Test #2

You will have 120 minutes to complete this test.

10 Point Essays – Choose 3 out of 5

1. Give three factors in the use of radio telescopes for wavelengths longer than that of visible light.
   One – atmosphere and interstellar medium is largely transparent to radio waves between 1-10 GHz.
   Two – It can be operated in all types of weather conditions (daytime, even in cloudy and sometimes rainy conditions).
   Three – The earth is much brighter than the sun (or other planets) in the radio part of the spectrum.

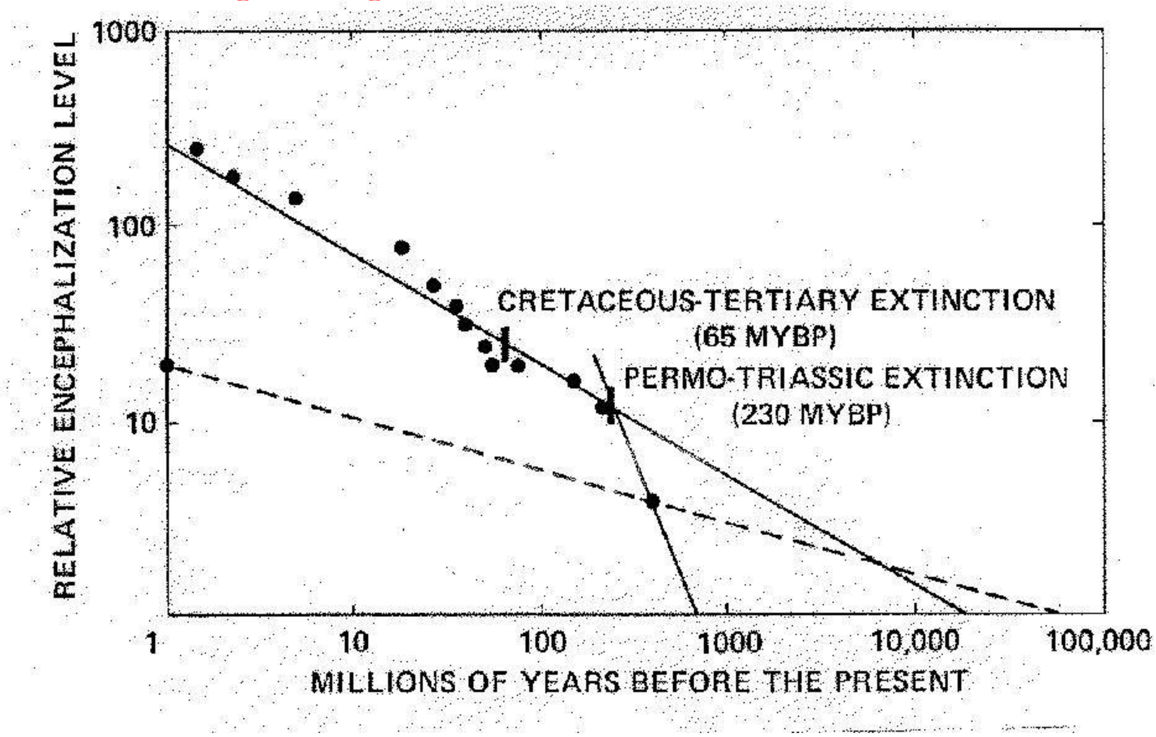
2. Give 2 anecdotal reasons why it is believed that the people developed large brains, and see if you can give 2 equally compelling reasons why these factors or others enumerated in LBE and the notes are not "the whole story" (i.e., think of other types of animals). Finally, why is the diagram shown below given as a reason for the "inevitability" of intelligence?
   The main reasons why intelligence developed (you pick any two of these):
   a. **free O_2 – allowing efficient metabolism.**
   b. **Sexual reproduction – allowing for greater rates of mutation and genetic variation.**
   c. **multicelled organisms – allowing for quicker environmental response and cell specialization.**
   d. **warm-bloodedness – allowing continuous operation.**
   e. **moving to land – making for a more stressful environment.**
   f. **development of complex sense organs and limbs such as hands, requiring the development of a larger and more complicated brain, leading to more sophistication of limbs and sense organs in a feedback process.**
   g. **tool use, which frees biological evolution.**
   h. **Social structure and language – allows for specialization among members of the group and the passing of non-genetic information.**

