














Note: We will start at 12:53 pm ET

Course Summary:

Date	Details	
Mon Feb 1, 2021	 18-441/741 Lecture 1	12:50pm to 2:50pm
Wed Feb 3, 2021	 18-441/741 Lecture 2	12:50pm to 2:50pm
Mon Feb 8, 2021	 18-441/741 Lecture 3	12:50pm to 2:50pm
Wed Feb 10, 2021	 18-441/741 Lecture 4	12:50pm to 2:50pm
Fri Feb 12, 2021	 18-441/741 Recitation 1 (Hybrid) -- Project-1 Intro -- Zoom / In-person (A-L)	12:50pm to 1:40pm
Sun Feb 14, 2021	 Quiz 1	due by 11:59pm
Mon Feb 15, 2021	 18-441/741 Lecture 5	12:50pm to 2:50pm
Wed Feb 17, 2021	 18-441/741 Lecture 6	12:50pm to 2:50pm
Mon Feb 22, 2021	 18-441/741 Lecture 7	12:50pm to 2:50pm
Wed Feb 24, 2021	 18-441/741 Lecture 8	12:50pm to 2:50pm
Fri Feb 26, 2021	 18-441/741 Recitation 2 (Hybrid) -- Project-2 Intro -- Zoom / In-person (M-Z)	12:50pm to 1:40pm
Sun Feb 28, 2021	 Quiz 2	due by 11:59pm
	 Project 1	due by 11:59pm

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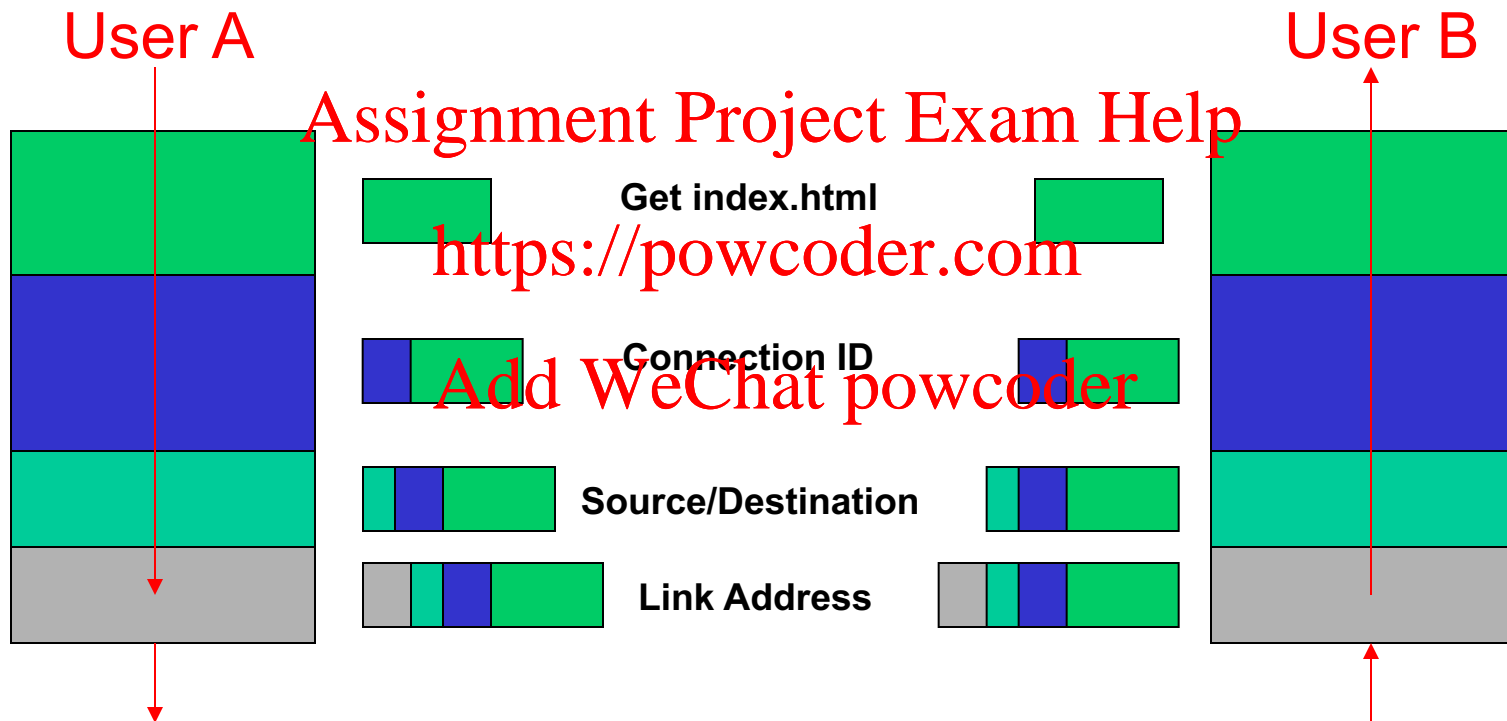


18-441/741: Computer Networks

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Lectures 3: Layers II & PHY I
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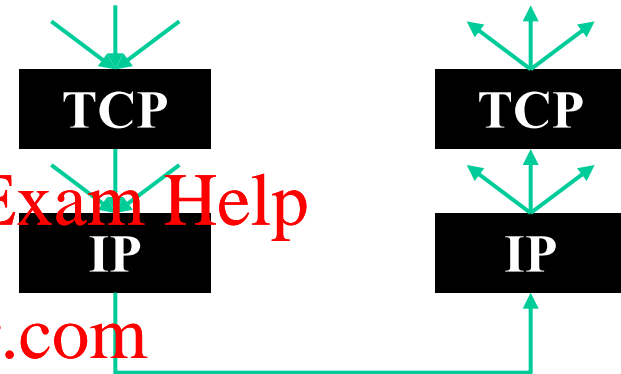
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Swarun Kumar

