ESSENTIAL CONCEPTS FOR BIOLOGICAL ENGINEERS

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ESSENTIAL CONCEPTS FOR BIOLOGICAL ENGINEERS

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Abstract
Biological engineering courses and curricula can result in graduates who vary greatly in their abilities to deal with biological systems. Whereas there has been general agreement about a better understanding of biology and biological applications for all biological engineers, specific recommendations of competencies have not heretofore been formulated. A minimal list of principles and basic concepts expected of all biological engineering graduates would standardize commonalities no matter what educational institution attended. This paper supplies a list of 25 of these.

I. Introduction

Biological engineering is the science-based engineering discipline that comingles engineering with biology. It has been defined in general terms, without specific applications (Garrett et al, 1992; Johnson and Phillips, 1995; Johnson and Schreuders, 2003). It has had several disciplinary roots, including evolution from agricultural engineering and chemical engineering, both of which claim possession of true biological engineering approaches (Johnson, 2006). Sister engineering disciplines relating engineering to some aspect of biology or medicine suffer from the same historical lack of identity as does biological engineering. Exacerbating this problem for those of us attempting more general acceptance of biological engineering and related engineering fields is the fact that there is lack of uniformity within the educational curricula of most of these (Linsenmeier, 2003).

Before there can be any confidence in the uniformity of biological engineering education, there must be understanding of the necessary knowledge to be possessed by all biological engineers. Of course, uniformity will only come when there is consensus about the essentials that must be known to be successful biological engineers. At this point in its development, the field is too new as a separate discipline to have reached the consensus stage (Johnson et al, 2006).

Previous papers have dwelt on generalities related to biological engineering education. For instance, Costello and Carrier (2006) wrote about increasing the amount of biology and incorporating biological applications within the biological engineering curriculum. Scott (2006) presented a list of courses that he suggested should be taken by biological engineering undergraduate students. In both of these papers, as well as many others, there is no specific prescription for principles and concepts that should be known by all biological engineers as they graduate from colleges or universities. It is one thing to require biology to be taken. It is another to specify exactly what needs to be known about biology. Engineers who are expected to be problem solvers must know biology differently from biologists who are not.

Due to the present overwhelming popularity and importance of cellular and biomolecular biology, the field of biological engineering is being pulled in that reductionist direction. The result of this is that biological engineers are becoming more and more like applied scientists rather than engineers comfortable with biological applications at all levels. The philosophical foundations of biological engineering, however, describe biological engineers as "specialists in technical diversity", rather than specialists in applied cellular science.

The list of principles and concepts that follow are based on a vision that biological engineers, from whatever educational background they have, must be flexible in their abilities, versatile in their approaches, and capable of dealing competently with all levels of the biological realm. They are based on the three expectations for all biological engineers (Johnson, 2010) to possess the:

1. knowledge of biological principles and generalizations in order to design products and products involving living things.
2. ability to transfer knowledge from a known biological system to a different, unfamiliar biological system.
3. ability to avoid the unintended consequences involved when dealing with any biological component.

Thus, the set of concepts and principles set forth in this paper is intended as the minimum amount of knowledge that all biological engineers should possess to represent the field adequately. Basic science, engineering, mathematical, and liberal arts competencies have been assumed in addition to this list.

II. Basic Concepts and Principles

The following is one attempt to define the core knowledge that should be possessed by all practitioners of biological engineering. Each of these is listed, in no particular order except for the first, and some explanation is given for each. Explanations, however, are not meant to be exhaustive or complete, but rather as a short justification of the importance of that particular item to the listing.

