1. (6 points) Consider a bus-based cell switch with a sub-divided bus with 16 inputs and outputs. Suppose that each cell time, a cell arrives on each input with probability $p$ and that each cell is assigned randomly to a different output. Give an expression for the probability that in a given cell time, output 0 receives exactly one cell.

Suppose the OPP at output 0 has a knockout concentrator that can forward up to six cells per cell time into the OPP’s cell buffer. Give an expression probability that in a given cell time, more cells arrive at output 0 than can be placed in the buffer.

Give an expression the probability that an arriving cell is discarded.
2. (10 points) Consider a ring-based ATM switch with 16 external links operating at 1 Gb/s each. Assume that the ring is 32 bits wide and that the circuit technology being used supports point-to-point lines operating at up to 200 MHz. If the switch adds seven bytes of internal header information to each cell before sending it on the ring, what is the maximum average traffic load that can be supported on the outgoing links?

Assume the ring uses a slotted ring protocol with a busy/idle bit, where each ring interface with a cell to send uses the first empty slot that it sees to send its cell. Suppose traffic is arriving at 1 Gb/s at each of inputs 0 through 7 and this arriving traffic is all going to outputs 8 through 15. What fraction of its traffic is each input actually able to send?
3. (12 points) Fill in the following table.

<table>
<thead>
<tr>
<th>x</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>11</th>
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<tbody>
<tr>
<td>τ_{5,3}(X)</td>
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</tbody>
</table>

What is σ(2,92) in D_{256,4}?

What is σ(3,522) in Y_{4096,8}?
4. (10 points) Give an example showing that i-SLIP can require up to 5 iterations to complete a packet scheduling operation for a 5 port crossbar. Specifically, give an initial state of the crossbar, showing which inputs have packets to send to which outputs, and initial values of all the “pointers” used by the i-SLIP algorithm. Then show what happens in each of the remaining steps. In particular, show the state of the pointers and which inputs have been matched to which outputs, when the algorithm terminates. The figures shown below are provided to save you time. Be sure to label them appropriately.
5. (10 points) The figures below show the state of a crossbar with virtual output queues. In particular, the number in row i, column j denotes the number of cells waiting in the VOQ at input i going to output j. The numbers in the bottom row represent the number of cells in the queues at each of the outputs.

Show how the LOOFA algorithm matches inputs to outputs, assuming that the outputs select inputs, based on which input has the longest VOQ for the output. Use the extra copies of the figure to show what matches are made after each step by circling the selected entries. Make sure you label the diagrams you are using to indicate each step. At the end, show how the status of the VOQs changes as a result of the selected cell transfers.
6. (12 points) Consider a multistage network in which each switch element has four inputs and four outputs, and there is an eight slot output queue associated with each output. Suppose the four queues contain 2, 5, 6 and 7 cells, respectively. If the system uses grant flow control, how many grants can be sent to the upstream neighbors, at the start of the cell cycle? Why?

Suppose the system uses acknowledgement flow control and each of the upstream neighbors sends a cell to the given switch element. What is the maximum number of cells that may be acknowledged by the switch element in this situation? Why? What is the minimum number? Why?

Suppose that the switch element uses a single shared buffer with a total capacity of 24 cells, and the queue contains 2 cells for output 0, 5 cells for output 1, 6 for output 2 and 7 for output 3. In this case, how many grants will be given to the upstream neighbors, if grant flow control is used? Why? If acknowledgement flow control is used, how many acks will be given? Why?
7. (10 points) Draw a picture of the network defined by the expression 
$X_{3,3} \otimes (X_{3,2} \times X_{2,2}) \otimes X_{3,2}$.

How many paths are there between an input $x$ of this network, and an output $y$?

Suppose this network is used to implement an ATM switch that uses dynamic routing and balances the load evenly across all available paths in the network. Suppose there is a virtual circuit with a bandwidth of 60 Mb/s from input 13 to output 5. On your diagram, highlight all the links that carry traffic from this virtual circuit and label them with the amount of bandwidth used on each line.
8. (15 points) Given the following permutation, construct the corresponding connection graph for the Benes network $B_{16,2}$. Color the edges of this graph and then draw a diagram showing how the connections are routed through each of the top level subnetworks. You need not construct complete routes through all the subnetworks.

<table>
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<th>input</th>
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</thead>
<tbody>
<tr>
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<td>11</td>
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