THE UNIVERSITY OF BRITISH COLUMBIA

BIOL/PHYS 438

Sessional Examination

08:30 AM — 27 April 2007 — ANGUS 425

TIME: $2\frac{1}{2}$ HOURS

FULL NAME: ______________________ STUDENT # : ______________

SIGNATURE: ______________________

This Examination paper consists of 8 pages (including this one). Make sure you have all 8.

INSTRUCTIONS:

Open Book & Notes

This exam has 4 parts:

Q1 Answer *all* Short Answer questions.

Q2 Answer *2 out of 4* questions.

Q3 *Everyone answer this question.*

Q4 Write an *essay* on one of the topics.

Use backs of pages for "scratch work".

A diagram is often essential to a clear answer!

MARKING:

Q1	/20	**Q3**	/20
Q2.1	/20	**Q4**	/20
Q2.2	/20	**TOTAL**	/100

NAMES OF INSTRUCTORS: Jess H. Brewer *and* Jeremy Goldbogen

Q1 SHORT ANSWER QUESTIONS [20 marks — 4 each]

(*a*) Could a **heron** on the airless **Moon** get off the ground (while holding its breath) by flapping its wings? *Explain.*[1]

(*b*) Explain briefly how a shark can detect a **magnetic** field.[2]

(*c*) Name three animals *other than* mammals, frogs or birds that produce *sounds*, and explain the mechanisms involved. One should be in water, one on land, and one in the air.[3]

(*d*) Explain why everything looks out of focus when you open your eyes under water without a face mask or goggles. If you could make special underwater contact lenses to correct for this, what properties should they have?[4]

(*e*) How fast would a 100 kg Giant Goose fly, if it could, and why couldn't it?[5]

Q2 ANSWER TWO (2) out of the following 4 questions [40 marks — 20 each]

(*a*) **Scaling of Metabolic Rate**: Answer briefly or underline the correct answer:

i) What is metabolic rate and what determines its magnitude?[6]

ii) Metabolic rate scales { isometrically | allometrically } with body size.[7]

iii) Write down the equation that relates metabolic rate to body mass. Define each symbol in the equation.[8]

iv) A mouse has { a higher | the same | a lower } metabolic rate compared with an elephant.[9]

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[1] If the heron's wings are fairly massive (which they are), it can lift them up over its head (raising its centre of gravity) and then bring them down quickly. In that short moment, the downward acceleration of gravity doesn't have time to lower the centre of gravity significantly, so the rest of the bird has to rise to compensate the wings coming down. The bird's feet leave the ground. Of course, they come back rather soon, but that was not part of the question.

[2] The shark only detects *electric* fields directly, but when it *moves* through a magnetic field, an electric field is *induced* by the HALL EFFECT, and this field is easily detected by the shark.

[3] In the water, *shrimp* snap their tails and make a "popping" sound by *cavitation*. On the ground are numerous *insects*, who make noise by a variety of means such as rubbing across rows of bumps on their legs. There are also reptiles like rattlesnakes that warn off intruders with a "buzz". In the air there are also many noisy insects, notably the dread *mosquito*, whose reasons for warning us she is coming are unknown.

[4] The eye focuses light using two lenses: the first is the curved *cornea*, which has a higher index of refraction than air and so acts as a converging lens; the second is the adjustable lens behind the corvea, which has a still higher index of refraction. When the eya is immersed in water (which has nearly the same index of refraction as the eye itself), the curved cornea no longer has much effect, which changes the overall focal length by too much for the adjustable lens to compensate. In order to compensate for this loss, a contact lens would need to have an index of refraction much higher than that of water and be very dramatically convex on the outside; it would probably be rather uncomfortable to wear.

[5] The Great Flight Diagram says $U = 15M^{1/6}$ where U is in m/s and M is in kg. You can plug into this formula to get $U = 32.3$ m/s or just read it off the graph: $U \approx 30$ m/s. However, the metabolic power required to overcome the drag force (which increases with U) increases with the mass of the bird so that the maximum velocity the bird can sustain with its metabolism (*i.e.* the "metabolic velocity" U_m) *decreases* with mass as $U_m = 40M^{-1/4}$. For a 100 kg Giant Goose this would be $U_m = 12.65$ m/s, which is well below U. The Giant Goose could probably get into the air for a short flight, but then it would have to spend the rest of the day eating to recover the energy squandered in that heroic effort.

