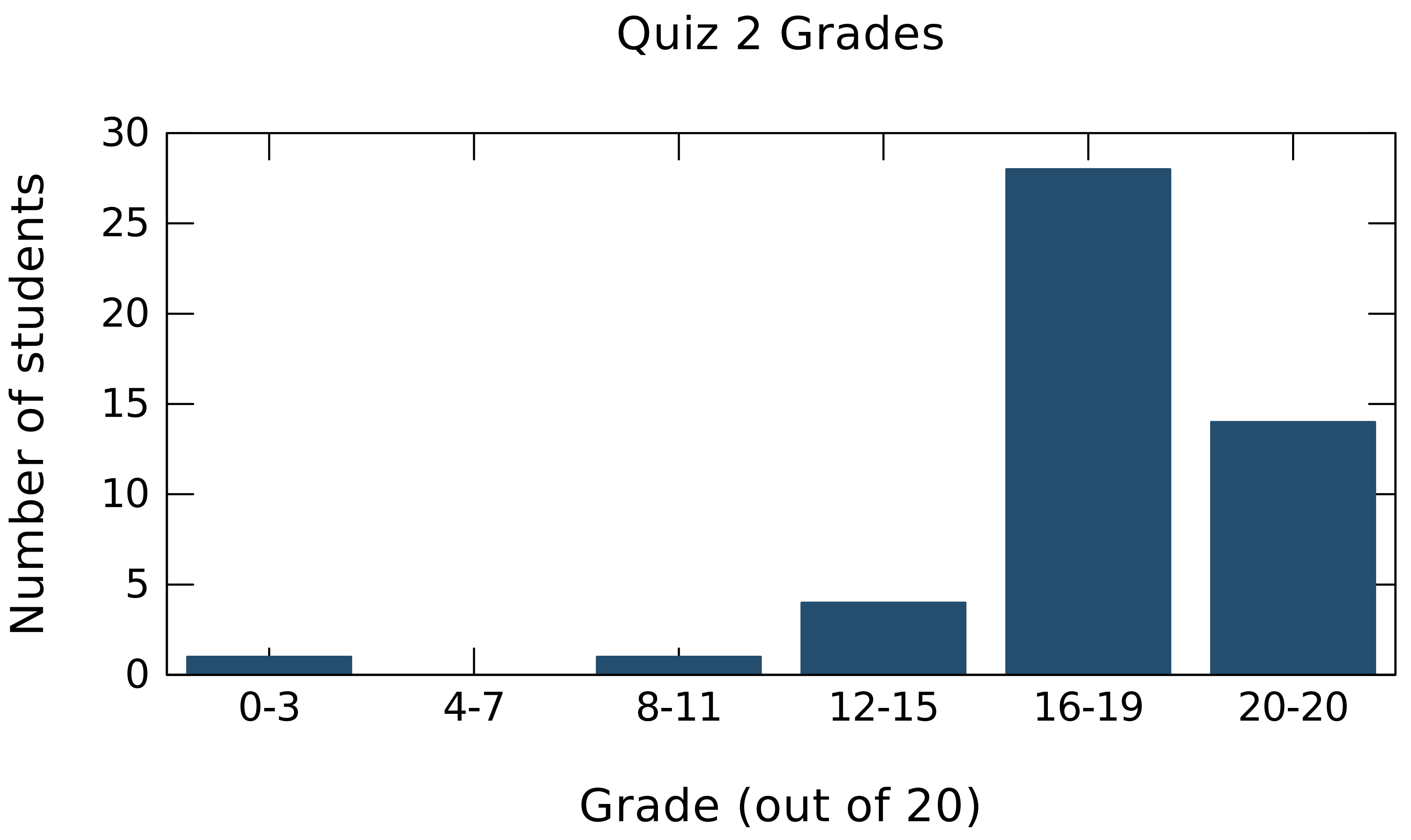
- **My office door is always open**

Announcements

- **Please fill out the feedback**
    - I emailed a link

- If you have a conflict with prelims/finals
    - **Let me know by 03/15**
    - I'll do everything I can to accommodate!

Quiz 1 distribution



Mean	17.875
Median	19
Std. deviation	3.344

Goals for Today's Lecture

- Acknowledge:
  - We have studied a lot of protocols in last few lectures
  - If you do not understand how they fit together
    - Don't worry; you'll soon!
    - In couple of lectures, we'll come back to bigger picture

- **The Internet Protocol**

Network Layer

- THE functionality: **delivering the data**

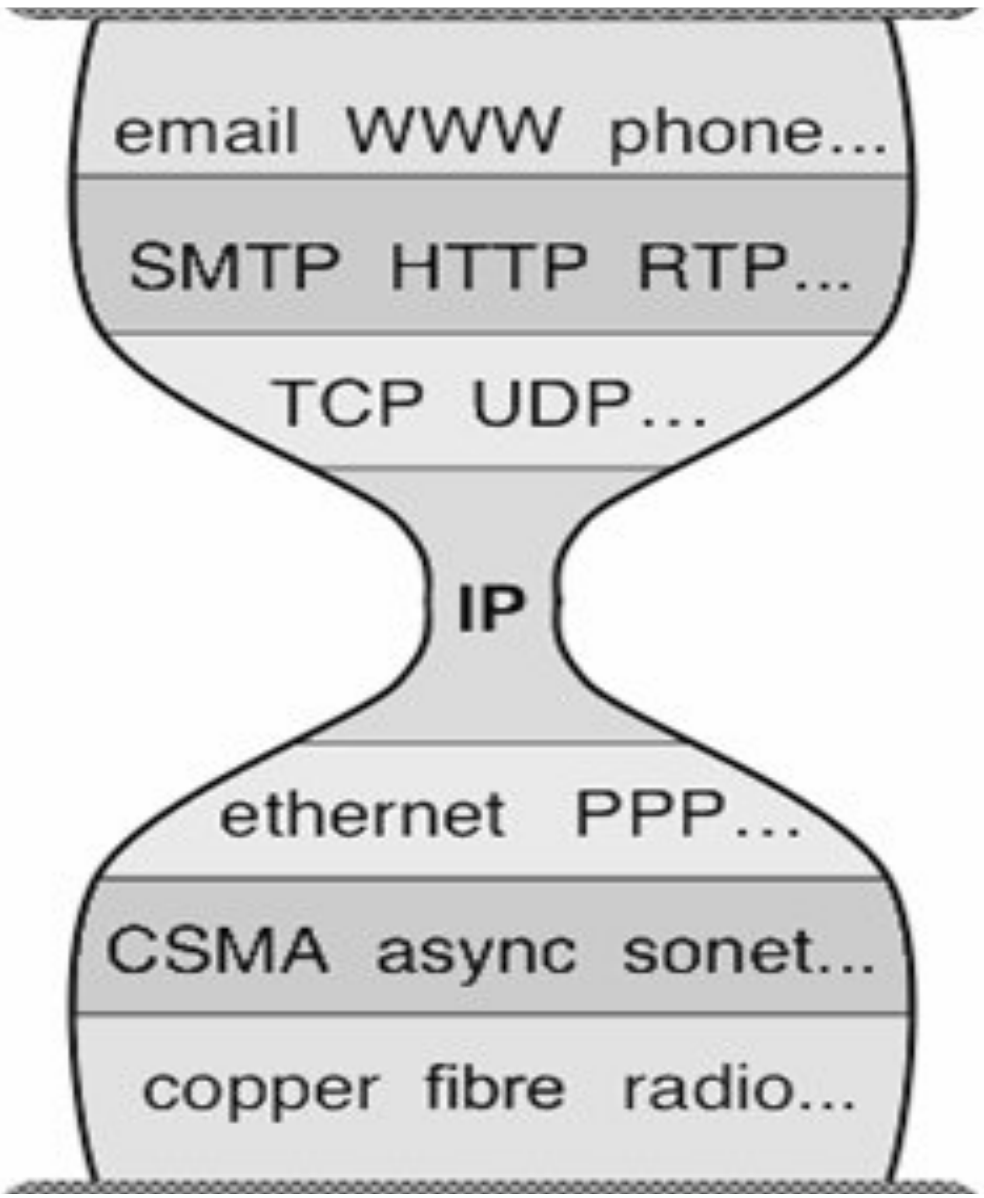
- **THE protocol: Internet Protocol (IP)**
  - To achieve its functionality, IP protocol has **three** responsibilities
    - **Addressing hosts**
    - **Forwarding packets (actually datagrams)**
    - **Routing (link-state, distance vector; several more lectures)**