Layer Encapsulation



Multiplexing and Demultiplexing

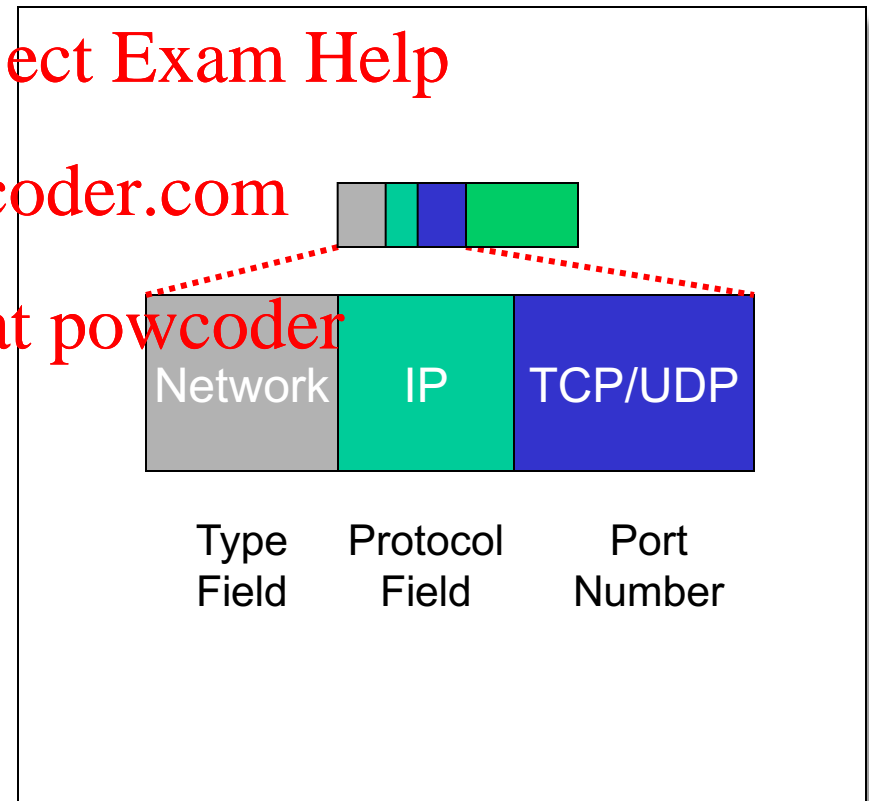
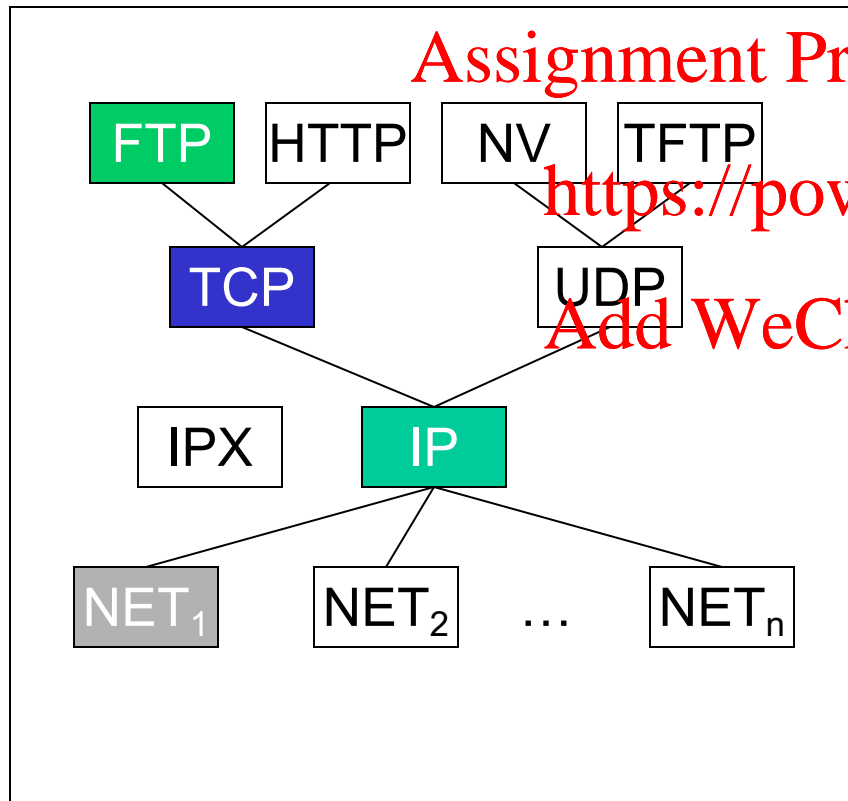
- There may be multiple implementations of each layer.
 - How does the receiver know what version of a layer to use?
- Each header includes a demultiplexing field that is used to identify the next layer.
 - Filled in by the sender
 - Used by the receiver
- Multiplexing occurs at multiple layers. E.g., IP, TCP, ...



V/HL	TOS	Length
ID		Flags/Offset
TTL	Prot.	H. Checksum
Source IP address		
Destination IP address		
Options..		

