THE EFFECT OF NATURAL LANGUAGE PROCESSING IN BIOINSPIRED DESIGN

A Thesis

by

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ABSTRACT

Bioinspired design methods are a new and evolving collection of techniques used to extract biological principles from nature to solve engineering problems. The application of bioinspired design methods is typically confined to existing problems encountered in new product design or redesign. A primary goal of this research is to utilize existing bioinspired design methods to solve a complex engineering problem to examine the versatility of the method in solving new problems. Here, current bioinspired design methods are applied to seek a biologically inspired solution to geoengineering. Bioinspired solutions developed in the case study include droplet density shields, phosphorescent mineral injection, and reflective orbiting satellites. The success of the methods in the case study indicates that bioinspired design methods have the potential to solve new problems and provide a platform of innovation for old problems.

A secondary goal of this research is to help engineers use bioinspired design methods more efficiently by reducing post-processing time and eliminating the need for extensive knowledge of biological terminology by applying natural language processing techniques. Using the complex problem of geoengineering, a hypothesis is developed that asserts the usefulness of nouns in creating higher quality solutions. A designation is made between the types of nouns in a sentence, primary and spatial, and the hypothesis is refined to state that primary nouns are the most influential part of speech in providing biological inspiration for high quality ideas. Through three design experiments, the author determines that engineers are more likely to develop a higher quality solution using the primary noun in a given passage of biological text.

The identification of primary nouns through part of speech tagging will provide engineers an analogous biological system without extensive analysis of the results. The use of noun identification to improve the efficiency of bioinspired design method applications is a new concept and is the primary contribution of this research.

DEDICATION

This thesis is dedicated to my mother and father, without whose love, prayers, support, and encouragement I could not have made it this far.

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I would like to thank my committee members, Dr. Julie Linsey and Dr. Bryan Boulanger, for their support throughout the analysis and writing process. I would especially like to thank my committee chair, Dr. Daniel A. McAdams, for his tough love approach, guiding suggestions, and patience throughout the course of this research.

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NOMENCLATURE

TCM	Terrestrial Carbon Management
SRM	Solar Radiation Management
NLP	Natural Language Processing
PBR	Photobioreactor
CCN	Cloud Condensation Nuclei
CO2	Carbon Dioxide
EM-E	Electromagnetic Energy

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1. INTRODUCTION

1.1 Overview

Nature's solutions to problems have often served as inspiration for those engineered by humans [1]. The inspiration derived from nature, however, has typically been found informally with no structured method. Currently, the creation of systematic and formal methods to find solutions to engineering problems in nature is an expanding field of research [2] [3] [4] [5]. The intentional extraction and application of biological principles to engineering problems is a practice known by many different terms, including biomimicry, biomimetic design, and biologically inspired design. Here, we will use the term bioinspired design.

Bioinspired design research has produced several methods that enable engineers to access biological principles and apply them to engineering designs. The application of bioinspired design methods is typically confined to existing problems encountered in new product design or redesign [6-9]. In these exploratory cases, the bioinspired design methods suggest concepts that are innovative and novel, thus supporting the notion that these methods offer the potential to find innovative solutions. Along with finding innovative solutions, a long-term goal of design methods supporting concept generation is that application of the methods will enable engineers to find solutions to problems for which there is no known solution. Such problems can occur in many cases, including those in which the solution space is highly constrained or those in which the problem is large in scope and highly complex. An overarching goal of the research presented here is the successful application of existing bioinspired design methods to a complex engineering problem.

Bioinspired design methods evolved from the creation of BioTRIZ, an adaptation of Genrich Altshuller's Theory of Inventive Problem Solving [10], which enables engineers

to utilize biological principles to solve design conflicts [8]. Formal bioinspired design methods have continued to improve and have recently begun to utilize computational tools to access the biological domain. Idea-Inspire, for example, is a software package designed to provide biological knowledge to engineers using a verb, noun, adjective search format [11]. Additionally, Shu et al. have developed a method that allows engineers to search for potentially inspiring systems with biologically connotative search terms and a computational tool [12]. Similar to this approach, Nagel et al. have utilized the Functional Basis to create an Engineering-to Biology thesaurus by translating engineering functions into their biological material, signals, and energy correspondents [13]. The process used by Nagel also incorporates a computational search tool [14].

The methods used in bioinspired design all share two commonalities: the use of natural language aspects to search the biological domain and the application of computing capabilities to accomplish the search. Using a natural language based search can help engineers identify functionally analogous biological systems that may suggest solution ideas for engineering problems. However, the technical language of biologists, botanists, entomologists, and other similar natural scientists is often unfamiliar to engineers and impedes proper use of current bioinspired design tools. Additionally, use of the computational search tools results in copious amounts of biological text passages that must be parsed by the designer. This requires large amounts of time for post-processing and contributes to the inefficiency of current bioinspired design methods. A second hindrance is identified from the lack of biological knowledge: engineers do not always understand the biological systems ascertained from application of the bioinspired design methods. Without knowledge of the biological systems presented by application of the method, the engineer cannot reasonably form a coherent biologically inspired solution.

For bioinspired design methods to be widely used and accepted, both impediments must be solved. Bridging verbs [15] and Engineering-to-Biology thesauri have solved the one of the impediments, but the other remains a research opportunity.

1.2 Research Contribution

A primary goal of this research is to utilize existing bioinspired design methods to solve a complex engineering problem to examine the versatility of the method in solving new problems. Additionally, by applying emerging methods to large-scale complex problems, we can better discover the current shortcomings in the existing bioinspired design methods. Here, we will apply current bioinspired design methods to seek a biologically inspired solution to geoengineering. Geoengineering is the intentional modification of the earth's climate to prevent harmful anthropogenic warming [16]. The application of the methods is presented in a case study and will be discussed in subsequent sections.

A secondary goal of this research is to help engineers use bioinspired design methods more efficiently and without extensive knowledge of biological terminology using natural language processing (NLP). NLP has been used successfully in established design research [17-19]. NLP has been applied to bioinspired design successfully in the development of a method that utilizes bridging verbs to identify nonobvious search terms to facilitate the retrieval of cross-domain information [20]. While the method does make use of natural language applications, it does not directly identify nouns or specify noun types as the basis for concept generation. This research explores the effect of parts of speech, particularly nouns, on biological inspiration. It is hypothesized that a particular type of noun will result in a better bioinspired design when presented to an engineer. The implication of this hypothesis is that, if proven correct, it can provide a means by which an engineer can utilize biological systems for design inspiration without the technical knowledge of a natural scientist. The identification of an inspirational part

of speech will also eliminate the need for extensive post-processing of the results from the computational search tools.

An additional research activity is the modification of an existing computational search tool to support the hypothesis described above. The identification of a specific part of speech that will lead an engineer to a biologically inspired solution, in conjunction with the modified search tool, will make bioinspired design methods more efficient and accessible to those without biological knowledge. This research will help to bridge the gap between the engineering and biological domains and establish the versatility of the method in solving both simple and complex problems.

1.3 Research Approach

The case study applied in this research seeks to apply bioinspired design methods to a significant and unsolved engineering challenge, thus testing the method for practical use outside traditional product design applications. The method used in this case study combines traditional functional modeling with available engineering-to-biology thesauri and computational search tools to seek a solution to the complex, emerging, and as yet unsolved problem of geoengineering. The method provides the designer with biological systems, and the designer develops conceptual solutions to geoengineering based on these biological systems. The case study is then validated using a comparison between existing proposed solutions formulated by the scientific community and those developed through application of the bioinspired design methods.

Successful application of existing bioinspired design methods to geoengineering demonstrates that the method has the ability to address complex engineering problems. This success, however, is dependent on the designer's ability to navigate the unfamiliar biological lexicon that results from the method application. The raw text output of the computational search tool requires engineers to parse countless passages of biological

text, a difficult feat without the technical knowledge of natural scientists. It is thus critical to understand how engineers without inherent knowledge of biological systems can formulate successful biologically inspired solutions using the existing methods. In exploring this, the hypothesis emerges that a particular part of speech is more likely to result in a higher quality solution to a given problem. The hypothesis is developed from a preliminary test conducted with twelve participants. The test presents geoengineering as a design problem, provides biological text passages, and asks the engineers to formulate solutions based on these passages. The idea of the test is to analyze the correlation between part of speech and quality of the solution. With these variables, it is possible to identify a part of speech using NLP that is more useful to engineers in formulating a biologically inspired solution.

Analysis of the data collected in the preliminary test indicates that nouns are the most used part of speech in formulating high quality solutions. Moreover, two types of nouns emerge as inspirational parts of speech, here termed primary and spatial. A primary noun refers to the noun that performs the searched biological function, and the spatial noun is the noun most closely located, within the passage, to the searched function. Further exploration of the hypothesis is conducted in a second study, in which twenty-one participants are divided into three groups and given packets of biological text passages. Each group in the study receives a packet with the primary noun highlighted, the spatial noun highlighted, or no highlighting and is asked to formulate solutions to the geoengineering problem based on the highlighted (or non-highlighted) portions of text. Analysis of the data collected in the second study indicates that primary nouns result in higher quality solutions. A high quality solution is considered an idea that demonstrates feasibility, innovativeness, and completeness.

A final study is conducted to test the revised hypothesis developed through the second study. In the final study, the participants are divided into three groups but are given packets of biological text passages that have been modified. The first group receives the

full biological text passage, the second group receives only the part of the passage that includes the primary noun, and the third group receives only the part of the passage that includes the spatial noun. An additional aspect of the final study is that participants are presented with two design problems: geoengineering and human transportation. The results between the two design problems can be compared, and the effectiveness of the method in solving complex problems can be better evaluated.

2. LITERATURE REVIEW

2.1 Bioinspired Design

Design inspiration relies primarily on chance discoveries and "aha" moments experienced by the designer that are unreliable and unpredictable. This ad-hoc inspiration is most particularly observed in bioinspired designs, most notably with the development of Velcro by George de Mestral [21]. The creation of formal bioinspired design methods is a field still in its infancy, although it is rapidly expanding with current research [2-5].

Current research has produced several methods that appear sufficiently developed to enable engineers to apply biological principles in practical engineering design situations. One of these methods is BioTRIZ, an adaptation of the Theory of Inventive Problem Solving (TIPS) [3]. Since the introduction of BioTRIZ, the field has expanded to include various methods for achieving the successful extraction of design inspiration from nature. The majority of these methods have a common theme: using computational tools to search the biological domain. Another emerging bioinspired design method is that developed by Chakrabarti and Srinivasan [11]. They addressed natural to engineered knowledge domain transfer through the development of Idea-Inspire, a software package that allows the user to search a collective database of biological and engineered systems [4].

Shu et al. have done instrumental work in creating methods and tools that allow engineers to search for potential solutions in text based biological knowledge. The methods allow a search that incorporates a natural language approach to facilitate designer inspiration through biologically meaningful keyword searches with a computational tool [12].

Similar to the approach developed by, and in collaboration with Shu, Nagel et al. have developed biological solution search methods based on finding analogies with functions formally represented using the Functional Basis [5]. The Functional Basis specifies a standardized vocabulary and provides levels of increasing specificity to accurately capture designer intent within the functional representation. This formal function based approach has been extended to create biological correspondents to the lexicon of the Functional Basis [13]. The translation of engineering materials, signals, and energy into biological components provides a foundation for utilizing the Functional Basis in conjunction with biological keyword searches. The process used by Nagel also incorporates a computational search tool [14].

The recent methods developed in bioinspired design all share two commonalities: the use of natural language aspects to search the biological domain and the application of computing capabilities to accomplish the search. A natural language based search can help engineers identify functionally analogous biological systems that may suggest solution ideas for engineering problems. Despite the use of Engineering-to-Biology thesauri [13, 22] as a translation tool between the engineering and biological domains, the technical language of natural scientists is still unfamiliar to engineers. While engineers have a well-developed knowledge of physical and mathematical principles, the lexicon of the natural world is still difficult to understand. The disparity of the lexicon between the two domains can be problematic for engineers using bioinspired design methods.

Also problematic in the use of bioinspired design methods is the question of their capacity to address a wide range of engineering problems. Engineering application of the developed bioinspired design methods is limited. Cases include the handling and assembly of microparts [6], the development of a smart flooring product [7], the creation of a ‘cat-paw’ wheel [8], and the structural redesign of a roof to promote passive cooling [9]. The application of bioinspired design methods is typically confined to existing

problems encountered in new product design or redesign. While these are certainly necessary applications, there are many problems much larger in scope and complexity that are not so well defined. These complex emerging problems are not defined in terms of customer feedback and requirements but must be solved just the same. The success of bioinspired design methods at identifying solution concepts that are innovative and novel for consumer products supports the notion that these methods offer the potential to find innovative solutions for more complex problems.

The usefulness of the method to provide engineers with biologically inspired design solutions is contingent on the ability of the method to solve both large and small problems and the ability of the computational tools to help engineers navigate the unfamiliar biological lexicon. The ability of bioinspired design methods to fulfill these contingencies is explored in this research through an applied case study and sequential design experiments, all of which utilize geoengineering as the design problem.

2.2 Geoengineering

Geoengineering is the intentional modification of the environment with the objective of altering the global temperature in the event of unwanted anthropogenic climate change [16]. The failure of participating countries to meet specified Kyoto Protocol emission reductions has motivated experimentation and research directed towards the design of engineered solutions that could prevent planetary temperature increases [23]. Early analysis regarding feasibility of existing solution proposals for geoengineering dates back to a U.S. National Academy of Sciences published report in 1992 [24]. The rising concern within the scientific community regarding climate change and its implications for the future has resulted in continued experimentation and analysis of climate engineering.

Geoengineering research has resulted in several proposed conceptual solutions. The proposed conceptual solution approaches to geoengineering are presented and organized here. The solutions can be categorized into two primary mitigation modes of action: terrestrial carbon management (TCM) and solar radiation management (SRM). TCM is a form of emissions mitigation that prevents further climate warming by controlling existing carbon dioxide in the atmosphere. SRM prevents warming by managing incoming solar radiation and increasing surface reflectivity. Specific mechanisms of TCM focus on enhancing existing carbon sinks through augmentation of natural processes. The TCM mode of action can be further categorized into five basic mechanisms: ocean injection, iron ocean fertilization, forestation, synthetic trees, and biomass cultivation as shown hierarchically in Figure 1. Similarly, the SRM mode of action can be categorized into four basic mechanisms: marine cloud albedo enhancement, atmospheric aerosol injection, insolation reduction, and surface-based albedo modification, as shown in Figure 2.

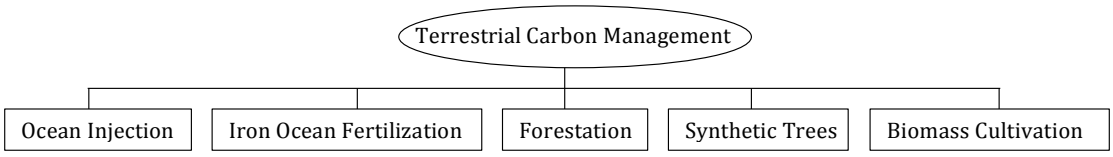

Figure 1. Diagram of TCM mechanisms.

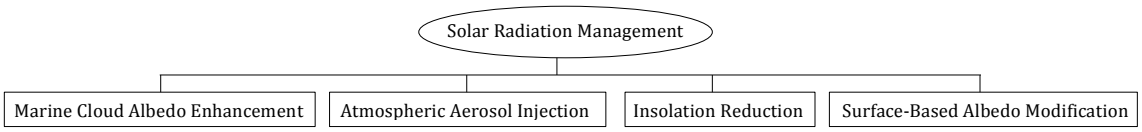

Figure 2. Diagram of SRM mechanisms.

2.2.1 Geoengineering through Terrestrial Carbon Management

The management of atmospheric carbon dioxide through sequestration and storage is called TCM. Currently proposed mechanisms for TCM include ocean injection, iron ocean fertilization, forestation, synthetic trees, and biomass cultivation. Each of these is discussed below to clarify how the mechanism achieves the desired mode of action.

2.2.1.1 Ocean Injection

Due to its large size and natural ability to sequester carbon dioxide, the ocean offers a mechanism for carbon storage. Results for numerical approximations of permanent ocean carbon storage capacity vary, given that permanent storage is dependent on surface-ocean chemistry, but in a scenario where atmospheric carbon concentrations do not increase past the current value of 380 parts per million (ppm), 80% of atmospheric carbon dioxide can be permanently sequestered [25].

Ocean storage is an attractive solution for geoengineering because it can be implemented with little to no reduction in the use of fossil fuels, will result in large amounts of carbon stored for long periods of time, and is estimated to be less costly than other proposals. However, lack of knowledge about ocean current dynamics and the potential for disruption of marine ecosystems are shortcomings of ocean injection. Additionally, the acidification of oceans caused by excess carbon dioxide saturation and disruption of the natural atmosphere-to-ocean carbon cycle are crucial criticisms of ocean injection [26].

To execute the ocean-based carbon storage mechanisms, methods of dispersion and isolation are proposed. Isolation entails the injection of carbon dioxide into hollows in the deep seabed (effectively creating CO2 “lakes”).

Dispersion involves the dissolution of liquid carbon dioxide in the ocean using towed pipe processes, dry ice release, or the formation of buoyant or gravity droplet plumes [26]. Using a towed pipe process entails the steady release of liquid carbon dioxide through a nozzle at the end of a pipe connected to a ship on the ocean surface. Experiments conducted by Ozaki et al. predict that releasing carbon dioxide droplets at a depth of 2000 meters (m) will from a plume that rises for 900 m over a period of 3.5 hours before completely dissolving [26]. Dry ice release is the manufacture of carbon dioxide dry ice blocks and subsequent release into the ocean by dropping the dry ice from a moving ship. It is estimated that dry ice blocks 3 to 4 m in volume would sink 3000 m before releasing 50% of the carbon dioxide [27]. Droplet plumes describe the instantaneous injection of liquid carbon dioxide at a specified depth. Buoyant plumes are designed to rise after injection, and gravity plumes are designed to sink after injection. Whether the plume sinks or floats is dependent on depth, rate of release, and droplet diameter of the injected carbon dioxide [28].

2.2.1.2 Iron Ocean Fertilization

A second mechanism for Terrestrial Carbon Management is iron ocean fertilization. In Iron ocean fertilization, ocean surfaces are fertilized with iron to promote plankton growth thus enhancing carbon sequestration through increased rates of photosynthesis. Carbon sequestration occurs naturally in oceans through a biological pump, in which surface organisms, such as phytoplankton and algae, store carbon dioxide. The surface organisms consume carbon with photosynthetic processes, subsequently release carbon in the form of organic matter that sinks into the ocean, and produce carbon dioxide through respiration that gets released into a deep water column [29]. This naturally occurring carbon sequestration process does not currently operate at its full potential due to a lack of necessary nutrients, such as iron, for phytoplankton and algal growth in many oceanic regions. The identification of iron as a limiting nutrient, known as the Iron Hypothesis, has prompted thorough study of ocean fertilization, the process in which the

addition of iron to ocean surface waters causes increased sequestration of atmospheric carbon dioxide [30].