[6] The metabolic rate Γ is the rate [in Watts] at which the animal "burns" fuel with oxygen to "keep its motor running".

[7] Metabolic rate scales allometrically with body size. Whether you interpret "size" to mean dimensions, volume or mass, the metabolic rate cannot be considered to scale isometrically with size.

[8] The *resting* metabolic rate Γ_0 scales with body mass M as

$$\Gamma_0 \approx 4M^{3/4} .$$

[9] A mouse has a lower metabolic rate than an elephant.

YOUR FULL NAME:

v) A mouse has { a higher | the same | a lower } mass-specific metabolic rate compared with an elephant.[10]

vi) A cell in a smaller organism generally has { a higher | the same | a lower } metabolic rate compared with a cell from a larger organism.[11]

vii) When the same cells from the previous question are taken out of each organism and their metabolic rates are again measured *in vitro*, the cell from the smaller organism has { a higher | the same | a lower } metabolic rate compared with the cell from the larger organism.[12]

viii) Attempt to explain the answers to the previous two questions from first principles.[13]

ix) The scaling of metabolic rate has important implications for air-breathing vertebrates that must dive for long periods of time in order to search for food. Explain why being bigger is better specifically in this context. In other words, why can large whales dive longer than birds?[14]

x) Give 3 more examples of why being bigger is better in the context of metabolic rate.[15]

(*b*) **Communication with Waves**: Answer briefly or underline the correct answer:

i) Fish eyes in the deep sea are most sensitive to { blue | green | red } light because light is more strongly attenuated at { short | long } wavelengths.[16]

ii) Many deep-sea organisms appear { blue | green | red } under white light, so that they are invisible with respect to deep-sea ambient light.[17]

iii) Why might a fish produce either red or blue bioluminescence in the deep sea?[18]

iv) What physical principle causes certain parts of a butterfly wing to appear invisible under white light?[19]

v) Sound is more strongly attenuated at { low | high } frequencies.[20]

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[10] The mass-specific metabolic rate is the metabolic rate per unit mass, or $\Gamma/M \propto M^{-1/4}$. Therefore A mouse has a <u>higher</u> mass-specific metabolic rate than an elephant.

[11] Assuming that the cells are roughly the same size in both organisms, a cell in a smaller organism should have a <u>higher</u> metabolic rate then a cell from a larger organism, because the former has a higher metabolic rate per unit mass, and the mass of the cells are presumed to be the same.

[12] This gets interesting. It is believed that the higher efficiency (lower metabolic rate per cell) of the larger organism has to do with the sharing of reseources by many cells in close proximity with each other. If this is true, then the isolated cells *in vitro* would all have <u>the same</u> metabolic rate.

[13] The explanation was offered with the answer in each case.

[14] Because they need less fuel (and therefore less oxygen) per unit body weight, but their blood volume (which cetaceans use as their primary oxygen store) scales linearly with body mass. Lung capacity (auxiliary oxygen storage) also scales approximately linearly with body mass.

[15] Many possibilities. . . . See *e.g.* Sections **2.4.2**, **5.3.2** and **6.2.1** in textbook.

[16] Fish eyes in the deep sea are most sensitive to <u>blue</u> light because light is more strongly attenuated at <u>long</u> wavelengths. (This is opposite to what one might expect from Rayleigh scattering. Presumably this is for the same reason that sea water looks blue at relatively short range: it *absorbs* red light preferentially.)

[17] Many deep-sea organisms appear <u>red</u> under white light, so that they are invisible with respect to deep-sea ambient light.

[18] Blue bioluminescence will be seen by all the other critters, so it is good for advertising one's presence (*e.g.* to make a "lure"). Red bioluminescence will be invisible to most of the other critters, so it makes a good "flashlight" for seeing one's way (especially when looking for reddish prey). Of course, this requires parallel evolution of red-sensitive vision. . . .

[19] Small bumps (smaller in diameter than the wavelength of visible light, but tall enough to make the index of refraction "fade gradually" from $n = 1$ of air to that of the wing material) minimize reflection even more effectively than a "quarter-wave plate" nonreflective coating, because they work on a wide range of wavelengths.

