1 (15%)

(a) Indicate the lower three layers in the ISO OSI seven-layer model. (ch 1.5)
Physical layer, (Data-) Link layer, Network layer (each 1%)

(b) Please determine the Internet checksum of the following two bit streams: 1000101001111110 and 0011101111001111. (ch 3.3.2)
Sum of bit streams→1's complement→0011100110110010 (0.5% per bit)

(c) Compare *datagram network* and *virtual-circuit network* in terms of their connection setup, addressing, effect of router failure (i.e., who will be affected?), QoS support flexibility, and operational complexity. (ch 4.2)

	Datagram network	Virtual-circuit network
Connection setup	No needed	Required
Addressing	Each packet contains full source and destination address	Each packet contains a short VC number
Effect of router failure	None, except for packets lost during the crash	All VCs that passed through the failed router are terminated
QoS support flexibility	Difficult	Easy if enough resources can be allocated in advance for each VC
Operational complexity	Low	High

(d) Please list five key TCP features. (ch 3)
Point-to-point, reliable, in-order byte stream, pipelined, connection-oriented, flow-controlled, full duplex data, send & receive buffers, packet-switching, fairness

(e) Use simple words to describe routing and forwarding. (ch 4.1.1)
forwarding: move packets from router's input to appropriate router output (1.5 %)
routing: determine the route or path taken by packets as they flow from a sender to a receiver (1.5%)

2 (10%)

Compare the delay in sending and *x*-bit message over a *k*-hop path in a circuit switched network and in a lightly packet switched network. The circuit setup time is *s* sec, the propagation delay is *d* sec per hop, the packet size is *p* bits, and the data rate of each link is *b* bps. Under what conditions does the packet switched network have a lower delay?

(Circuit switched) $s + kd + \frac{x}{b}$ (1% + 2% + 2%)

(Packet switched) $\mathrm{kd} + \frac{\mathrm{x}}{\mathrm{b}} + (k-1)\frac{p}{b}$ (1% + 2% + 2%)

Packet switched network has a lower delay if $\mathrm{s} > (\mathrm{k}-1)\frac{p}{b}$ (2%)

3 (20%)

Suppose a 100-Mbps link is being setup between Earth and a new lunar colony. The distance from the moon to Earth is approximately 385,000 km, and data travels over the link at the speed of light $3\mathrm{x}10^8$ m/s.

(a) Calculate the minimum RTT for the link.
The minimum RTT is two times of the propagation delay on the link:
minimum RTT = 2 * Distance / Speed of propagation = 2 * 385,000,000 m / (3 * 10^8 m/s) = 2.566s (3%)

(b) Using the RTT as the delay, calculate the delay x bandwidth product for the link.(1)
delay x bandwidth product = 2.566 s * 100 Mbps = 256.66 Mbits = 32.08 Mbytes. (1%)

(c) What is the significance of the delay x bandwidth product computed in (b)?
The delay x bandwidth product computed in (b) measures the number of bits that can be "inflight", i.e., the amount of data the sender can spend up before receiving a response. (3%)
Minimum receive window size to keep the pipe full. (ch 3.5.5 flow control)

(d) A camera on the lunar base takes pictures of Earth and saves them in digital format to disk. Suppose mission control on earth wants to download the most recent image, which is 25MB. What is the minimum amount of time that will elapse between when the request for the data goes out and the transfer is finished?
Full size = 25 MB = 25 * 1024 * 1024 bytes = 26,214,400 bytes = 26,214,400 * 8b = 209,715,200 bits (2%)
Transmission time = File Size / Bandwidth = 209,715,200 bits / 100,000,000 bits / s = 2.097512 s
Minimum amount of time = transmission time + 2*(1/2)*RTT = 2.097152 s + RTT = 2.097152 s + 2.566 s = 4.663152 s = 2+2.57 = 4.57 s (3% + 2%)

4 (20%)

Compare Go-Back-N (GBN), Selective Repeat (SR), and TCP (no delayed ACK). Assume that the timeout values for all three protocols are sufficiently long such that 5 consecutive data segments and their corresponding ACKs can be received (if not lost in the channel) by the receiving host (Host B) and the sending host (Host A), respectively. Suppose Host A sends 5 data segments to Host B; and the

2^{nd} segment (sent from A) is lost. In the end, all 5 data segments have been correctly received by Host B.

How many segments has Host A sent in total and how many ACKs has Host B sent in total? What are their segment numbers? Answer this question for all three protocols.