1. **Survival and Reproduction of the Genes.** This is the first principle of biology, and the dominating theme of all biological actions. Living things will compete, control, modify, adjust, kill, sneak, cover up, and scrap in order to survive and reproduce. Death is so catastrophic to any living thing that no measure is spared in order to live

   Survival and reproduction is important at many hierarchical levels. The obvious level for which survival and reproduction are important is at the organism level, but it is the genes that are driven to survive and reproduce. They do this in cooperation with other genes by surrounding themselves with survival mechanisms built into cells, tissues, organs, and organisms. There is competition among genes causing some genes to take advantage of others. So-called cheating genes duplicate themselves at the expense of other genes. *Transposons* are genes that move from one genetic location to another in order to duplicate themselves within the genome. Killer genes cause toxins to be produced that eliminate competitive genes. The ultimate competition in biology is among the genes.

   Survival and reproduction extends to groups of individuals as much as to individuals themselves. Forming herds, schools, or human families gives mutual cooperative support in survival mechanisms. Members of these groups assist each other to fend off threats posed by predators and to locate sufficient food and other resources to meet the group demands. If the survival advantage of group membership is great enough, then there may be a large sacrifice in order to belong to the group. Examples of this are ceding of breeding rights to dominant males in a herd or physical mutilation for some human groups.

   Even among plants, there are group survival mechanisms in play. *Masting* in oak trees occurs when all oaks in an area form copious quantities of acorns in certain years and not others. This increases the probability that some acorns will survive consumption by hungry animals. Seventeen year locusts synchronize emergence for the same reasons. Plants also communicate attacks by insect pests through airborne chemicals that induce other plants to buttress defenses.

2. **Form is Related to Function.** Related to modularity is the realization that form and function are closely aligned. More acute hearing requires larger ears. Night vision requires pupils that allow more light to be captured. Heat maintenance requires heavy insulation. Efficient mass transfer requires a large surface area. Each of these can be predicted from the laws of physics or chemistry. From form, one can infer function; from function, one can predict form.

   Realizing that organisms have been perfected over many generations to deal with environmental stresses is the key to using biological solutions to solve engineering problems of a similar nature. Copying biological solutions is called *biomimetics*, and this is one of the easiest and surest ways to formulate a problem solution.

3. **Modularity and Incremental Change.** Biology and technology operate similarly. Each begins with a new prototype and proceeds from there toward improvements by making incremental changes. Successful parts are maintained; others are improved. This similarity between biological evolution and technological evolution is the paradigm for all of technological progress.

   It is useful for biological engineers to be familiar with this concept. Not only does it supply context for engineering efforts, but it also can be a vehicle for greater understanding of biological organisms and why they appear as they do.

4. **Environment Influences Outcomes.** Actions and structures of living beings are strongly dependent on physical, chemical, and biological environmental factors. Biological actions and responses are not made without accounting for environmental factors. These actions can take the form of organismal cooperation or competition (biological environment), initiating heat loss mechanisms (physical environment), or detoxification of cyanide (chemical environment).

   But environment has more profound effects at the genetic level. Environmental factors can determine expression of certain genes. The ultimate manifestation of this is the formation of *epigenetic markers* that determine genetic expression for generations at a time.

   Biological engineers must be aware constantly of the role that environment plays in biological responses. Environment can determine not only the degree of action, but also whether it occurs at all.

5. **Physical Limits Cannot Be Exceeded.** Living things do not abrogate the laws of physics; they reaffirm them. Mechanical strengths of materials do not change because they are included into living creatures. Exceed these limits, and they break.

   Likewise, diffusion limits do not change because materials move inside living cells. The maximum distance that oxygen can diffuse passively at a rate sufficient to sustain life is equal to the thickness of two cells. Any farther than this, and other mechanisms (such as circulation) must be used to deliver oxygen.

   To accommodate physical limitations, biological things can manipulate shapes, sizes, and compositions of materials. The means that biology has developed to circumvent physical limitations are often good models for engineering designs, but, in the final analysis, physical limitations must be recognized.

6. **Relationships Among Energy, Order, Entropy, and Information.** Passing information from one biological unit to another requires communications

channels. These channels may involve chemical, visual, auditory, touch, taste, magnetic, electrical, or neural mechanisms. Many communications in nature are chemical. Bacteria communicate their presences to others within a biofilm with chemicals called *autoinducers*. Insects indicate the presence of mating adults by airborne chemicals called *pheromones*. Many mammals mark their territories with chemicals sprayed on prominent physical features.

Communications are important for organisms not only to know the presence of others, but to anticipate the intentions of others. Thus, signals of aggression, acceptance, threats, or love elicit emotional responses that are meant to enhance survival.

Communications result in information that leads to order. This, in turn, reduces entropy, at least locally. In order to maintain order, a constant supply of energy is necessary. Stop the flow of energy, and death ensues, the organism decays, and entropy again increases. Shannon's relationship between information and the probability of the occurrence of an event, where information content is higher for rarer events, can also be used to determine the entropy of the order maintained by an abundant supply of energy (Shannon and Weaver, 1949).

7. **Reversible Chemical Reactions.** Chemical reactions that are extremely vigorous, generate too many products, or have extreme behavior in one way or another are not usually useful biologically. Life requires agility, both physically and chemically. Chemical reactions that can easily be reversed are the useful kind.

For instance, adenosine triphosphate (ATP) is a very useful compound for storing and releasing chemical energy. ATP is converted into adenosine diphosphate (ADP) through hydrolysis, with the liberation of energy to drive other chemical reactions. ATP is used almost universally in living things as an energy storage chemical. ATP is neither a very energetic compound nor a very unenergetic compound; it is intermediate in energy. That way, it can store and release energy when needed.

Maintaining human blood alkalinity level at about pH of 7.4 is necessary for maintenance of internal equilibrium. A bicarbonate buffering system is used to convert circulating carbon dioxide into carbonic acid or bicarbonate ion. These processes either soak up or release hydrogen ions. Thus, human blood pH can be maintained constant even during severe exercise when metabolic acids are released into the blood.

Proteins are used that have different forms and purposes with little change in energy levels. Thus, very little energy is needed to control protein configurations and functions.

Not all of these reactions are strictly reversible chemically, but they do represent reactions that move easily between reactants and products, so the energy differences between chemicals on both sides of the equation are small.

8. **Molecular Shapes and Chemical Mass Action.** Much of the chemical action attributed to enzymes and proteins is the result of molecular shape. The complex folding of proteins from simple strings of amino acids into molecules resembling knotted ropes results in parts of the molecule that fit well with other molecules. When two or more such molecules physically locate next to each other they are usually close enough to react readily.

   The chemical law of mass action states that chemical reactions are much more likely to progress when concentrations are high. Enzymes, by bringing reactants close together, increase the local concentrations many-fold. As an added benefit, because enzymatic action is based on physical shape, the enzyme does not take part directly in the chemical reaction and is not consumed.

   Chemistry inside a cell depends very strongly on physical shapes of molecules. In addition to the enzymes described above, genetic duplication depends upon the complementary shapes of the *pyrimidines* cytosine and thymine fitting physically with the *purines* adenine and guanine. Also, the physical integrity of the cell structure depends on the physical gel resulting from the way that polar water molecules line up with one another.

9. **Osmosis.** Osmotic pressure is a powerful motivator. For instance, tall trees do not have any physical means to pull water from the ground to the very top of the tree if the tree is taller than the height of water that can be supported by atmospheric pressure. This height is about 30m. However, water that evaporates from leaves at the tree top reduces the concentration of water, so this diffusion gradient pulls water as far up as it needs to go.

10. **Benefits of Redundancy and Alternative Pathways.** The success of biological entities is largely a result of dependency on redundancy and alternative pathways. This gives organisms the ability to adjust to new environments and new challenges.

    Redundancy is at the heart of the immune system. There are many ways to deal with foreign invaders, and, if one or several of these is overwhelmed, there are other lines of defense to be overcome. The organism is thus usually successful at maintaining self-integrity.

    There are alternate metabolic pathways that allow the organism to substitute one type of metabolism for another. Thus, the muscles normally act with aerobic metabolism, but are capable of anaerobic metabolism when oxygen is in short supply. Microbes in a bioreactor can be induced to produce certain biochemical products when given reactants different from those that are most efficiently used or preferred. In this way, alternative pathways can be exploited for economic benefit.

One place where redundancy has not usually been consciously recognized is in the information legacy to pass information from one generation to the next. This function has usually been recognized as belonging to the genome. It is the genes, after all, that are uniquely posed to supply the basic information source for the chemical mechanisms of the cell. Nevertheless, there are at least three other transgenerational information sources that have not been as widely recognized. The first of these is *memes*, or cultural information taught by certain individuals to others. Through this cultural information, survival is enhanced among animals, such as meerkats that teach their young how to catch and eat dangerous prey, or sheep and goats that teach their young about the differences between poisonous and nonpoisonous plants, or humans who school their young for an extended childhood. The second additional information legacy is the microbes passed from one individual to another. These microbes have a profound effect on health and well-being. Probiotic microbes are passed from mothers to their young to help them digest food, calibrate their immune systems, and prevent dangerous diseases. The third, and perhaps not the last, information legacy is in the form of misfolded proteins, called *prions*, that have been found to be able to be passed from one generation to another, and have also been found to be able to replicate without a genetic DNA or RNA model. Many prions are associated with dangerous diseases, such as *transmissible spongiform encephalopathy*, or *Alzheimer's disease*. Other prions, however, help yeast cells cope with radically different environments, or assist in animal memory retention by altering frequently-used neural synapses (Saltus, 2010).

The principle of redundancy has been taken very seriously when failures cannot be tolerated. NASA depends upon redundant components for its space ventures, for instance. Automobile safety systems are also highly redundant. The biological engineer attempting to control a dangerous microbe, as an example, should incorporate redundant controls to assure that the objectives of the process are met.

11. **Adaptation Requires Energy and Resources.** Life has developed as a means to survive and reproduce, with the emphasis on reproduction. Energy and resources are required to form new offspring, and energy and resources needed to adapt to environmental demands uses energy and resources otherwise able to be used to reproduce. Thus, environments that demand adaptation in order to survive reduce the ability to reproduce.

    If maximum reproduction is desired, then optimum environments need to be supplied to the organism. Such would be the case for breeding animals or producing a field of grain.

    If reproduction is not the goal, but something else is desired, then reproduction will suffer. Such is the case in a bioreactor to produce an economically-important chemical from genetically-modified organisms. Modification of the genome to improve the yield of a desired metabolite reduces the ability of the organism to reproduce. Thus, there may be more of the desired product, but it may take longer for the population to reach the critical level.

12. There is Competition for Limited Resources. It can be assumed that every niche that can support life, however limited, will contain living things to the maximum extent possible. This makes all biological systems limited by resource availability.

Competition among species and among individuals of the same species keeps them from unchecked growth. *Staphylococcus aureus,* a dangerous microbe, is present on the skin of nearly all humans, yet normally causes little or no trouble because other microbes compete successfully with *Staph* and limit its influence. Human beings, as a matter of fact, contain about 10^{14} cells, only about 10% of them of human origin. The remainder are bacteria, small mites, and other microbes that compete for space and resources on the skin or in the digestive system.

It would be wrong to ignore competition among microbes. *Competitive inhibition* keeps most microbes in check and does not allow them to become a threat to the host. Trying to disinfect all microbes, therefore, removes many benign competitors of the more dangerous types. The result can be worse than if no disinfection was attempted.

Competitive inhibition can be used to control diseases of plants as well as of humans. A biological problem can often be solved in a biological way. To control one organism, it is often best to look for a natural enemy.