   Some anecdotal reasons why these may not be the "whole story" are that:
   a. **There are areas of the sea that are just as "stressful," if not more so, than life on land. Some examples include coral reefs.**
   b. **One could postulate that anaerobic life could develop intelligence, as long as it was competitive with other life. An example could include a planet on which aerobic life never developed.**
   c. **The use of wings in birds requires a great deal of processing power, that inevitably led to a high neuron density in birds' brains. Why didn't they develop intelligence?**
   d. **All that we can say for sure is that tools are evidence of intelligence and growing brain size – that is, sophisticated tool use and increasing brain**

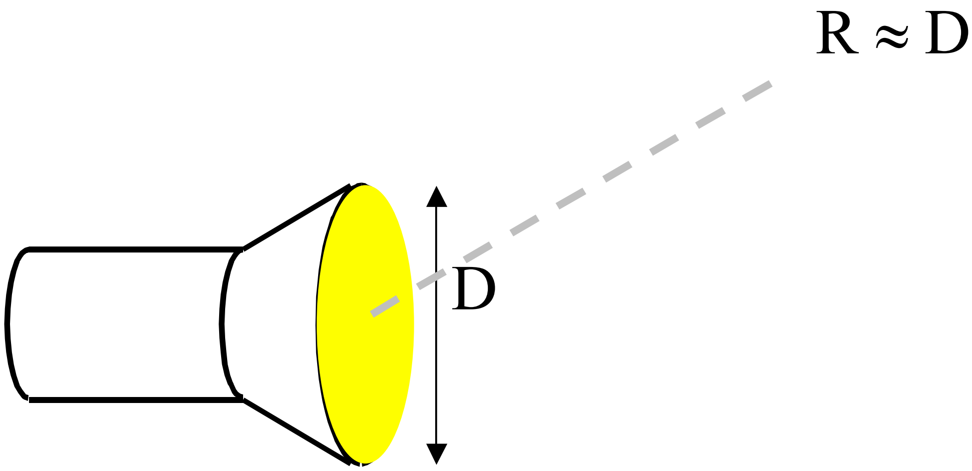
size (and hence intelligence). But correlation does not mean causation (in this case, increased tool use led to increased intelligence).

e. **What about devolution – our big brains are a pretty costly evolutionary trait, that happened to be worth more than its cost. If the pressure for keeping this brain big is removed, might we not "devolve" into unintelligent organisms? After all, this happens to birds that move to islands without predators that can prey on them – they lose the ability to fly.**

The diagram below is taken as evidence that intelligence was "inevitable" because for the past few hundred million years, the brain sizes of the higher animals have gotten larger as time went on.



3. What specifically is the problem of "hot Jovians," recently discovered from astrometric measurements, in planetary formation models? How is it believed that they reach their orbits – where do they form, and how do they get to their inner orbits?
   These "hot Jovians" are located in orbits for which it would have been impossible for icy grains such as water, ammonia, and methane to condense, and hence form into these gas giants – thus, people were at a loss to explain how such large gas giants could form in these regions. It is believed they form in the outer parts of their star systems, like Jupiter, but then decay into closer orbits due to friction with the disk material.
4. Consider the following transmitter of diameter D transmitting light of wavelength λ much smaller than D. An observer is located at a distance R from the center of the transmitter, where $R \approx D$. Would you expect that the opening angle of the radiation to be $\theta = \lambda / D$ as seen from this short distance away, and why (or why not)? **Hint**: consider Fraunhofer diffraction and how it was described in class.



some EM transmitter, where λ << D

The condition that Fraunhofer diffraction describes the radiation pattern from some transmitter emitting light of wavelength $\lambda << D$, where D is the diameter of the aperture, is that the light leaves the transmitter almost parallel to its aperture, thus the condition that $D/R << \lambda/D$, where R is the distance between transmitter and observer. In this situation, the radiation does not leave "parallel" to the surface, so we do not expect that the angular size of the radiation transmitted is given by $\theta = \lambda/D$ -- in fact it is something different.