Current estimates predict that approximately 7-11 Gt of carbon dioxide per year could be extracted from the atmosphere through fertilization [24]. Initial exploration of this basic premise indicates that iron ocean fertilization would be comparatively low cost [29]. The low cost of such an operation makes it an appealing alternative. However, the addition of iron ocean surfaces can increase nitrification rates, which amplifies the production and release of nitrous oxide, a strong greenhouse gas, caused by chemical reactions in the seawater [31]. Additionally, the increase in photosynthetic processes caused by iron fertilization would deplete dissolved oxygen in the ocean at faster rates, thus creating oxygen-starved regions in the ocean that cannot support marine life [29].

2.2.1.3 Forestation

The third proposed TCM mechanism is forestation. Trees naturally sequester carbon through photosynthetic processes that result in carbon storage in the plant. The replanting of previously forested areas (reforestation) and the planting of forests in new areas (afforestation) are both methods of forestation.

The moderation of atmospheric carbon dioxide through forestation techniques is advantageous due to its simple implementation, relatively low cost, and consequential improvement of aesthetics and air quality [24]. Weaknesses of forestation include the limited potential for large carbon sequestration and the land use conflicts that might arise given large reforestation/afforestation efforts. Estimates by Moulton et al. predict that carbon sequestration by forests can reach values up to 720 Mt of carbon per year with the application of various forestry techniques [32].

Despite its appeal as a low cost, low impact solution, further research is needed to fully comprehend forest ecology and climate interactions to understand the long-term potential of forestation as a geoengineering solution.

2.2.1.4 Synthetic Trees

Similar to forestation, synthetic trees offer a mechanism for TCM. A synthetic tree, also known as an engineered tree, replicates the photosynthetic process in plants to sequester carbon dioxide mechanically. Synthetic trees operate by capturing carbon dioxide from the air using filters made of a sorbent material, such as sodium hydroxide [33]. The carbon dioxide is then removed from the filter and stored. The application of synthetic tree capture systems is a novel solution due to its low adverse environmental impacts and minimal maintenance requirements. The lack of promising carbon capture filters, coupled with the high initial cost of implementing air capture mechanisms, are weaknesses of synthetic trees as TCM geoengineering solutions.

A notable strength of air capture systems, such as synthetic trees, is their ability to address non-point sources, such as transportation emissions, because they are portable and can be strategically placed to address these sources. To mitigate carbon emission from transportation, for example, synthetic trees can be placed along highways. Additionally, these synthetic trees offer enhanced carbon sequestration when compared to real trees. Estimates for synthetic tree systems indicate they are capable of capturing all non-energy sector emissions if employed worldwide, approximately 14.2 Gt/yr of carbon dioxide sequestration [33].

2.2.1.5 Biomass Cultivation

The fifth proposed mechanism for TCM is biomass cultivation. Biomass cultivation is the use of algal cultures to achieve high rates of carbon sequestration and potential energy production through photosynthesis. As a distinction from the iron ocean

fertilization mechanism, the growth of algae is accomplished in enclosed tubes called photobioreactors (PBRs), which are designed to promote algal growth through constant provision and balance of light, temperature, and nutrients. These enclosed tubes operate either by pumping carbon dioxide and air into a fluid filled medium with continuous loop circulation, or by pumping carbon dioxide and air bubbles into one end of a closed, fluid-filled tube [34]. The provision of light and constant balance of nutrients is critical to the success of algal growth in a photobioreactor.

The small-scale application of algal growth allows it to be regulated and controlled more efficiently, and the potential for biomass fuel from harvested algae provides the opportunity for further carbon dioxide reduction [29]. Javanmardian et al. estimate that an optimally designed PBR needs 1-2 mW/cm2 of usable light, a specific surface area of 5-10 cm2/cm3 and an algal cell density of 10,000,000,000 cells per milliliter of fluid [35]. The requirements of a PBR under these conditions are manageable, but replicating this operation at a large scale, in meters rather than centimeters, is difficult to achieve and currently limits photobioreactors to small-scale applications [36].

2.2.2 Geoengineering through Solar Radiation Management

The second mode of action for geoengineering is Solar Radiation Management (SRM). SRM increases planetary albedo through reflection of incoming solar radiation. SRM can be accomplished by one of four mechanisms: marine cloud albedo enhancement, atmospheric aerosol injection, insolation reduction, and surface-based albedo modification.

2.2.2.1 Marine Cloud Albedo Enhancement

One mechanism for SRM is to make low-lying marine clouds larger and more reflective to incoming radiation. Marine cloud albedo is increased by the addition of cloud

condensation nuclei (CCN) into existing marine clouds. Cloud condensation nuclei are tiny particles around which water coalesces to form clouds and is typically either sea salt particles or manufactured sulfur dioxide [29]. The larger concentrations of CCN increase the volume of the cloud, giving it a larger surface area that can reflect more solar radiation.

Marine cloud albedo enhancement can be done with existing technologies and can thus be done quickly and with reasonably low cost. Also, marine cloud albedo enhancement offers regionalized control, which eliminates the need for a truly global effort, thus lowering the cost. Assuming a doubling of atmospheric CO2, it is estimated that a 4% increase in marine stratocumulus clouds is sufficient to offset positive forcing and warming effects [24]. The high level of control over the amount of cooling and the lack of adverse environmental effects are key advantages of the cloud albedo enhancement mechanism [37].

2.2.2.2 Atmospheric Aerosol Injection

A second mechanism for SRM is atmospheric aerosol injection. Atmospheric aerosol injection is the introduction of particles into the atmosphere to reflect and scatter incoming solar radiation. Aerosols work by reflecting infrared radiation back into space and scattering visible radiation that reaches the surface of the earth. As atmospheric aerosol concentrations increase, planetary albedo will be increased and a net cooling affect achieved [38]. The surface properties, densities, sizes, compositions, and refractive indices of the aerosols determine the amount of infrared radiation that is reflected back into space. Estimates quantifying the aerosol loading necessary for cooling are typically modeled assuming a doubling of atmospheric CO2 and fall between 1 and 5 Megatons (Mt) of sulfur per year [29].

The implementation of aerosol injections requires consideration of the particle production, timing and location of dispersal, and the amount of aerosol needed to produce the desired cooling effect [39].

2.2.2.3 Insolation Reduction

The SRM mechanism of insolation reduction relies on reflecting incoming solar radiation to prevent atmospheric warming. A variety of shielding techniques are included in the insolation reduction mechanism category [40]. The shielding techniques are categorized as either continuous or scatter. Continuous schemes focus on deployment of a single entity to achieve shading of incoming sunlight, such as the reflective solar shield proposed by Early [41]. Scatter techniques involve the formation of multiple reflecting entities to create a refractive cloud, such as the autonomous spacecraft cloud proposed by Angel [42].

Insolation reduction techniques are valued for their effectiveness, low maintenance, and predictability. However, cost analysis indicates that solar reduction methods could be expensive, and the technology to employ proposed designs is not advanced to the point of production [43].

2.2.2.4 Surface-Based Albedo Modification

The fourth mechanism proposed to achieve the SRM mode of action is surface-based albedo modification. Surface-based albedo modification is the alteration of city surfaces to reduce heat gain and increase reflectivity. The modification of surface albedo has both local and global effects; local in its ability to reduce the heat absorbed and thus lower the heat island effect of cities and global in the potential for carbon emissions reduction by decreasing cooling requirements that will ultimately weaken reliance on fossil fuels for energy. Before deployment on a large scale, however, testing of new materials is

necessary to determine reflective abilities so that the use of hot light-colored materials that adversely affect albedo values will not be used [44].

Methods to increase urban albedo on a national level are estimated to prevent the emission of 27 Mt of carbon dioxide. Globally, the potential of a fully functional albedo enhancement program would result in an estimated savings of $10 billion in energy costs and 27 million tons in harmful emissions [44].

The described mechanisms have been proposed as solutions to achieve the modes of geoengineering but none have been formally accepted or implemented. Geoengineering remains unsolved and is thus considered a suitably complex engineering problem to test the capacity of bioinspired design methods. In the section that follows, a case study will scope the design problem of geoengineering, apply the design methods, develop bioinspired solutions, and evaluate the effectiveness of the design method in supporting the effort to generate solutions to the complex problem of geoengineering.

3. CASE STUDY: GEOENGINEERING

3.1 Problem Scope and Functional Decomposition

Prior to application of the bioinspired design methods, the problem must be scoped adequately. Specifically, the problem statement must be refined until a coherent functional model can be constructed. The scoping of the problem begins with the creation of a black box model, shown in Figure 3. Maintaining a simple and abstract representation of the problem, the flows into and out of the black box model are energy flows, here in the form of electromagnetic energy. To reduce fixation on a particular solution, the material and signal flows are not modeled here.

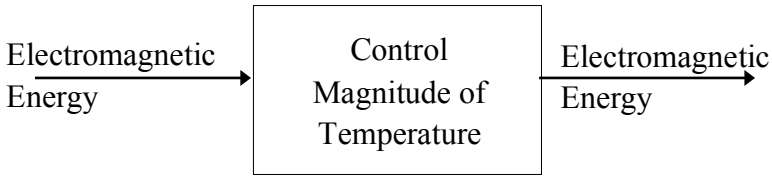

Figure 3. Black box model of geoengineering.

Electromagnetic solar energy enters the earth's atmosphere in the form of short wave radiation, also known as visible light [45]. Some of this incoming electromagnetic energy is reflected immediately back into space as short wave radiation; the remaining electromagnetic energy continues to the earth's surface and is either absorbed or reflected back to the atmosphere as long wave radiation, also known as infrared radiation. This re-emitted energy is either passed through the earth's atmosphere and into space or reflected back to the earth's surface by clouds or atmospheric gases [46]. The reflection of outgoing long wave radiation back to the earth is thought to result in a warming effect of the global temperature, which is the primary concern of geoengineering. Thus, to accurately scope the problem, we must account for both the

immediate incoming short wave radiation and the outgoing long wave radiation that is reflected back to the earth. Based on these solar energy flows, a functional model for the design problem of geoengineering is constructed and shown in Figure 4. This model defines the boundaries of the problem as the earth's atmosphere and highlights the need to stop incoming short wave radiation and guide outgoing long wave radiation through the atmosphere to outer space.

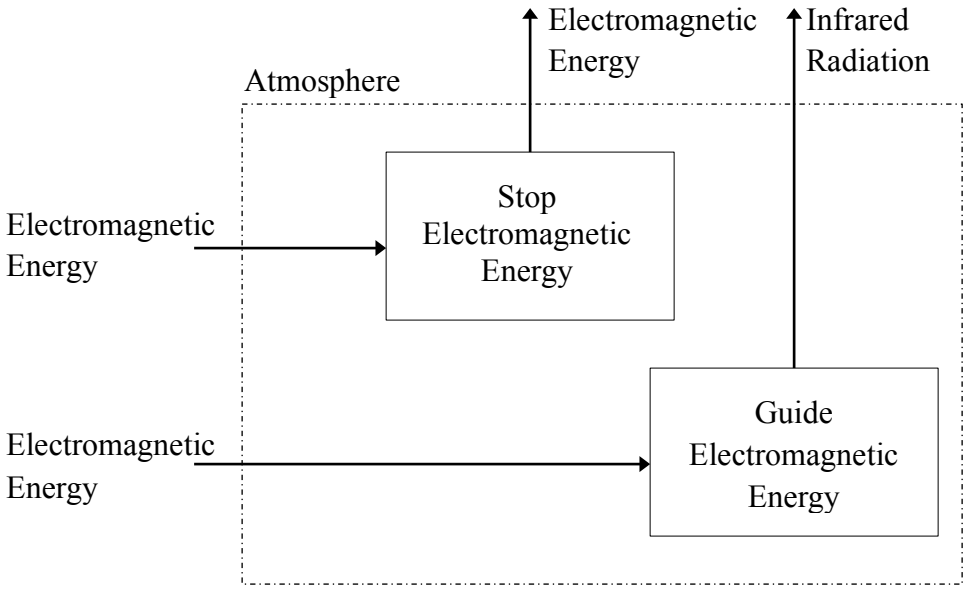

Figure 4. Functional model of geoengineering.

The functional model naturally defines two modes of action: stop electromagnetic energy and guide electromagnetic energy. These two functions can be decoupled: independent execution of either of these functions fulfills the black box function. Thus, we can scope the design problem to treat each independently as a black box design problem. The first black box model, shown in Figure 5, contains the function stop electromagnetic energy and is functionally consistent with the first mode of operation of geoengineering known as solar radiation management.

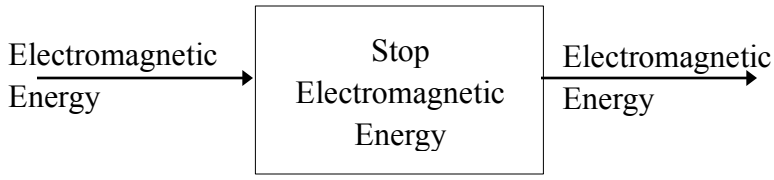

Figure 5. Black box model of SRM.

A functional model is developed from the black box function in Figure 5. This functional model is shown in Figure 6. To simplify figures, in this model and those hereafter, electromagnetic energy is designated as "EM-E."

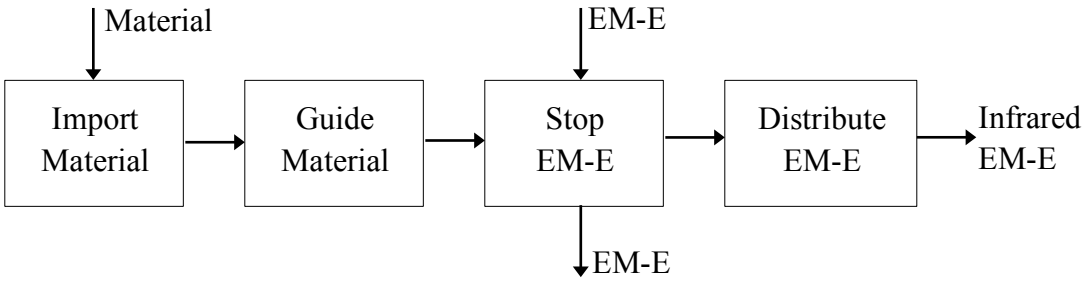

Figure 6. Functional model of SRM.

Below in Table 1, we create a morphological matrix of the SRM functions and specific functional solutions as taken from the currently proposed mechanisms.

Table 1. Morphological matrix of SRM mechanisms.

Function	**Solution**			
Import Material	Ships	Airplane	Rocket	Human
Position Material	Spray nozzle and pump	Elevation and speed	Rotation of the earth	Machine
Stop infrared EM-E	Water droplets	Aerosol particles	Mirror	Lightened surface
Distribute EM-E	Clouds	Clouds	Mirror	Surface

The second function from Figure 4, shown as a black box model in Figure 7, is to guide the outgoing electromagnetic energy, in the form of infrared radiation, out of the earth's atmosphere and back into deep space. To guide electromagnetic energy to deep space and reduce the amount reflected back to earth, elements that reflect long wave radiation must be removed from the atmosphere. Table 2 shows this as an abbreviated morphological matrix for the *Guide Electromagnetic Energy* black box function.

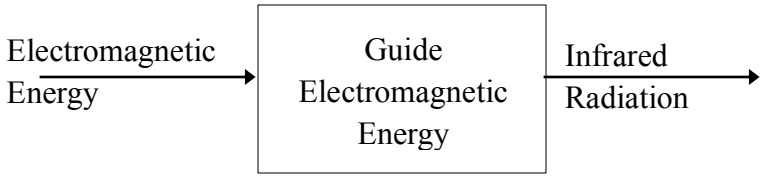

Figure 7. Second black box model of geoengineering.

Table 2. Morphological matrix for the second black box model.

Function	**Solution**			
Guide EM-E	Remove carbon	Remove methane	Reduce atmospheric water vapor	Reduce particulates from pollutants

The solutions listed in the initial morphological matrix are primarily focused on reducing or removing the atmospheric gases that reflect outgoing electromagnetic energy back to the earth's surface. The only one of these solutions that has received significant consideration in the context of geoengineering is the removal of carbon from the atmosphere. Thus, we restate the design problem specifically in the context of removing carbon from the atmosphere. This design problem is shown as a black box model in Figure 8. At this level of abstraction, the function of remove carbon is equivalent to the TCM mode of action. This black box is expanded to a functional model in Figure 9.

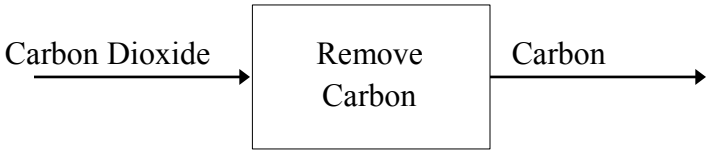

Figure 8. Black box model of TCM.

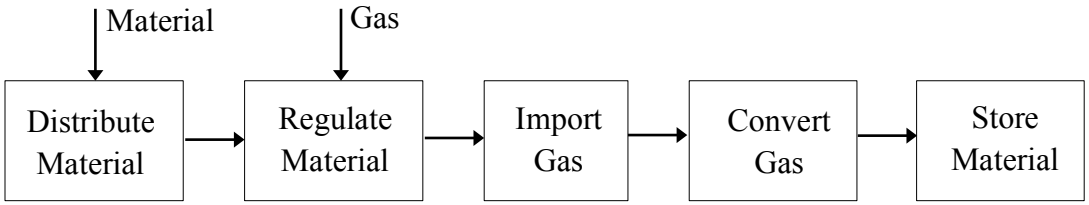

Figure 9. Functional model of TCM.

Below in Table 3, we create a morphological matrix of the TCM functions and specific solutions as taken from currently proposed mechanisms discussed above.

Table 3. Morphological matrix of TCM mechanisms.

Function	Solution				
Supply material	Ships	Ships	Trucks	Trucks	Human
Distribute Material	Towed pipes	Towed hose	Trucks	Planting Machine	Pump
Regulate Material	Depth and Speed	Speed and Amount	Airflow speed	Water	Light and Feedstock
Import Gas	Ocean currents	Algae	Filters	Trees	Algae
Convert Gas	Compression	Algae	Chemical Reaction	Trees	Algae
Store Material	Ocean	Algae	Depleted O&G Reservoirs	Trees	Algae

From the functional models shown in Figure 6 and Figure 9, the function based bioinspired design method can be executed. The morphological analysis shown here in Tables 1 and 3 organize the currently proposed solutions, functionally the supporting the accuracy of the functional models. Additionally, the morphological tables here are used to provide a function-by-function comparison of the bioinspired solutions developed below.