13. Antagonistic Mechanisms Give Precise Control. When it is necessary to control a process to a very close tolerance, antagonistic mechanisms are used. The idea is to attempt to control in two directions simultaneously. Then the resulting movement is the difference between the two efforts. Fine movements of the fingers are achieved with antagonistic muscle control. Exquisite control of glucose level in the blood is achieved by means of two hormones, insulin and glucagon, that have opposite effects.

An alternative to antagonistic control is to use active control in one direction and use stored energy to restore the system to its resting position. Such is the case with human respiration at rest. Inhalation is active, and passive exhalation is achieved when stored gas in the lungs is released into the atmosphere. The restoring force is produced by gas compression and elastic stretching of the tissues. Active exhalation is initiated during exercise, when it becomes important to remove gases quickly from the lungs.

Biological systems, even up to the ecological level, use a lot of antagonistic control, sacrificing energy efficiency for rapidity and precision.

14. **Optimization Saves an Incremental Amount of Energy.** Life is energy intensive. Thus, it may not appear to make much sense to save additional energy through optimization. Nevertheless, the biological environment is competitive, so, in a place where all the competition uses as much energy as is available, a small difference in energy requirements may have a large reproductive effect.

    Especially subject to optimization are overhead processes, such as blood circulation, and digestion, or survival processes, such as locomotion. It appears that heart pumping and respiration, especially during heavy exercise, are optimized to reduce the rate of energy consumption. So is the energy use of walking and running. There are probably optimized biochemical processes, and nutrient recovery and utilization in whole ecosystems appear to be optimized.

    Optima may either be narrow and highly precise, or broad with little penalty for deviation from the optimum value. Biological optima usually conform to the latter. Thus, we find that the rates of respiration around the optimum value to minimize energy expenditure during exercise vary both above and below the best rate, but center on the optimum. The same can be seen to be true both for heart rates and walking speeds.

    One intriguing question remaining in biology is why there are so many genetic variants still present in the genomes of different organisms. Selective survival should have extirpated the less favorable genes many generations ago. Looking at the genome as an optimal solution, however, infers that there will remain genetic variability in a manner similar to other biological optima.

    A slightly smaller energy demand in an organism could pay off in a huge difference in reproductive potential.

15. **Directed Evolution.** Relatively recently, it has been realized that evolutionary principles can be used as an engineering design tool. These principles are simple: set a series of design goals, start the design process with a prototype, make some change by some process that may include randomness, test the resulting new prototype against the design goals. If the new prototype is better than the old, even incrementally, keep it and make another change. Test again and change again. Continue to cycle until the design goals are met or until no further improvement can be made.

    Directed evolution has been used to design improved microwave antennas, buildings, and new enzymes that do not exist in nature.

16. **Analogical Thinking.** The ability to see connections among different physical and biological systems can be valuable for the biological engineer. If, for

instance, all biological units, whether they are at the cellular, tissue, organ, organism, group, population, or ecosystems levels have certain traits in common. Some of these have been described above. If these commonalities can be understood as concepts, then they can be useful in forecasting expected biological behaviors at all levels, and help to achieve the three biological engineering goals given in the introduction section.

Analogical thinking begins with characterizing physical laws obeyed by biological entities. Classifying all variables into either effort or flow, and understanding the relationships between these two can be a start (Johnson, 1999; Schreuders and Johnson, 1999). Analogical concepts in chemistry and the engineering sciences follow. When these are all brought together, biology is no longer a science consisting of a long list of facts, but is, instead, a coherent set of concepts and fundamentals that can be of value in formulating designs for new and improved products and processes

17. **Looping and Successive Approximation.** Although it may appear as if there are elegant control algorithms embedded in the central nervous systems of animals, the real control mechanisms more likely involve trial-and-error procedures. Sensors feeding information directly to the brain can invoke motor responses that result in changes of sensor outputs. These, in turn, would invoke other changes. If these other changes bring the control system closer to the set point, then further changes in the same direction are attempted. This continues until the set point is passed, and then the invoked change is in the opposite direction. This successive approximation procedure results in hunting around the desired set point. The exact set point is not always met, but deviations are usually small.