5. Some civilization observes the solar system in the radio. First, what is special about the radio emission from the solar system? Second, although it would be almost impossible to spatially resolve Earth from a nearby star system, how would they go about determining the latitude of various radio sources from Earth? Finally, how would they determine the period of Earth's year?
Our solar system is "special" in that it puts out much more power in the radio than the sun does naturally – perhaps being evidence of some artificial source. Second, they would measure the shift in Doppler frequencies of various radio signals to see that there is a 24 hour cycle to the Doppler shifts. The amplitude of the Doppler shift in frequency will give an idea of the latitude at which the signals originated. The amplitude and longer 365-day period periodic Doppler shift of the frequencies can tell us the period of Earth's year.

30 Point Essays – Choose 3 out of 4

1. The neurons within the brain send signals, and stores information, via the synapses within the brain. A typical synaptic "switch" takes 10^{-3} seconds. Now suppose that there are 10^{15} synapses within the brain (each storing a bit), and there are 10^{13} synaptic "switches" per second (corresponding to the number of calculations per second).
   a. 5 points – What fraction of the total number of synapses switch every second?
   Divide the number of switches by the total number of synapses, to get that $10^{13}/10^{15} = 0.01$**, or 1%, of the synapses switch every second.**
   b. 10 points – On average, each of the 10^{11} neurons has 10,000 synapses. What is the number of synapses switched by each neuron, on average, each second?

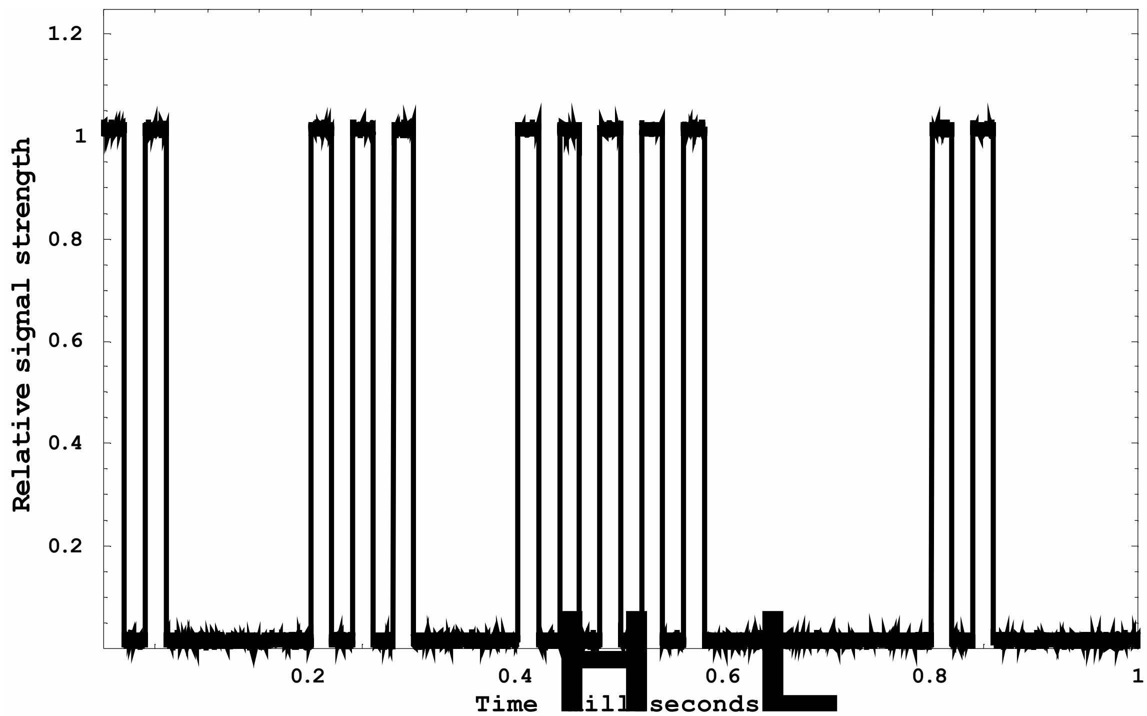
Since 1% of the synapses switch every second, we expect that 100 synapses/neuron on average switch each second.

c. 15 points – Assume that each synaptic connection has a "downtime" associated with it after the switch, preventing the continuous activation of each synapse. Given your answer in (a), the total number of synapses switched every second over the total number of synapse, what is the average "downtime" of each synapse? An easy way to calculate this is to think of the time it would take for all the synapses (on average) in the brain to switch.