If the timeout values for all three protocols are much longer than 5 RTT, then which protocol successfully delivers all five data segments in shortest time intervals?

(1) Total Packet Number (0.5%) Sequence Number(1% or 1.5%)

	GBN	SR	TCP
Total Tx Pkt	9	6	6
Seq.	0,1,2,3,4,1,2,3,4	0,1,2,3,4,1	0,1,2,3,4,1
Total Rx Pkt	8	5	5
Seq.	0,0,0,0,1,2,3,4	0,2,3,4,1	1,1,1,1,5

Answer (8%) Reason (2%)

(2) TCP (8%) TCP + other (4%) All (2%)

TCP, the time of duplicate ACK is shorter than timeout

5 (10%)

Suppose TCP operates over a 1-Gbps link. Assuming TCP could utilize the full bandwidth continuously, how long would it take the sequence numbers to wrap around completely?

TCP uses 32 bits to represent its sequence number so sequence number will wrap around after 2^{32} bytes transmission.

$2^{32} \times 2^3 / 10^9 = 34.36$ or 32 s.

6 (15%)

Suppose that between hosts A and B there is a router R. The A-R bandwidth is infinite (that is, packets are not delayed), but the R-B link introduces a delay of 1 packet per second (that is, 2 packets take 2 seconds, etc.). Acknowledgments from B to R, though, are sent instantaneously. R has a buffer size of three, in addition to the packet it is sending. Host A sends data to Host B over a TCP connection, using slow start but with an infinite receive window. Fast retransmit is done on the ***second*** duplicate ACK (i.e., the third ACK of the same packet). At each second, the sender first processes any arriving ACKs and then responds to any timeout. The timeout interval is fixed at 5 seconds, and slow start is used on a timeout. Ignore fast recovery. Give a table showing, for the first 15 seconds, what are sent and received by A, R, and B? Please also indicate A's congestion window size in each second. (Note: B sends ACK*x* to A for pkt*x*.)

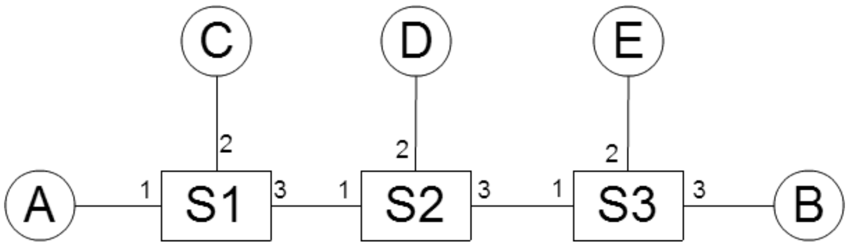
Cwnd & A's sending (4%) Timeout event (4%)

Lost event (4%) Fast retransmit (3%)

Time	A recv ACK	Event (lost, timeout, fast rtx)	Cwnd	A sends	R sending /R's queue
T = 0			1	1	1/
T = 1	1		2	2,3	2/3
T = 2	2		3	4,5	3/4,5
T = 3	3		4	6,7	4/5,6,7
T = 4	4	9 lost	5	8,9	5/6,7,8
T = 5	5	11 lost	6	10,11	6/7,8,10
T = 6	6	13 lost	7	12,13	7/8,10,12
T = 7	7	15 lost	8	14,15	8/10,12,14
T = 8	8	17 lost	9	16,17	10/12,14,16
T = 9	8	9 timeout	1	9	12/14,16,9
T = 10	8	Fast retransmit, 10 11 timeout	1		14/16,9
T = 11	8	12 13 timeout	1		16/9
T = 12	8	14 15 timeout	1		9/
T = 13	10	16 17 timeout	1	11	11/
T = 14	12		2	13,14	13/14
T = 15	14		3	15,16,17	15/16,17

7 (10%)

Consider the virtual circuit switches in Fig. 1. Table 1 lists, for each switch, what (Interface, VCI) pairs are connected to the others. Connections are bidirectional. List all end-to-end connections.



S1			
Incoming		Outgoing	
Port	VCI	Port	VCI
1	2	3	1
1	1	2	3
2	1	3	2

S2			
Incoming		Outgoing	
Port	VCI	Port	VCI
1	1	3	3
1	2	3	2

S3			
Incoming		Outgoing	
Port	VCI	Port	VCI
1	3	2	1
1	2	3	1

Table 1: VC Tables for S1

A→S1→S2→S3→E (4%)

A→S1→C (3%)

C→S1→S2→S3→B (3%)