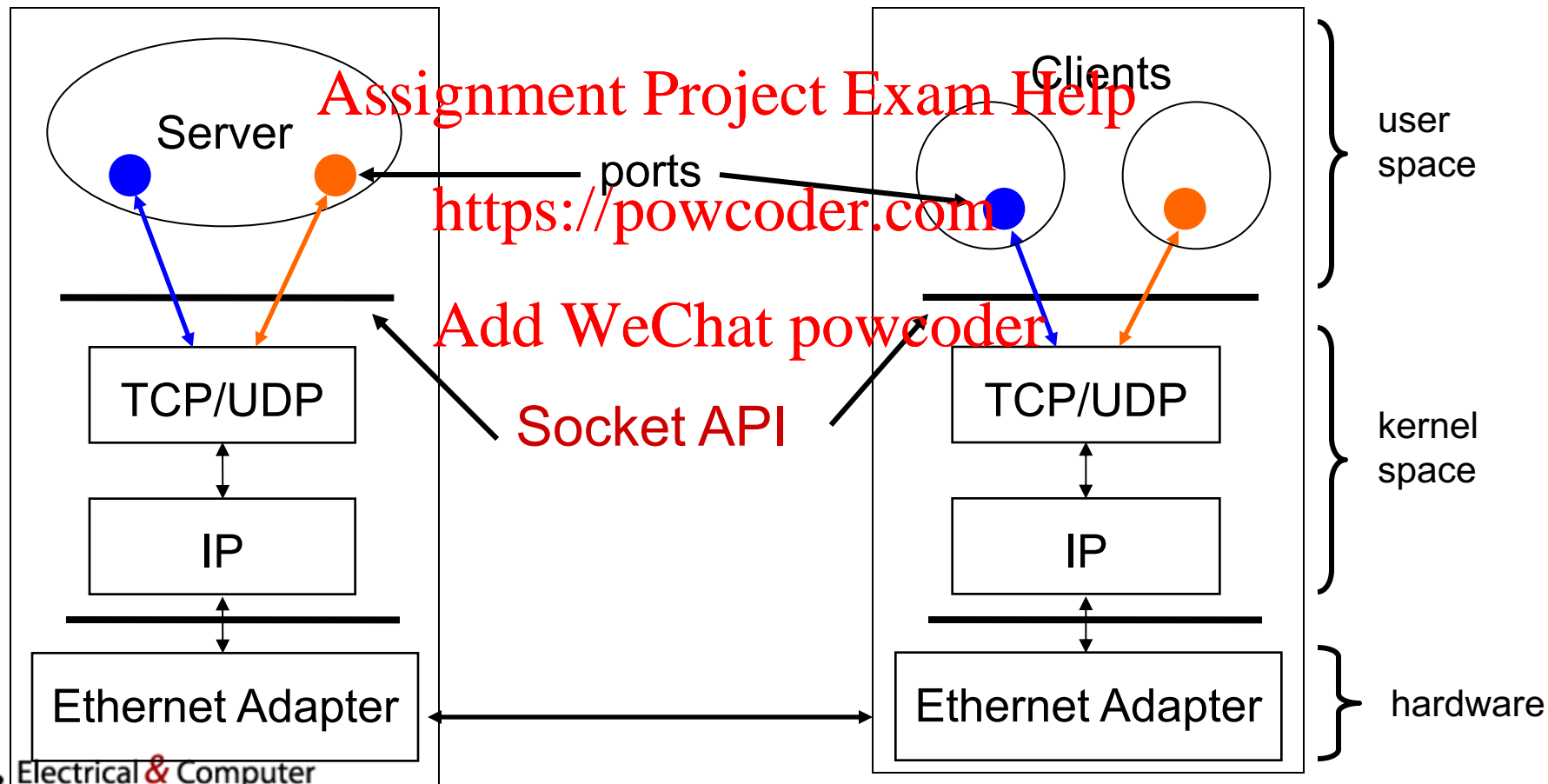
Protocol Demultiplexing

- Multiple choices at each layer

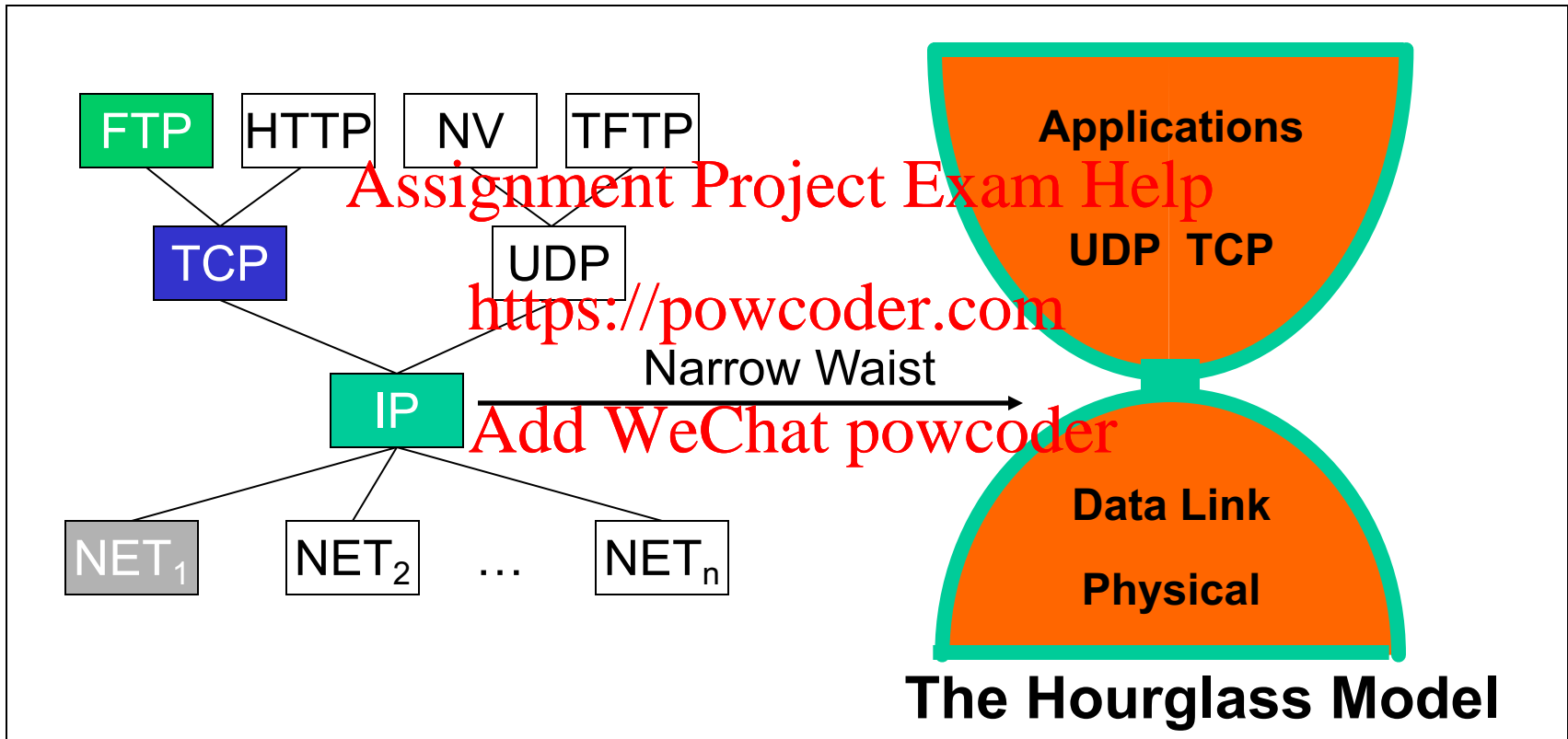


Server and Client

Server and Client exchange messages over the network through a common **Socket API**



The Internet Protocol Suite



The waist facilitates interoperability
... but evolution is hard

IP based on a Minimalist Approach

- Dumb network
 - IP provide minimal functionalities to support connectivity
 - Addressing, forwarding, routing
- Smart end system
 - Transport layer or application performs more sophisticated functionalities
 - Flow control, error control, congestion control
- Advantages
 - Accommodate heterogeneous technologies (Ethernet, modem, satellite, wireless)
 - Support diverse applications (telnet, ftp, Web, X windows)
 - Decentralized network administration

Sample Quiz Question

- Question: Which of these will be hardest launch at Internet-scale:

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[Option A] a new version of TCP,

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[Option B] a new version of IP

[Option C] or a new version of WiFi

- Answer: New IP (why?)

Today's Lecture

- Network applications
 - Requirements
 - Latency and bandwidth
- Internet architecture
 - A layered design
 - Protocols
 - Life of a packet
- Network utilities

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Protocol Stack (cotd.)

- Network applications
 - Requirements
 - Latency and bandwidth
- Internet architecture
 - A layered design
 - Protocols
 - Life of a packet
- Network utilities

Network tools

- ping
- traceroute Assignment Project Exam Help
- ipconfig <https://powcoder.com>
- tcpdump Add WeChat powcoder
- ...

ping

- Application to determine if host is reachable
- Based on Internet Control Message Protocol
 - ICMP informs source host about errors encountered in IP packet processing by routers or by destination host
 - ICMP Echo message requests reply from destination host
- PING sends echo message & sequence #
- Determines reachability & round-trip delay
- Sometimes disabled for security reasons

```
PING google.com (68.65.124.59): 56 data bytes
64 bytes from 68.65.124.59: icmp_seq=0 ttl=60 time=13.022 ms
64 bytes from 68.65.124.59: icmp_seq=1 ttl=60 time=16.723 ms
64 bytes from 68.65.124.59: icmp_seq=2 ttl=60 time=16.057 ms
64 bytes from 68.65.124.59: icmp_seq=3 ttl=60 time=13.777 ms
64 bytes from 68.65.124.59: icmp_seq=4 ttl=60 time=17.644 ms
^C
--- google.com ping statistics ---
5 packets transmitted, 5 packets received, 0.0% packet loss
round-trip min/avg/max/stddev = 13.022/15.445/17.644/1.760 ms
```

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```
Swaruns-MacBook-Pro-4:~ swarun$ ping weibo.com
PING weibo.com (123.125.104.197): 56 data bytes
64 bytes from 123.125.104.197: icmp_seq=0 ttl=41 time=232.848 ms
64 bytes from 123.125.104.197: icmp_seq=1 ttl=41 time=297.449 ms
64 bytes from 123.125.104.197: icmp_seq=2 ttl=41 time=316.311 ms
64 bytes from 123.125.104.197: icmp_seq=3 ttl=41 time=235.104 ms
^C
--- weibo.com ping statistics ---
4 packets transmitted, 4 packets received, 0.0% packet loss
round-trip min/avg/max/stddev = 232.848/270.428/316.311/37.066 ms
```

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traceroute

- Find route from local host to a remote host
- Time-to-Live (TTL)
 - IP packets have TTL field that specifies maximum # hops traversed before packet discarded
 - Each router decrements TTL by 1
 - When TTL reaches 0 packet is discarded
- Traceroute
 - Send UDP to remote host with TTL=1
 - First router will reply ICMP Time Exceeded Message
 - Send UDP to remote host with TTL=2, ...
 - Each step reveals next router in path to remote host
- **tracert** (windows), **tracpath** (linux)