If we assume that all the synapses in the brain participate in computation equally, then we have that on average it will take $10^{15}/10^{3} = 100$ **seconds for the all the synapses to switch.**

The actual downtime between switches is about 10 seconds. This tells us that only a small fraction of the brain is this active – hence the ~10% of the brain which is extremely active, through which most of the neural activity occurs.

2. Consider the following type of signal sent by a SETI beacon somewhere out in space – the first three prime numbers – with a (somehow) low signal to noise ratio.



a. 15 points – given what the SETI community would expect for SETI beacons from space, what area of the electromagnetic spectrum would this signal lie and why?

This signal (since it can be seen) would lie in the optical. It is probably not radio because the noise level is so high from transients (lightning, sparkplugs, other industrial noise). Furthermore, Doppler shifts of visible radiation from even small velocities results in shifts in signal that cannot be resolved easily with spectral analyzers. Furthermore, spectral analyzers (since they are made of metal components of about the size of a millimeter or larger) are especially suited for the frequency analysis in

the microwave and radio. The wavelengths of visible light are much smaller – making the creation of spectral analyzers as effective as those at radio highly unlikely. Remember, radio – spikes in frequency spectrum; optical – spikes in time.

b. 5 points – why is it unlikely that this signal would come across within the infrared part of the spectrum?

In order to be seen in the infrared, it would have to be enormously powerful – it is unlikely that anything that is less than 6 orders of magnitude more powerful than what we can make would ever be seen in the infrared. This is due to the fact that infrared is so effectively absorbed by our atmosphere.

c. 5 points – given what you know about the transmission of signals across space, do you think it is likely that a SETI beacon would be pulsed over fractions of a millisecond and why?

It is unlikely (so we think) that the signal is pulsed with time widths of a few tenths of a millisecond, since this would require enormous amounts of energy (recall, a 10^{15} laser pulsed over milliseconds would require about 10^{12} Joules of energy per pulse). Of course, this could be possible, simply (to our knowledge of OUR OWN society and level of technology) unlikely.

d. 5 points – what is (to our knowledge) an unequivocal way in which we could determine this signal is of extraterrestrial artificial origin? That is, think of something an intelligence could do to this radiation that could not be done naturally?

A very simple way would be to send completely circularly polarized light. This is something not seen at all in nature – the best polarization achieved is on the order of 1% or so, and only in the presence of magnetic fields 10^{12} times stronger than we can create in the laboratory.

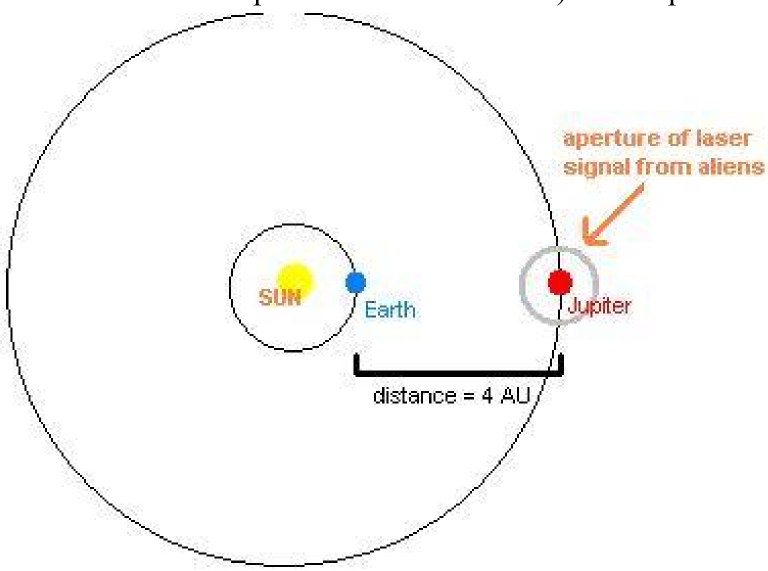
3. Some aliens want to communicate with us. They do not know where we are and they would not search for planets like Earth, because their chemistry consists of iron-nickel-cobalt crystals in a solution of liquid iron carbonyl and a few hundred atmospheres of carbon monoxide (their homeworld is the stripped core of a gas giant).

a. 15 points – These aliens might think of searching in radio. Assume an Arecibo-type telescope could "just" detect signals from Earth at 10 pc. Arecibo is a dish approximately 305 meters in diameter. Given the following formula for the power entering the detector, $L_{\det ect} = \frac{L_{source}}{4\pi R^2} A_{\det ect}$, showing that the power entering a detector goes as D^2, the diameter of the detector, and goes as R^{-2}, the distance from the source. Suppose they are located 20 parsecs away; what is the size of their detector, if it can "just" detect signals from Earth?