3.2 Application of Bioinspired Design Methods

Based on the above functional analysis and clarification of the problem, we will only pursue the design problem for the SRM mode of action. Given the functional model shown in Figure 6, the next step is to translate these Functional Basis functions into biological keywords. Translating the Functional Basis terms into biological keywords requires the engineering-to-biology thesaurus developed by Nagel, Stone, and McAdams [13], the biological keyword set developed by Srinivasan and Chakrabarti [11], and the set compiled by Cheong et al. [47].

The Functional Basis terms and corresponding translated keyword sets can be seen in Table 4. In the current keyword thesauri, there are multiple equivalent biological keywords for each Functional Basis term. Additionally, the computational search returns a large number of results for each biological keyword search. Thus, not all functionally equivalent biological keywords are searched. Based on familiarity of the geoengineering design problem gained during the problem clarification effort, the biological keywords that most closely represent the engineering function in the geoengineering context are chosen from the keyword lists. For example, the functional basis term stop, in the context of the functional model for SRM, is meant to describe the prevention of electromagnetic energy from reaching the earth's surface. One of the engineering-to-biology keyword sets lists *cover, destroy, inhibit*, and *surround* as biological correspondents for the function stop [47]. As shown in Table 4, we consider *inhibit* to be the most accurate biological representation of the function *stop* provided in the engineering-to-biology keyword sets. Additionally, no biological keywords were chosen for the function *import*. The function *import* within SRM refers to importing reflective, or a similarly functioning, material into the system that is then used to stop incoming electromagnetic energy. There were no biological keywords that were coherent in this context. Perhaps of note, the biological keyword lists are active and developing research and thus future additions to the lists are expected.

Table 4. Functional terms and biological keywords.

Functional Basis Terms	*Biology Keyword Set 1*	*Biology Keyword Set 2*
Import	-	-
Guide	Position	Slide
Stop	Inhibit	Obstruct
Distribute	Disperse	Spread

With keywords identified, we can search a biological corpus for analogous solutions. Computational design tools have been developed to aid in the search [2, 14]. The two

search tools used in this case study search the same biology textbook [48]. Once a keyword match is found, the tools output a text passage from the corpus that contains the biological keywords. The two search tools present the returned passage differently. One tool displays the text passages as small paragraphs from the literature so that the context in which the keyword is used is also included. The other search tool provides only the sentence in which the keyword is used.

In this case study, the search iteration is performed using both tools and all biological keywords contained in the Table 4. Examples of biological systems identified from the returned text passages from the search are summarized in Table 5 below. This example uses the functional term *stop* and its biological correspondents *inhibit* and *obstruct*. Although they are not shown, the remaining biological keywords listed in Table 4 are analyzed similarly. Comparing the identified biological systems for each keyword shown in Table 5, it can be seen that the tools identify some common systems. The commonality can be attributed to the fact that both search tools utilize the same corpus for the keyword search. The differences in identified systems can be attributed to the operation of each tool. Tool #1, for example, contains a list of exempted words hidden from the user that the tool excludes from being returned. Tool #2 provides an option for the user to specify exempted words.

Table 5. Results of the biological searches for keywords *inhibit* and *obstruct*.

Keyword	***Tool #1***	***Tool #2***
Inhibit	• Spermicides • Stretch receptors • Nucleosomes • Cytokinins • Benzodiazepines • Interferons • Antifreeze proteins	• Spermicides • Stretch receptors • Nucleosomes • Cytokinins • Covalent bonds • Vaccines • Water • Light • Cryptochromes • Phototropin • Synapse
Obstruct	• Mucus • Muscle contraction • Blood vessels	• Mucus • Muscle contraction • Xylem

The final step in the method is the processing of the text passages. The biological systems discovered from the search tools are collected and analyzed to construct bioinspired solutions to geoengineering. These processing methods, as well as the resulting solutions, are discussed in the following section.

3.3 Results and Solution Concepts

Post-processing consists of analyzing the returned text passages to find an identified biological system that suggests a mechanism to achieve geoengineering. In the context of this case study, we are seeking biological systems with characteristics and mannerisms that suggest feasible solutions for the SRM mode of action. Continuing with the biological keywords inhibit and obstruct as an example, Table 6 compares the number of text passages returned versus the number of biological systems that suggested a solution concept. These biological systems are previously listed in Table 5.

Table 6. Comparison of returned text passages and biological systems.

Biological Keyword	Text Passages	Biological Systems
Inhibit	127	18
Obstruct	14	6

From the search results of the biological keywords, three solutions have been formulated. They are presented below. The bioinspired solutions presented here appear feasible in concept and principle. However, a formal and rigorous evaluation has not been performed nor have they been compared to previously proposed solutions in terms of quality and practicality.

Several of the bioinspired solutions indicate a relation to proposed solutions to geoengineering that have been developed without bio-inspiration. It is important to note that the proposed mechanisms of geoengineering, to the knowledge of the authors, are not developed using bioinspired design methods. A morphological matrix comparison of the proposed solutions to the bioinspired solutions for SRM is shown in Table 7. The restriction of the search space to a single corpus [48] limits the range of biological systems searched.

Table 7. Morphological matrix of proposed and bioinspired solutions.

Function	**Previously Proposed Solutions**				**Bioinspired Solutions**		
Import Material	Ships	Airplane	Rocket	Human			
Position Material	Spray nozzle and pump	Elevation and speed	Rotation of the earth	Machine			
Stop infrared EM-E	Water droplets	Aerosol particles	Mirror	Lightened surface	Water Droplets	Mineral Powder	Reflective Pigments
Distribute EM-E	Clouds	Clouds	Mirror	Surface	Density Shields	Mineral clouds	Mirrored satellite

3.3.1 Bioinspired Concept 1: Droplet Density Shields

One of the results from the biological keyword search for the biological correspondent position of the functional basis term guide yielded the following sentence:

"When a DNA sample is dissolved in CsCl and centrifuged at about 100,000 times the force of gravity, the DNA gathers in a band at a position in the tube where the density of the CsCl solution equals its own density [48]."

Additionally, the following sentence was identified in a search for the biological function *inhibit*, a correspondent of the function *stop*.

"For the embryo to begin developing, seed dormancy must be broken by one of several physical mechanisms, such as exposure to light, mechanical abrasion, fire, or leaching of inhibitors by water [48]."

The result from the biological function position above indicates that density serves as a sorting mechanism for solutions of varying mass, here described by DNA separation. The result from the biological search for the term inhibit describes the physical mechanisms that promote seed growth in plants. In this second case, the keyword inhibit is expressed as a derivation (i.e. inhibitor), but the passage identifies water as a solution for removing the inhibitor in order to promote seed growth. This is an example of indirect and nonobvious biological inspiration.

The functional representation of the SRM mode of operation requires the solution to guide material to the upper atmosphere to stop incoming electromagnetic energy. Combining the results from the biological searches, a solution is suggested in which water droplets serve as the electromagnetic energy inhibitor in the upper atmosphere. The use of water droplets utilizes density differences between the droplets and

atmospheric gases to suspend the water, creating droplet density shields. These shields stop electromagnetic energy from reaching the earth's surface by reflecting the energy back into space. This solution operates similarly to the marine cloud albedo enhancement mechanism, as it uses dispersed water to form natural shields against incoming solar radiation.

3.3.2 Bioinspired Concept 2: Fluorescent Mineral Injection

The search results from the biological keyword position found the following:
"In their natural environment-the murky waters of tropical rainforests-these fish can tell the identity, sex, and social position of another fish by its electric signals [48]."

In this result, the biological keyword is not manifested as expected, in the form of a verb, but the keyword identifies a sentence that contains other potentially inspirational biological systems. Here, we choose to research electrical and visual signals among animals, particularly the generation of light-emitting signals. It was found that the majority of electrical signals among animals are intended for communication purposes, and the firefly was cited as a prime example due to its light-emitting abilities, called bio-luminescence, that help it signal a warning to predators [49]. Further research of bioluminescence pointed to fluorescence and the biological systems that are capable of emitting light due to fluorescence. It was found that minerals such as calcite have the ability to fluoresce and phosphoresce when exposed to ultraviolet light. Phosphorescence is the ability of a mineral to emit light after the light source is removed [50]. Minerals phosphoresce by absorbing ultraviolet light that is invisible to the human eye and converting it into a wavelength within the visible spectrum [51].

The introduction of a powdered phosphorescent mineral, such as calcite, has the potential to deter incoming electromagnetic energy from reaching the earth's surface if injected into the atmosphere. By absorbing the immediate solar radiation, powdered

phosphorescent minerals could achieve SRM and be a solution to geoengineering. This solution is similar to the mechanism of atmospheric aerosol injection, given the use of powdered phosphorescent minerals to act as a barrier to incoming solar radiation. Developing this solution concept required additional query and research. Such a sequence of events is not surprising considering the complexity and scope of the geoengineering problem. However, such a result does illustrate how the function based biological keyword search method can point an engineer, with limited knowledge of biology, in a direction that leads to a solution concept. Certainly, it is not clear how such discovery and exploration would have initiated without the search method.

3.3.3 Bioinspired Concept 3: Reflective Orbiting Satellites

The searches for the biological keyword spread lead to the identification of color changing mechanisms in animals:

"To darken the animal, the muscle fibers contract and spread the chromatophores over more of the body surface. These chromatophores can change so rapidly that they are used in some species for communication during courtship and aggressive interactions [48]."

Chromatophores are groups of cells attached to muscles that control a sac filled with pigments [52]. Exploration of color change pigments leads to the chameleon, an amphibian known for its rapid color change abilities. The chameleon controls the chromatophores with muscle contraction, initiated primarily by light and temperature [53]. In bright light, for example, the chameleon turns green to reflect light more effectively. Extending this principle to geoengineering via the SRM mode of action, light-sensitive pigments could be used to cover large, flat satellites placed in outer earth orbit. These pigments would lighten when direct sunlight hits the satellite surface and darken when there is no sunlight. The satellites would be optimally designed to have

large areas of reflectivity and able to passively maintain rotation around the earth. Light-sensitive pigments used to cover these satellites could also be used to paint mechanisms involved in air travel (i.e. airplanes, rockets, etc.) to increase the amount of incoming solar radiation reflected.

The use of color-changing pigments to control solar energy is in some ways analogous to the surface-based albedo enhancement efforts that are designed to achieve solar radiation management. Although the two solutions operate at different levels, surface and atmosphere, the use of light-sensing pigments is in some sense the biological equivalent of reflective synthetic materials.

3.4 Discussion

Geoengineering is a large and complex problem. Any design solution that is aimed at achieving geoengineering through one of the two modes of action, SRM or TCM, is also likely to be large and complex. Moreover, the biological systems identified in keyword searches are diverse. The diversity and large number of text passages identified in the biological keyword searches pose challenges in creating a coherent solution. The challenge exists in both the time required to review all the returned text passages and the cognitive challenge of identifying a principle that can solve the design problem, given the diversity of biological systems found in the text passages.

The total number of returned passages grows large, even when the design problem is accurately modeled with a limited number of functions. In the case study presented here, the decision to represent the problem using four functions describes the process needed to achieve SRM from a technical standpoint. However, since each function must be translated into its biological equivalent and searched, a four-function design problem resulted in six independent biological keywords. Each keyword must be searched, and, assuming the amount of results for each biological keyword to be the mean of the results

shown in Table 6 for inhibit (e.g. 63), the designer can be faced with 378 results, representing a significant diversity of organisms and principles, to post-process. The time required to post-process these results can be significant and a practical inhibitor to a designer using the method.

In this case study, solution concepts are generated primarily from a single search result. The diversity in biological systems identified through the biological keyword searches, in addition to the large amount, makes it difficult to form a solution based on biological systems found for each keyword. This is especially true since each biological keyword will results in a different set of identified biological systems. It is more likely that a solution will be created that is inspired by one or two biological keywords that can be traced back to either one or two engineering functions, as is demonstrated in the solutions formulated above. Thus, it seems likely that an extension to bioinspired design methods that identifies connections between biological search results can help designers utilize all translated functional terms rather than a select few.

Given the careful extraction of principles that is needed for a successful transition from the biological results to an engineered solution, a comprehensive understanding of the two domains is beneficial to the designer. In the case study presented here, the designer lacked the familiarity needed to understand the search results without additional research into the specific biological organism or principle found.

The computational tools, while helpful, do not consistently provide enough contextual information to understand the biological terminology. One tool [2] displays results as clipped passages of the text that include the sentence containing the keyword in addition to a few of the surrounding sentences. Utilizing this search tool, the designer is provided with contextual information that can sometimes help in filling the knowledge gap between domains. However, the inclusion of extra sentences extends the time for post-processing by a sizeable amount.

The other tool [14] used displays only the sentence that contains the biological keyword. A single-sentence display, while not consistently providing full contextual reference, helps the designer to work quickly in post-processing applications. Such a display, however, sometimes forces the designer to research biological terminology whose meaning cannot be deduced from returned passage.

The case study presented does not include an analysis to declare a 'best' tool; the use of one over another for any design problem is strictly based on the preferences of the user. For the problem of geoengineering, both tools are utilized equally and present comparable results.

3.5 Conclusions

The existing proposed solutions to geoengineering focus on achieving one of two modes of operation: stopping electromagnetic energy or storing carbon. These modes have been functionally decomposed, thus representing the problem at a workable scope. The functional model for the mode of solar radiation management has been translated to and searched within the biological domain. The identification of biological principles that can be extended to form a feasible solution to a new technological problem reinforces the idea that emerging design methods can be useful in finding solutions to emerging design problems. Moreover, the identification of existing proposed solutions for geoengineering through biological keyword search results implies that emerging design methods can also solve existing technical problems that might already have solutions. Thus, emerging design methods, particularly bioinspired design methods, have the potential to solve new problems and provide a platform of innovation for old problems.

While the bioinspired design methods have the potential to solve new problems, it is still a time consuming and often frustrating process for engineers who are unfamiliar with biological terminology. The computational search tool, for example, is useful for

providing information quickly to designers outside the biological domain. In addition, it allows the designer to search for multiple forms of the biological keyword, potentially resulting in more matches. However, despite its flexibility, the raw text format of the results can be difficult to parse quickly. The immediate shortcoming of the current function-based design methods is the large volume of results that lack content from which a designer can draw an analogy. Providing an element of control over the results presented, and the manner in which they are presented, can address this shortcoming. Modification of the output from the method, however, first requires an understanding of the characteristics of biological passages considered inspirational by engineers.

4. RESEARCH APPROACH AND DESIGN STUDIES

4.1 Hypothesis Development

Application of bioinspired design methods to the geoengineering problem reveals shortcomings with the method, most notably in the raw text output format of the results. In order to modify the results, it is necessary to understand what engineers consider inspirational when parsing the results from the bioinspired design methods. By understanding how engineers think about a design problem and process the biological systems presented by the method, the most useful portions of text can be identified and presented in a concise manner. This would reduce the text that must be parsed and thus allow the engineer to more quickly identify analogous biological systems.

The research presented here uses natural language processing (NLP) to analyze the output from the bioinspired design methods. NLP has been used successfully in established design research. Segers highlighted the usefulness of word associations in the creative process of architectural design [17], and Yang et al. explored the use of natural language in the generation of thesauri to augment the search for design information in design notebooks [18]. Fu et al. explored the use of latent semantic analysis and part of speech tagging to identify structural similarities of text passages to aid in the categorization of patents [19]. Latent semantic analysis is a method for the extraction of the contextual meaning of words through statistical computations [54]. Part of speech tagging is a form of syntactic analysis that identifies how words and phrases are related in a sentence [55]. The output of a phrase tagger typically displays the word and the part of speech for each element within the input text. An example of an analyzed biological text passage is shown in Table 8.

Table 8. Part of speech example.

Biological Text Passage:		
Colorful pigments stored in the chromoplasts of flowers like this begonia may help attract pollinating insects.		
Text	**Base**	**Part of Speech**
Colorful	colorful	adjective
pigments	pigment	plural noun
stored	store	main verb
in	in	preposition
the	the	determiner
chromoplasts	chromoplasts	noun
of	of	prepostition
flowers	flower	plural noun
like	like	clause marker
this	this	pro-nominal
begonia	begonia	noun
may	may	verb
help	help	main verb
attract	attract	main verb
pollinating	pollinate	main vert
insects	insect	plural noun
.	.	boundary

The success of research with applied NLP naturally leads to the idea that it can help easily isolate particular parts of speech that engineers find inspiring in the biological computational search results. Applying NLP to the passages of text used in the case study to find solutions, it is observed that the biological systems chosen for further research are all nouns, the majority of which are performing the searched function. This is not a surprising observation, as it is expected that the biological system (i.e. the noun) performing the searched function will embody the physical principles that perform the function. Since we are interested in extending these physical principles to an engineering design that can achieve the search function, it is logical to state that closer examination of the noun performing the function will lead to a biological analogy. Based on the effectiveness of the selected nouns in the case study to provide biological inspiration for a novel solution to geoengineering, it is hypothesized that nouns will result in better bioinspired designs when presented to engineers. The implication of this

hypothesis is that, if proven correct, it can provide a means by which an engineer can utilize biological systems for design inspiration without the technical knowledge of a natural scientist. It also implies that an engineer can more easily find a biological analogy for a solution to a design problem if presented with only nouns, and that this will effectively reduce post-processing time required to find design inspiration.

4.2 Preliminary Design Study

To explore this hypothesis, a preliminary design study is conducted using the geoengineering problem. For the study, however, the design problem is limited to the SRM mode of action to ensure that the cognitive load on the engineers is controlled and manageable. Presenting geoengineering in its entirety as the design problem, particularly to individuals who have no prior knowledge of the concept, introduces uncertainties and uncontrollable variables into the study that can negatively impact the results.

4.2.1 Method

Using solar radiation management as the design problem, the first task is to define the problem in terms that can be readily understood, using the bioinspired design methods. Thus, SRM is defined using the Functional Basis [56] and a simple functional model is created, shown below in Figure 10. It should be noted that this functional model is different from the one used in the case study. The difference is due to the simplification of SRM to its most basic functions for presentation to an audience unfamiliar with the geoengineering problem. The functional decomposition of the problem is limited to only the most necessary functions so that the problem statement is clear but concise, since the audience is unfamiliar with the geoengineering problem. The use of three functions is also beneficial in reducing the number of text passages returned from the biological search tools.