[20] Sound is more strongly attenuated at <u>high</u> frequencies.

vi) Mammals can generate { infrasonic sounds | ultrasonic sounds | both infrasonic and ultrasonic sounds }; insects can generate { infrasonic sounds | ultrasonic sounds | both infrasonic and ultrasonic sounds } (relative the the range of human hearing).[21]

vii) A bat would not be able to echolocate to detect fish in water because of ________________ mismatching. (This physical principle also explains why echolocating dolphins cannot detect birds flying just above the water.)[22]

viii) What physical principle allows a dolphin to maintain directional hearing even though sound can travel readily through its head, which is almost like water.[23]

ix) There is a sound focusing organ called the ________________ within a dolphin's head. This organ has a { low | high } sound-velocity core with a { low | high } sound-velocity outer shell, which acts to focus sound as predicted by Snell's Law.[24]

x) At dawn, there is often a layer of cold, dense air close to the ground (0-20 m height) with a layer of warm air on top of it. Explain why many birds prefer to call at dawn.[25]

(*c*) **Acoustic Sunset**:

The scattering of *light* is strongly frequency dependent, as one might expect: scattering is more effective when the size of the objects doing the scattering is comparable to the wavelength of the scattered light. Consequently, *molecules* do not scatter visible light very much, since they are much smaller than the wavelength. However, they do scatter *a little*, and the "cross section" for scattering increases dramatically with increasing frequency, as the wavelengths get shorter and closer to the size of the molecules. This Rayleigh scattering cross section is proportional to the fourth power of the frequency. Thus blue light is more strongly scattered than red light, with the result that the light scattered down from the clear sky is blue and the remaining unscattered light coming straight from the Sun is more red. *Voila!* Sunsets!

Now suppose you are swimming deep in the open ocean and using a directional microphone to detect sound. Some distance away there is a point source of "white noise" (all sound frequencies). If you face toward the point source, there is a school of large fish off to your left, a school of small fish off to your right, and open water above, below and in between you and the point source. Describe qualitatively the sounds you would expect to detect when you point the microphone in various directions, *and why*:

i) toward the point source;[26]

ii) straight up;[27]

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[21] Mammals can generate both infrasonic and ultrasonic sounds; so can insects!

[22] A bat would not be able to echolocate to detect fish in water because of impedance mismatching.

[23] Impedance mismatching allows a dolphin to prevent sound from penetrating its head uniformly: both bone and air sacks can be used for this purpose.

[24] There is a sound focusing organ called the "melon" within a dolphin's head. This organ has a low sound-velocity core with a high sound-velocity outer shell, which acts to focus sound as predicted by Snell's Law.

[25] The cold, dense air has a higher index of refraction than the warm air above it, so sound "rays" propagating upward at a small angle will be bent back down by the same phenomenon as "total internal reflection" and thus their intensity will fall off slower than the $1/r^2$ dependence of isotropic radiation. (Recall the whales' "Sofar Channel".) The birds' songs will be heard from further away at dawn.

[26] You hear the lower frequencies unattenuated. (The higher frequencies are scattered out to the sides).

[27] In this case you hear *only* the (higher) scattered frequencies.

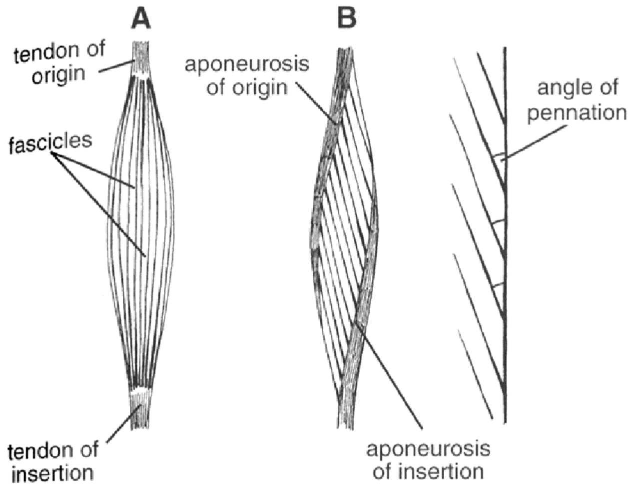
iii) to your left;[28]

iv) to your right.[29]