```

Swaruns-MacBook-Pro-4:~ swarun$ traceroute facebook.com
traceroute to facebook.com (31.13.69.228), 64 hops max, 52 byte packets
 1 pod-w-vl75.gw.cmu.net (128.237.128.1) 62.820 ms 5.246 ms 1.859 ms
 2 core255-pod-w-cyh.gw.cmu.net (128.2.255.241) 1.966 ms 1.548 ms 1.755 ms
 3 pod-i-dcns-core255.gw.cmu.net (128.2.255.194) 86.446 ms 2.744 ms 1.807 ms
 4 100.121.0.37 (100.121.0.37) 2.053 ms 2.089 ms 2.169 ms
 5 tr-cps.pennren.3rox.net (147.73.18.141) 2.336 ms 2.851 ms 2.030 ms
 6 et-4-0-0.512.sdn-sw.pitt.net.internet2.edu (198.71.47.181) 9.345 ms 4.421 ms 3.444 ms
 7 et-8-3-0.4079.sdn-sw.ashb.net.internet2.edu (162.252.70.52) 12.930 ms 12.143 ms 12.822 ms
 8 lo-0.8.rtr.ashb.net.internet2.edu (64.57.29.131) 12.823 ms 12.352 ms 12.783 ms
 9 ae14.pr06.iad3.tfbnw.net (103.4.97.230) 14.077 ms
   dc5.pr01.iad2.tfbnw.net (206.126.236.191) 13.729 ms
   ae21.pr05.iad3.tfbnw.net (103.4.97.144) 13.153 ms
10 po104.psw04.iad3.tfbnw.net (31.13.28.99) 12.135 ms
   po106.psw04.iad3.tfbnw.net (157.240.43.131) 12.683 ms
   po105.psw01.iad3.tfbnw.net (31.13.31.169) 11.950 ms
11 173.252.67.27 (173.252.67.27) 12.508 ms
   173.252.67.111 (173.252.67.111) 13.686 ms
   173.252.67.139 (173.252.67.139) 12.432 ms
12 edge-star-mini-shv-01-iad3.facebook.com (31.13.69.228) 12.942 ms 12.665 ms 12.358 ms

```

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ipconfig

- Utility in Microsoft Windows to display TCP/IP information about a host
- Many options
 - Simplest: IP address, subnet mask, default gateway for the host
 - Information about each IP interface of a host
 - DNS hostname, IP addresses of DNS servers, physical address of network card, IP address, ...
 - Renew IP address from DHCP server

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```
Swaruns-MacBook-Pro-4:~ swarun$ ifconfig en0
en0: flags=8863<UP, BROADCAST, SMART, RUNNING, SIMPLEX, MULTICAST> mtu 1500
    ether b8:f6:b1:1b:9a:d5
    inet6 fe80::32:64c1:b470:7030%en0 prefixlen 64 secured scopeid 0x7
    inet 128.237.142.42 netmask 0xffffffff broadcast 128.237.143.255
    nd6 options=201<PERFORMNUD, DAD>
    media: autoselect
    status: active
```

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netstat

- Queries a host about TCP/IP network status
- Status of network drivers & their interface cards
 - #packets in, #packets out, errored packets, ...
- State of routing table in host
- TCP/IP active server processes
- TCP active connections

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Swaruns-MacBook-Pro-4:~ swarun\$ netstat

Active Internet connections

Proto	Recv-Q	Send-Q	Local Address	Foreign Address	(state)
tcp4	0	0	swaruns-mbp-4.wv.61551	198.98.22.58.https	ESTABLISHED
tcp4	0	0	swaruns-mbp-4.wv.61540	ec2-52-4-191-33..https	ESTABLISHED
tcp4	0	0	swaruns-mbp-4.wv.61536	upload-lb.eqiad..https	ESTABLISHED
tcp4	0	0	swaruns-mbp-4.wv.61535	text-lb.eqiad.wi.https	ESTABLISHED
tcp4	0	0	swaruns-mbp-4.wv.61530	www.ece.cmu.edu.https	ESTABLISHED
tcp4	0	0	swaruns-mbp-4.wv.61523	172.217.3.98.http	ESTABLISHED
tcp4	31	0	swaruns-mbp-4.wv.61491	162.125.33.7.https	CLOSE_WAIT
tcp4	0	0	swaruns-mbp-4.wv.61441	172.217.10.10.https	CLOSE_WAIT
tcp4	0	0	swaruns-mbp-4.wv.61427	172.217.10.234.https	CLOSE_WAIT
tcp4	0	0	swaruns-mbp-4.wv.61420	172.217.3.106.https	CLOSE_WAIT
tcp4	0	0	swaruns-mbp-4.wv.61419	172.217.6.202.https	CLOSE_WAIT
tcp4	0	0	swaruns-mbp-4.wv.61404	151.101.202.49.https	ESTABLISHED
tcp4	0	0	swaruns-mbp-4.wv.61397	151.101.202.49.https	ESTABLISHED

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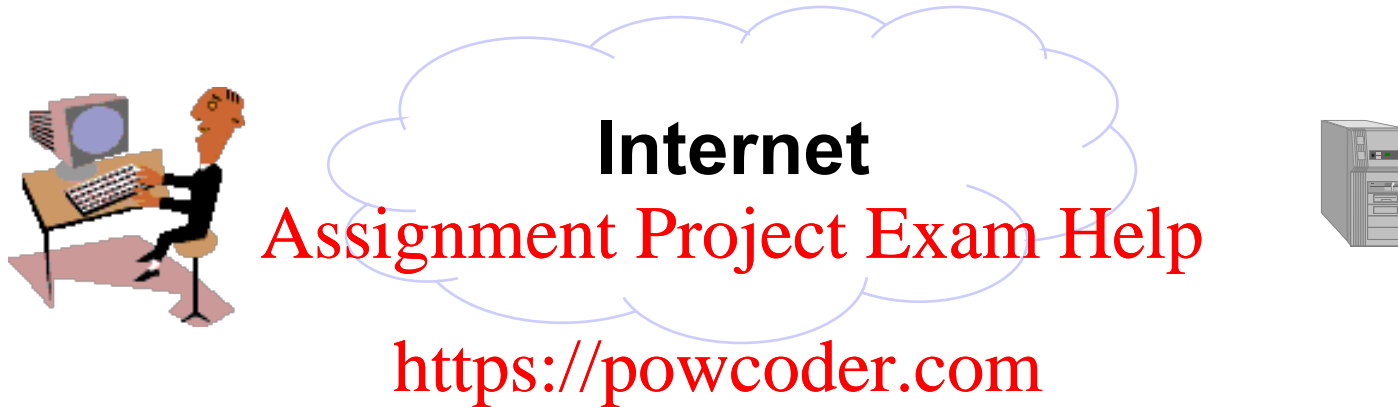
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tcpdump and Network Protocol Analyzers

- tcpdump program captures IP packets on a network interface (usually Ethernet NIC)
- Filtering used to select packets of interest
- Packets & higher-layer messages can be displayed and analyzed
- tcpdump basis for many network protocol analyzers for troubleshooting networks
- We use the open source Ethereal analyzer to generate examples (or wireshark, etc.)
 - www.ethereal.com

How the layers work together: Network Analyzer Example



- User clicks on [Add WeChat powcoder](https://powcoder.com)
- *Ethereal* network analyzer captures all frames observed by its Ethernet NIC (or Wireshark)
- Sequence of frames and contents of frame can be examined in detail down to individual bytes

Top Pane shows
frame/packet
sequence

Middle Pane shows
encapsulation for a
given frame

nytimespac

File Edit Capture

No.	Time	Source	Destination	Protocol	Info
1	0.000000	128.100.11.13	128.100.100.128	DNS	Standard query A www.nytimes.com
2	0.129976	128.100.100.128	128.100.11.13	DNS	Standard query response A 64.15.247.200 A 64.15.247.24
3	0.131524	128.100.11.13	64.15.247.200	TCP	1127 > http [SYN] Seq=1396200325 Ack=0 win=16384 Len=0
4	0.168286	64.15.247.200	128.100.11.13	TCP	http > 1127 [SYN] Seq=1396200325 Ack=3638689753 win=17
5	0.168320	128.100.11.13	64.15.247.200	TCP	1127 > http [ACK] Seq=1396200326 Ack=1396200326 win=17
6	0.168688	128.100.11.13	64.15.247.200	HTTP	GET / HTTP/1.1
7	0.205439	64.15.247.200	128.100.11.13	TCP	http > 1127 [ACK] Seq=1396200326 Ack=3638690402 win=32
8	0.236676	64.15.247.200	128.100.11.13	HTTP	HTTP/1.1 200

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Frame 1 (75 bytes on wire, 75 bytes captured)

Ethernet II, Src: 00:90:27:96:b8:07, Dst: 00:e0:52:ea:b5:00

Internet Protocol, Src Addr: 128.100.11.13 (128.100.11.13), Dst Addr: 128.100.100.128 (128.100.100.128)

User Datagram Protocol, Src Port: 1126 (1126), Dst Port: domain (53)

Domain Name system (query)

Offset	Hex	Text
0000	00 e0 52 ea b5 00 00 90 27 96 b8 07 08 00 45 00	..R.....'.....E.
0010	00 3d 54 41 00 00 80 11 76 19 80 64 0b 0d 80 64	..=TA....v..d...d
0020	64 80 04 66 00 35 00 29 49 83 00 a5 01 00 00 01	d..f.5.) I.....
0030	00 00 00 00 00 00 03 77 77 77 07 6e 79 74 69 6dw ww.nytim
0040	65 73 03 63 6f 6d 00 00 01 00 01	es.com.. ...