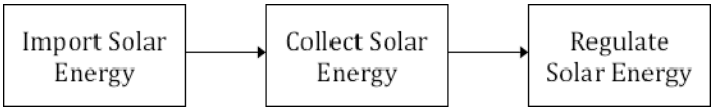

Figure 10. SRM functional model for preliminary study.

Continuing with the bioinspired design methods, the next step is to select the appropriate biological keywords using the available engineering-to-biology thesauri previously mentioned. The engineering functions and their respective biological keywords are shown below in Table 9.

Table 9. Engineering functions and biological keywords for preliminary study.

Engineering Function	Biological Correspondent
Import	Attract
Collect	Absorb
Regulate	Regulate

The biological keywords are then searched using the computational tools mentioned above [2, 14]. Once a keyword match is found, the tools output a text passage from the corpus that contains the biological keywords. Using the biological keywords in Table 9, the tools returned a total of 465 text passages. These passages are collected in an Excel spreadsheet to aid in the creation of the study packets. An example of a packet, including the problem statement, can be found in Appendix A. Since the design study is intended to test the method on a complex engineering problem (i.e. geoengineering) and the portions of biological text that inspire solutions, the participants in the study are not asked to apply bioinspired design methods. Here, the quality of the solutions and the inspiration that caused these solutions is considered more important. For this reason, the participants in the study are given packets consisting of the returned text passages and asked to formulate solutions, based on these passages, capable of fulfilling the functions required to achieve SRM.

The participants in the design study are engineers of varied design experience, academic background, and age. Table 10 shows the classification of the study participants according to these factors.

Table 10. Preliminary design study participants.

	Graduate	**Undergraduate**
Mechanical Engineering	5	5
Other Engineering	2	-

The mechanical engineering students in the study have significantly greater design experience than the students in other engineering disciplines. Additionally, the graduate mechanical engineering students have a more thorough design experience than the undergraduates, as they have learned both the processes and the methodologies. Students at the undergraduate level typically focus on design process applications rather than design theory.

The participants were each given a packet of the biological text passages and a brief problem statement with instructions. They were asked to highlight the portion of each passage that inspired an idea for a solution and record the idea using either words or sketches. If the passage did not inspire a solution, they were asked to leave the space beneath the passage blank. Given the large number of text entries contained in the packet, it was not possible to complete the exercise in one sitting. The students were given one week to complete the study and asked to record time spent working on it. At the conclusion of the study, packets were collected, and the data analysis proceeded.

4.2.2 Analysis and Results

Preliminary analysis of the parsed data indicates that nouns are the most used part of speech in formulating high quality solutions. From the study, a total of 554 solutions are generated for the solar radiation management problem. A total of 318 solutions, of these 554, correspond to passages where the highlighted sections contain 50% nouns or more. From this, it is concluded that nouns will provide the greatest inspiration to engineers who are unfamiliar with the biological lexicon.

There are, however, different types of nouns within a single sentence. Here, we refer to these as primary and spatial nouns. The primary noun is typically the subject of the sentence and is the one that always performs the action described in the passage, which is almost always the biological keyword. Spatial nouns are often direct objects within the sentence and are those nouns most closely located to the biological keyword. An example of a primary and spatial noun is shown in Table 11. In theory, the primary noun should be the most inspiring since it is the biological system performing the biological keyword. This means that these biological systems are capable of satisfying the biological equivalent of the engineering function and should provide a direct analogy to a solution.

Table 11. Primary and spatial noun example.

Biological Passage:	In many animals, the parts of the gut that absorb nutrients have evolved extensive surface areas.
Primary Noun:	Parts (of the gut)
Spatial Noun:	Nutrients

Considering the primary noun as an inspirational system, further research can reveal the mechanisms by which the system achieves the biological keyword. These mechanisms have the potential to provide functional analogies for good engineering designs.

The notion that the use of primary nouns as inspiration will produce better solutions requires a standard for determining whether an idea is good or bad. Solutions generated in the preliminary study are classified as either high quality or low quality based on the following criteria:

1. Clarity: Can a second party (in this case, the researcher rating the solution idea) understand the idea without consulting the designer?
2. Feasibility: Is the idea reasonably possible?
3. Novel: Does the idea solve the problem differently/better than current methods?

These criteria present a basic outline of what can be reasonably considered a good idea. To reduce bias in the preliminary study, participants are not informed of these criteria. Table 12 shows an example of a good idea and a bad idea.

Table 12. Example of a good and bad solution.

Biological Passage	Good Idea	Bad Idea
In many animals, the parts of the gut that absorb nutrients have evolved extensive surface areas.	Create an incredible surface area of photoreceptors, like a layered farm.	Use large surface areas.

The good idea in Table 12 is considered a good idea because the engineer clearly describes the design intention, and it is a feasible idea. Although the idea sounds similar to large existing solar panel operations, the concept of layering the array is a novel configuration. The bad idea presented in Table 12 is unclear. Here, the engineer does not specify how the large surface area is to be used or what should have the large surface area, and without consulting the engineer, the solution could not be implemented. In the collected data, there are 263 total highlighted passages of spatial only or primary noun only. Table 13 shows a summary of the types of noun highlighted and the quality of the

corresponding idea. From visual inspection of the collected data, it is hypothesized that the type of noun highlighted influences the quality of the idea.

Table 13. Noun type versus solution quality.

	Good Idea	**Bad Idea**	*Total*
Primary Noun Only	65	23	88
Spatial Noun Only	48	127	175
Total	113	150	263

To prove or disprove the hypothesis that primary nouns enhance bioinspired design, however, a quantitative analysis must also be performed on a formal hypothesis. Here, a Z-test is used to determine the differences between the proportions of good ideas for primary and spatial nouns. The first step in the Z-test is to formulate the null, H_0, and alternative hypotheses, H_A:

H_0: The proportion of good ideas generated by primary nouns is the same as the proportion of good ideas generated by spatial nouns

H_A: The proportion of good ideas generated by primary nouns is not the same as the proportion of good ideas generated by spatial nouns.

The Z-test used here compares the proportion of good ideas for primary nouns to the proportion of good ideas for spatial nouns. The results of the Z-test are summarized below in Table 14. Since the differences between the proportion sizes are large, the sampling distribution is assumed to follow a normal distribution. Using a level of significance equal to 0.05, the Z-test statistic is found to be 7.178. Since this value is greater than the value of $Z = 1.96$, the upper value of the normal distribution corresponding to the 0.05 level of significance, the null hypothesis is rejected. It is then stated that the proportion of good ideas generated by primary nouns is much higher than

the proportion generated by spatial nouns. Further testing is required, however, to establish a statistically significant difference using a larger population.

Table 14. Summary of Z-test results.

Primary Proportion	0.739
Spatial Proportion	0.274
Proportion Difference	0.465
Average Proportion	0.430
Z-test Statistic	7.178

4.3 Pilot Design Study

To further validate the hypothesis formulated from the preliminary study, a second experiment is conducted. The purpose of the pilot experiment is to test the hypothesis from a narrower perspective by specifying the parts of the biological passage that the engineer can use to formulate an idea. Specifically, the pilot study addresses only the effects of primary and spatial nouns on the quality of the generated idea. The design problem selected for the primary study is the same as that for the preliminary study, but a single engineering function, taken from the black box model for solar radiation management, is used to describe the overarching goal of the solution. This black box model is shown in Figure 11. Using a single function rather than multiple functions allows the design problem to be described concisely and eliminates the need for participants to combine multiple functions to create a coherent solution. The corresponding biological keywords can be seen in Table 15. The participants are again not given any information regarding the bioinspired design process and are asked to formulate ideas based on biological text passages as an entry-level engineer in a design firm.

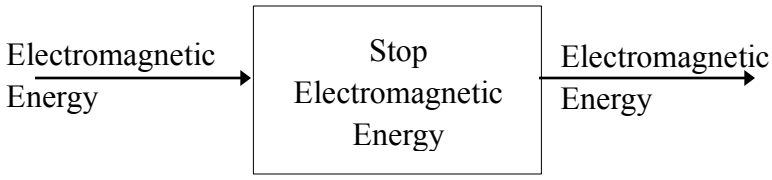

Figure 11. Pilot study black box model of SRM.

Table 15. Engineering functions and biological keywords for pilot study.

Engineering Function	Biological Correspondent
Stop	• Inhibit • Cover • Destroy • Surround • Constrain • Clog • Seal • Suspend

4.3.1 Method

The pilot study samples 21 students in a Mechanical Engineering capstone design course. The students are at the junior and senior level, and the study is given in a closed, quiet classroom environment. The script for the pilot study can be found in Appendix B. The students are separated into three groups: primary, spatial, and control. As in the preliminary study, each group is given a packet containing fifty biological text passages from a previously conducted biological search. The packet given to each group contains the same text passages, but the instructions for deriving biological inspiration differs between groups. The primary group is given packets with the primary noun in each passage highlighted. These students are asked to formulate solutions based only on the highlighted portion. Similarly, the spatial group is given packets with the spatial noun in each passage highlighted and asked to use only the highlighted portion for idea generation. The control group packets contain no highlighting, and the students are told

to use the entire passage to develop a solution. An actual example packet for each group, including the problem statement, can be found in Appendices C-E.

An example of a biological passage given to each group is shown in Table 16. The participants are given two hours to generate solutions. At the end of the experiment, the packets are collected, and the participants are asked to provide feedback via a distributed questionnaire.

Table 16. Example of biological passage used in the pilot study.

Group	Biological Passage
Control	The body wall surrounding each segment has two muscle layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise.
Primary	The body wall surrounding each segment has two muscle layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise.
Spatial	The body wall surrounding each segment has two muscle layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise.

4.3.2 Analysis and Results

Analysis of the pilot study necessitates the development of a more descriptive scaling model than that used in the preliminary study to categorize idea quality on the basis of three characteristics: feasibility, completeness, and innovation [57]. The scoring model is a modified 6-point scale that operates from zero to five and is described below in Table 17. The researcher and a second rater quantitatively define the metrics from an exercise in which a sample packet is rated and discussed. Figure 12 shows a decision flowchart that describes the scoring model. The decision flowchart shows the decision process a rater would use when evaluating a solution, and the quality score that defines

each combination of completeness, feasibility, and innovation. Examples of scored passages can be found in Appendix J.

Table 17. Scoring model to determine idea quality.

Score	Metric
0	Incoherent
1	Incomplete, infeasible, already exists
2	Incomplete, not feasible with current technology, not innovative
3	Complete, not feasible with current technology, innovative
4	Complete, mostly feasible with current technology, innovative
5	Complete, immediately feasible, highly innovative

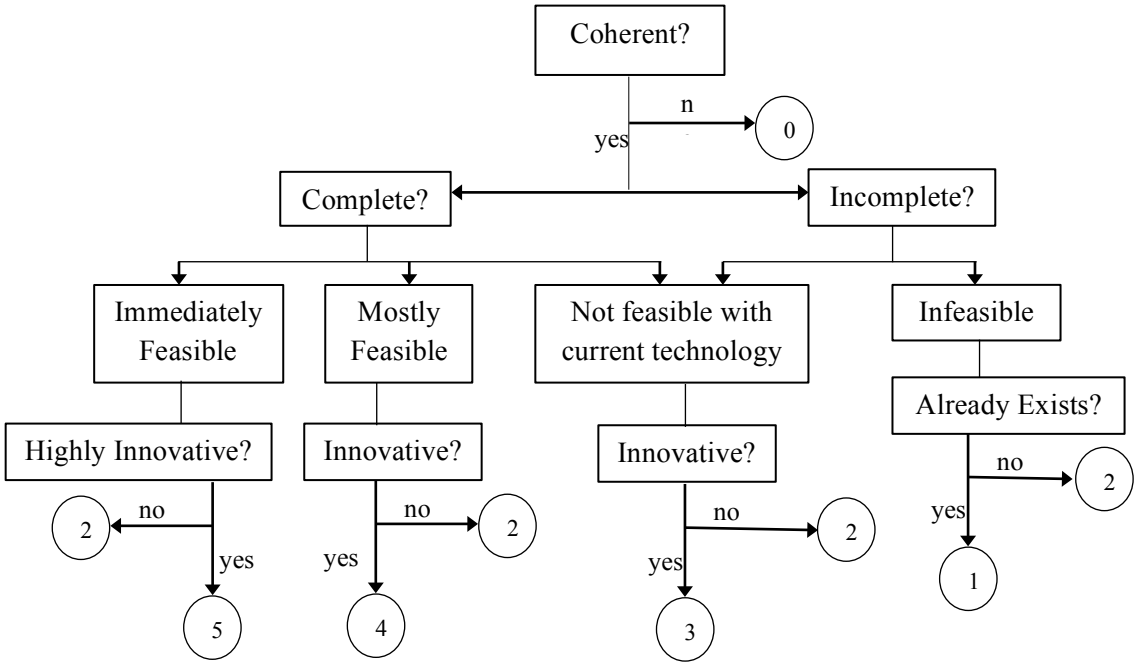

Figure 12. Decision flowchart for scoring model.

The solutions for every packet are read and scored according to the metrics presented in Table 17. Passages without solutions are not counted and do not affect the average score

for each packet. To establish consistency in the rating system, a second rater is used to evaluate the packets, and a value for Cohen's weighted kappa is calculated. Here, the weighted kappa is used since the data is ordinal and disagreements between ratings must be given partial credit, rather than be graded using the binary yes/no format of the standard Cohen's kappa [58]. For the pilot study, Cohen's weighted kappa is calculated to be 0.8390 with a standard error of 0.0542. According to Landis and Koch, the kappa value can be interpreted as shown in Table 18 [59].

Table 18. Kappa value interpretation.

Kappa Value	Interpretation
< 0	Poor agreement
0.0 – 0.20	Slight agreement
0.21 – 0.40	Fair agreement
0.41 – 0.60	Moderate agreement
0.61 – 0.80	Substantial agreement
0.81 – 1.00	Almost perfect agreement

Following interrater agreement, the scores are collected for each packet, and standard descriptive statistics for each group are calculated, shown in Table 19.

Table 19. Table of descriptives for pilot study.

	N	Mean	Std. Deviation	Std. Error	95% CI interval for Mean		Minimum
					Lower Bound	Upper Bound	
Control	7	1.9022	0.58500	0.22111	1.3611	2.4432	1.13
Primary	7	2.3561	0.38252	0.14458	2.0024	2.7099	1.82
Spatial	7	1.6104	0.68376	0.25844	0.9780	2.2428	0.4
Total	21	1.9562	0.62103	0.13552	1.6736	2.2389	0.4

As in the preliminary study, null and alternative hypotheses must be established:

H_0: The mean quality of ideas generated by all groups in the study will be the same

H_A: The mean quality of ideas generated by all groups in the study will not be the same.

Here, three independent groups are analyzed, so a one-way analysis of variance (ANOVA) is applied to the data. First, however, the data is tested for normality and homogeneity of variances to ensure that the assumptions for ANOVA are correct. A Q-Q plot, shown in Figure 13 below, visually confirms the normality of the data since the values follow a linear pattern tracing the x-y line.

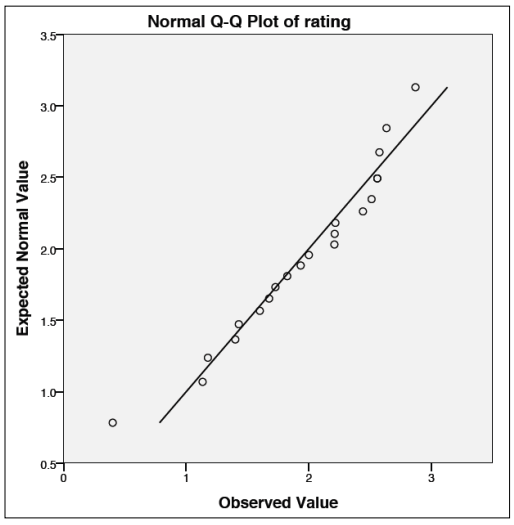

Figure 13. Q-Q plot of normality for pilot study.

In addition to testing the distribution, the assumption of homogenous variances between the groups is also verified. This is done with the Test of Homogeneity of Variances, which uses the Levene statistic. The results from this test can be seen in Table 20 below, and since the significance value (p) is greater than 0.05, the assumption of homogeneity of variances holds true. The confirmation of assumptions necessary for ANOVA guarantees correctness of the results.

Table 20. Homogeneity of variances for pilot study.

Levene Statistic	Degree of Freedom 1	Degree of Freedom 2	p
0.523	2	18	0.602

Using a value of significance at the 0.1 level, ANOVA results in a p-value of 0.07 ($F(2,18) = 3.102$, $p = 0.07$), shown in Table 21. This indicates a statistically significant difference between the means of the three groups, thus allowing rejection of the null hypothesis that all means are equivalent. To determine which of the groups specifically differ, a Bonferroni post hoc test is applied. It is standard practice among statisticians to use the Tukey test as a post hoc evaluator, but in the case of unequal sample sizes, the Bonferroni test is accepted as a standard [60]. The results of the post hoc analysis are collected in Table 22.

Table 21. One-way ANOVA for pilot study.

	Sum of Squares	DF	Mean Square	F	p
Between Groups	1.977	2	0.989	3.102	0.070
Within Groups	5.736	18	0.319		
Total	7.713	20			

Table 22. Bonferroni post hoc test results for pilot study.

					90% Confidence Interval	
Condition (I)	Condition (J)	Mean Difference	Standard Error	p	Lower Bound	Upper Bound
Control	Primary	-0.45396	0.30175	0.449	-1.1493	0.2414
	Spatial	0.29175	0.30175	1.000	-0.4036	0.9871
Primary	Control	0.45396	0.30175	0.449	-0.2414	1.1493
	Spatial	0.74571	0.30175	0.071	0.0504	1.4411
Spatial	Control	-0.29175	0.30175	1.000	-0.9871	0.4036
	Primary	-0.74571	0.30175	0.071	-1.4411	-0.0504

Inspection of the post hoc test reveals that the quality of the solutions generated by the primary group (2.3561 ± 0.382, P = 0.071) is statistically significantly higher than the quality of the solutions generated by the spatial group (1.9562 ± 0.621). The post hoc test therefore confirms the assertion that primary nouns have a greater effect on idea quality than spatial nouns. From the pilot study, it is therefore concluded that engineers will develop better bioinspired solutions if given primary nouns from biological text passages.

4.4 Final Design Study

Although the results of the pilot study provide convincing evidence of the effectiveness of primary nouns, they are based on the assumption that participants in the study only used the highlighted words in the passages to formulate solutions. In reality, participants could use the entire text despite being to only use the highlighted portion. Thus, a final design study is necessary to test the effectiveness of primary versus spatial nouns in generating quality solutions using reduced biological text passages.