Routing versus Forwarding

- Routing: **“control plane”**
  - Computing paths the packets will traverse
  - Distributed protocol leads to state at each router
  - Can be done slowly (tens of milliseconds)
  - But must scale to size of network!
- Forwarding: **“data plane”**
  - Directing a packet toward the destination
  - Individual switch/router use their routing tables
  - Must be done quickly (nano seconds)
- Different goals, different constraints, different mechanisms
  - So far we have learnt about the first one

Internet Protocol

- THE functionality: **delivering the data**
- **THE protocol: Internet Protocol (IP)**
  - To achieve its functionality, IP protocol has **three** responsibilities
- Unifying protocol

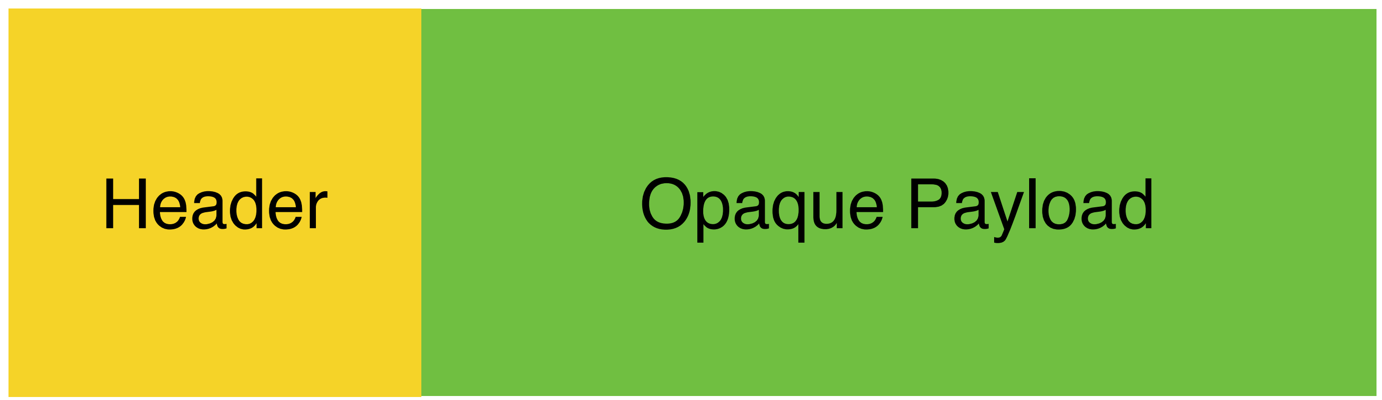


What is “designing” a protocol?

- Specifying the syntax of its messages
    - Format
- Specifying their semantics
    - Meaning
    - Responses

What is Designing IP?

- Syntax: format of packet
  - Nontrivial part: packet “header”
  - Rest is opaque payload (**why opaque?**)



- Semantics: meaning of header fields
  - Required processing

Packet Header as Interface

- Think of packet header as interface
    - Only way of passing information from packet to switch
- Designing interfaces:
    - What task are you trying to perform?
    - What information do you need to accomplish it?
- Header reflects information needed for basic tasks

What Tasks Do We Need to Do?

- Read packet correctly
- Get the packet to the destination
- Get responses to the packet back to source
- Carry data
- Tell host what to do with the packet once arrived
- Specify any special network handling of the packet
- Deal with problems that arise along the path

Reading Packet Correctly

- Where does the header end?
- Where the the packet end?
- What version of IP?
  - Why is this so important?

Getting to the Destination

- Provide destination address
- Should this be location or identifier (name)?
  - And what’s the difference?
- If a host moves should its address change?
  - If not, how can you build scalable Internet?
  - If so, then what good is an address for identification?

Getting Response Back to Source

- Source address
- Necessary for routers to respond to source
    - When would they need to respond back?
        - Failures!
    - Do they really need to respond back?
        - How would the source know if the packet has reached the destination?

Carry Data

- Payload!

Questions?

List of Tasks

- Read packet correctly
- Get the packet to the destination
- Get responses to the packet back to source
- Carry data
- Tell host what to do with packet once arrived
- Specify any special network handling of the packet
- Deal with problems that arise along the path

Telling Destination How to Process Packet

- Indicate which protocols should handle packet
- What layers should this protocol be in?
- What are some options for this today?
- How does the source know what to enter here?

Special Handling

- Type of service, priority, etc.
- Options: discuss later

Dealing With Problems

- Is packet caught in loop?
  - TTL
- Header corrupted:
  - Detect with Checksum
  - What about payload checksum?
- Packet too large?
  - Deal with fragmentation
  - Split packet apart
  - Keep track of how to put together