Filter:

Bottom Pane shows hex & text

Top pane: Sequence

DNS Query

TCP Connection
Setup

HTTP
Request &
Response

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The image shows a Wireshark packet capture of a network sequence. The top pane displays a list of packets with the following details:

No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	128.100.11.13	128.100.100.128	DNS	60	Standard query A www.nyti
2	0.129976	128.100.100.128	128.100.11.13	DNS	60	Standard query response
3	0.131324	128.100.11.13	64.15.247.200	TCP	60	1127 > http [SYN] Seq=363
4	0.168286	64.15.247.200	128.100.11.13	TCP	60	http > 1127 [SYN, ACK] Seq=1
5	0.168320	128.100.11.13	64.15.247.200	TCP	60	1127 > http [ACK] Seq=36386
6	0.168688	128.100.11.13	64.15.247.200	HTTP	100	GET / HTTP/1.1
7	0.205439	64.15.247.200	128.100.11.13	TCP	60	http > 1127 [ACK] Seq=1396200326
8	0.236676	64.15.247.200	128.100.11.13	HTTP	100	HTTP/1.1 200 OK

The bottom pane shows the details of Frame 1 (75 bytes on wire, 75 bytes captured):

- Ethernet II, Src: 00:90:27:96:b8:07, Dst: 00:e0:52:ea:b5:00
- Internet Protocol, Src Addr: 128.100.11.13 (128.100.11.13), Dst Addr: 128.100.100.128 (128.100.100.128)
- User Datagram Protocol, Src Port: 1126 (1126), Dst Port: domain (53)
- Domain Name system (query)

The packet bytes pane shows the raw data in hexadecimal and ASCII:

```
0000  00 e0 52 ea b5 00 00 90 27 96 b8 07 08 00 45 00  ..R.....'.....E.
0010  00 3d 54 41 00 00 80 11 76 19 80 64 0b 0d 80 64  .=TA....v..d...d
0020  64 80 04 66 00 35 00 29 49 83 00 a5 01 00 00 01  d..f.5.)I.....
0030  00 00 00 00 00 00 03 77 77 77 07 6e 79 74 69 6d  .....w ww.nytim
0040  65 73 03 63 6f 6d 00 00 01 00 01                es.com.. ...
```

Middle pane: Encapsulation

nytimespackets - Ethereal

File Edit Capture Display Tools Help

No.	Time	Source	Destination	Protocol	Length
6	0.168688	128.100.11.13	64.15.247.200	HTTP	GET

Ethernet Frame

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Protocol Type

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Ethernet Destination and Source Addresses

Ethernet II, Src: 00:90:27:96:b8:07, Dst: 00:e0:52:ea:b5:00
Destination: 00:e0:52:ea:b5:00 (Foundry_ea:b5:00)
Source: 00:90:27:96:b8:07 (Intel_86:b8:07)
Type: IP (0x0800)

Internet Protocol Version 4, Src: 128.100.11.13, Dst: 64.15.247.200
Version: 4
Header length: 20 bytes
Differentiated Services Field: 0x00 (DSCP: Default)
Total Length: 60
Identification: 0
Flags: 0x00 (Not set)
Fragment offset: 0
Time to live: 128
Protocol: TCP (0x06)
Header checksum: 0xe0b8 (correct)
Source: 128.100.11.13 (128.100.11.13)
Destination: 64.15.247.200 (64.15.247.200)

Transmission Control Protocol, Src Port: 1127 (1127), Dst Port: http (80), Seq: 3638689753, Ack: 139620032
Hypertext Transfer Protocol

0000 00 e0 52 ea b5 00 00 90 27 96 b8 07 08 00 45 00 ..R.....'.....E.
0010 02 b1 54 45 40 00 80 06 e0 b8 80 64 0b 0d 40 0f ..TE@... ..d...@.
0020 f7 c8 04 67 00 50 d8 e1 ff d9 53 38 53 86 50 18 ...g.P.. ..S8S.P.
0030 43 a4 87 81 00 00 47 45 54 20 2f 20 48 54 54 50 C....GE T / HTTP
0040 2f 31 2e 31 0d 0a 41 63 63 65 70 74 3a 20 69 6d /1.1..Ac cept: im

Filter: / Reset Apply File: nytimespackets

Mid Encapsulation

And a lot of other stuff!

IP Packet

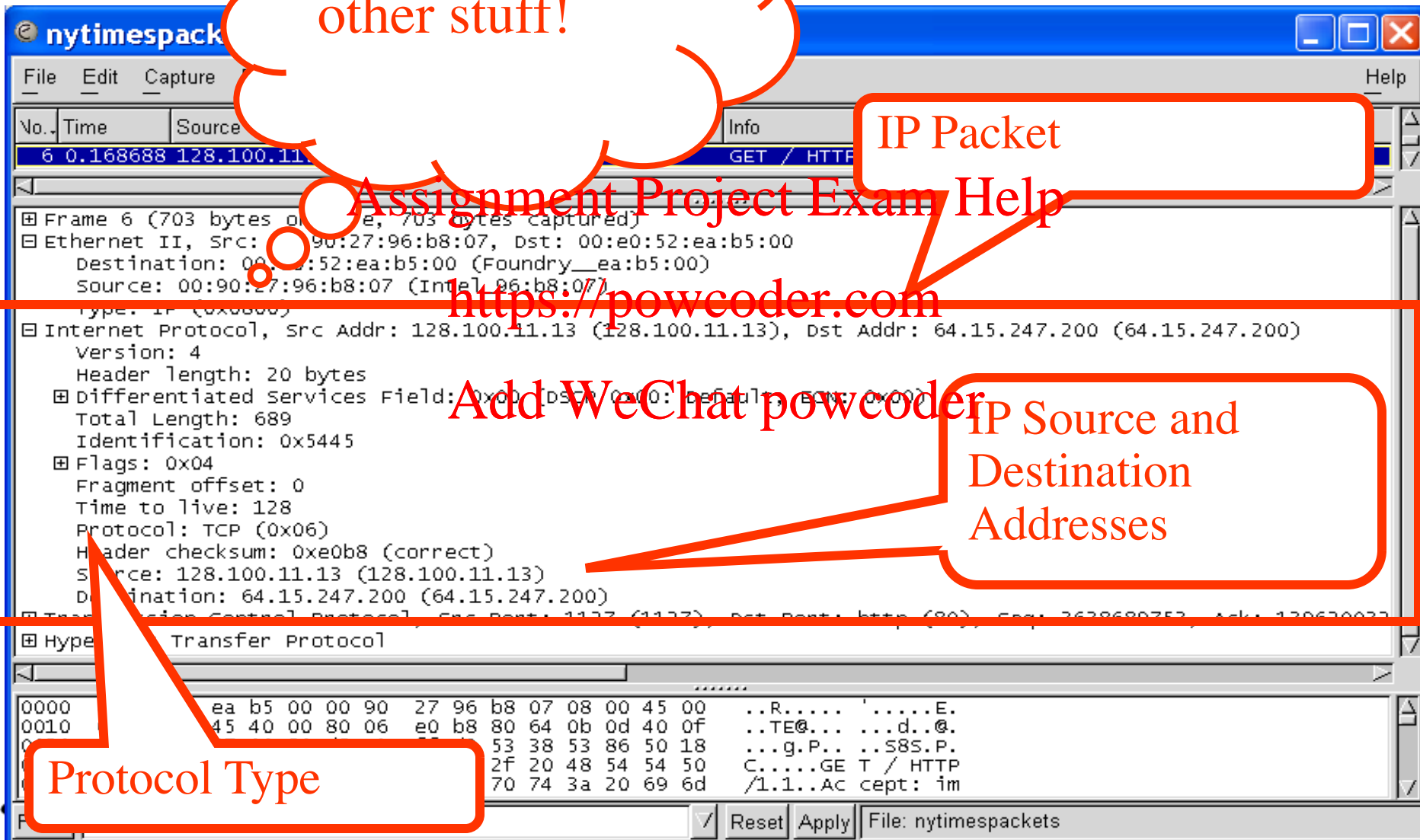
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IP Source and Destination Addresses