18. **Reliability Curves.** These are so universal in shape that they apply to automobiles, computers, and tools, as well as to human beings. A product just off the assembly line has a relatively high probability of failure. This is a result of faulty components or improper assembly. After this initial high rate of failure, called the *burn-in* period, comes a relatively long period of satisfactory performance with low rate of failure. This is the normal working period. When aging begins, the rate of failure again increases and continues to climb. For very, very old products, the failure rate seems to level off at a high rate.

    This progression of failures, high when new, decreasing to a low value for most of its working life, and then increasing again with age has been attributed to redundant faulty components. Failure of one or two components can be tolerated as long as other parts can assume the functions of those that no longer function. When the last part fails, the whole product fails.

    Humans and other organisms are assembled from redundant, imperfect components. They follow the classical reliability curve just as human-made products do (Gavrilov and Gavrilova, 2004). All engineers should be aware of the product reliability cycle and plan accordingly.

19. **Immediate Availability with Circulatory System.** Instant hot water in your hotel room? With a hot water circulation system, hot water is transported in a cycle from source to far end and back again. Tapping into this circulation avoids the wait while pipes are purged of noncirculating cold water.

    Circulatory systems in higher level animals have common design characteristics that engineers are well to be aware of. First, to deliver oxygen to the tissues, the smallest vessels must be in intimate contact with the tissues. Small vessels have large resistances that dissipate large amounts of power. To overcome this, flow rates in these small vessels must be kept low, so there must be a large number of them in parallel. Also to minimize energy requirements, there must be a small number of very large vessels to feed the smaller ones and collect from the smaller vessels. Thus, there must be a branching pattern from large to small and from small to large vessels.

    Living things use circulatory systems to deliver oxygen, glucose, and hormones to various locations in the body whenever and wherever they are needed, without the delay that would be present without a circulatory system. This mechanism works so well that it can be used for applications other than in living beings.

20. **Proportional Plus Derivative Sensors.** It is common that biological receptors produce outputs (usually neural in animals) that are related not only to the level of the stimulus but also to the rate of change of the stimulus. This incorporates a derivative element in the downstream control. Derivatives anticipate future stimulus positions, so improve stability of the control system.

    For stimuli that are chronically present, the control system that includes sensors and controller often adapts to the continuous presence of the stimulus. This has the effect of saving attention for those elements of the environment that have meaning.

21. **Weber-Fetchner Law.** Biological sensing is inherently nonlinear, giving rise to the Weber-Fetchner Law, and its variants, Weber's Law and Stevens's Power Law. Each of these is somewhat different quantitatively, but expresses the fact that the just noticeable difference in a stimulus depends on the level of that stimulus already present. Thus, the ability to see a light depends on the background light level; the ability to hear an additional sound depends on the background sound level, and so on.

    The effective additional level of a stimulus appears to be so universal in biology that the same principle should be expected for enzymes, neural activity, and running speed, to name a few. To expect the ability to recognize an additional component to be influenced by the amount already there can influence biological engineering designs of all kinds. Perhaps the most important part of understanding the concept behind the Weber-Fetchner relationship is that it clearly identifies limits to discernment sensitivity.

22. **Young's Principle.** Very selective, narrowband sensors require a lot of energy to operate. In addition, there are only a few instances in biology where such selectivity is warranted. One of these is the detection of pheromones to indicate reproductive opportunities.

Biological sensors are nearly all broadband, with responses that spread over a wide range of input qualities. Signals from these sensors are not very informative, because they could represent a wide range of possible stimuli. Yet, organisms are very much aware of their specific surroundings. How is this possible?

The answer is a number of broadband sensors with center stimuli that differ from each other by finite amounts. Their outputs overlap. When contributions from each of these sensors are compared, the contribution of each sensor, when added to the others, can determine exactly what type of stimulus has been received.