Additionally, the preliminary and pilot studies focus on the same complex problem of geoengineering, which is a largely unfamiliar problem to the target participant population. The bioinspired design process is conducted the same as in the pilot study; the black box model, engineering function, and biological keywords are all the same.

Although primary nouns prove useful in providing innovative solutions for this type of problem, it is also necessary to explore the use of primary noun inspiration in familiar design problems. The final design study also tests the effectiveness of primary and spatial nouns on a familiar design problem and compares the results to those obtained for the abstract problem of geoengineering. The chosen design problem is described further in the following section.

4.4.1 Method

The final study samples 59 students in two mechanical engineering design courses. The students are junior and senior level students, and the study is conducted in a closed, quiet environment. The script for the final design study can be found in Appendix F. The 59 students are again divided into three groups: primary, spatial, and control. The biological text passages given to the control group are the same as those given to participants; however, the text passages presented to the primary and spatial groups have been altered. The participants in the primary group receive passages that only include the primary noun and the searched biological keyword. Those participants in the spatial group receive passages that only include the searched biological keyword and the spatial noun. An added dimension of study is the modification of the control group passages to include alternate nouns in place of the primary and spatial nouns contained in the original biological passage. The purpose of replacing the original nouns is to test the effectiveness of the noun in the context of the biological passage. By replacing the original spatial and primary nouns with randomly generated nouns [61], it is possible to test whether the inspiration is derived from any noun or a specific biological noun by comparing the results from the control group in the final study to those of the pilot study. An example of each type of packet given to the participants for one of the design problems can be found in Appendices G-I.

A sample passage from a primary, spatial, and control group packet is shown below in Table 23. Reducing the length of the passage in the primary and control group packets to include only the relevant noun and the biological search term focuses the participant on the biological system represented by either the primary or spatial noun. An increased focus on a particular noun type reduces the possibility of a high quality solution inspired by parts of speech other than the noun in question.

Table 23. Example of biological passage used in the final study.

Original Biological Passage	
The body wall surrounding each segment has two muscles layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise [48].	
Group	**Altered Biological Passage**
Control	The body hippopotamus surrounding each coat has two muscle layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise.
Primary	The wall surrounds.
Spatial	It surrounds each segment.

An additional modification made in the final study is the inclusion of a second problem statement. The first design problem is the geoengineering problem. The passages used in the pilot study are the same as those used here, with the exception of the modified passages for each group. The second design problem is posed as a human transportation problem, in which a human must be transferred from one unspecified location to another. To keep this design problem simple and similar to the geoengineering problem, a black box model is created and its function is translated into its biological correspondents. The black box model is shown below in Figure 14. Only a single function is used to prevent design fixation and help define the problem in vague terms so as not to bias the participants towards a particular mode of transportation. Specifying *position human*, for example, as a functional requirement, implies that the human must be in a particular stance when operating the transporting vehicle. The specificity of such a problem statement could cause participants to fixate on existing vehicles that require humans to be in a certain position when in operation, such as cars and trucks. This fixation would prevent participants from seeking creative solutions over the entire design space and fully utilizing the bioinspired design methods.

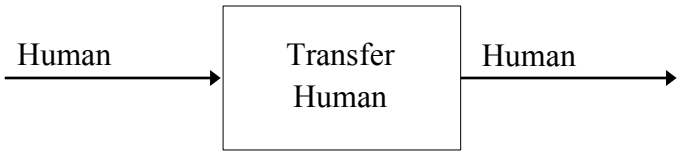

Figure 14. Black box model for final study (transportation).

From the black box model function, the biological keywords that most accurately describe modes of transfer are chosen and searched using the computational tool. Table 24 shows the function and keywords used in the preparation of the design study.

Table 24. Engineering function and keywords for final study (transportation).

Engineering Function	Biological Keywords
Transfer	• Fly • Displace • Shift • Jump • Swim • Bounce • Conduct • Circulate • Pump • Diffuse • Migrate • Transfer

The design study is composed of two one-hour long design sessions in which one set of packets is distributed to the groups, and participants are asked to create solutions based on the biological text passages in the packets for one hour. The first set of packets is collected, and the second set is distributed to the same groups. The participants are then given another hour to generate solutions based on the text passages, and the packets are collected. The participants are then given a short survey based on their experience, and they are dismissed from the design study.

4.4.2 Analysis and Results

Analysis of the packets collected in the final study is treated similarly as those collected in the pilot study. Each group of packets is evaluated using the categorical scale presented in Table 17, and a second rater is used to compute an interrater reliability score for the data. Table 25 below shows the results of the Cohen's weighted kappa calculation for the primary study.

Table 25. Cohen's weighted kappa values for final study.

Design Problem	Weighted Kappa	Standard Error
Sunlight	0.7445	0.0680
Human Transportation	0.6717	0.0628

Following interrater agreement, descriptive statistics are generated for the data generated by the sunlight problem statement. These statistics can be seen in Table 26. For the primary study, the same null and alternative hypotheses are used as in the pilot study. Analysis proceeds in the same manner, with the selection of the one-way ANOVA test and confirmation of assumptions. The homogeneity of variances is calculated, shown in Table 27, and a Q-Q plot, shown in Figure 15, is generated to test for normality.

Table 26. Table of descriptives for final study (sunlight).

	N	Mean	Std. Deviation	Std. Error	95% CI interval for Mean		Minimum
					Lower Bound	Upper Bound	
Control	19	1.2381	0.58674	0.13461	0.9553	1.5209	0.31
Primary	20	2.1737	0.33232	0.07431	2.0182	2.3293	1.50
Spatial	20	1.1755	0.46071	0.10302	0.9598	1.3911	0.38
Total	59	1.5340	0.65321	0.08504	1.3638	1.7042	0.31

Table 27. Homogeneity of variances for final study (sunlight).

Levene Statistic	Degree of Freedom 1	Degree of Freedom 2	p
3.444	2	56	0.039

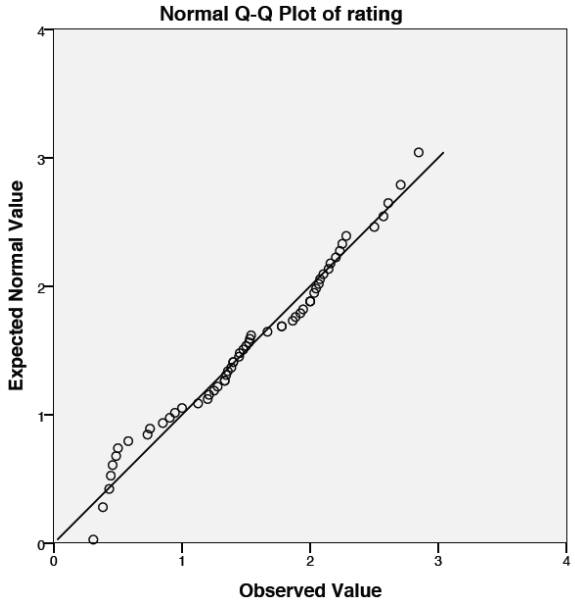

Figure 15. Q-Q plot of normality for final study (sunlight).

It should be noted that the significance value (p) for the homogeneity of variances test is below 0.05, which indicates that the variances among groups are not similar and thus the assumption does not hold. Despite the normality of the data, visually obtained from the Q-Q plot, the assumptions used for the one-way ANOVA test are not true, which means that it cannot be used to analyze the data. In the case of dissimilar variances, however, a Welch test can used to compare the means of normally distributed populations [62]. Results for the Welch test are shown in Table 28.

Table 28. Welch test results for final study (sunlight).

	Statistic	DF 1	DF 2	p
Welch	38.263	2	34.992	0.000

The results of the Welch test ($F(2, 34.992) = 38.263$, $p < 0.001$) indicate a statistically significant difference at the 0.05 level in the mean quality of ideas produced by the three groups. While the null hypothesis can be rejected based on the Welch statistic, it is useful to know the specific groups in which the mean differs. Since the variances are similar, the Games-Howell post hoc test is applied [63]. The results of this test are shown in Table 29.

Table 29. Games-Howell post hoc test results (sunlight).

					95% Confidence Interval	
Condition (1)	**Condition (2)**	**Mean Difference**	**Standard Error**	**p**	**Lower Bound**	**Upper Bound**
Control	Primary	-0.93567	0.15376	0.000	-1.3160	-0.5553
Control	Spatial	0.06259	0.16951	0.928	-0.3527	0.4779
Primary	Control	0.93567	0.15376	0.000	0.5553	1.3160
Primary	Spatial	0.99825	0.12702	0.000	0.6872	1.3093
Spatial	Control	-0.06259	0.16951	0.928	-0.4779	0.3527
Spatial	Primary	-0.99825	0.12702	0.000	-1.3093	-0.6872

Based on the post hoc results of the data generated using the geoengineering problem statement, it can be stated that the quality of ideas produced by the groups using primary nouns (2.1737 ± 0.332, $p < 0.001$) is statistically significantly higher than the quality of ideas produced by both the spatial (1.1755 ± 0.461) and control (1.2381 ± 0.587) groups.

The results are similar for the human transportation problem statement. Descriptive statistics are generated for the data collected, shown in Table 30, and analysis proceeds first with the check of one-way ANOVA assumptions. Based on Figure 16, it can be visually verified that the data follows a normal distribution. However, Table 31 shows that the variances are similar, and the Welch test must be used in place of a one-way ANOVA.

Table 30. Table of descriptives for final study (transportation).

	N	Mean	Std. Deviation	Std. Error	95% CI interval for Mean		Minimum
					Lower Bound	Upper Bound	
Control	19	1.2763	0.15852	0.15852	0.9433	1.6094	0.13
Primary	20	1.8936	0.14462	0.14462	1.5909	2.1963	0.07
Spatial	20	1.3636	0.06975	0.06975	1.2176	1.5096	0.89
Total	59	1.5152	0.08162	0.08162	1.3518	1.6786	0.07

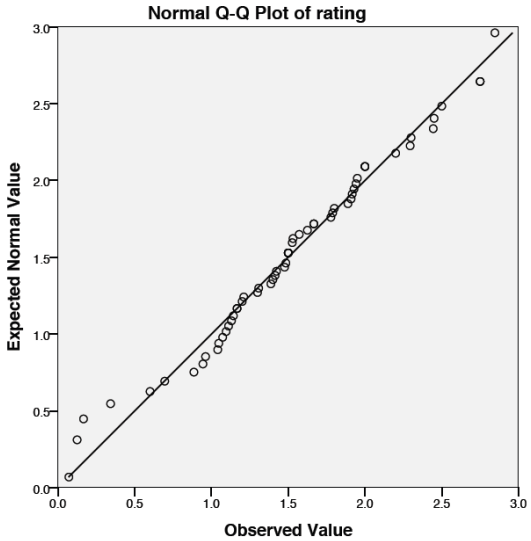

Figure 16. Q-Q plot of normality for final study (transportation).

Table 31. Homogeneity of variances for final study (transportation).

Levene Statistic	Degree of Freedom 1	Degree of Freedom 2	p
3.471	2	56	0.038

Since the significance value (p) produced by the Homogeneity of Variances test is less than the accepted value of 0.05, the variances of the groups are similar. The Welch test is performed in place of a one-way ANOVA; these results are shown in Table 32.

Table 32. Welch test results for final study (transportation).

	Statistic	DF 1	DF 2	p
Welch	5.928	2	32.106	0.006

The Welch test value (F(2, 32.106), p = 0.006) shows that the mean quality of ideas produced by the groups for the human transportation problem is significantly different. Again, to determine which groups significantly differ, the Games-Howell post hoc test is performed. The results of this are shown in Table 33.

Table 33. Games-Howell post hoc test results (transportation).

					95% Confidence Interval	
Condition (I)	**Condition (J)**	**Mean Difference**	**Standard Error**	**p**	**Lower Bound**	**Upper Bound**
Control	Primary	-0.61728	0.21458	0.018	-1.1415	-0.0931
Control	Spatial	-0.08730	0.17319	0.870	-0.5189	0.3443
Primary	Control	0.61728	0.21458	0.018	0.0931	1.1415
Primary	Spatial	0.52998	0.16056	0.007	0.1322	0.9278
Spatial	Control	0.08730	0.17319	0.870	-0.3443	0.5189
Spatial	Primary	-0.52998	0.16056	0.007	-0.9278	-0.1322

Based on the post hoc results for the data collected using the human transportation problem statement, it can be stated that the quality of ideas produced by participants in the primary group (1.8936 ± 0.647) is statistically significantly higher than the quality of ideas produced in the control group (1.2763 ± 0.691, p = 0.018) and the spatial group (1.3636 ± 0.312, p = 0.007).

The data collected from both problem statements in the final study supports the idea that primary nouns will lead to higher solution quality. The implication of these results will be discussed further in the following section.

4.5 Discussion

The preliminary experimental results indicate that primary nouns are the most inspirational part of speech in biological text passages. Thus, the identification of primary nouns within the bioinspired design process will result in better design solutions. This is a logical conclusion, as it is expected that the biological system performing the searched function (i.e. biological keyword) will provide a useful analogy for achieving the function. Consider the following passage of text:

Colorful pigments stored in the chromoplasts of flowers like this begonia may help attract pollinating insects [48].

Here, the biological keyword is *attract*, and the primary noun is *pigment*. A syntactical analysis of the passage indicates a direct relationship between the keyword and the primary noun; that is, pigments in the flowers are responsible for attracting the pollinators. Based on the results from the preliminary study, it can therefore be inferred that researching the mechanisms by which pigments attract can inspire a solution for attracting solar radiation. By identifying the primary nouns in each biological text passage, engineers can obtain inspiration more quickly without possessing a comprehensive knowledge of biological terminology.

The results of the preliminary study are validated in the pilot study using the same design problem but altering the allotted time, solution quality metrics, and number of biological passages. Although the pilot study confirms the findings in the preliminary study, a comparison between percentages of high quality ideas and low quality ideas generated from primary nouns in each study shows a smaller deficit for solution quality in the pilot study. Shown in Table 34 below, participants in the preliminary study formulated higher quality solutions 73.86% of the time a primary noun was selected as design inspiration. In the pilot study, however, good ideas were only generated 52.43%

of the time by participants in the primary group. A possible explanation for the reduced percentage is the level of design experience between the participation groups, in addition to the classifications of the participants. The preliminary study is composed mostly of graduate students with multiple years of design-based research experience, and the pilot study participants are all undergraduate students with minimal design experience. Additionally, the participants in the preliminary study are allotted a week to finish the design study, while those in the pilot study were only given two hours. Participants in the preliminary study have the advantage of exposure to external stimuli that can further the creative design process, allowing them to identify inspiration in biological systems that might go unrecognized under a time constraint.

Further observation of the results collected from the preliminary and pilot studies shows that, as anticipated, primary nouns in both studies result in a larger amount of higher quality solutions, and spatial nouns result in a greater amount of lower quality solutions. The results from these studies reinforce the hypothesis that primary nouns produce better solutions than spatial nouns when given to engineers.

Table 34. Comparison of solution quality between preliminary and pilot studies.

	Primary Noun		**Spatial Noun**	
	High Quality	**Low Quality**	**High Quality**	**Low Quality**
Preliminary Study	65 (73.86%)	23 (26.14%)	48 (27.43%)	127 (72.57%)
Pilot Study	108 (52.43%)	98 (47.57%)	74 (33.79%)	145 (66.21%)

In addition to changing the number of passages given to participants in the pilot study, the format of the passages is slightly altered. The intention is to focus participants on using a designated part of speech, either the primary or spatial noun, to formulate a design solution. Participants in the pilot study are instructed to use only the highlighted part of speech; however, there is no method to determine if the participants used only the

indicated text. In the final study, this is addressed by reducing the amount of text provided to the two test groups for primary and spatial nouns.

The biological text passages used in the final study are reduced to only include a particular noun, either primary or spatial, the biological search term, and supporting text. Shortening the text passages ensures that participants will use only the specified noun, thus eliminating the question of whether a high quality idea is inspired by the primary noun or the spatial noun. With only a single noun type in the given text passage, there is no question which biological system inspires the solution. Furthermore, decreasing the passage length also supports the logical conclusion that the biological system performing the function (i.e. the primary noun) will provide a higher quality bioinspired solution.

Comparison of the pilot study results and those obtained from the sunlight design problem in the final study confirms the effect of primary nouns on solution quality. Table 35 shows the average packet ratings for each of the three groups in the two studies. The primary groups in each study produced the highest solution quality, as expected, but the average rating for pilot study participants in the primary group is slightly higher than those in the final study. This could be attributed to the reduced text passage in the final study packets. Participants in the pilot study that received the entire passage with a highlighted section could have utilized the entire passage to formulate a solution, thereby artificially inflating the average rating. With the reduced passage in the final study, this artificial inflation of the score is eliminated, which could result in a lower average rating. Comparing the spatial groups in each study shows a significant difference between the average scores, a difference that could also be attributed to participants in the pilot study using the entire passage rather than the highlighted portion. The deficit in the control groups, however, cannot be caused by a passage reduction since participants in these groups are given the full biological text passage. This deficit can be explained by the substitution of the primary and spatial nouns with randomly selected nouns that often do not make sense in the context of the passage. The noun

substitution also causes the difference between the control and spatial group averages within the final study (0.063) to be closer together than those in the pilot study (0.292). This reduced difference supports the idea that a context-supported noun will lead to a higher quality bioinspired design solution.

Table 35. Comparison of average ratings for pilot and final (sunlight) studies.

	Control	**Primary**	**Spatial**
Pilot Study	1.902	2.356	1.610
Final Study (sunlight)	1.238	2.174	1.175

An added element of the final study is the inclusion of a second design problem that is more familiar to the participants. Here, the effectiveness of bioinspired design methods on problem type (familiar versus unfamiliar) can be evaluated. Comparing the average packet ratings between the two design problems given in the final study, shown below in Table 36, it can be seen that the primary group still produces the highest overall idea quality. Evaluation of the other two groups reveals that the participants were able to formulate better solutions using the transportation design problem. However, these differences are so marginal (control = 0.038, spatial = 0.188), that no absolute conclusions can be made. With the sunlight design problem, the ordering of highest to lowest average rating by group (primary, control, spatial) maintains the ordering of average ratings found in the pilot study. In the transportation problem, the ordering from highest score to lowest changes to primary, spatial, and control. It can therefore be concluded that primary nouns will lead to the highest quality solution, but no definitive conclusions can be made based on the control and spatial groups. A general observation can be made that spatial nouns and whole passages of text will lead to lower quality ideas than those inspired by the primary noun.

Table 36. Comparison of average ratings within the final study.