(*d*) **Muscles & Running**:

i) What geometrical feature determines the amount of force a muscle can produce?[30]

ii) Based on your previous answer, why should a pennate muscle (**B**) generate more force than a regular muscle (**A**) of the same size? *Explain*.[31]



iii) In order to determine the work a muscle can perform it is necessary to examine the relationship between two physical parameters. Name these parameters and describe how you could calculate work from them.[32]

iv) By looking at the relationship determined in the previous question, locomotor muscles within organisms that are swimming, flying or running can generate { positive work | negative work | very little work | any of these }.[33]

v) { true | false }: Animals' muscles can function as motors, brakes, struts and springs.[34]

vi) Explain why bigger animals should theoretically be in danger of breaking their bones during locomotion.[35]

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[28] Now it gets interesting. Big fish reflect all but the very longest wavelengths (lowest frequencies) and so you will hear approximately the full "white noise" spectrum with only a few very low frequencies missing, plus the higher frequency sounds scattered by the water itself. This is sort of like the setting sun reflected off some big white clouds, which scatter the sunset's red light down to you, while in between you still see patches of blue sky.

[29] The only difference between big fish and little fish is the "cutoff" of scattered frequencies: little fish do not scatter the longer wavelengths (lower frequencies) as well as big fish, so the "missing lows" extend higher than for the big fish.

[30] All muscles exert roughly the same force per unit cross-sectional area, $f_0 = F/A \approx 2 \times 10^5$ Pa (about 2 atm). Thus the force is proportional to the cross-sectional area of the muscle.

[31] The cross-sectional area is always perpendicular to the muscle fibers; thus the pennate muscle applies more fibers to make a bigger force. Note however that the same fractional length contraction of the pennate fibers produces a smaller contraction between the tendons of origin and insertion because the fibers contract at an angle to that axis.

[32] Work = force times parallel distance. Thus a normal muscle and a pennate muscle of the same overall size and shape will produce the same work: the extra force of the pennate muscle is exactly offset by its smaller contraction due to the same geometrical factor.

[33] Any of the listed possibilities can be achieved, depending upon what sort of cycle the muscle contraction and expansion execute.

[34] True. A Mechanics purist might quibble that a "strut" can support *compression* forces as well as *tension*, whereas, "You can't push on a muscle."

[35] If you simply "scale up" an animal, its weight scales as the cube of its linear dimensions while the strength of its bones only scales as the square of same. So the bone strength/weight ratio decreases linearly with the size of the animal, for isometric scaling.

YOUR FULL NAME:

vii) Explain how bigger animals *avoid* breaking their bones during locomotion.[36]

viii) During locomotion limbs must oscillate back and forth. Muscles that swing the limbs back and forth use approximately { 0% | 25% | 50% | 75% | 100% } of the total energy expended by a running bird.[37]

ix) If we model the oscillatory nature of locomotion as a spring, we would predict that animals could save energy if they move their limbs at a resonant frequency. What mechanisms and/or structures allow animals to save energy in this way?[38]

x) A black bear on the northern BC coast is running on hard, rocky ground at a slow, steady speed. The bear suddenly encounters a soft, sandy beach. In order to maintain its initial speed, what does the bear have to do and what mechanical mechanisms underlie this behavioral adjustment?[39]

Q3 EVERYONE DO THIS: [20 marks]

Giants of the Deep:

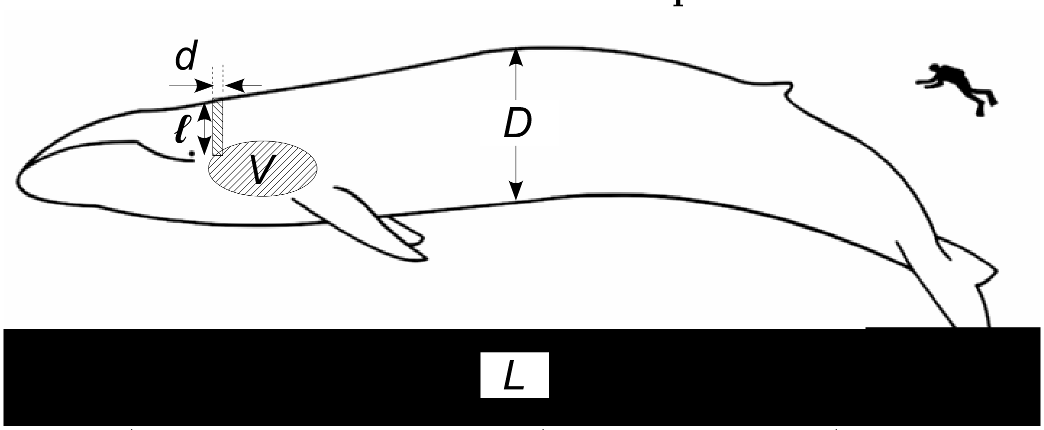

Fig. 1 - **Human** (height = 2 m, mass = 70 kg) *vs.* **Blue Whale** (length L = 30 m, mass M = 100,000 kg, windpipe length ℓ = 1.5 m, windpipe diameter d = 0.3 m, lung volume $V = 2.0\ \mathrm{m}^3$, cruising velocity v = 2 m/s).

(*a*) The blue whale's favorite food, krill, has a typical energy content of h = 5 MJ/kg. How much krill does the whale have to ingest daily in order to supply its basic (resting) metabolic needs?[40]

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[36] For starters, they do not scale isometrically. Larger animals tend to evolve disproportionately thicker bones. However, the allometric power is 0.89, not far off linear, so this is (on average) a modest effect. Probably more important (see slides 20-23 of the *Running* lecture) is the *change of gait* — they give up running and walk instead. (And they are very, very careful.... :-)

[37] Muscles that swing the limbs back and forth use approximately 25% of the total energy expended by a running bird, according to blood flow measurements on an actual running bird. See Jeremy's lecture.

[38] Elastic structures such as tendons and ligaments store energy when stretched and deliver almost all of it back when they contract.

[39] The bear will change the *stiffness* of its legs, either by changing its EMA or *via* neural control of its leg muscles.

[40] The resting metabolism $\Gamma_0 = \Delta H/\Delta t$ is given by the fundamental allometric relation $\Gamma_0 = 4M^{3/4}$ where Γ_0 is in watts (W) and M is in kg. Thus we expect the blue whale to need $\Gamma_0 \approx 4 \times 100,000^{0.75} = 22,494$ W. In one day ($24 \times 60 \times 60 = 86,400$ s, this adds up to $22,494 \times 86,400 = 1.94 \times 10^9$ J or 1.94×10^3 MJ. At $h = 5$ MJ/kg this requires $1.94 \times 10^3/5$ or $\boxed{389\ \text{kg/day}}$.

YOUR FULL NAME:

(*b*) The whale's cross-section is actually rather oval, but we may treat it as circular, with a maximum diameter of $D = 4$ m. If the whale's streamlined shape gives it a drag coefficient $C_D = 0.12$, what is the fluid resistance (drag force F_D) on the whale at its cruising speed?[41]

(*c*) Assuming a mechanical efficiency of $\eta = 25\%$, what is the ratio $b = \Gamma_c/\Gamma_0$ of the metabolic rate Γ_c of the "cruising" whale to the metabolic rate Γ_0 of the resting whale?[42]

(*d*) Now pretend that the whale's shape is a uniform circular cylinder of length L and diameter D. If the whale "cruises" *straight up*, how high will its center of mass rise above the water surface before it stops and falls back?[43]

(*e*) Blue whales can generate 1.2 W of acoustic power. If this power is radiated isotropically, what is the sound intensity [in Watt/m^2] at a distance of 500 m?[44]

(*f*) Blue whales are known to produce sounds of 5-20 Hz. Why do these animals use such low frequencies?[45]

(*g*) These sounds are generated inside the animal. The sound could be produced in a cavity filled with air, or by some vocal cords, or .... The Figure at the beginning of this question shows the body cavities and some dimensions. Consider the various resonators (Helmholtz resonators, organ pipes, ...) described in Section **9.4** of the textbook. What mechanism do you think is used by the animal to make this low frequency sound? *Explain.*[46]

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[41] For a large body like this, Stokes drag is negligible compared with hydrodynamic drag, for which we have $F_D = \frac{1}{2}C_D A \rho_w v^2$ where $A = \pi(D/2)^2 = 12.57$ m^2 and $\rho_w = 1025$ kg/m^3 is the density of sea water. Thus $F_D = \frac{1}{2} \times 0.2 \times 12.57 \times 1025 \times 2^2$ or $\boxed{F_D = 5152 \text{ N}}$.