Protocol Type



Middle pane: Encapsulation

nytimespackets - Ethereal

File Edit Capture Display Tools Help

No.	Time	Source	Destination	Protocol	Info
6	0.168688	128.100.11.13	64.15.247.200	HTTP	GET / HTTP

Frame 6 (703 bytes on wire (703 bytes captured))

Ethernet II, Src: 00:90:27:96:b8:07, Dst: 00:0e:92:ea:b5:00

Transmission Control Protocol, Src Port: 1127 (1127), Dst Port: http (80), Seq: 3638689753, Ack: 1396200326

Source port: 1127 (1127)

Destination port: http (80)

Sequence number: 3638689753

Next sequence number: 3638690402

Acknowledgement number: 1396200326

Header length: 20 bytes

Flags: 0x0018 (PSH, ACK)

Window size: 17316

Hypertext Transfer Protocol

GET / HTTP/1.1\r\n

Accept: image/gif, image/x-xbitmap, image/ineg, image/pjpeg, application/vnd.ms-powerpoint, application,

Accept-Language: en-us\r\n

Accept-Encoding: gzip, deflate\r\n

User-Agent: Mozilla/4.0 (compatible; MSIE 6.0; windows NT 5.0)\r\n

Host: www.nytimes.com\r\n

Connection: keep-alive\r\n

Cookie: RMID=80e7478f5a393db9fc19f2c4; NYT-S=1002xV091grjagxb2AZ9oxq41qdEE; n=ak385x0NErE87eqe2qome5m08Re\r\n

0000 00 e0 52 ea b5 00 00 90 27 96 b8 07 00 00 00 00

0010 02 b1 54 45 40 00 80 06 e0 b8 80 64 0b 00 00

0020 f7 c8 04 67 00 50 d8 e1 ff d9 53 38 53 80 00

0030 43 a4 87 81 00 00 47 45 54 20 2f 20 48 50 00

0040 2f 31 2e 31 0d 0a 41 63 63 65 70 74 3a 20 00

Filter:

Reset Apply

nytimespackets

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TCP Segment

Source and Destination Port Numbers

GET

HTTP Request

Goals [Clark88]

0 Connect existing networks

initially ARPANET and ARPA packet radio network

1. Survivability

ensure communication service even in the presence of network and router failures

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2. Support multiple types of services

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3. Must accommodate a variety of networks

4. Allow distributed management

5. Allow host attachment with a low level of effort

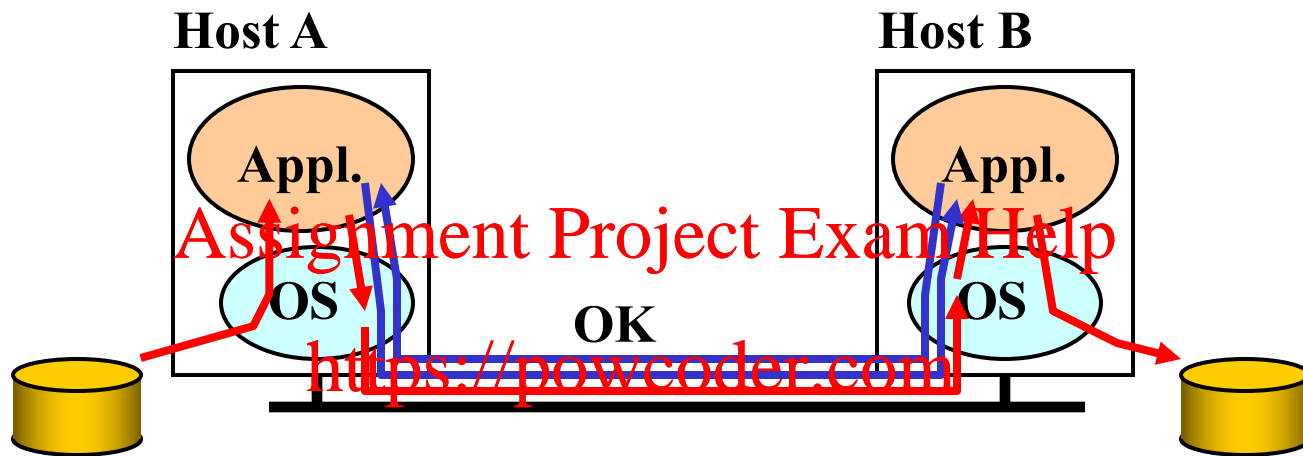
6. Be cost effective

7. Allow resource accountability

Principle: End-to-End Argument (Saltzer'81)

- Focus of the paper is “system”
 - Not a pure networking paper
- Deals with where to place functionality
 - Inside the network (in switching elements)
 - At the edges
- Argument: Some functions can only be correctly implemented by the endpoints – do not try to implement these elsewhere
 - Not a law – more of a “best practices”

Example: Reliable File Transfer



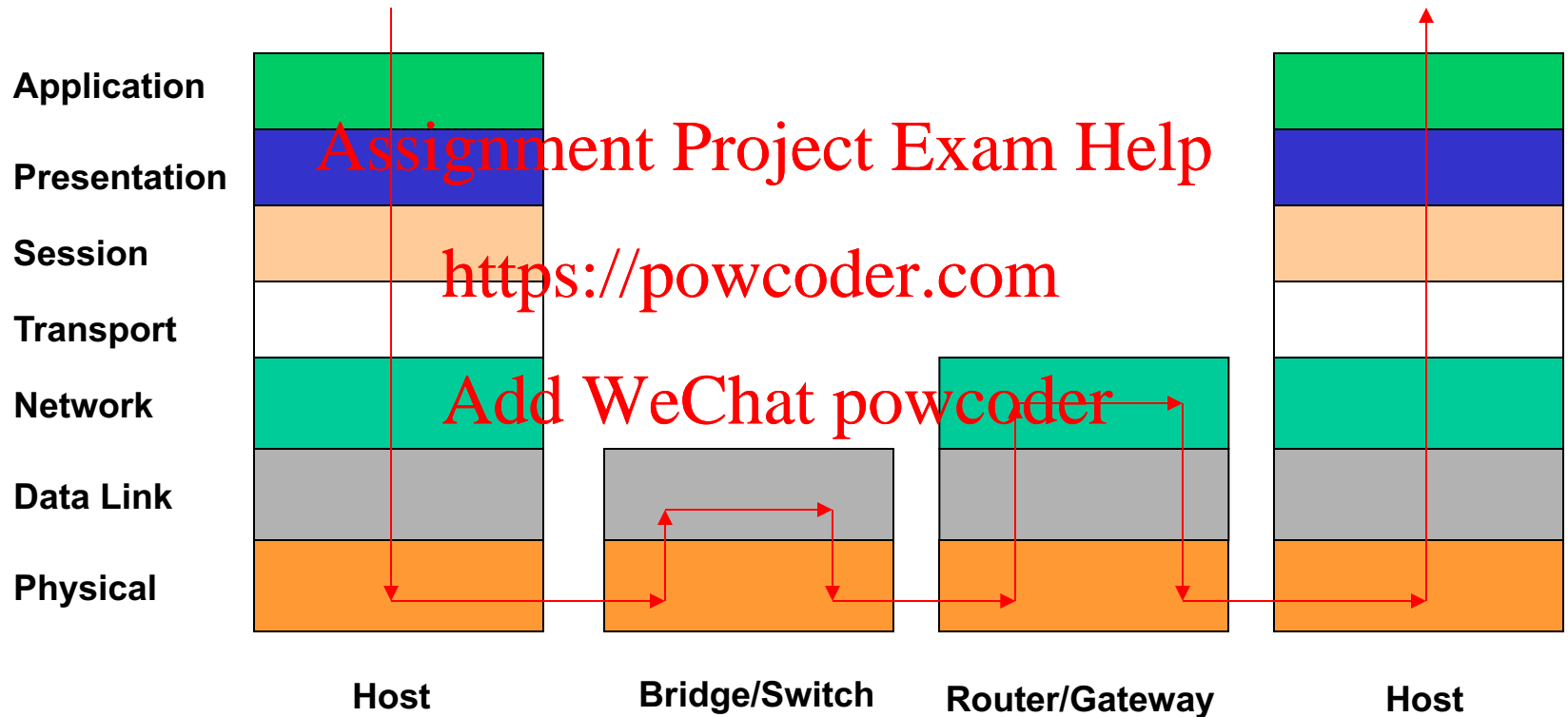
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- Solution 1: make each step reliable, and then concatenate them
- Solution 2: end-to-end check and retry