	Control	Primary	Spatial
Final (sunlight)	1.238	2.174	1.175
Final (transportation)	1.276	1.894	1.363

The computational search tool is useful for providing information quickly to engineers unfamiliar with biological lexicon. In addition, it allows the engineer to search for multiple keyword forms, potentially resulting in more matches. However, despite its flexibility, the raw text format of the results can be difficult to analyze quickly. The incorporation of a part of speech designator can offer engineers the ability to control display options for easier inspiration. In this research, an open source software program called Link Grammar is added to the computational search tool. Figure 16 shows an example search using the modified tool with the function *channel*, biological keyword *absorb*. In Figure 17, the Link Grammar output for the keyword search is displayed. Link Grammar is based on a formal grammatical system that links sequences of words together based on established rules. The grammar system is composed of words with linking requirements and descriptives compiled in a dictionary [64]. The descriptives tag the words with their natural language functionality, and the linking requirements form a set of rules for determining how the words are syntactically assembled. When the Link Grammar parser processes a sentence, linkages based on the functional descriptive tags are formed above the sentence to show syntactic connectivity between the words. Noun-verb linkages, for example, typically begin with the label "S." In addition to showing physical links between words, Link Grammar also designates the part of speech using a "._" after each word. A simple example of a Link Grammar parse is shown in Figure 18 [65]. In this example, the noun (mother) and verb (enjoys) are connected using "Ss," and *mother* and *enjoys* are designated as the noun and verb, respectively, with the notations *mother.n* and *enjoys.v*.

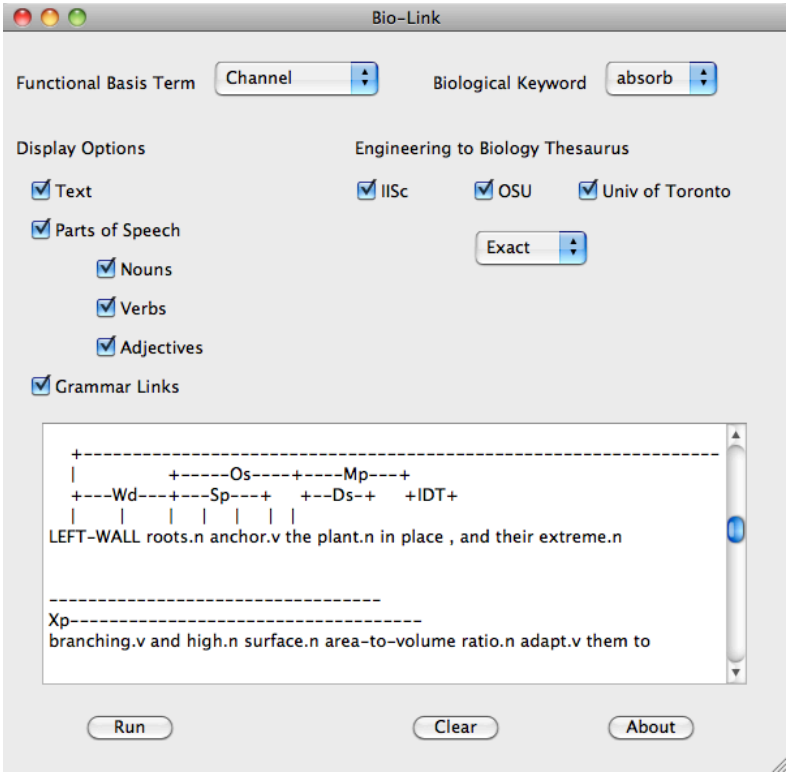

Figure 17. Modified search tool with Link Grammar.

The rules that guide the overall functionality of Link Grammar must be fully satisfied before a parse can be considered complete. The first rule is based on the phenomenon that relationships exist between words in a sequence such that, if lines are drawn above the words to connect these relationships visually, no two lines will cross. This is referred to as planarity and serves as the first rule of Link Grammar. The second rule is that the connectivity within a sequence of words must be satisfied; that is the links within a sequence must connect all words together. The third rule is that the links must satisfy the linking requirements for each word in the sequence [66]. All sequences passed through the Link Grammar parses strictly adhere to these meta-rules. The underlying structure of Link Grammar is defined by connectivity rules and formulas that are outside the scope of this research.

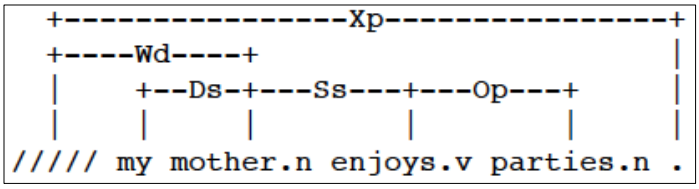

Figure 18. Example of a simple Link Grammar parse.

Using Link Grammar, engineers can choose to display only nouns from the returned passages or view the syntactical relationships within the sentence. Although this research does not study the influence of syntax on bioinspired design, engineers may find it useful to visualize the connections between words in the passage.

The modified computational search tool will reflect the findings of this research by allowing engineers to more immediately identify the biological system fulfilling the searched function by presenting lists that only including a particular part of speech (i.e. nouns). The engineer can then research the biological systems found in the noun lists and generate a bioinspired solution more quickly. A more efficient search tool will increase the effectiveness of bioinspired design methods by reducing post-processing times for designers using computational search tools to identify analogous biological systems.

5. CONCLUSIONS AND FUTURE WORK

5.1 Summary and Conclusions

Bioinspired design methods are a new and evolving collection of techniques used to extract biological principles from nature to solve engineering problems. Bioinspired design research has produced several methods that enable engineers to access biological principles and apply them to engineering designs. The application of bioinspired design methods is typically confined to existing problems encountered in new product design or redesign [6-9]. A primary goal of this research is to utilize existing bioinspired design methods to solve a complex engineering problem to examine the versatility of the method in solving new problems. Here, current bioinspired design methods are applied to seek a biologically inspired solution to geoengineering. Geoengineering is the intentional modification of the earth's climate to prevent harmful anthropogenic warming [16].

The existing proposed solutions to geoengineering focus on achieving one of two modes of operation: stopping electromagnetic energy or storing carbon. These modes have been functionally decomposed, thus representing the problem at a workable scope. The functional model for the mode of solar radiation management has been translated to and searched within the biological domain. Bioinspired solutions developed in the case study include droplet density shields, phosphorescent mineral injection, and reflective orbiting satellites. In addition, a comparison between the bioinspired solutions and the proposed mechanisms for SRM shows similarities.

The identification of biological principles that can be extended to form a feasible solution to a new technological problem reinforces the idea that emerging design methods can be useful in finding solutions to emerging design problems. Moreover, the identification of existing proposed solutions for geoengineering through biological

keyword search results implies that emerging design methods can also solve existing technical problems that might already have solutions. Thus, emerging design methods, particularly bioinspired design methods, have the potential to solve new problems and provide a platform of innovation for old problems. However, the use of organized computational search tools provides copious amounts of analogous biological entities that require extensive post-processing to determine biological systems that suggest solutions to geoengineering.

A secondary goal of this research is to help engineers use bioinspired design methods more efficiently and without extensive knowledge of biological terminology using natural language processing (NLP). NLP has been used successfully in established design research [17-19]. The research presented here seeks to reduce the need for extensive post-processing of the results by applying natural language processing techniques. Using a natural language approach, it is possible to isolate a particular part of speech from a designated text. The use of natural language processing in engineering research is not a new topic; it is however, a novel concept in bioinspired design.

Using the complex problem of geoengineering, a hypothesis is developed that asserts the usefulness of nouns in creating higher quality solutions. A designation is made between the types of nouns in a sentence, primary and spatial, and the hypothesis is refined to state that primary nouns are the most influential part of speech in providing biological inspiration for high quality ideas. Here, a primary noun refers to the noun that performs the searched biological function, and the spatial noun is the noun most closely located, within the passage, to the searched function. A pilot study confirms the hypothesis, and a final experiment is conducted that tests the refined hypothesis on the highly abstract geoengineering problem and a human transportation problem. Through these three experiments, the author determines that engineers are more likely to develop a higher quality solution using the primary noun in a given passage of biological text. Thus, using part of speech designation in bioinspired design can increase the efficiency of

these methods and provide biological inspiration for engineers unfamiliar with the natural sciences.

To further improve the methods, modifications to the computational search tool includes the part of speech findings discussed above. The modification incorporates open source grammar parsing software that outputs the biological text passages with part of speech designations [66]. The software also displays syntactical dependencies between the words in a sentence as physical links. The user interface of the combined search tool can be seen in Figure 19. The modified search tool contains the functional keywords and the corresponding biological keyword lists [13] [11] [47]. The user also has the ability to select multiple display options, which include the original biological text, various parts of speech, and the Link Grammar output. The tool retains the original search options of exact, partial, or derivatives of the biological keyword.

The connectivity between the words in Link Grammar provides designers the opportunity to visually determine the biological systems that perform the searched functions. Since current bioinspired design methods require extensive post-processing of the results, the application of natural language processing to the biological text results can reduce the time needed identify inspiring biological systems. Specifically, the identification of primary nouns through part of speech tagging will provide engineers an analogous biological system without extensive analysis of the results. The use of noun identification to improve the efficiency of bioinspired design method applications is a new concept and is the primary contribution of this research.

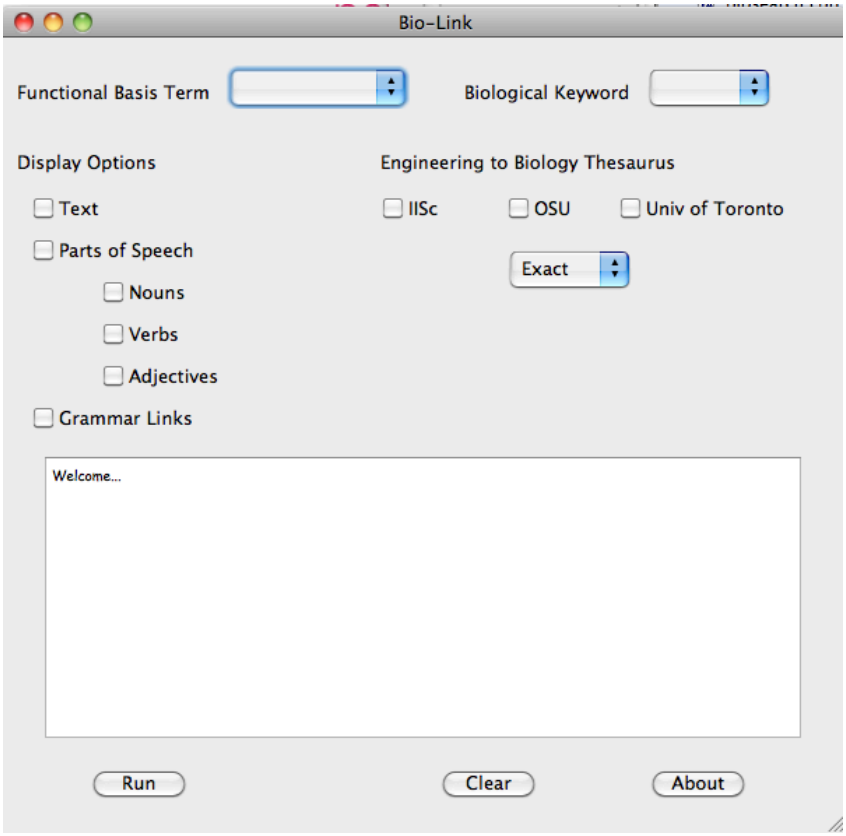

Figure 19. Interface of modified computational search tool.

The findings of this research, in conjunction with the improved computational search tool, will help engineers find the biological inspiration needed to create innovative solutions based on the perfectly engineered world they inhabit.

5.2 Future Work

Despite continued improvements to bioinspired design methods, the process is not widely utilized outside the academic field. In applications of the method, the designer can experience trouble translating the biological results into engineered solutions. It can be difficult to make this translation, particularly in the case of complex, large-scale problems like geoengineering. Augmentation of the existing method to address the

translation issue from a reverse perspective (i.e. biology back to engineering) could result in a larger solution space generated by the designer. Given the wide variety of results produced solely within the domain of biological systems, a process for connecting the search results in a logical manner to formulate a coherent solution is also needed. Modification of the bioinspired design process to enhance the user experience will help eliminate cross-domain translation problems.

The computational search tool is useful for providing information quickly to designers outside the biological domain. In addition, it allows the designer to search for multiple forms of the biological keyword, potentially resulting in more matches. The modified search tool described in this research provides a limited amount of control over the results presented to the user. Modification of the computational search tool to limit the results to only the primary or spatial noun, rather than all nouns, can reduce the post-processing time needed to identify an analogous biological system. Conversely, the part of speech found to be inspirational in this research may not be considered inspiring to all users of the tool. With part-of-speech software incorporated in the search tool, designers can filter the results based on parts of speech that are considered more relevant on a case-by-case basis. An adjective within a returned passage that describes a biological system, for example, might provide greater inspiration for the designer than a noun. In this case, the designer might wish to only display the adjectives within each returned passage. Future work on the tool to include additional parts of speech and extensive user control over display options will help the designer parse text passages more efficiently.

In addition to enhanced user controls, the provision of a dictionary within the computational search tool would help reduce the need for specialized knowledge. Users could see definitions of unfamiliar terminology within the search tool, eliminating the need for additional research. Furthermore, reducing the need for specialized knowledge would allow designers outside the field of engineering to successfully apply the method.

Another modification to the search tool is the amendment of the tool to utilize literature bases outside the current corpus. The text passages returned in this document are found using a single biological textbook [48]. The extension of the text corpus to include scientific journals, specifically those related to biology, could provide more opportunities for identifying inspirational biological systems. Initial expansion of the corpus could include general biological journals, while further expansion could explore specific categories of biological knowledge (i.e. cellular biology, zoology, botany, etc.).

Future work also includes application of the natural language processing bioinspired design method presented here to other fields of study. For example, can other domains unrelated to biology serve as inspiration for solutions to engineering problems? To answer this question, the engineer must select a desired domain, develop new translational thesauri between the selected domain and the engineering domain, and build a database of literature to search using the computational search tool. Design studies must then be conducted to validate the effectiveness of the selected domain in providing analogous systems for the engineering problem. Successful application of these methods using domains other than biology can lead to an expansion of the process, thereby increasing its utility and potential solution space.

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APPENDIX A

PRELIMINARY DESIGN STUDY SAMPLE PACKET

Geoengineering Design Simulation

Problem Background

Global warming is a hotly debated topic within the scientific community and has more recently inspired interest in the engineering domain. Engineers and scientists are pursuing technical solutions designed to offset further climate warming. The study, formation, and testing of these technical solutions to global warming is called Geoengineering. Geoengineering is more formally defined as the intentional modification of the earth's environment to prevent planetary warming resulting from anthropogenic carbon emissions.

The solutions currently proposed by scientists can be classified into the mode by which the solution operates. There are two primary modes of Geoengineering: solar radiation management (SRM) and tertiary carbon management (TCM). Solutions that utilize SRM are designed to manage short wave radiation, the earthbound solar energy within the visible, UV, and NIR spectrum. The purpose of this design simulation is to focus specifically on ideas that manage incoming solar energy rather than carbon emission management.

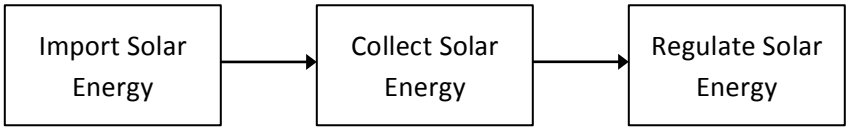
Objective: Formulate ideas to manage earthbound solar energy by gaining inspiration from passages found with a biological search tool.

Method Background

Many methods currently exist to inspire engineers and designers in new product design and redesign. One such method, functional modeling, requires the design to be represented as a series of pre-defined function verbs and flow nouns. The method has been appended for use in bio-inspired design to include an Engineering-to-Biology thesaurus that translates the pre-defined function verbs into biological verbs. A designer can use these biological verbs to search biology texts, examine the results, and, in the process, gain inspiration from the results. The

idea is that the biological text results will provide the designer with analogous systems that can inspire an engineered solution based on a biological concept.

The functional model for the design problem of Geoengineering is found below. These engineering functions have been translated into biological verbs, and the results of the text searches are presented in the following pages.



Engineering Function	Biological Keyword
Import	Attract
Collect	Absorb
Regulate	Regulate

Directions

Please read each text passage carefully and formulate an idea to manage incoming solar energy based on what you read. Please also include the part or parts of the passage that inspired your idea (i.e. the word(s) and/or concepts that gave you an idea for a solution to Geoengineering).

You should include all ideas, even those you think might be impossible to realistically implement. Space has been provided below each passage to record your ideas.

1. Upon absorbing blue light, phototropin initiates a signal transduction pathway leading to phototropic curvature.
2. To keep noncyclic electron flow going, both photosystems I and II must constantly be absorbing light, thereby boosting electrons to higher orbitals from which they may be captured by specific oxidizing agents.
3. Humans and other endotherms sometimes adjust their behavior to control their heat exchange with the environment.
4. Horsehair worms may feed only as larvae, absorbing nutrients from their hosts across their body wall, but many continue to grow after they have left their hosts, suggesting that adults may also absorb nutrients from their environment. roundworms. Roundworms (phylum Nematoda) have a thick, multilayered cuticle secreted by the underlying epidermis that gives their body its shape.
5. Water and ions are absorbed in the large intestine so that waste matter is consolidated into feces, which are periodically excreted.
6. If per capita birth and death rates are unrelated to a population's density, the population is not regulated. The density of a population is determined by the combined effects of all density-dependent and density-independent factors affecting it.
7. It depends on how many positive charges a nucleus has (nuclei with more protons are more positive and thus more attractive to electrons) and how far away the electrons are from the nucleus (closer means more electronegativity).
8. The dermal tissue system consists of the epidermis, part of which forms the root hairs that are responsible for absorbing water and minerals. The ground tissue system of a young root is the cortex, whose innermost cell layer, the endodermis, controls access to the stele.
9. Although each such interaction is brief and weak at any one site, the summation of many such interactions over the entire span of a large nonpolar molecule can produce substantial attraction. van der Waals forces are important in maintaining the structures of many biologically important substances, as we will see in Chapter 3.
10. The plant secretes enzymes to digest the insect and later absorbs the carbon- and nitrogen-containing products of digestion. None of the carnivorous plants must feed on insects.
11. Thus we and all other organisms must regulate our metabolism.
12. Some genes whose protein products regulate apoptosis have been identified. Plants have organ identity genes that interact to cause the formation of sepals, petals, stamens, and carpels.
13. Osmoregulators regulate the concentration of their tissue fluids. All animals have some solutes in their tissue fluids.
14. Each of the feedback controls regulates a part or various parts of the energy-harvesting pathways and keeps them operating in harmony and balance.