[42] To cruise horizontally at constant speed, the whale must exert a constant forward thrust equal to the above drag force. This requires a mechanical power $P = F_D \times v = 10{,}304$ W. At 25% efficiency the whale must "burn" 4 times this amount of metabolic "fuel": $\Gamma_c = 41{,}218$ W, so that $\boxed{b = \Gamma_c/\Gamma_0 = 1.832}$.

[43] This problem is a "ringer" for the Physics enthusiast.

The crudest approximation is to **ignore** the drag force F_D (which, for an actual cylinder, would cease as soon as the top end of the cylinder emerged from the water's surface — *i.e.* for $y = -L/2$, if we define y as the height of the center of mass above the surface) and the buoyant force $F_B = \rho_w g A(L/2-y)$ due to the displaced water (which starts decreasing gradually as soon as the top end of the cylinder emerges from the water's surface) and the thrust $T = Mg + \frac{1}{2}C_D A\rho_w v^2 - \rho_w g A L$ which the whale had to exert in order to swin straight up at its cruising speed.

If all these are neglected, then the problem reduces to a simple trajectory problem: how high does M get after leaving the water with an initial vertical velocity v? The answer is familiar: setting the initial kinetic energy equal to the final potential energy gives $\frac{1}{2}Mv^2 = Mgh$ or $h = v^2/2g = 2^2/2 \times 9.81$ or $\boxed{h = 0.2 \text{ m}}$. Not very high.

What if we include the effects of a dwindling buoyant force? Relative to the above case this decreases the effective weight pulling the whale down, so we would expect to get a little higher value for h.

What if we assume the whale "keeps pushing" as it climbs skyward, with the same thrust T as before it reached the surface? Now we have an additional upward force acting to drive the whale higher. How much higher? What are the equations of motion?

This is a fun problem to mull over, but you get full marks for the crude approximation above, and extra credit for noting (on paper) that there is more to the problem than that. I won't spoil your extra fun by giving away the anwswers to the hard parts....

[44] Neglecting any absorption of energy by the water, the total power is distributed over a sphere of radius $r = 500$ m, which has a total area of $A = 4\pi r^2 = 3.14 \times 10^6$ m^2, giving an intensity of $I = P/A = 1.2/3.14 \times 10^6$ or $\boxed{I = 0.382 \times 10^{-6} \text{ W/m}^2}$ anywhere on that sphere.

[45] Lower frequencies carry further because they are not attenuated by scattering or absorption in the water.

[46] One possibility is a Helmholtz resonator (see Eq. (9.41) on p. 340 in the textbook): a windpipe $\ell = 1.5$ m long and $d = 0.3$ m in diameter attached to a lung of volume $V = 2.0$ m^3 should resonate at a frequency $f_0 = (v_s/2\pi)\sqrt{A/\ell V}$ where $v_s = 340$ m/s is the speed of sound and $A = \pi(d/2)^2 = 0.0707$ m^2 is the cross-sectional area of the windpipe. This gives $f_0 = (340/2\pi)\sqrt{0.0707/(1.5 \times 2)}$ or $\boxed{f_0 = 8.3 \text{ Hz}}$. So this is a plausible mechanism.

YOUR FULL NAME:

Q4 Write a short ESSAY on ONE of the following topics. [20 marks]

Indicate clearly *which* topic you choose. Explain what physical principles were involved and what expected and unexpected results were described. Mathematical equations and symbols may be used as abbreviations for familiar principles or quantities, but you will be marked on the clarity, conciseness and quality of your *writing*.

- One of the **term project posters** (not your own!).

— OR —

- One of the **guest lectures** this term (the CAP Lecture on "*Neurophysics*" by André Longtin, Dan Dudek's lecture on "*Inverted Pendula & Roach Legs*", John Gosline's lecture on "*Strong Materials*" or Boye Ahlborn's lecture on "*Optics*").

There are no "right" or "wrong" essays (although any essay may contain factual or logical mistakes). We look for good writing that effectively and efficiently conveys a clear understanding of the topic. (First you must *have* such an understanding, of course.)

YOUR FULL NAME: