Question 1 (2 points)
Why would optical fiber be preferred over wireline or coaxial cable (i.e., electrical cabling) for a network link?

Fiber is preferred over electrical cabling because of high bandwidth, long distance ability, and immunity to electromagnetic interference are required. Any one of these was sufficient for two points.

Question 2 (8 points)
List four advantages of an optical fiber link for carrying digital data.

Possible answers include:

1) Extremely high transmission capability
2) Low signal attenuation per unit link length
3) Low crosstalk between fibers
4) Immunity to EMI and RFI
5) Outstanding external data security
6) Very long lifetime in service
7) Lighter and less bulky to handle than copper wire
8) Easy to accommodate increases in optical signal bandwidth

Question 3 (6 points)
List three disadvantages of an optical fiber link for carrying digital data.
Possible answers include:

1) Greater expertise is needed for installation (special equipment needed)
2) Limited to use on the ground
3) Cost effective generally only for long-term operation
4) Unidirectional signal propagation
5) Fragility: silica is not as robust as copper (greater care in installing it)
6) Difficult to splice fiber in field

Question 4 (6 points)

List three principal methods for delivering Internet service to the home, in addition to Fiber to the Home (FTTH).

Possible answers include:

1) DSL
2) Cable
3) Satellite
4) Wi-Fi
5) Cellular

Question 5 (5 points)

Describe a packet-switched network and explain briefly how it works.

Packet-switched describes the type of network in which relatively small units of data, called packets, where smart routers send these packets through a network based on the destination address contained within each packet. Breaking communication down into packets allows the same data path to be shared among many users in the network. Packet-switched networks avoid having dedicated connections and are more efficient in the allocation of bandwidth. They are also more reliable under adverse conditions.

See figure below for illustration of a packet-switched network.
Packet Switching Network

- Transfers packets between users
- Transmission lines + packet switches (routers)
- Origin in message switching

Two modes of operation:
- Connectionless
- Virtual Circuit

https://www.slideshare.net/sangusajjan/unit-i-packet-switching-networks

**Question 6 (4 points)**

Name two advantages of a packet-switched over the old telephone network (i.e., circuit-switched network).

Some possible answers include:

1) Many networks can share the same channels and/or links
2) Better use of network bandwidth
3) Cost effective and time tested via the Internet
4) No need to wait for dedicated connection to become available
5) Packet re-routing utilized when required (aka smart routing)
6) Priorities can be assigned to important communications
7) Better security that with circuit-switched networks

**Question 7 (4 points)**

Draw a representative attenuation per unit length vs. wavelength characteristic for a silica optical fiber and label its key features or noteworthy characteristics. Use the graph given below for your sketch.
Solution will look something like this drawing (noting Rayleigh scattering, OH⁻ absorption peak and its general shape). Minimum is near 1.6 micrometers and absorption peaks are due to OH⁻ ions. Note also the lattice absorption (also known as infrared absorption).


**Question 8 (3 points)**

List three different optical fiber loss mechanisms in a silica fiber.

Different optical fiber loss mechanisms:

1) Rayleigh scattering
2) Absorption
3) Macroscopic and microscopic bends

**Question 9 (3 points)**

What is the physical meaning of the material’s index of refraction?

The index of refraction of a material is a dimensionless number that describes how fast light travels through the material. It is defined as \( n = \frac{c}{v} \) where \( c \) is the speed of light in vacuum and \( v \) is the phase velocity of light in the medium.
Question 10 (4 points)

State Snell’s law and illustrate it on the figure given below.

\[ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \]

I did not specify if \( n_1 \) was greater than or less than \( n_2 \), so there were several ways to sketch the rays in the above diagram.

Question 11 (5 + 3 points)

You are given an optical fiber with a defect. The defect in the core of the fiber is a bubble as shown below. (1) Describe how the bubble will change the signal propagation in the optical fiber. (2) Does the size of the bubble have any influence on the behavior of the fiber?
Answer:

(1) Bubbles in optical fiber are not common but do occur in splicing optical fibers. They scatter light and the scattered light is diverted in directions such that it is lost signal power. **A key point then is attenuation results from the bubble.** It also phase shifts the light passing through the bubble so that it destroys the coherence of the photons involved.

(2) Air bubbles smaller than the wavelength of the signal don’t strongly scatter light, whereas, a bubble larger than the wavelength of the signal will strongly scatter light. Of course, the larger the bubble, the greater number of light rays are affected by its presence.

**Question 12 (4 points)**

Explain modal dispersion in a multimode fiber (you can use the fiber diagram below if you wish).

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**Modal dispersion** is a distortion mechanism occurring in multimode fibers, in which the signal is spread in time because the propagation velocity of the optical signal is not the same for each mode. It is the result of each mode having a different travel length leading to a dispersion in the arrival times of the modes.