15. The motile female gamete produces a pheromone, a chemical that attracts the swimming male gamete. The gametes fuse in pairs, and then their nuclei fuse to form a diploid zygote.
16. The chemical signals associated with the reaction attract the phagocytes that are largely responsible for healing the wound.
17. The longevity of mRNA in the cytoplasm can also be regulated. The longer an mRNA exists in the cytoplasm, the more of its coded protein can be made.
18. The function of the kidneys is to regulate the volume, the osmolarity, and the chemical composition of the blood, and indirectly, of the tissue fluid.
19. Some Ectotherms Regulate Blood Flow to the Skin. Galápagos marine iguanas control blood flow to the skin to alter their heating and cooling rates.
20. A dominant male displays bright colors that help attract females to his spawning pit. Most males are not dominant at any given time, but fighting for and winning a vacated territory causes hormonal changes that transform a nondescript, non-dominant male into a showy, dominant male.
21. The hyphae then quickly invade the prey, growing and branching within it, spreading through its body, absorbing nutrients, and eventually killing it. A more dramatic adaptation for predation is the constricting ring formed by some species of Arthrobotrys, Dactylaria, and Dactylella (Figure 30).
22. This reversibility of the effects of red and far-red light regulates many other aspects of plant development, including flowering and seedling growth. The basis for the red and far-red effects resides in certain bluish photoreceptor proteins called phytochromes.
23. ADH also helps regulate blood osmolarity. Sensors in the hypothalamus monitor the solute potential of the blood. If blood osmolarity increases, these osmosensors stimulate increased release of ADH to enhance water resorption from the kidneys.
24. You can see that if excess H+ ions are added to this reaction mix, the reaction will move to the left and absorb the excess H+. On the other hand, if H+ ions are removed from the reaction mix, the reaction will move to the right and supply more H+ ions.
25. Human papilloma viruses, which cause cervical cancer (see Chapter 18), target the cell division inhibitory protein p53 for proteasomal degradation, so that unregulated cell division-and cancer-results. Although eukaryotes have more DNA in their genomes than prokaryotes, in some cases there is no apparent relationship between genome size and organism complexity.
26. Hormones are regulatory compounds that act at very low concentrations at sites distant from where they are produced.
27. Amino acids, monosaccharides, and many inorganic ions are absorbed by the microvilli of the mucosal cells. In many cases specific carrier proteins in the membranes of these cells transport nutrients into the cells.

28. These substances attract other insects that feed on the caterpillars.
29. The mate attraction pheromone of the female silkworm moth is a good example (see Figure 45.4). Male moths as far as several kilometers downwind are informed by these molecules that a female of their species is sexually receptive.
30. Auditory systems use hair cells to sense sound waves. At the end of the lower canal, the displacement is absorbed by the outward bulging of the round window. If the oval window vibrates in and out rapidly, the waves of fluid displacement do not have enough time to travel all the way to the end of the upper canal and back through the lower canal.
31. Its small size, its ease of cultivation, and its short generation time made this animal an attractive experimental subject. Beginning in 1909, Thomas Hunt Morgan and his students established Drosophila as a highly useful laboratory organism in Columbia University's famous "fly room," where they discovered the phenomena described in this section.
32. The photon may be absorbed by the molecule. In this case, the photon disappears. Its energy, however, cannot disappear, because energy is neither created nor destroyed.
33. Light (an environmental cue) acts directly on photoreceptors, which in turn regulate processes such as the many changes accompanying the growth of a young plant out of the soil and into the light.
34. Compartmentalization is the key to eukaryotic cell function. Recall that prokaryotic cells are surrounded by a plasma membrane that regulates molecular traffic into and out of the cell. In addition, eukaryotic cells have "cells within cells"-interior compartments surrounded by membranes that regulate what enters or leaves that compartment.
35. When they do eat, food is present in the gut and nutrients are being absorbed for some period of time after the meal, called the absorptive period. Once the stomach and small intestine are empty, nutrients are no longer being absorbed.
36. Heliconia bracts support flowers and attract pollinators.
37. A hallmark of living cells is their ability to regulate what enters and leaves their cytoplasm. This is a function of the plasma membrane, which is composed of a hydrophobic lipid bilayer with associated proteins.
38. In a seedling that has never been exposed to light, all the phytochrome is in the red- absorbing (Pr) form. Exposure to light converts Pr to Pfr (the far-red-absorbing form), and the Pfr initiates reversal of the etiolation phenomena: Chlorophyll synthesis begins, shoot elongation slows, the apical hook straightens out, and the leaves start to expand.
39. The durability of pheromonal signals enables them to be used to mark trails, as ants do, or to indicate directionality, as in the case of the moth sex attractant. However, it also means that the message cannot be changed rapidly. This

inflexibility makes pheromonal communication unsuitable for a rapid exchange of information.

40. The small intestine is the major site of digestion. Across this surface the small intestine absorbs all the nutrient molecules derived from food. The small intestine has three sections. The initial section-the duodenum-is the site of most digestion; the jejunum and the ileum carry out 90 percent of the absorption of nutrients.
41. Roots anchor the plant in place, and their extreme branching and high surface area-to-volume ratio adapt them to absorb water and mineral nutrients from the soil.
42. Males attract mates in varied ways. Males employ a variety of tactics to induce females to copulate with them.
43. To attract a mate, the female silkworm moth releases a pheromone called bombykol from a gland at the tip of her abdomen.
44. Placed in the upper region of the vagina, the contraceptive sponge blocks, absorbs, and kills sperm. The sponge stays effective for about a day. It is easier to use than the diaphragm and has about the same failure rate.
45. Another way to regulate transcription is to make the promoter work more efficiently.
46. Posttranscriptional events can also regulate gene expression. As we have seen, the processing of pre-mRNA can be controlled after transcription.
47. The energy of this photon, however, is somewhat less than the energy the pigment absorbed (recall the second law of thermodynamics), and so the emitted photon has a longer wavelength than the absorbed one. In any case, there can be no chemical changes or biological consequences-no chemical work is done.
48. Parathormone elevates blood calcium. It also promotes the activation of vitamin D, which stimulates the digestive tract to absorb calcium from food. Parathormone and calcitonin act antagonistically to regulate blood calcium levels: Parathormone elevates and calcitonin reduces.
49. Thus, the excitation ends up in the one pigment molecule in the antenna that absorbs the longest wavelength; this molecule occupies the reaction center of the antenna (Figure 8.11).
50. The five amino acids that have electrically charged side chains attract water and oppositely charged ions of all sorts. The four amino acids that have polar side chains tend to form weak hydrogen bonds with water and with other polar or charged substances.
51. In prokaryotes, the expression of some genes is regulated; their products are made only when they are needed. Other genes, called constitutive genes, whose products are essential to the cell at all times are constantly expressed.

52. Protein synthesis can be controlled by increasing promoter efficiency. Another way to regulate transcription is to make the promoter work more efficiently. Suppose that a bacterial cell lacks a supply of glucose, its preferred energy source, but instead has access to another sugar.
53. There are many other chlorophyll a molecules in the antenna, but all of them absorb light at shorter wavelengths than does the molecule in the reaction center.
54. Ion channels can alter membrane potential. For example, if positively charged Na+ ions enter the cell through sodium channels at one location, that positively charged area on the inside of the membrane attracts negative charges from surrounding areas, and thus there is a flow of electric current. However, this local flow of electric current does not spread very far before it diminishes and disappears.
55. To osmoregulate in salt water, animals must conserve water and excrete salts; thus they tend to produce small amounts of very concentrated urine.
56. Because chlorophyll in the leaves above it absorbs the light first, the shaded seedling "sees" a spectrum relatively rich in far-red (and poor in red); the ratio of far-red to red is increased as much as 10-fold to 20-fold in the shade.
57. Gap genes encode transcription factors that regulate the expression of pair rule genes. The products of the pair rule genes are transcription factors that regulate the segment polarity genes.
58. As the chylomicrons circulate through the liver and to adipose (fat) tissues throughout the body, receptors on the capillary walls recognize their protein coats, and lipases begin to hydrolyze the fats, which are then absorbed into liver or fat cells. Thus the protein coat of the lipoprotein both makes it water-soluble and serves as an "address" that directs it to a specific tissue.
59. Commercial seawater evaporating ponds, such as these in San Francisco Bay, are attractive homes for salt-loving archaea.
60. An excited pigment molecule may give off some of its absorbed energy as fluorescent light when the molecule returns to its ground state.
61. Some genes, such as i, produce proteins whose sole function is to regulate the expression of other genes.
62. What is Earth's present carrying capacity for people? Today's carrying capacity is set by Earth's ability to absorb the by-products-especially CO2-of our enormous consumption of fossil fuel energy and by whether we are willing to cause the extinction of millions of other species to accommodate our increasing use of environmental resources.
63. Some of this noncoding DNA maintains structural integrity at the ends of chromosomes, and some regulates gene expression. But the presence of much of this noncoding DNA remains an enigma. In contrast to the single main

chromosome of most prokaryotes, the eukaryotic genome is partitioned into several separate chromosomes.

64. Endotherms can regulate their body temperatures by producing heat metabolically or by mobilizing active mechanisms of heat loss.
65. Certain leaves of poinsettias, dogwoods, and some other plants are brightly colored and help attract pollinating animals to the often less striking flowers.
66. The fungi are superbly adapted for absorptive nutrition: They secrete digestive enzymes that break down large food molecules in the environment, then absorb the breakdown products. The kingdom Fungi encompasses heterotrophic organisms with absorptive nutrition.
67. Cholesterol is absorbed from foods such as milk, butter, and animal fats. An excess of cholesterol in the blood can lead to its deposition (along with other substances) in the arteries, a condition that may lead to arteriosclerosis and heart attack.
68. Gibberellins regulate the growth of some fruits and cause bolting in some biennial plants. Studies of phototropism led to the discovery and isolation of auxin (indoleacetic acid).
69. This quantity of the repressor is enough to regulate the operon effectively-to produce more would be a waste of energy.
70. Given the number of processes regulated by auxin, it is hardly surprising that there appear to be multiple receptors and signal transduction pathways for this hormone.
71. The chromoplasts have no known chemical function in the cell, but the colors they give to some petals and fruits probably help attract animals that assist in pollination or seed dispersal. (On the other hand, carrot roots gain no apparent advantage from being orange).
72. Ulva, a green alga, absorbs no light of wavelengths longer than 750 nm. Purple sulfur bacteria can conduct photosynthesis using the longer wavelengths that pass through the algae.
73. Metabolism is organized into pathways. So a cell must regulate all its metabolic pathways constantly.
74. The colon absorbs water and ions, producing semisolid feces from the slurry of indigestible materials it receives from the small intestine.
75. However, rather than emitting the photon's energy as fluorescence, the pigment molecules may pass the absorbed energy along. The pigments in photosynthetic organisms are arranged into energy-absorbing antenna systems.
76. This motif appears in the proteins that activate genes involved in embryonic development (homeobox proteins; see Chapter 16) and in the proteins that regulate the development of the immune and central nervous systems. The zinc finger motif has loops that form when a zinc ion is held by the amino acids cysteine and histidine.

77. They absorbed substrates, catalyzed reactions, and let the products diffuse back into the aqueous solution.
78. Thus, the expression of eukaryotic genes must precisely regulated. Regulation of gene expression can occur at many points. This section describes the mechanisms that control the transcription of specific genes.
79. Cytokinins increase the expansion of cut pieces of leaf tissue, and may regulate normal leaf expansion. Cytokinins delay the senescence of leaves. If leaf blades are detached from a plant and floated on water or a nutrient solution, they quickly turn yellow and show other signs of senescence.
80. When a molecule absorbs a photon, it acquires the energy of that photon. It is thereby raised from a ground state (lower energy) to an excited state (higher energy).
81. A hallmark of living cells is their ability to regulate what enters and leaves their cytoplasm.
82. The level of calcium in the blood is regulated by two hormones. Calcitonin, produced by the thyroid, lowers blood calcium. Parathormone, produced by the parathyroid glands, raises it.

83. Humans use a variety of technologies to control fertility. A device simpler than the diaphragm is a circular, highly absorbent, polyurethane sponge permeated with a spermicide. Placed in the upper region of the vagina, the contraceptive sponge blocks, absorbs, and kills sperm.
84. Parathormone elevates blood calcium. Parathormone and calcitonin act antagonistically to regulate blood calcium levels: Parathormone elevates and calcitonin reduces. A similar antagonistic relationship is true of hormones of the pancreas, which regulate blood glucose levels.
85. This quantity of the repressor is enough to regulate the operon effectively-to produce more would be a waste of energy. There is no operator between pi and the i gene.
86. The most common cause of pernicious anemia, however, is not a lack of vitamin B12 in the diet, but an inability to absorb it. Normally, cells in the stomach lining secrete a peptide called intrinsic factor, which binds to vitamin B12 and makes it possible for it to be absorbed in the ileum of the small intestine.
87. Biologists are exploring possible ways to regulate the permeability, number, and form of plasmodesmata as a means of modifying traffic in the plant.
88. They apparently feed on prokaryotes, which they digest outside their bodies and absorb either through a membrane that covers the oral surface or via a shallow saclike stomach. The most familiar echinoderms are the sea stars (class Asteroidea; Figure 33).
89. Because heat always moves from a warmer to a cooler object, any change in the temperature of the environment causes a change in the temperature of an

organism in that environment-unless the organism does something to regulate its temperature. Living cells function over only a narrow range of temperatures. If cells cool to below 0°C, ice crystals damage their structures, possibly fatally.

90. Pigments absorb light in the visible spectrum. Absorption of a photon puts a pigment molecule in an excited state that has more energy than its ground state.
91. The winner rapidly assumes the appearance and behavior of a dominant male: brightly colored, big, aggressive, and attractive to females. What accounts for this dramatic change? Russell Fernald and his students at Stanford University has shown that soon after the nondescript male's victory, certain cells in his brain enlarge and secrete a chemical message.
92. Endotherms can regulate their body temperatures by producing heat metabolically or by mobilizing active mechanisms of heat loss.
93. Similar tissue layers are found in all regions of the vertebrate gut. In some regions of the gut, nutrients are absorbed across the plasma membranes of the mucosal cells; the plasma membranes of these absorptive cells have many folds that increase their surface area (see Figure 50).
94. Naturally occurring inhibitors regulate metabolism; artificial ones can be used to treat disease, to kill pests, or in the laboratory to study how enzymes work.
95. Instead, each tissue regulates its own blood flow through autoregulatory mechanisms that cause the arterioles supplying the tissue to constrict or dilate.
96. Sweating: A Regulated Membrane Activity: an athlete at work can lose up to 2 liters of water in an hour by sweating.
97. The DNA carries the genetic information; the proteins organize the chromosome physically and regulate the activities of the DNA.
98. Here we find the blood and lymph vessels that carry absorbed nutrients to the rest of the body. The submucosa also contains a network of nerves; these neurons are both sensory (responsible for stomach aches) and regulatory (controlling the various secretory functions of the gut).
99. Many fungi are saprobes that absorb nutrients from dead matter, others are parasites that absorb nutrients from living hosts.
100. Photoperiodic plants regulate their flowering by measuring the length of light and dark periods.
101. They satisfy most of their needs from the air and from rainwater, augmented by minerals absorbed from their rocky substrate. A lichen begins to grow shortly after a rain, as it begins to dry.
102. That individual, a young female known to the world as Lucy, attracted a great deal of attention because her remains were so complete and well preserved. Lucy has been assigned to the species Australopithecus afarensis, the most likely ancestor of humans.

103. Complement proteins attract macrophages to the site, where they engulf bacteria and dead cells. Four features characterize the immune response: specificity, the ability to respond to an enormous diversity of antigens, the ability to distinguish self from nonself, and memory.
104. In photosystem I, P700 absorbs photons, becoming excited to P700*, which then leads to the reduction of an oxidizing agent, ferredoxin (Fd), while being oxidized to P700+.
105. Thus the communication between a photoreceptor and its bipolar cell can be influenced by the amount of light absorbed by neighboring photoreceptors. This lateral flow of information enables the retina to sharpen the perception of contrast between light and dark patterns.
106. Instead, the opening and closing of channels and the action of membrane pumps regulate levels of the ion in a cellular compartment. There are many signals that can cause Ca2+ channels to open, including IP3 (see the previous section) and the arrival of a nerve impulse at a muscle cell.
107. Fungi are absorptive heterotrophs. In the forest, for example, the invisible mycelia of fungi absorb nutrients from fallen trees, thus decomposing their wood. Fungi are the principal decomposers of cellulose and lignin, the main components of plant cell walls (most bacteria cannot break down these materials).
108. While many secondary products have protective functions, others are essential as attractants for pollinators and seed dispersers. Table 39.1 gives the major classes of secondary plant products and their biological roles.
109. Fungi absorb food substances from their surroundings and break them down (digest them) within their cells. They are important as decomposers of the dead bodies of other organisms.
110. The products of the pair rule genes are transcription factors that regulate the segment polarity genes. Activation of the segmentation genes leads to the activation of the appropriate homeotic genes in different segments.
111. Regulated hypothermia can also last for days or even weeks, with drops to very low temperatures; this phenomenon is called hibernation.
112. Certain leaves of poinsettias, dogwoods, and some other plants are brightly colored and help attract pollinating animals to the often less striking flowers. Many plants, such as peas, have tendrils-modified leaves that support the plant by wrapping around other plants.
113. Nutritional studies also reveal that most fungi are unable to synthesize their own thiamin (vitamin B1) or biotin (another B vitamin), and must absorb these vitamins from their environment. On the other hand, fungi can synthesize some vitamins that animals cannot.