Using the relation $L_{\det ect} = \frac{L_{source}}{4\pi R^2} A_{\det ect}$, we have that the power (luminosity) entering the detector, we suppose that we keep the luminosity entering the detector, $L_{\det ect}$, the same in both cases. We do not

expect that the total power leaving in the form of radio signals is different, so that L_{source} is the same in both cases. Now since the distance is 2 times further away (20 pc as opposed to 10 pc), then the detector area has to be $2^2 = 4$ times larger to compensate. Thus, the diameter of the detector has to be 2 times larger. Arecibo is 305 m in diameter. This telescope then has to be 610 meters in diameter.

b. 15 points – Now suppose they use gigantic optical lasers, operating at 500 nanometers 5×10^{-7} meters. However, they point it at Jupiter instead of Earth. What is the maximum size of the laser aperture beyond which Earth will be missed by these aliens? Assume the aliens' homeworld is located at right angles to the Earth's orbit. Earth and Jupiter are separated by 4 AU (6.0×10^{11} km), and the aliens are 20 pc away (65.2 light-year away, where a light-year is 10^{16} meters). Also, the opening angle of the laser (equal to the angular resolution of the telescope of the same diameter) must equal the angular



separation of Earth and Jupiter seen from 20 pc away.

For the signal to be seen from Earth, the angular separation between Earth and Jupiter must be 4 AU. I can go through more involved math, but suffice to say that a 1 AU separation seen from 1 pc away will have an angular separation of 1 arcsecond (try this out for yourself). Thus, a 4 AU spatial separation seen from 20 pc away will have an angular separation of 0.5 arcseconds, which is equal to $\theta = 0.5/3600/180*\pi = 2.42\times10^{-6}$ **radians. The wavelength of light is** $\lambda = 5\times10^{-7}$ **meters. Thus from the angular resolution formula** $\theta = \lambda / D$**, we have that** $D = (5\times10^{-7})/(2.42\times10^{-6}) = 0.207$ **meters. An aperture of 20.7 centimeters is typical of these high-powered fusion lasers.**

4. The minimum energy required to perform a calculation or to store a bit is determined by the temperature of a system. This minimum energy $E_{\min} = k_B T$, where $k_B = 1.38\times10^{-23}$ Joules/Kelvin is Boltzmann's constant and T is the ambient temperature.

a. 15 pts – Assume some kind of superbrain operating at this limit. It uses up 25 W of power, the same as the human brain. At room temperature, 300 Kelvins, what is the number of calculations per second this brain can do?

For T = 300 K, $E_{\min} = 1.38\times10^{-23}\times300 = 4.14\times10^{-21}$ Joules/calculation. The energy usage of the brain is 25 Joules/second. Therefore the number of calculations per second is $R = 25/\left(4.14\times10^{-21}\right) = 6.04\times10^{21}$ calculations per second.

b. 10 pts – How many times more is this than the human brain, which can process 10^{13} calculations per second?

This calculation rate is $6.04\times10^{21}/10^{13} = 6.04\times10^{8}$ times the calculation rate of the human brain. Our brain does not operate at the thermodynamic limit.

c. 5 pts – Consider an intelligent life that uses the spin-flip transition of atomic hydrogen, at 1421 MHz, as a bit switch. Given that the energy of this transition is given by $E = h\nu$, where $h = 6.63\times10^{-34}$ Joules and ν is the frequency in Hertz, what does the temperature T have to be in order for this life to operate?

To calculate this, the energy of a photon with a frequency of 1421 GHz is $E = \left(6.63\times10^{-34}\right)\left(1.42\times10^{9}\right) = 9.42\times10^{-25}$ Joules. Divide this number by k_B to get that the maximum temperature at which this cloud could operate, $T = 9.42\times10^{-25}/\left(1.38\times10^{-23}\right) = 0.0682$ Kelvins. This is much colder than the ambient temperature of the cosmic background.