Sample Quiz Question

- Question: A switch and a router both cost \$100 and have similar specs and achieve similar performance in packet switching/routing. As a rational buyer, I would buy the router. [True/False]
- Answer: True, the router (why?)

Life of Packet



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Physical Layer (PHY) - I
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Physical Layer: Outline

- Digital networking
- Modulation
- Characterization of Communication Channels
- Fundamental Limits in Digital Transmission
- Modems and Digital Modulation
- Line Coding
- Properties of Media and Digital Transmission Systems
- Error Detection and Correction

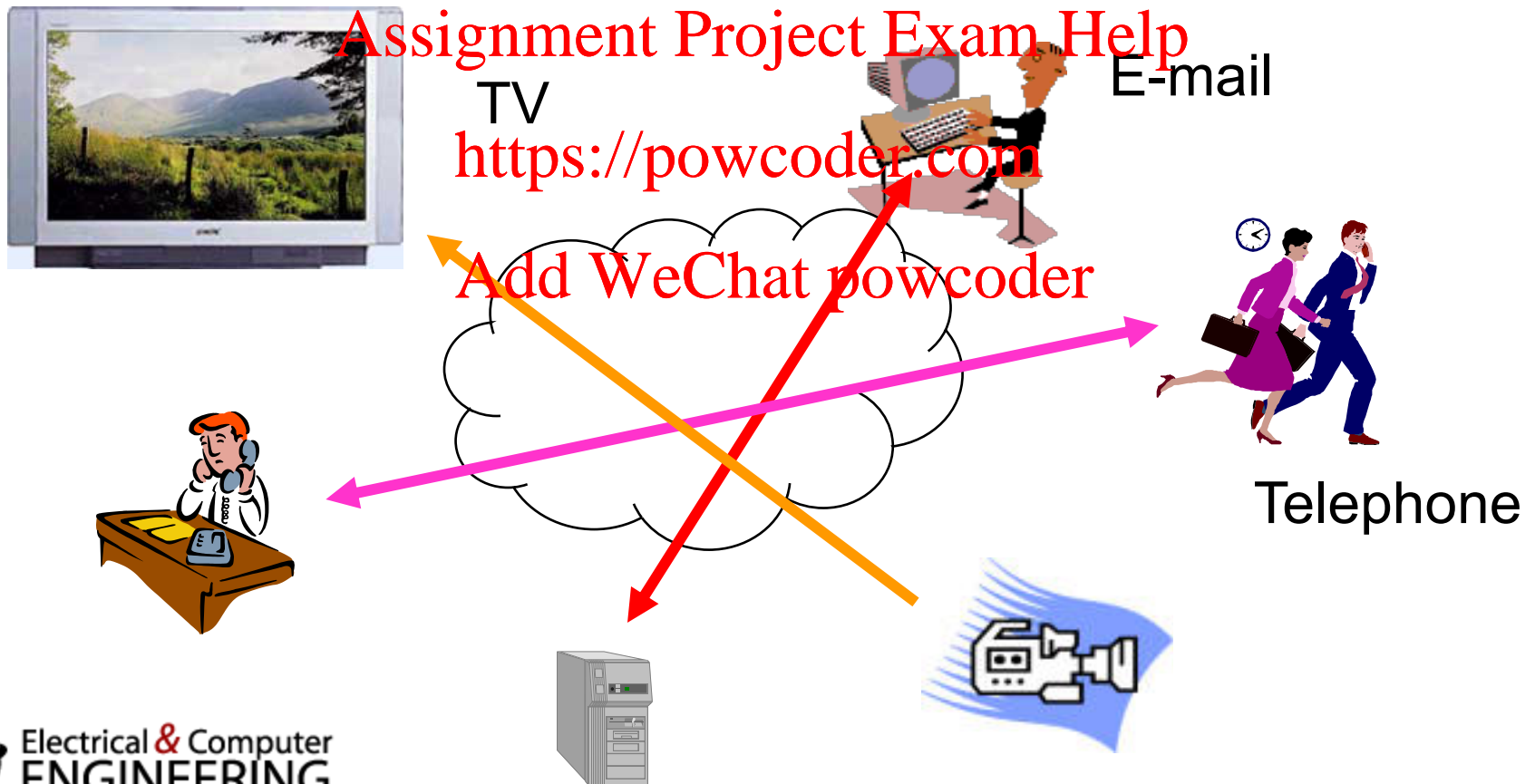
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Digital Networks

- Digital transmission enables networks to support many services



Analog versus Digital Information

- Analog information takes on continuous values [Assignment Project Exam Help](https://powcoder.com)
 - Sound, images, etc.
- Digital information takes on discrete values [Add WeChat powcoder](https://powcoder.com)
 - Text, banking data, etc.
- Can convert between the two representations of information
 - Sampling and interpolation

Block vs. Stream Information

Block

- Information that occurs in a single block

- Text message
- Data file
- JPEG image
- MPEG file

- Size = bits / block

or Bytes/block

- 1 KByte (KB) = 2^{10} bytes
- 1 MByte (MB) = 2^{20} bytes
- 1 GByte (GB) = 2^{30} bytes

Stream

- Information that is produced & transmitted continuously

- Real-time voice
- Streaming video

- Bit rate = bits / second

- 1 Kbps = 10^3 bps
- 1 Mbps = 10^6 bps
- 1 Gbps = 10^9 bps

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Many Types of Information

	Analog	Digital
Stream	Voice, video	Stock market
Block	Images, radar map, ...	Spreadsheets, text file, ...

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Traditional Communication Options

- Send analog information over analog networks
 - Voice over the telephone network
 - Video using broadcast TV
 - Pictures using the USPS
- Send digital information over digital networks
 - Messages via telegraph: beacons ... electrical
 - Internet: many applications, e.g., http, (text) email, ssh, social networks, ...