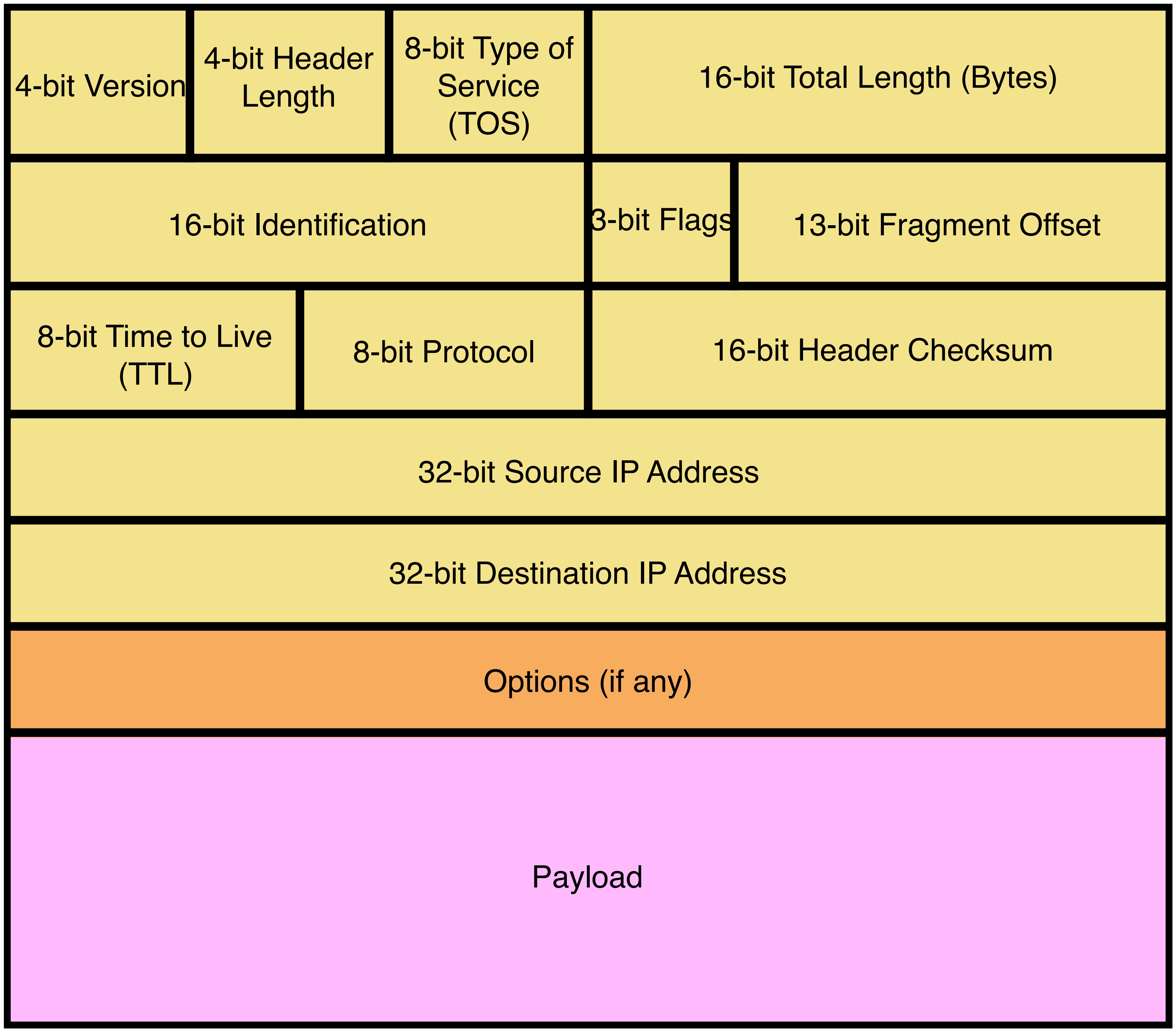
Are We Missing Anything?

- Read packet correctly
- Get the packet to the destination
- Get responses to the packet back to source
- Carry data
- Tell host what to do with packet once arrived
- Specify any special network handling of the packet
- Deal with problems that arise along the path

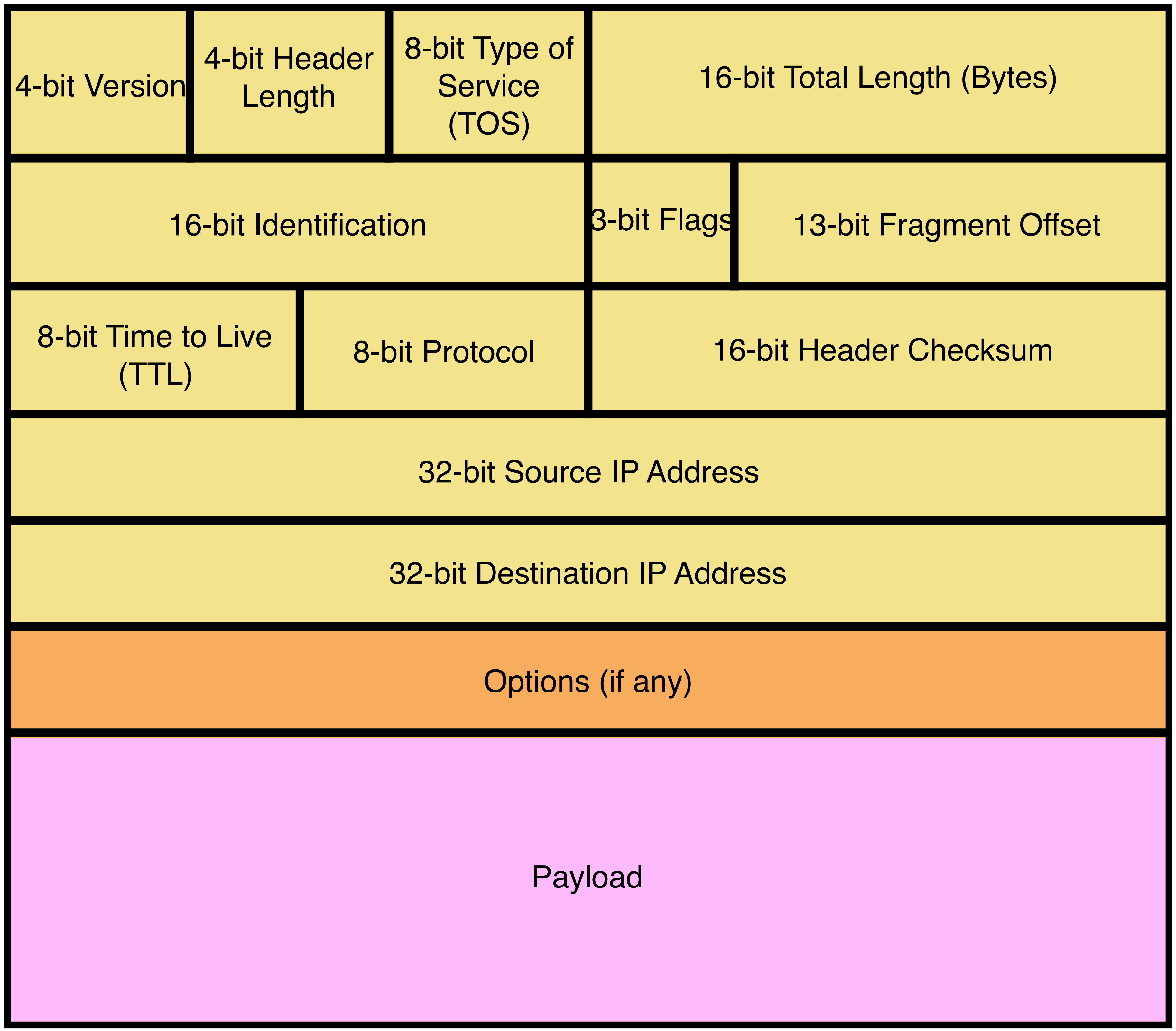
From Semantics to Syntax

- The past few slides discussed the kinds of information the header must provide
- Will now show the syntax (layout) of IPv4 header, and discuss the semantics in more detail

IP Packet Structure



20 Bytes of Standard Header, then Options



Next Set of Slides

- Mapping between tasks and header fields
- Each of these fields is devoted to a task
- Let’s find out which ones and why…

