Name:__________________________ Student ID:______________________

There are <u>three</u> questions. You must complete <u>all</u> of them. Ensure that you show your work (that is, equations, calculations and units). Excessive length is not encouraged.

QUESTION ONE

The mass of a normal human heart is about 400 grams. If the height of the human is increased to the height of the tallest tree (that is, from *about* 2 to 100 meters):

• Calculate the heart size required to pump blood an additional 98 meters in height. Show your work *with clarity*.

• Would changes in the internal diameters of the arteries and veins and/or the heart beat rate affect the required heart size? Explain.

You may (or may not) need to know that human blood pressure is 16 kPa (systolic) and 10 kPa (diastolic, this declines to 5.3 kPa in the head). Actually, blood pressure is remarkably invariant among mammals, averaging 12.9 kPa. The human heart beats at a rate of 72 min^{-1}. Our hearts pump a body mass (*about* 70 kg) of fluid every 10 minutes (1×10^{-4} m^{-3} s^{-1}). Artery and capillary radii are 2.0 mm and 0.003 mm, respectively. Please assume that arteries and capillaries are strong enough to withstand any internal pressure without rupturing.

QUESTION TWO

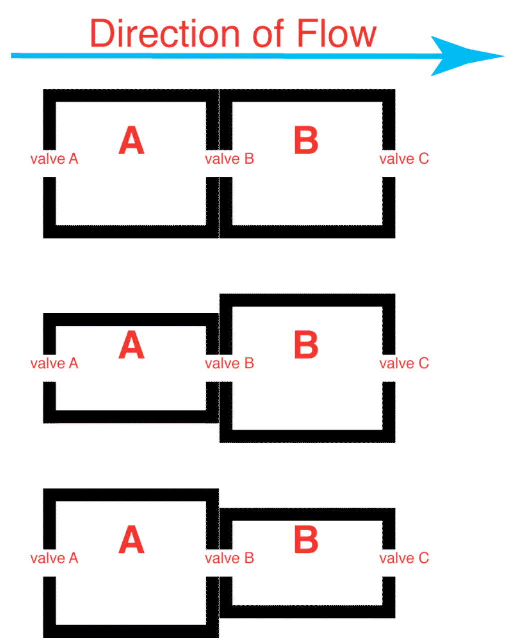
What is a Poise? Explain its physical meaning and relation to force. Remember that Dr. Lew is not a physicist, and he believes that units are important.

QUESTION THREE

Consider a two chamber heart, controlled by valves A, B and C, as shown in the diagram.

• Show the location and directionality of the valves that would allow flow from left to right as Chamber A contracts, followed by Chamber B contraction while Chamber A was re-filling.

• Could valves A, B and C be replaced by a valve-less system to control flow direction? Explain.



Viscosities (and other data) for various liquids (and air)

Fluid	**Density, ρ (kg • m^{-3})**	**Viscosity, η (Pa • sec) (kg • m^{-1} • sec^{-1})**	**Viscous critical force ($f_{critical}$) (N)**
Air	1	$2 \cdot 10^{-5}$	$4 \cdot 10^{-10}$
Water	1000	$9 \cdot 10^{-4}$	$8 \cdot 10^{-10}$
Olive Oil	900	$8 \cdot 10^{-2}$	$7 \cdot 10^{-6}$
Glycerine	1300	1	$8 \cdot 10^{-4}$
Corn Syrup	1000	5	$3 \cdot 10^{-2}$

Nota bene. The viscous critical force, $f_{critical} = \eta^2/\rho$, is a measure of the force required to shift from laminar flow to turbulent flow. It depends on viscosity and density, but is not a dimension-less number (like the Reynolds Number R_e).

Nota bene. Kinematic viscosity is sometimes used, and is equal to η/ρ (with units of m^2 sec^{-1}).

Nota bene. Two other units are sometimes used to describe viscosity. One is the poise (with cgs units of g cm^{-1} sec^{-1}). The other is the stoke, for kinematic viscosity (with cgs units of cm^2 sec^{-1}).

Source: Philip Nelson. Biological Physics. pp. 165.

term test one
(2011)
KEY

Q1. To estimate the new heart size, we have to consider work (w):

$$w \propto m_{heart}$$

that must be performed due to the new height. We can take our inspiration from the jump of a flea (or human):

$$w \propto m\,h$$

(mass) (height)

but it must be re-cast to account for the additional pressure head that the heart must overcome:

$$\rho \cdot g \cdot h$$

(density) (gravity) (height)

we have:

$$\frac{w_{tall}}{w_{normal}} = \frac{\rho \cdot g \cdot h_{(100\,m)}}{\rho \cdot g \cdot h_{(2\,m)}} = 50$$

(10/20)

Thus the mass of the new heart $0.4 \times 50 = 20$ kg.
(many students invoked Galileo scaling ($A \propto M^{2/3}$) and were given partial credit for effort)

<u>Aside</u>: If one uses the actual heart to head distance (0.4 instead of 2 m), one obtains the more realistic 100 kg. As an internal check, a giraffe is about 5.5 m tall and has a heart 10 kg in size.
Caution is advised! In larger animals, the heart must pump through a larger volume. In this case, heart mass is linearly proportional to body mass:

$$m_{heart} \propto m_{body}^{1}$$

a phenomenon completely separate from the relation between m_{heart} and height.