Examples in biology abound. One of the best examples is the color sensors in the retina of the eye. There are three types of receptors, each sensitive to a different range of light frequencies. They are broadband, and their outputs overlap. A specific color is determined by the relative contributions of each of these receptors. Thus, perception of a myriad of colors is possible from the outputs of only three types of receptors. A similar mechanism allows determination of the physical position of touching without having to have touch sensors at each location on the skin.

23. **Hägen-Poiseuille Formula.** This formula relates vessel resistance to fluid viscosity, vessel length, and vessel diameter. What it tells us is that resistance is extremely sensitive to diameter, being inversely proportional to diameter to the fourth power. A small difference in diameter can have a large effect on resistance.

This equation was developed for laminar flow in a uniform, straight conduit. These conditions rarely apply in biology. Nevertheless, the Hägen-Poiseuille formula is a simple, quantitative explanation of the effects of changing vessel size, and, as such, is a valuable rough guide even when flow is turbulent and the vessel is not straight or uniform.

In the bodies of animals, there are many sphincter muscles that encircle fluid flow passageways. The Hägen-Poiseuille formula tells us that it is not necessary for the sphincter muscles to completely close these passageways in order to control fluid flowing in them. A small contraction has a large effect. When exposed to nitric oxide, arteriolar sphincter muscles relax and blood rushes in. It doesn't take much.

24. **The Law of Laplace.** The Law of Laplace (Johnson, 1999) results from a force balance on the shell of a sphere or cylinder and relates pressure inside the object to tensile stress in the wall, wall thickness, and radius of the object. It gives a clear reason why bacteria are rounded, flimsy capillaries can contain blood at high pressure, and why lung surfactant is necessary to keep respiratory alveoli from collapsing into one huge sac with surface area too small to sustain life. The implications of the Law of Laplace are counterintuitive, because it states that smaller vessels can contain higher internal pressures without bursting. Architects have used the Law of Laplace as the basis of building shell designs that withstand high loads without heavy thick roofs and walls. Biological engineers should understand this principle in order to avoid intuitive errors in judgment.

25. **Class 3 Levers.** Class 1 levers come to mind whenever a mechanical advantage is sought. Class 1 levers place the fulcrum between the applied force and the load such that a smaller force can be applied to lift a heavier load by lengthening the moment arm. However, the arms and legs don't work that way.

    Muscles produce high forces, but cannot produce them very quickly or with large displacements. Thus, they are matched well with class 3 levers where the force is applied between the load and the fulcrum. There is a mechanical disadvantage of a class 3 lever; the applied force must be higher than the load force. However, the class 3 lever multiplies both the speed and the amplitude of the force displacement, so it allows more rapid motion and larger excursions than muscles are capable of generating by themselves.

III. Additional Concepts

Other concepts taught to engineering students are, of course, also important for competent biological engineers to know. These include force, mass, and energy balances, Bernoulli's equation, Fick's equation, Ohm's Law, thermodynamic laws, Newton's Laws, and others. Maxwell's equations, Kirchhoff's Laws, and the Navier-Stokes equations are just as important for specialists within biological engineering. These have not been included in the above list because they are not as unique to biological engineering as are many of the above. Understanding them does not necessarily assist in understanding biological nature. The same is true for concepts related to mathematical modeling, chemical equilibrium, pharmacokinetics, chemical kinetics, and a whole host of other information important for some biological engineers. What were listed, however, are concepts and principles suggested to be expected of all biological engineers, as the core of what distinguishes biological engineering from other disciplines.