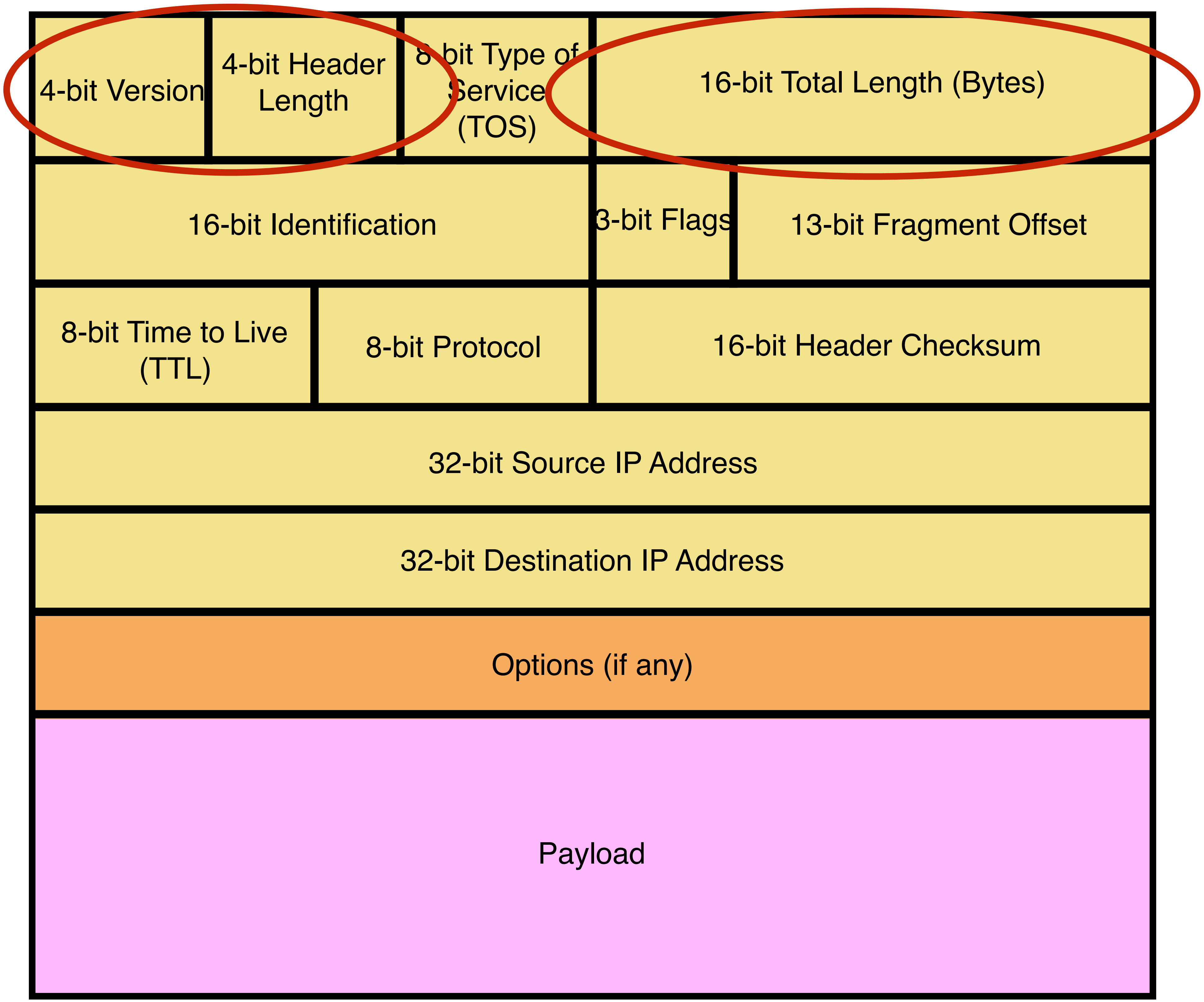
Go Through Tasks One-by-One

- Read packet correctly
- Get the packet to the destination
- Get responses to the packet back to source
- Carry data
- Tell host what to do with packet once arrived
- Specify any special network handling of the packet
- Deal with problems that arise along the path

Read Packet Correctly

- **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
- **Total length** (16 bits)
  - Number of bytes in the packet
  - Maximum size is 65,535 bytes (2^16 -1)
  - … though underlying links may impose smaller limits