Q1. (continued) Both artery size & beat rate might have an effect on heart size. Both will affect volume flow

$$J_v = \left(\frac{\Delta P}{l}\right)\left(\frac{\pi}{8\eta}\right)R^4$$

increased artery size will strongly affect volume flow, as will more compression cycles per second

$$J_v = \left(\text{pulse rate}\right)\left(\text{chamber volume}\right)$$

However, increased volume flow will require a larger pump chamber volume. This would be offset by a faster rate of compressive cycles

(10/20)

Aside In fact, $\frac{\text{heart stroke volume}}{\text{pulse time}}$ is a constant (0.9)

independent of body mass.

Q.2. Poise is a term used to describe the viscosity of a medium. It is an older term, cast in cgs units $g\,cm^{-1}s^{-1}$.

It has been re-cast in SI units as Pa·s

$$Pa \cdot s \rightarrow N/m^2 \rightarrow \frac{kg \cdot m}{s^2} \cdot \frac{1}{m^2} \cdot \frac{s}{1} \rightarrow \left[\frac{kg}{m \cdot s}\right]$$

(4/10)

Viscosity plays a role in "retarding" (resisting) acceleration and impedes (decelerates) inertial momentum $p = mv \left(\frac{kg\,m}{s}\right)$

we usually envision it as a thick liquid which is slow to pour out of a bottle. In biophysics, it plays a role in laminar flow — dominant in bacterial motility, water flow in a tree, blood flow in circulatory systems, etc. Physically, it is a metric for resistance to shearing. (2/10)

What is its relationship to force?

$$F = ma\,(N) = \frac{\eta^2}{\rho}$$

η → viscosity (Pa·sec)

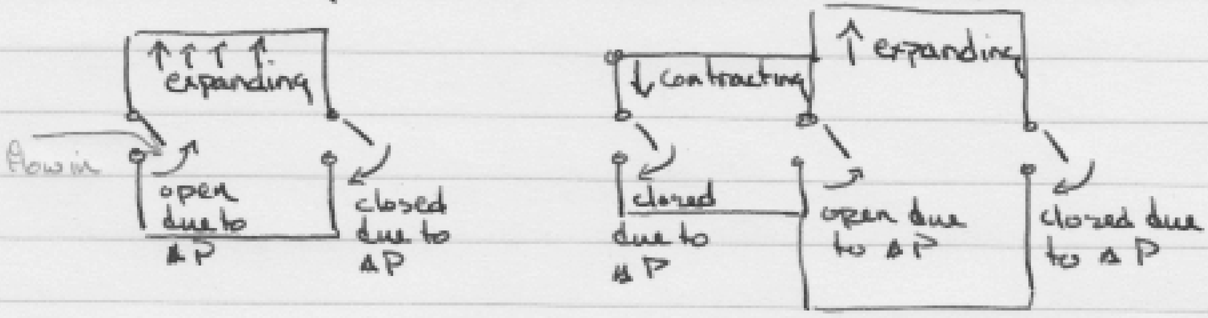
ρ → density (kg/m^3)

the so-called critical force where laminar flow shifts to turbulent flow

$$\left(\frac{kg^2}{m^2 s^2}\right)\left(\frac{m^3}{kg}\right) \rightarrow \frac{kg \cdot m}{s^2}$$

(4/10)

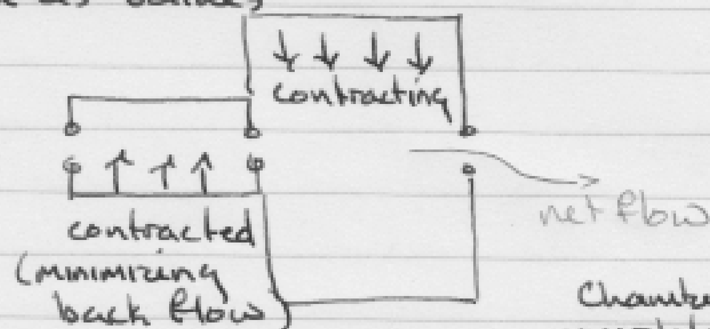
Q 3. Passive flaps will work to create net flow.



etcetera....

(5/10)

Value-less is more complicated, but it is possible. As one example, the chambers themselves could function as values



(5/10)

Chamber B would be completely contracted while chamber A re-fills

These would mimick a peristaltic pump. Ciliated movement might also work?