But Can Mix and Match

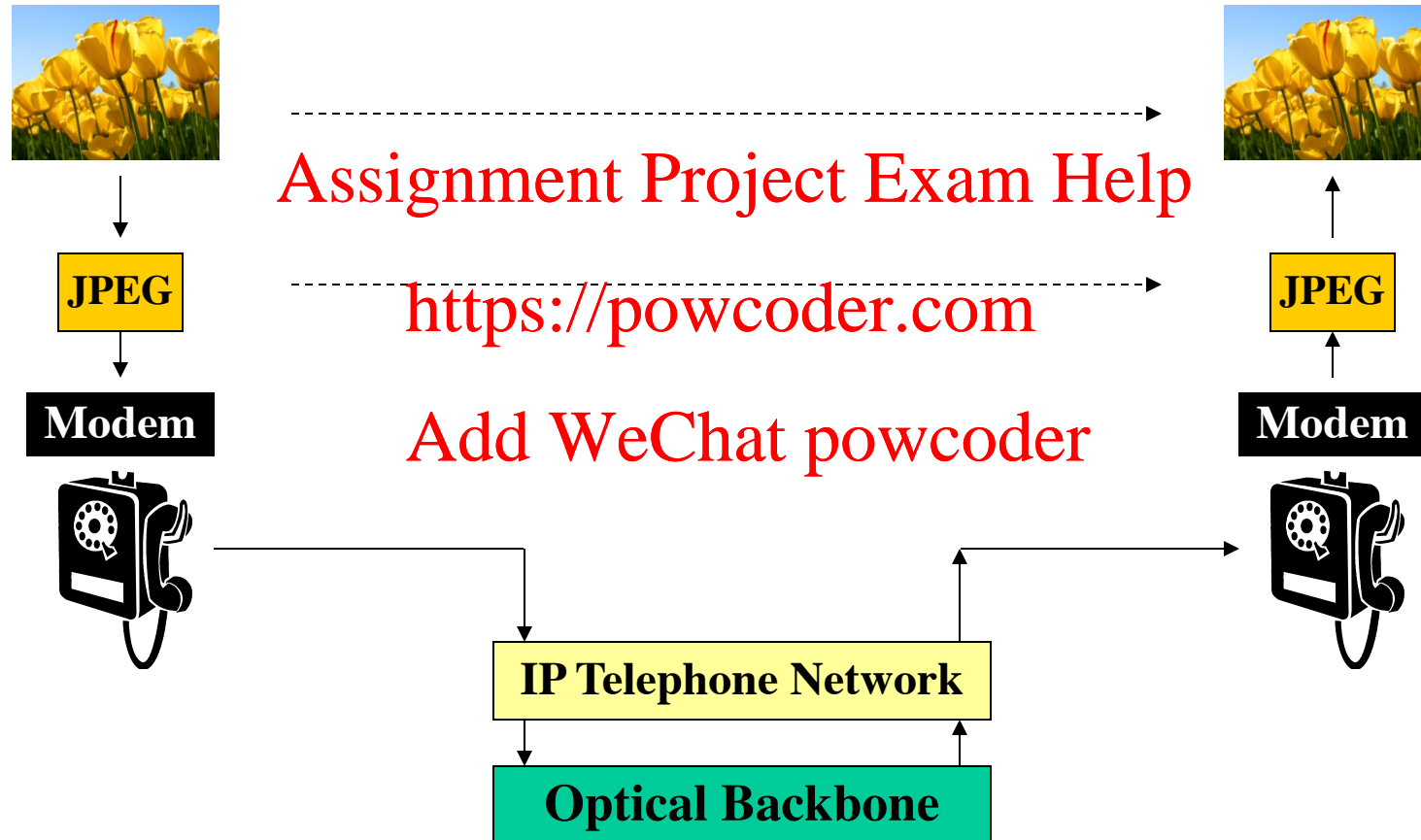
- Analog information can be digitized and sent over digital network
 - Video becomes MPEG
 - Image becomes JPEG
- Digital networks use analog channels
 - Bits are encoded on analog waveforms
 - But switching is done based on the bits

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Example



Why Use a Single Digital Network?

- Economically advantageous to have a single network
- Multimedia applications want to mix different types of data
 - More convenient if a single networks is used
- Computers operate only on digital data
- Digital transmission can recover from errors (e.g. noise, distortion)
 - Not possible when transmitting analog information over an analog network

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Analog Transmission

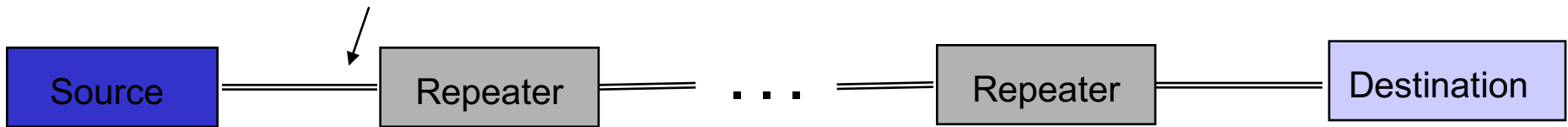
All details must be reproduced accurately

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Why digital? Problem with Analog Long-Distance Communications

Transmission segment

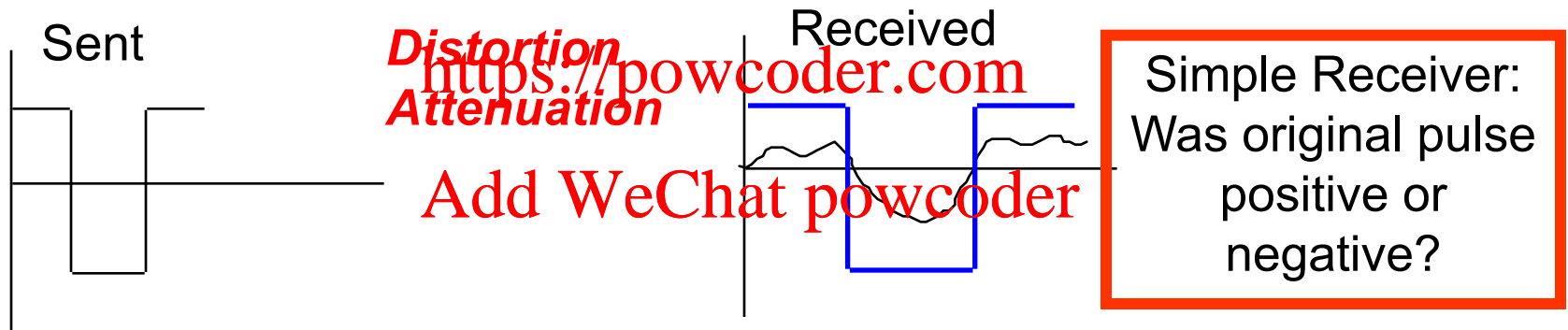


- Each repeater attempts to restore analog signal to its original form
- Restoration is imperfect
 - Distortion is not completely eliminated
 - Noise & interference is only partially removed
- Signal quality decreases with # of repeaters
- Communications becomes distance-limited
- Still used in analog cable TV systems
- Analogy: Copy a song using a cassette recorder

Digital Transmission

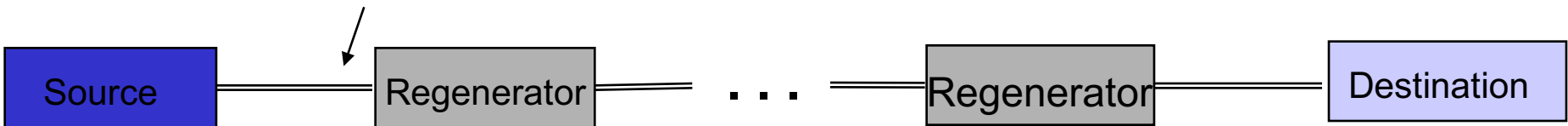
Only discrete levels need to be reproduced

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Digital Long-Distance Communications

Transmission segment



- Regenerator recovers original data sequence and retransmits on next segment
- Can design so error probability is very small
- Then each regeneration is like the first time!
- Analogy: copy an MP3 file
- Communications is possible over very long distances
- Digital systems advantage over analog systems
 - Less power, longer distances, lower system cost
 - Monitoring, multiplexing, coding, encryption, protocols...