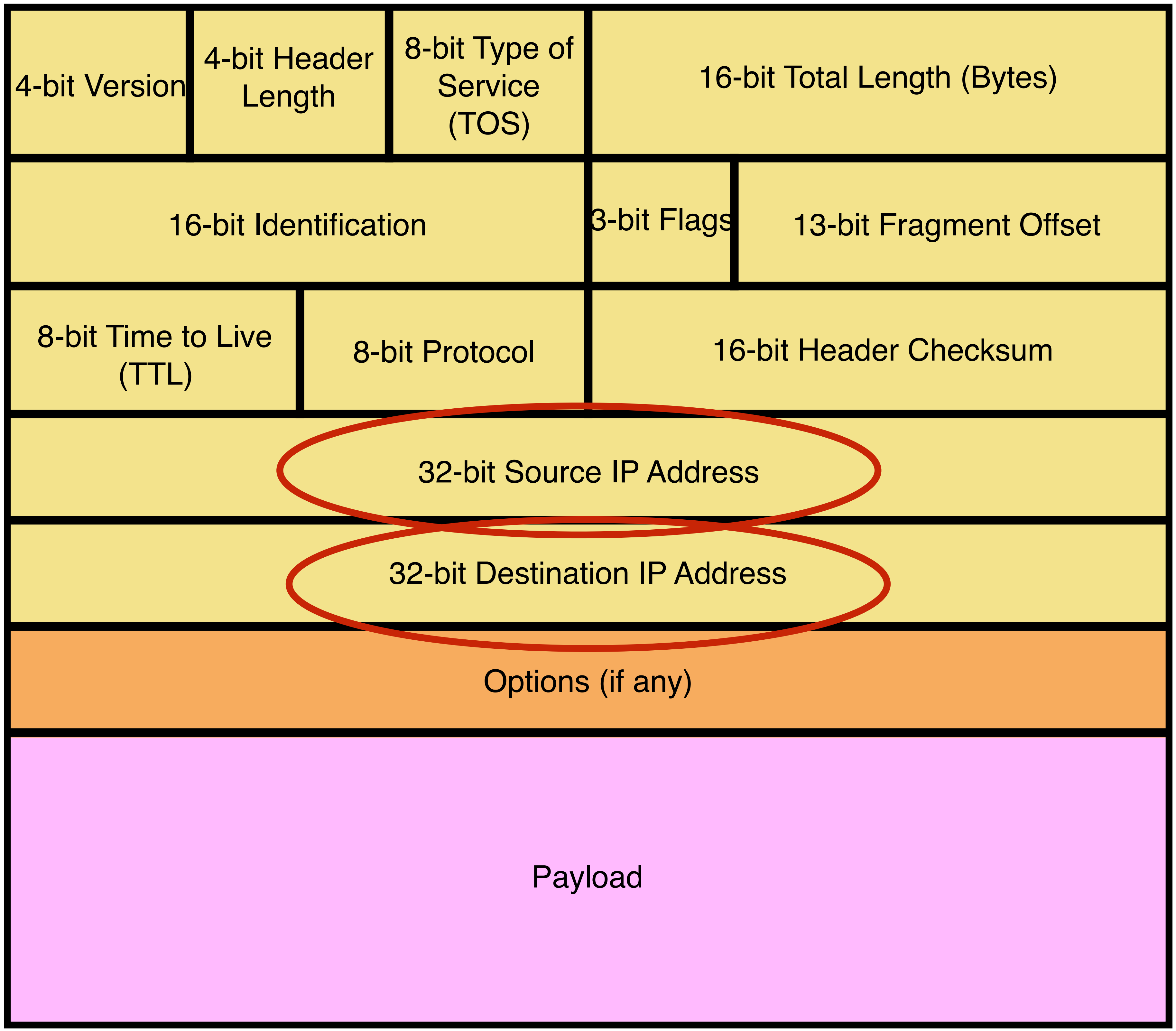
Fields for Reading Packet Correctly



Getting Packet to Destination and Back

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

Fields for Reading Packet Correctly



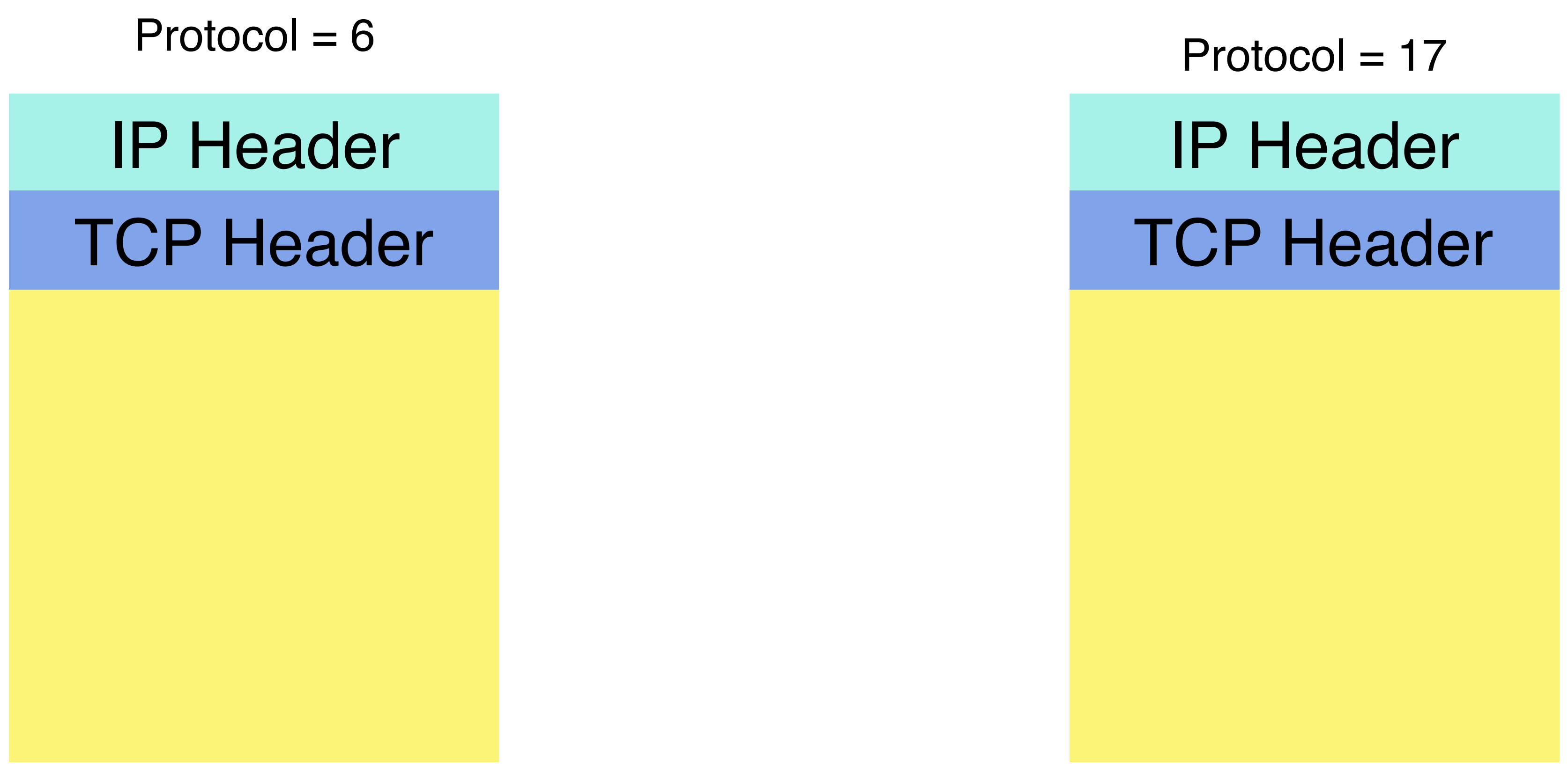
Questions?

List of Tasks

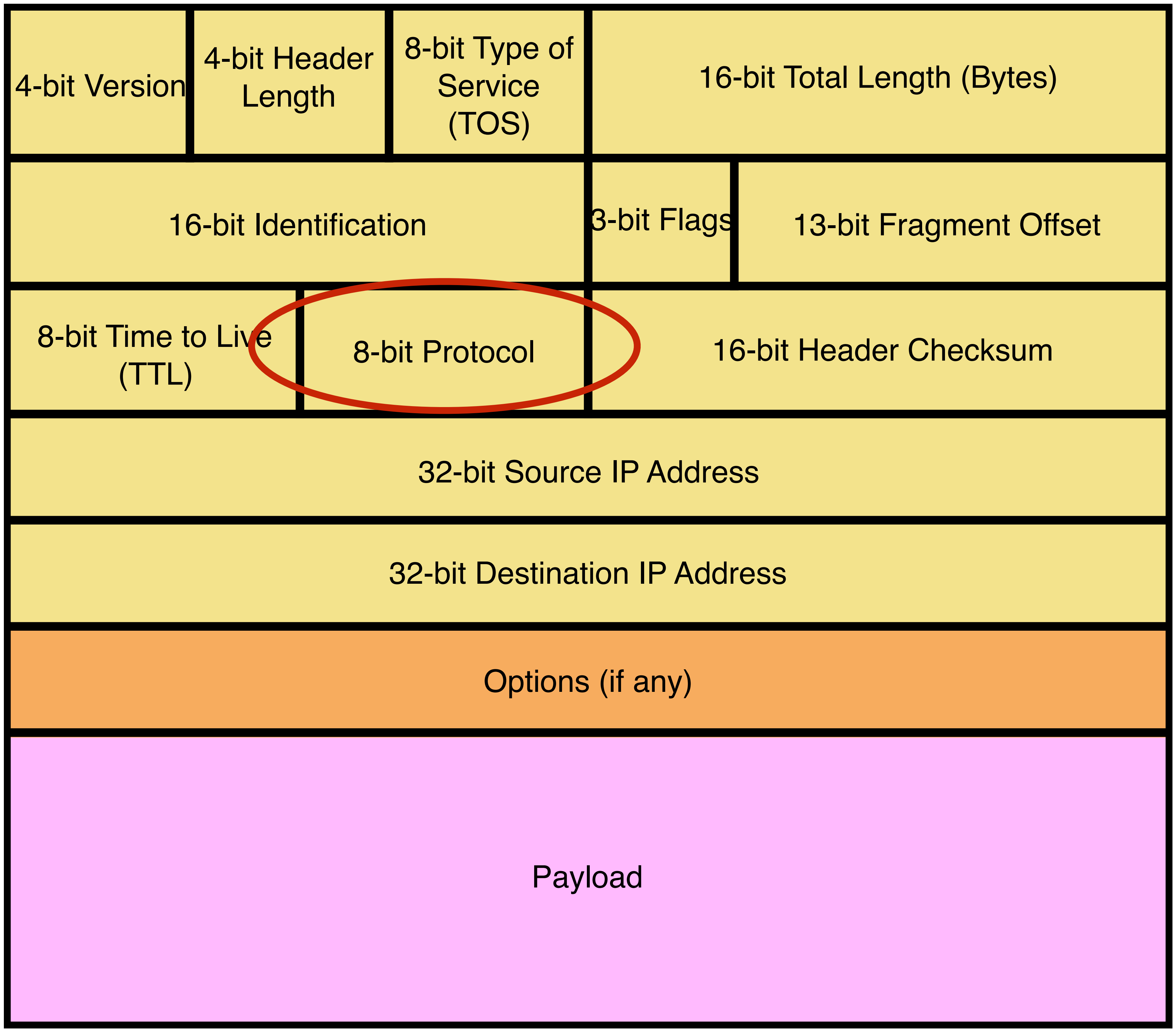
- Read packet correctly
- Get the packet to the destination
- Get responses to the packet back to source
- Carry data
- **Tell host what to do with packet once arrived**
- Specify any special network handling of the packet
- Deal with problems that arise along the path