IV. Discussion

Many of these concepts are not presently taught in many Biological Engineering curricula. Nor are they taught to Biomedical Engineering, Biomechanical Engineering, Chemical and Biomolecular Engineering, Bioengineering, Biosystems Engineering, or Civil and Environmental Engineering students. Nevertheless, each of these bio-based engineering curricula would benefit from the ability to appreciate a basic understanding of biology, similarly to the ability to understand physics, chemistry, and engineering sciences and the means to utilize these in engineering designs. Instead of attempting to incorporate each of these, and others, in various engineering courses already full to overflowing with material that must be taught, these concepts could be most appropriately taught in a course on Biology for Engineers (Johnson, 2010). This course, with a focus on the ways in which living things work and how they can be utilized by engineers, could be taught as an engineering science course centered on the realm of biological applications. Such a course has been taught at the University of Maryland both at the freshman level and senior level. For incoming freshmen, the course has provided a prospective context in which further education can be understood to be needed; for seniors, the course gave a retrospective view of information that students may or may not have been exposed to, but puts this information in a biological context. Both of these have been experienced, but the upper class course has probably been somewhat better at Maryland because of prerequisite requirements for later sophomore courses. Seniors are less likely to be flummoxed by the range of ideas in such a course.

The preceding 25 concepts were suggested as a means to an end. They were not necessarily intended to be exhaustive nor were they meant to be arbitrarily dictated dogma. They are, however, given as a starting point for further discussions regarding specific information items to be expected of all competent biological engineers (in the broadest sense) by someone who has explored biology from an engineering prospective, continues to be fascinated by advances in biological knowledge, and has had extensive experience teaching biology to undergraduate biological engineering students. If these concepts are to be incorporated into all biological engineering curricula, then some uniformity of expectations of graduates would follow. This would be good for the graduates, for the profession, and for the quality of eventual biological engineering applications. The local means to incorporate these concepts, as with so many other requirements, depends largely on individual faculties and the ways they can best serve their students.

References

Costello, T.A., and D.J. Carrier, 2006, Emergence of Biological Engineering at the University of Arkansas, *Internat. J. Engr. Educ.,* 22(6): 1149-1156.

Gavrilov, L., and N. Gavrilova, 2004, Why We Fall Apart, *IEEE Spectrum,* 41(9): 30-35 (Sept).

Garrett, R.E., D.C. Davis, D.M. Edwards, A.T. Johnson, and G.E. Rehkugler, 1992, Improvement of Competencies of Agricultural and Related Biological Engineers, Report of CSRS USDA Agreement No. 90-38411-5734, University of California, Davis, CA.

Johnson, A.T., 1999, *Biological Process Engineering,* John Wiley and Sons, New York, ISBN 0-471-24547-X.

Johnson, A.T., 2006, The Making of a New Discipline, *Internat. J. Engr. Educ.* 22: 3-8.

Johnson, A.T., 2010, *Biology for Engineers*, Taylor and Francis, Boca Raton, FL.

Johnson, A.T., H. Montas, A. Shirmohammadi, and F.W. Wheaton, 2006, Change Is Necessary in a Biological Engineering Curriculum, *Biotechnol. Prog.* 22: 167-172.

Johnson, A.T., and W.M. Phillips, 1995, Philosophical Foundations of Biological Engineering, *J. Engr. Educ.* 84: 311-318.

Johnson, A.T., and P.D. Schreuders, 2003, Bringing Life to Engineering: Biological Engineering at the Graduate Level, *Eur. J. Eng. Educ.* 28: 37-46.

Linsenmeier, R.A., 2003, What Makes a Biomedical Engineer? *IEEE Engr. Med. Biol. Mag.* 22(4): 32-38 (Jul/Aug).

Saltus, R., 2010, A Silver Lining, *HHMI Bulletin*, 23(2):22-27.

Scott, N.R., 2006, DNA of Biological Engineering, *Internat. J. Engr. Educ.*, 22(1): 9-13.

Schreuders, P.D., and A.T. Johnson, 1999, A Systems Approach for Bioengineering, *Int. J. Engr. Educ.* 15: 243-248.

Shannon, C., and W. Weaver, 1949, *The Mathematical Theory of Communication*, University of Illinois Press, Urbana, IL.