**Full credit required noting the different path lengths involved is the origin of the differences in velocities.** Many of you did that by your sketch in the fiber’s cross-section drawing.
Question 13 (6 points)

We have the optical fiber link shown in the figure below. The transmitter puts out +10 dBm of signal power and the receiver can detect a power level of -17 dBm. The fiber has a loss of 0.6 dB/km, the connectors have a loss of 0.5 dB each, and the splice has a loss of 0.3 dB. If all the sections of the optical fiber link use the same type of fiber, how long can the optical fiber link be and stay within the link’s power budget?

Solution:

There are five connectors at 0.5 dB loss each, giving a total loss of 2.5 dB. Add in the loss from the splice adds 0.3 dB, making a total connector and splice loss of 2.8 dB. The power budget of the link is +10 dBm – (-17 dBm) = 27 dBm.

27 dBm minus a loss of 2.8 dB gives us the amount of loss we can tolerate from the optical fiber loss, which is 24.2 dB of allowable fiber loss.

At 0.6 dB/km loss for the fiber itself, then

\[
\text{Length} = \frac{24.2 \text{ dB}}{0.6 \text{ dB/km}} = 40.33 \text{ km}
\]
Question 14 (2 points)
Why is silicon not usually used for LEDs or lasers?

Answer: Silicon is not a direct bandgap and so it is extremely hard to create population inversion as required for laser operation.

Question 15 (5 points)
How does introducing an acceptor atom into a semiconductor crystal create a mobile hole? Explain.

When substituting for a Si atom in the crystal lattice, the three valence electrons of boron form covalent bonds with three of the Si neighbors, but the bond with the fourth neighbor remains unsatisfied. The initially electro-neutral acceptor becomes negatively charged (ionized). The unsatisfied bond attracts electrons from the neighboring bonds. At room temperature, an electron from a neighboring bond will jump to repair the unsatisfied bond thus leaving a hole (a place where an electron is deficient). The hole will again attract an electron from the neighboring bond to repair this unsatisfied bond. This chain-like process results in the hole moving around the crystal able to carry a current thus acting as a charge carrier.

Question 16 (4 points)
Write an expression for the frequencies of the longitudinal modes in a Fabry-Pérot cavity of length $L$ and index of refraction $n$. Let $m$ be an integer.

$$f = \frac{mc}{2nL}, \quad \text{where } m \text{ is an integer.}$$

Question 17 (4 points)
When an electron recombines with a hole in an indirect bandgap semiconductor, what is required for this transition to occur?

A photon of energy $hf$ and a phonon of crystal momentum $k$ must be correspondingly emitted to satisfy the conservation of energy and momentum laws.
Question 17 (4 points)
List the four basic properties of the output of a laser.

Answers included:
(1) coherence, (2) monochromaticity, (3) brightness, and (4) directionality

Question 18 (4 points)
Sketch the general shape of a semiconductor laser’s output power versus bias current.

Answer: You should have noted the laser operating region specifically.

![Graph of output power versus bias current]

Question 19 (4 points)
What usually limits the response time of a pn-junction photodiode?

Answer: The drift time through the depletion region.

Question 20 (4 points)
What are the advantages of the PIN photodiode structure over an ordinary pn-junction diode?

Possible answers included:
1) Wider depletion region allows for greater harvesting of carrier pairs
2) Wider depletion region gives greater width resulting in lower capacitance
3) Favors the faster drift process over the diffusion process
4) Higher breakdown voltage

Question 21 (4 points)
Describe what a heterojunction is.
Answer: A **heterojunction** is the interface that occurs between two layers or regions of dissimilar crystalline semiconductors. These semiconducting materials have unequal band gaps as opposed to the homojunction of a single material.

Question 22 (4 points)
Write an expression for maximum bandwidth of a photodiode with width $W$.

Answer: \[ BW_{\text{maximum}} = \frac{1}{2\pi t_{\text{drift}}} = \frac{v_{\text{drift}}}{2\pi W} \]

Question 23 (4 points)
How do you bias a solar cell for power output?

Answer: You do not specifically apply a bias voltage to a solar cell, rather, the incident light self-biases a solar cell establishing an operating current and forward voltage.
EXTRA CREDIT:

Question EX (10 points)

Explain the operation of a VCSEL (vertical cavity surface emitting laser) and use a diagram to illustrate its physical structure.

The VCSEL is a type of semiconductor laser diode with laser beam emission perpendicular from the top surface, contrary to conventional edge-emitting semiconductor lasers (also *in-plane* lasers) which emit from surfaces formed by cleaving the individual chip out of a wafer. VCSELS are used in various laser products, including computer mice, fiber optic communications and laser printers.

In a VCSEL, the active layer is sandwiched between two highly reflective mirrors (dubbed distributed Bragg reflectors, or DBRs) made up of several quarter-wavelength-thick layers of semiconductors of alternating high and low refractive index.

See cross-section below showing general features of the VCSEL. **Important to note the active region sandwiched between the two Bragg reflector regions.**

[Diagram showing cross-section of a VCSEL]