Telling Host How to Handle Packet

- **Protocol (8 bits)**
  - Identifies the higher level protocol
  - Important for demultiplexing at receiving host
- **Most common examples**
  - E.g., “6” for the Transmission Control Protocol (TCP)
  - E.g., “17” for the User Datagram Protocol



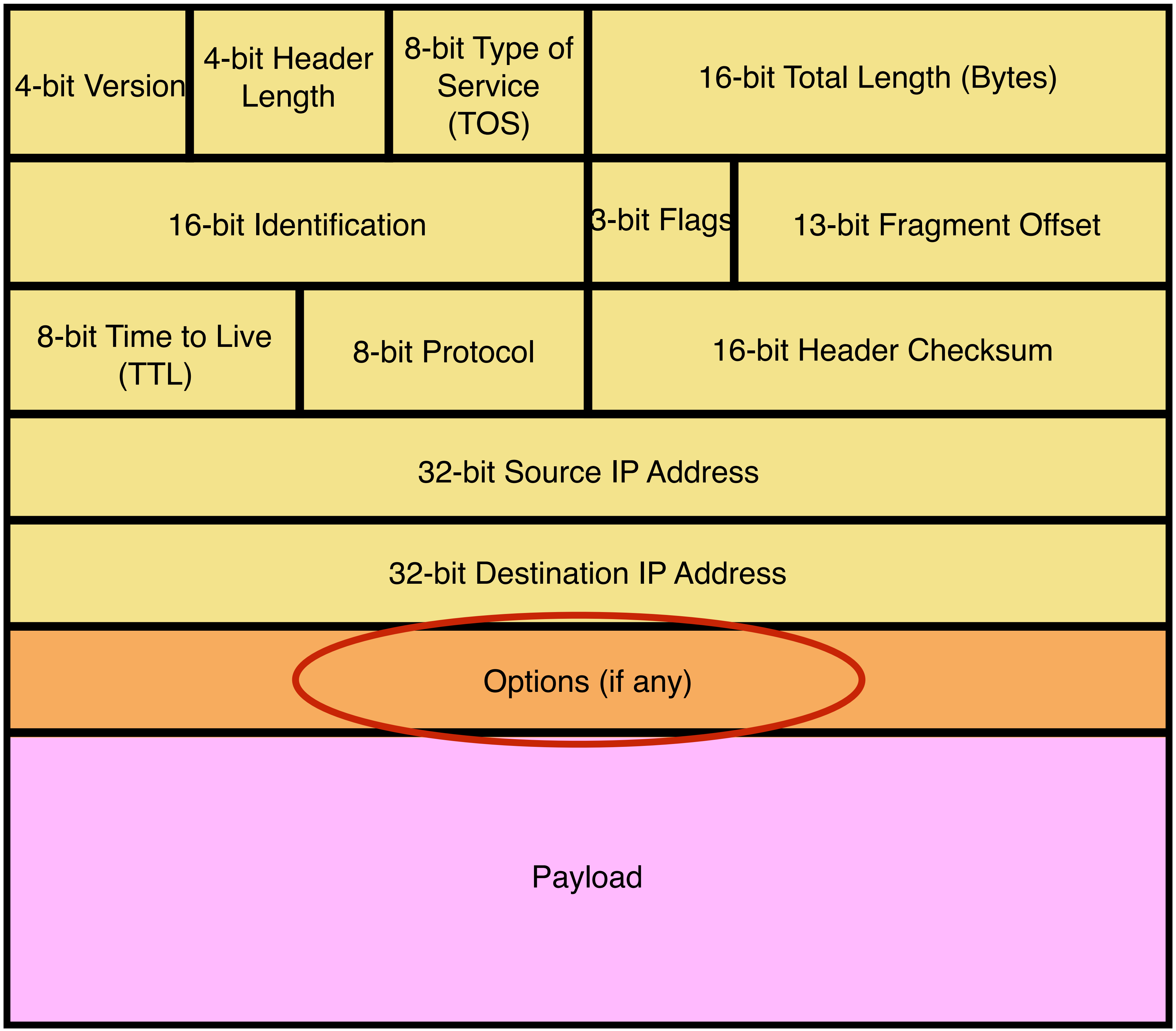
Fields for Reading Packet Correctly



Special Handling

- **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
  - Has been redefined several times, no general use
- **Options**
  - Ability to specify other functionality
  - Extensible format (later)

Fields for Reading Packet Correctly



Option Field Layout

Field	Size (bits)	Description
Copied	1	Set if field copied to all fragments
Class	2	0 = control, 2 = debugging/ measurement
Number	5	Specified option
Length	8	Size of entire option
Data	Variable	Option-specific data

Examples of Options

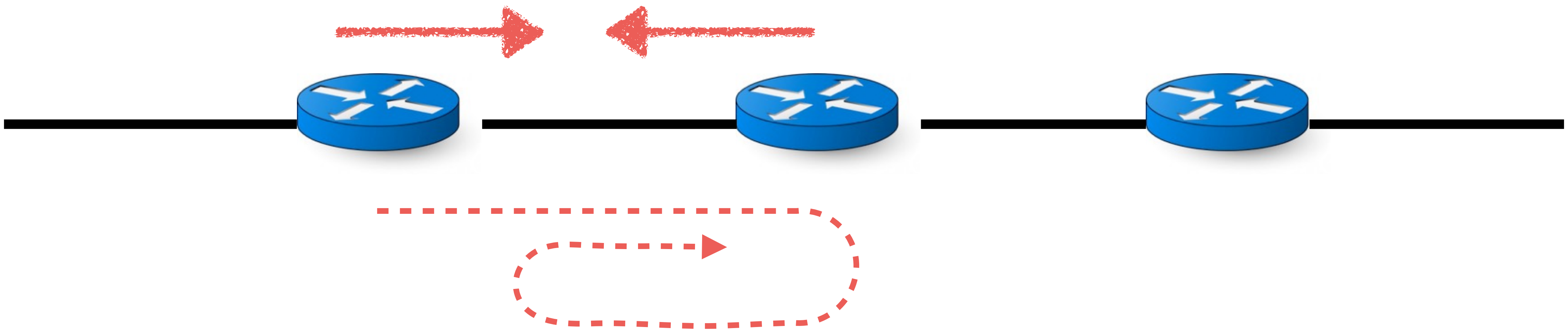
- Record Route
- Strict Source Route
- Loose Source Route
- Timestamp
- Traceroute
- Router Alert
- …

Potential Problems

- Header Corrupted: **Checksum**
- Loop: **TTL**
- Packet too large: **Fragmentation**

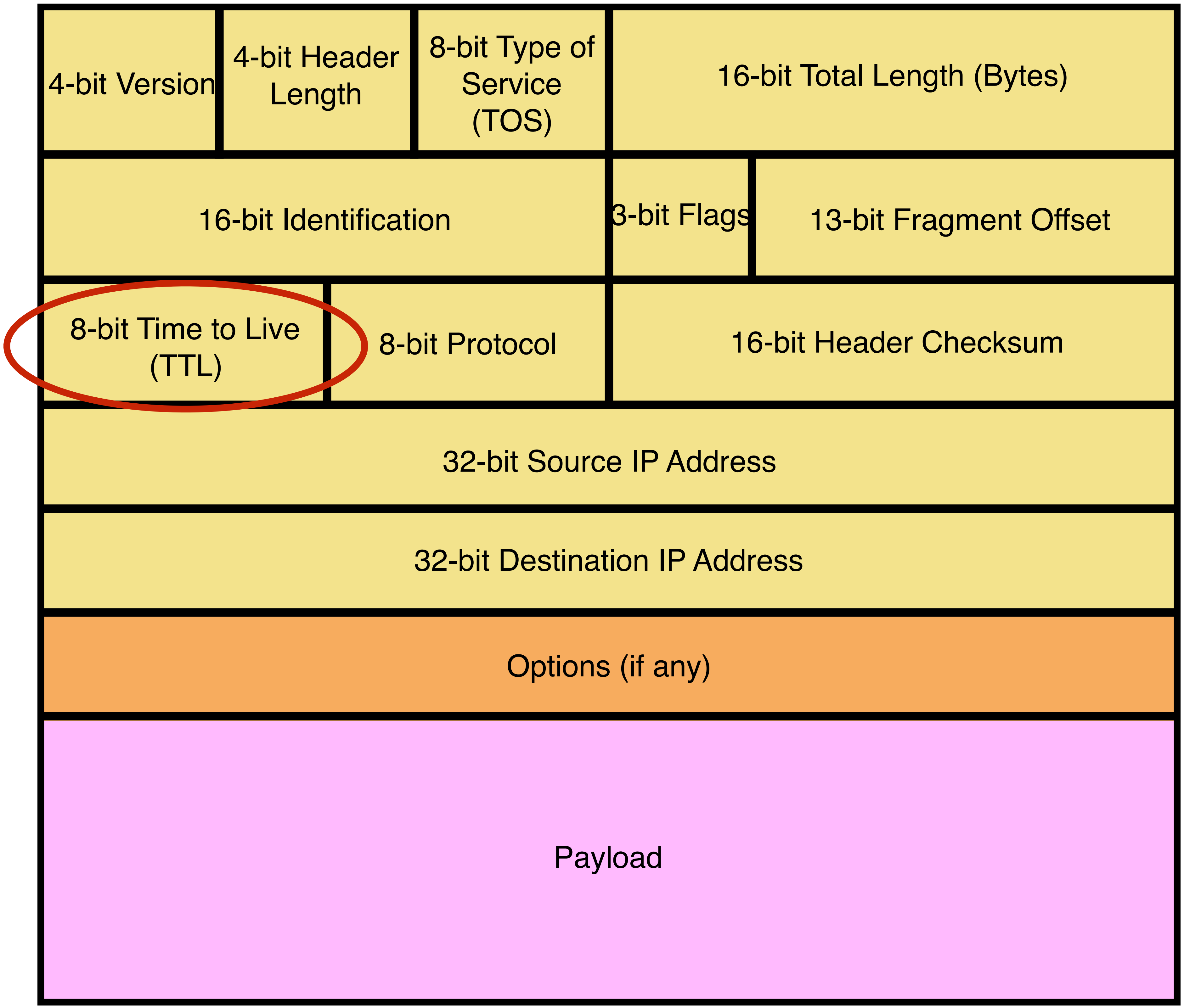
Preventing Loops

- Forwarding loops cause packets to cycle forever
  - As these accumulate, eventually consume all capacity



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

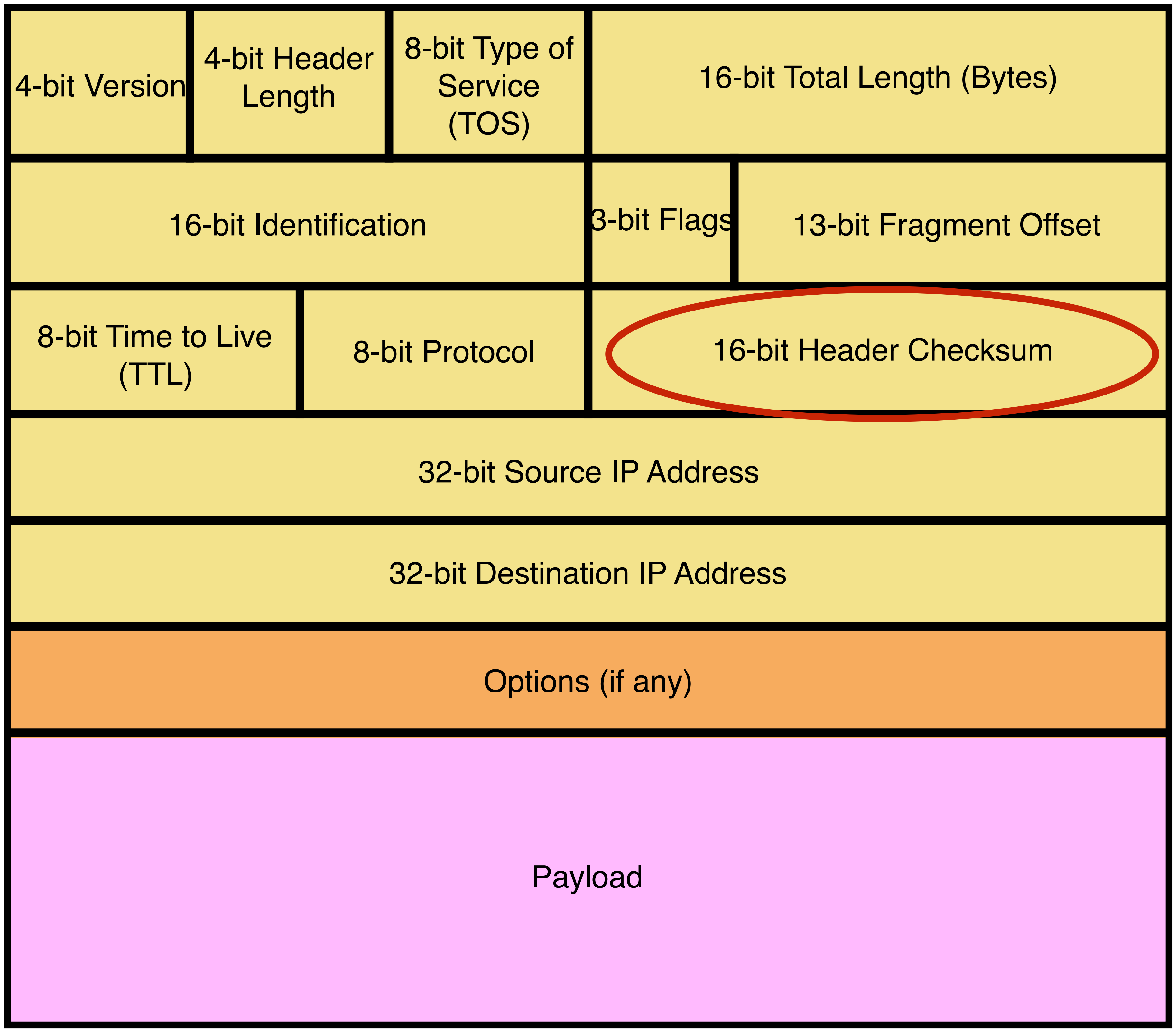
TTL Field


4-bit Version
4-bit Header Length
8-bit Type of Service (TOS)
16-bit Total Length (Bytes)
16-bit Identification
3-bit Flags
13-bit Fragment Offset
8-bit Time to Live (TTL)
8-bit Protocol
16-bit Header Checksum
32-bit Source IP Address
32-bit Destination IP Address
Options (if any)
Payload

Header Corruption

- Checksum (16 bits)
  - Particular form of checksum over packet header
- If not correct, router discards packets
  - So it doesn’t act in bogus information
- Checksum recalculated at every router
  - Why?
  - Why include TTL?
  - Why only header?

Checksum Field



Addressing

Addressing so far

- Each node has a "name"
  - We have so far worked only with names
  - Assumed that forwarding/routing etc. done on names
- Today:
  - Why do we need addresses?
  - Why do we assign addresses the way we assign addresses?
  - And why thats the wrong way!

Current Addressing

- Reflects series of necessary hacks
    - Necessary to survive, but not pretty
- No one would design such a system from scratch
- Let me walk you through the same that is today's addressing

Why addresses?

- Used by routers to forward packets to destination
  - A “Locator”, so to say …
- Sometimes also used as **identifiers**
  - Must let destination know packet was for them
    - Destinations know what their address is
- Typically, addresses are mostly locators
  - Contains information about **how to reach** the destination host

Two requirements for addressing

- **Scalable routing**
  - How much state must be exchanged to create paths?
  - How must state must be stored to forward packets?
  - How much state needs to be updated upon host arrival/departure?

- **Efficient forwarding**
  - How quickly can one locate items in routing table?
  - Some addressing schemes make this easier than others

- **Host must be able to recognize packet is for them**

Recognizing packets are for the destination

- Address can contain something intrinsic to the destination

- I know my current address
    - Can recognize that incoming packet is using that address

- Different layers handle this differently
    - L2 addresses are intrinsic
    - L3 addresses are assigned (and ephemeral)

Layer 2: "Flat" Addressing

- Typically uses MAC address
  - "Names", remember? Used as identifier
- Unique identifiers hardcoded in the hardware
  - No location information
- Local area networks route on these "flat" addresses
  - Each switch stores a separate routing entry **for each host**
- Works nicely with Spanning Tree Protocol
  - Routes set up "on demand"

How does this meet our requirements?

- Scalable routing
  - Can scale to size of L2 networks
- Efficient forwarding
  - Exact match lookup on MAC addresses
  - Only need table for “active” hosts
- Host must be able to recognize the packet is for them
  - MAC address does this perfectly
  - Conclusion: scaling limited by table size (#hosts)

How would you scale L2

- Suppose we want to design a much larger L2 network

- Must use MAC address as part of the address
  - Only way host knows that the packet is for them

- **But how do you avoid having separate routing entry for each host?**

How would you scale L2

- Lets try to design an addressing scheme to achieve our requirements:
    - Scalable routing on large networks
        - Small routing tables (less than #hosts)
        - Small number of updates upon each host arrival/departure
    - Efficient forwarding
        - Fast to look up from the table
    - Destination must be able to identify the packet is for it

Solution

- Addresses are of form — Switch:Host

- All internal forwarding done on switch addresses
  - Fewer in number (than hosts)
  - Very stable

- Mapping between hosts and switches
  - A mechanism we'll study soon …
  - Information only kept at the end-hosts

- Hosts know that packet is for them
  - Using MAC addresses
  - Don't need to know which switch they are at

How do we extend this to the entire Internet?

- Routing tables cannot have entry for each switch in the Internet
- Cannot flood when you don’t know where someone is

One solution

- Use addresses of the form — Network:Host

- Routers know how to reach all networks in the world
    - Routers ignore host part of the address
    - Hosts can recognize when packets are from them (host)

- Each network knows how to reach local hosts
    - E.g., using L2

- A lookup mechanism allows hosts to know where every host is
    - That is, which network to send to

- **This was the original IP addressing scheme**

What do I mean by "network"

- In the original IP addressing scheme …
  - Network meant an L2 network
  - Often referred to as a "subnet"
  - There are too many of them now to scale

Two key aspects of the solution

- Aggregation
- Mapping between identifier and locator

Aggregation

- Aggregation: single forwarding entry used for many individual hosts

- Example:
  - In our scalable L2 solution: aggregate was switch
  - L3: aggregate was network

- Advantages:
  - Fewer entries and more stable
  - Change of hosts do not change tables
    - Don’t need to keep state on individual hosts

Name/Identifier to Location Mapping

- Uses Domain Name System
  - Remember?
  - We are going to discuss this in a few lectures ….

- Use “name” as an identifier

- Returns the IP address as a locator

Where are we?

- Have a sensible addressing scheme for scaling L2
  - Use MAC addresses for host addressing
  - But forward based on destination switch addresses
- We have a sensible addressing scheme for L3
  - Use Network:Host addressing
  - Routers forward on network fields

How do these fit together?

- When sending a packet from A to B …
- A sends over L2 network to “edge” router
  - Using MAC address of router and L2 forwarding
- Series of routers carry packets to B’s L2 network
  - Looking at network portion of IP address
- B’s L2 network delivers packets to B
  - Using B’s MAC address and L2 forwarding
  - But, but, but ….
  - How do you find out what B’s MAC address is?
    - ARP (discussed later)

Hierarchical Structure

- The Internet is an “inter-network”
  - Used to connect networks together, not hosts

- Forms a natural two-way hierarchy
  - Wide area network (WAN) delivers to the right LAN
  - LAN delivers to the right host

Hierarchical Addressing

- Can you think of an example?

- Addressing in the US mail
    - Country
    - City, Zip code
    - Street
    - House Number
    - Occupant “Name”

Quick review

- Original IP addressing — Network:Host
- Elegant, but perhaps not sufficiently scalable
- How would you make it more scalable?

Extending the L3 solution

- If too many networks, then could add another layer
- ISP:Network:Host
- Network might be one of the many L2 networks within an ISP
- Can add additional levels of hierarchy (e.g., region)
- And can do flat routing at each level
    - Address can be both locator (prefix) and identifier (suffix)
- Simple, elegant, easy to implement, as scalable as one wants…
- But that’s not what happened :(

IP addresses

- Unique 32 bit numbers associated with an “interface” (link)
- Use dotted-quad notation, e.g., 12.34.128.5

Original Internet Addresses

- First eight bits: network address (/8)
  - Slash notation indicates network address

- Last 24 bits: host address

- Assumed 256 networks were more than enough!!!
  - Now we have millions!

Suppose we want to accommodate more networks

- We can allocate more bits to network address

- Problem?
    - Fewer bits for host names
    - What if some networks need more hosts?

Today’s Addressing: CIDR

- Classless Inter-domain Routing
- Flexible division between network and host addresses
- Must specify both address and mask
    - Clarifies the boundary between network and host
- Mask carried in routing algorithms
    - Not implicitly carried in address