114. The excitation passes from one pigment molecule in the antenna to another, moving from pigments that absorb shorter wavelengths (higher energies) to pigments that absorb longer wavelengths (lower energies) of light.
115. Once the stomach and small intestine are empty, nutrients are no longer being absorbed. During this postabsorptive period, the continuous processes of energy metabolism and biosynthesis must run on internal reserves.
116. Regulated growth is a vital characteristic of life. Speciation resulted in the millions of species living on Earth today.
117. The reaction center is the part of the antenna that converts the light absorbed into chemical energy. In plants, the pigment molecule in the reaction center is always a molecule of chlorophyll a.
118. Light energy comes in packets called photons, but it also has wavelike properties; Pigments absorb light in the visible spectrum; Absorption of a photon puts a pigment molecule in an excited state that has more energy than its ground state.
119. These tiny vesicles provide a large surface area across which the products of digestion may be absorbed by the rest of the cell.
120. A male can guard a clutch of eggs while attracting additional females to lay eggs in his nest. A female, on the other hand, can produce another clutch of eggs sooner if she resumes foraging immediately after mating than if she spends time guarding her eggs.
121. A few substances can be absorbed from the chyme across the stomach wall, including alcohol (hence its rapid effects), aspirin, and caffeine, but even these substances are absorbed in rather small quantities in the stomach. Peristaltic contractions of the stomach walls push the chyme toward the bottom end of the stomach.
122. One, gibberellin A1, regulates stem growth in most plants. Mutant plants that cannot produce normal amounts of gibberellins are dwarfs: Their stems are shorter than wild-type stems.
123. The hydrogen bond that we described earlier is a type of ionic bond, because it is formed by electrical attractions. However, it is weaker than most ionic bonds because the hydrogen bond is formed by partial charges ((+ and (-) rather than by whole-unit charges (+1 unit, -1 unit).
124. The concentration of NO, which breaks down quickly, can be regulated only by how much of it is made. The level of Ca2+, on the other hand, is determined by both membrane pumps and ion channels.
125. The binding of a substrate to the active site produces an enzyme-substrate complex held together by one or more means, such as hydrogen bonding, ionic attraction, or covalent bonding. The enzyme-substrate complex gives rise to product and free enzyme: E + S ? ES ? E + P where E is the enzyme, S is the substrate, P is the product, and ES is the enzyme-substrate complex.

126. Eventually the developing sporophyte elongates sufficiently to break out of the archegonium, but it remains connected to the gametophyte by a "foot" that is embedded in the parent tissue and absorbs water and nutrients from it. The sporophyte remains attached to the gametophyte throughout its life.
127. They also regulate their own metabolism, which enables them to perform their necessary functions. Motion is not a characteristic of plants; instead, we may think of plants as "growing machines."
128. The outer segments of the rods and cones are partly buried in a layer of pigmented epithelium that absorbs photons not captured by rhodopsin and prevents any backscattering of light that might decrease visual sharpness.
129. In some seeds, such as kidney beans, the nutrient reserves of the endosperm are absorbed by the cotyledons at the seed stage. In others, such as castor beans and corn, the reserves in the endosperm will be drawn on throughout the course of development.
130. Materials are exchanged in capillary beds by filtration, osmosis, and diffusion. Such capillaries are found in the digestive tract, where nutrients are absorbed, and in the kidneys, where wastes are filtered. Some capillaries have large gaps that permit the movement of even larger substances, such as red blood cells.
131. There are several ways in which cells can regulate the activity of a signal transduction mechanism.
132. Trail-marking and territory-marking pheromones tend to be relatively large molecules that diffuse slowly; sex attractants tend to be small molecules that diffuse rapidly.
133. Male widowbirds compete for display sites, at which they perform courtship displays to attract females. To examine the role of the tail in sexual selection, an ecologist shortened the tails of some males by cutting them, and lengthened the tails of others by gluing on additional feathers.
134. Testosterone and the estrogens are steroid hormones that regulate sexual development in vertebrates. Cortisol and related hormones play many regulatory roles in the digestion of carbohydrates and proteins, in the maintenance of salt balance and water balance, and in sexual development.
135. First the root releases flavonoids and other chemical signals that attract the Rhizobium to the vicinity of the root. Flavonoids trigger the transcription of bacterial nod genes, which encode Nod (nodulation) factors.
136. The knots that we find attractive in knotty pine but regard as a defect in structural timbers are cross sections of branches: As a trunk grows, the bases of branches become buried in the trunk's new wood and appear as knots when the trunk is cut lengthwise.
137. For example, microfilaments support the tiny microvilli that line the intestine, giving it a larger surface area through which to absorb nutrients. Such a

"submembrane skeleton" also helps keep the red blood cell in its familiar doughnut shape (Figure 4).

138. Ectotherms and endotherms can regulate body temperature through behavior. Heat exchange between a body and the environment is via radiation, conduction, convection, and evaporation.

139. Homeostasis depends on the ability to regulate the functions of the organs and organ systems to counteract influences that would change the physical or chemical composition of the internal environment.

140. Phytochromes help to regulate a seedling's early growth. The radicle, or embryonic root, is the first portion of the seedling to escape the seed coat.

141. The mouse, however, regulates its body temperature by increasing its metabolic rate, which increases its production of body heat.

142. A vital characteristic of living organisms is regulated growth. The growth of a multicellular organism requires a sequence of events leading from a single cell to a multicellular adult.

143. IPM combines chemical applications with cultural practices-crop rotation, mixed plantings of crop plants, and mechanical tillage of the soil-and biological methods-development of pest-resistant strains of crops, use of natural predators and parasites, and use of chemical attractants, such as pheromones-to control insect herbivores. The reduced use of toxic chemicals avoids most pollution problems and reduces the chance that pests will evolve resistance to pesticides.

144. Somatostatin is a hormone of the brain and the gut. Pancreatic somatostatin extends the period of time during which nutrients are absorbed from the gut and used by the cells of the body. Somatostatin also acts as a hypothalamic neurohormone that inhibits the release of growth hormone and thyrotropin by the pituitary.

145. Photoreceptors and hormones regulate seedling development, including growth. Eventually the plant flowers and forms fruit.

146. Lichens grow where no eukaryote has succeed. In spite of this hardiness, lichens are very sensitive to air pollution because they are unable to excrete toxic substances that they absorb. Hence they are not common in industrialized cities. Because of their sensitivity, lichens are good biological indicators of air pollution.

147. Some genes, such as i, produce proteins whose sole function is to regulate the expression of other genes. Certain other DNA sequences (operators and promoters) do not code for proteins but are binding sites for regulatory proteins.

148. We explore the environmental cues, photoreceptors, and hormones that regulate plant development, and consider the multiple roles that each plays in normal development.

149. How do these various proteins and DNA sequences-transcription factors, activators, repressors, regulators, enhancers, and silencers-regulate transcription? Apparently, all genes in most tissues can transcribe a small amount of RNA. But the right combination of all the factors is what determines the maximum rate of transcription.
150. We also describe how the expression of prokaryotic genes is regulated, and what DNA sequencing has revealed about the prokaryotic genome. Viruses are not prokaryotes.
151. Normally, cells in the stomach lining secrete a peptide called intrinsic factor, which binds to vitamin B12 and makes it possible for it to be absorbed in the ileum of the small intestine. Conditions that damage the stomach lining can therefore cause anemia.
152. Like hormones, photoreceptors regulate many developmental processes in plants. Unlike the hormones, which are small molecules, plant photoreceptors are proteins.
153. Let's review the life history of a flowering plant, from seed to death, focusing on how the developmental events are regulated. As plants develop, environmental cues, photoreceptors, and hormones affect three fundamental processes: cell division, cell expansion, and cell differentiation.
154. Herbivores have special adaptations to digest cellulose. As this cecal material passes through the stomach and small intestine, the nutrients it contains are digested and absorbed.
155. These positive charges electrostatically attract the negative phosphate groups on DNA.
156. Photosensitivity depends on the ability of rhodopsins to absorb photons of light and to undergo a change in conformation. A rhodopsin molecule consists of a protein, opsin (which by itself does not absorb light), and a light-absorbing prosthetic group, 11-cis-retinal.
157. Photosynthesis uses chlorophylls and accessory pigments that the chlorophylls absorb blue and red wavelengths, which are near the two ends of the visible spectrum. Thus, if only chlorophyll pigments were active in photosynthesis, much of the visible spectrum would go unused.
158. A pigment molecule enters an excited state when it absorbs a photon (see Figure 8.6). The excited state is an unstable potential energy state, and the molecule usually does not stay in it very long.
159. These positive charges electrostatically attract the negative phosphate groups on DNA. These interactions, as well as interactions among the histones themselves, form beadlike units called nucleosomes.
160. Digestion begins in the mouth and the stomach. A few substances can be absorbed from the chyme across the stomach wall, including alcohol (hence its

rapid effects), aspirin, and caffeine, but even these substances are absorbed in rather small quantities in the stomach.

161. The mechanisms that regulate embryonic development in the protostomes and deuterostomes are governed by homologous homeobox genes.

162. Thus we and all other organisms must regulate our metabolism. The regulation of the rates at which our thousands of different enzymes operate contributes to metabolic homeostasis.

163. If they absorb more cations than anions, they excrete H+ ions, thus lowering the soil pH. If they absorb more anions than cations, they excrete OH- ions or HCO3- ions, raising the soil pH.

164. Plant growth is regulated more by hormone interactions than by a single hormone. Auxin promotes stem elongation, but it inhibits the elongation of roots.

165. Finally, we present the mechanisms that control and regulate salt and water balance in mammals, giving the vampire bat and other species their remarkable abilities to exploit unusual diets and extreme environments.

166. Strategies for controlling and managing populations of organisms are based on our understanding of how populations grow and are regulated. A general principle of population dynamics is that the total number of births and the growth rates of individuals tend to be highest when a population is well below its carrying capacity.

167. Cations in solution are attracted to these negative ions. To become available to plants, the cations must be detached from the clay particles.

168. Allostery regulates metabolism. Glycolysis, the citric acid cycle, and the respiratory chain are regulated by allosteric control of the enzymes involved.

169. Unlike charges (+/-) attract each other; like charges (+/+ or -/-) repel each other.

170. But many other species have seeds whose germination is regulated in more complex ways. Seed dormancy may last for weeks, months, years, or even centuries. The mechanisms of dormancy are numerous and diverse, but three principal strategies dominate: •Exclusion of water or oxygen from the embryo by means of an impermeable seed coat •Mechanical restraint of the embryo by means of a tough seed coat •Chemical inhibition of embryo development The dormancy of seeds with impermeable coats can be broken if the seed coat is abraded as the seed tumbles across the ground or through creek beds, or passes through the digestive tract of an animal.

171. In many animals, the parts of the gut that absorb nutrients have evolved extensive surface areas.

172. The mucosal cells with microvilli produce peptidases, which cleave larger peptides into tripeptides, dipeptides, and individual amino acids that the cells can absorb. These cells also produce the enzymes maltase, lactase, and sucrase,

which cleave the common disaccharides into their constituent, absorbable monosaccharides-glucose, galactose, and fructose.

173. If they absorb more cations than anions, they excrete H+ ions, thus lowering the soil pH.

174. Thus, it is the presence or absence of lactose-the inducer-that regulates the binding of the repressor to the operator, and therefore the synthesis of the proteins needed to metabolize it.

175. The expression of prokaryotic genes is regulated by three different mechanisms: inducible operator-repressor systems, repressible operator-repressor systems, and systems that increase the efficiency of a promoter.

176. Without water to act as a solvent for biochemicals, to receive wastes, to absorb heat, and to participate directly in chemical reactions, life would not exist as we know it.

177. Evaporation of water is an effective way to lose heat. Having water in contact with the skin greatly increases heat loss because water has a much greater capacity for absorbing heat than air does. A gram of water absorbs about 580 calories of heat when it evaporates. Water is heavy, however, so animals do not carry an excess supply of it.

178. Different compartments within the long tubular gut specialize in digesting food, absorbing nutrients, and storing and expelling wastes. Accessory organs contribute digestive juices containing enzymes and other molecules.

179. Lignier, proposed an attractive hypothesis that is still widely accepted today. Lignier argued that the ancestors of the first tracheophytes grew by branching dichotomously.

180. If neither rate is density-dependent, there is no equilibrium and the population is not regulated. Fluctuations in the density of a species' population are determined by all the factors and processes, density-dependent and density-independent, acting upon it.

181. Female bluethroats are attracted to males whose throat feathers have high reflectance, which signals a healthy, high-quality mate.

182. Each macronucleus contains many copies of the genetic information, packaged in units containing very few genes each; the macronuclear DNA is transcribed and translated to regulate the life of the cell. Although we do not know how this system of macro- and micronuclei came into being, we do know something about the behavior of these nuclei, which we will discuss after describing the body plan of one important ciliate, Paramecium.

183. These substances attract other insects that feed on the caterpillars. Herbivores ranging from insects to elephants aren't the only challenges plants face.

184. The fungi absorb water and nutrients from the environment and provide these as well as a supporting structure for the microorganisms, which in turn provide the fungi with the products of photosynthesis.
185. What drives the opening and closing of the stomata? Certain wavelengths of blue light, absorbed by a pigment in the guard cell plasma membrane, activate a proton pump, which actively transports protons (H+) out of the guard cells and into the surrounding epidermis (Figure 35).
186. Complement proteins activate the inflammatory response and attract phagocytes to sites of infection.
187. Cyclin-Cdk complexes regulate the passage of cells from G1 into S phase and from G2 into M phase. In addition to the internal cyclin-Cdk complexes, controls external to the cell, such as growth factors and hormones, can also stimulate the cell to begin a division cycle.
188. In many animals, the parts of the gut that absorb nutrients have evolved extensive surface areas. In vertebrates, the wall of the gut is richly folded, with the individual folds bearing legions of tiny fingerlike projections called villi (Figure 50).
189. Chromatin consists of DNA and protein. The DNA carries the genetic information; the proteins organize the chromosome physically and regulate the activities of the DNA. By mass, the amount of chromosomal protein is equivalent to that of DNA.
190. The Hypothalamus Regulates Body Temperature. The observation that damage to the hypothalamus disrupts thermoregulation led to the finding that hypothalamus acts as a thermostat in the vertebrate body.
191. This heat is absorbed from the environment in contact with the water. Once again, much of the heat energy is used to break hydrogen bonds.
192. Segmentation and homeotic genes act after the maternal effect genes. Three classes of segmentation genesact, one after the other, to regulate finer and finer details of the segmentation pattern (Figure 16.14). First, gap genes organize large areas along the anterior-posterior axis.
193. Any pigment molecule with a suitable absorption spectrum can absorb an incoming photon and become excited. The excitation passes from one pigment molecule in the antenna to another, moving from pigments that absorb shorter wavelengths (higher energies) to pigments that absorb longer wavelengths (lower energies) of light.
194. These organisms ingest their food source, digest the food outside their cells, and then absorb the products. Animals get their raw materials and energy by eating other forms of life. Perhaps because we are animals ourselves, we are often drawn to study members of this kingdom, which is covered in Chapters 31, 32, and 33.

195. Urine is concentrated in the collecting ducts. As the solute concentration of the surrounding tissue fluid increases, more and more water is absorbed from the urine in the collecting duct. By the time it reaches the ureter, the urine has been greatly concentrated.
196. Just as water molecules interact with one another through their polarity-induced hydrogen bonds, any molecule that is itself polar will interact with other polar molecules by weak ((+ to (-) attractions in hydrogen bonds. If a polar molecule interacts with water in this way, it is called hydrophilic ("water-loving").
197. Drosophila development results from a transcriptionally controlled cascade. The two morphogens regulate the expression of the gap genes, although in different ways. Bicoid protein affects transcription, while Nanos affects translation.
198. We now know that two hormones working in sequence regulate molting: Cells in the brain produce brain hormone. Brain hormone is transported to and stored in a pair of structures attached to the brain, the corpora cardiaca (singular corpus cardiacum).
199. A plant may benefit from moderate herbivory by attracting animals that spread its pollen or that eat its fruit and thus distribute its seeds through their feces.
200. But how does the cell regulate these interconversions to maintain constant metabolic pools? Consider what happens to the starch in your burger bun.
201. If they absorb more anions than cations, they excrete OH- ions or HCO3- ions, raising the soil pH.
202. When air temperatures on the African savanna soar, an elephant may use a cool shower to thermo regulate.
203. Water and ions are absorbed in the large intestine coli and absorbed across the wall of the colon. Excessive or prolonged intake of antibiotics can lead to vitamin deficiency because the antibiotics kill the normal intestinal bacteria at the same time they are killing the disease-causing organisms for which they are intended.
204. Light regulates many aspects of plant development in addition to phototropism. The affected processes range from seed germination to shoot elongation to the initiation of flowering.
205. The earliest tracheophytes lacked roots and leaves. They were apparently anchored in the soil by horizontal portions of stem, called rhizomes, that bore water- absorbing rhizoids. These rhizomes also bore aerial branches, and sporangia-homologous with the nontracheophyte capsule-were found at the tips of these branches.

206. Thus, in a neutral solution, a molecule with an amino group will be attracted electrically to another molecule that has a carboxyl group, because both groups are ionized and they have opposite charges.
207. Molecules that absorb wavelengths in the visible region of the spectrum are called pigments. When a beam of white light (light containing visible light of all wavelengths) falls on a pigment, certain wavelengths of the light are absorbed. The remaining wavelengths, which are reflected or transmitted, make the pigment appear to us to be colored.
208. It is also important to remember that ions with opposite charges attract each other.
209. The sperm are aided in this task by chemical attractants released by the egg or the archegonium. Before sperm can enter the archegonium, certain cells in the neck of the archegonium must break down, leaving a water-filled canal through which the sperm swim to complete their journey.
210. We have now seen two basic ways to regulate the rates of metabolic pathways. In Chapter 6, we described allosteric regulation of enzyme activity (the rate of enzyme-catalyzed reactions); this mechanism allows rapid fine-tuning of metabolism.
211. The atmosphere regulates temperatures close to Earth's surface. The atmosphere is a thin layer of gases surrounding Earth.
212. One way to minimize pH changes in a chemical solution is to add a buffer-a substance that can either absorb excess hydrogen ions or supply hydrogen ions. The major buffer in the blood is the bicarbonate ion, HCO_3^-, which is formed from the disassociation of carbonic acid, which in turn is formed by the hydration of CO_2 according to the following equilibrium reactions (see Chapter 48).
213. Recent research suggests that bicarbonate ions in the capillary plasma are an important contributor to the osmotic attraction of water back into the capillary. As we saw in Chapter 48, CO_2 diffuses into the plasma as the blood flows through the capillary.
214. Once we understand how an organ or an organ system works, we can then ask how is it regulated. As an example, we will discuss in detail the system that regulates body temperature. But first, why is it necessary to regulate body temperature?
215. Arthropods use chemical signals to attract mates.
216. Each electron is attracted to both protons, but the two protons cannot come together because they repel each other. A covalent bond forms when the electron orbitals of the two atoms overlap.
217. Ultraviolet radiation from the sun (or a tanning lamp) is absorbed by thymine in DNA, causing it to form interstrand covalent bonds with adjacent nucleotides. This too creates havoc with DNA replication.

218. Calling in an Air Strike As this caterpillar of a corn earworm moth (Helicoverpa zea) munches on a cotton boll, it is triggering a series of reactions in the plant that may end in the attraction of other insects that will attack the caterpillar.
219. Cytokines may also attract phagocytic cells to the site of injury and initiates a specific immune response to the pathogen.
220. The opposite condition, diarrhea, results if too little water is absorbed or if water is secreted into the colon. (Both constipation and diarrhea can be induced by toxins from certain microorganisms).
221. Membranes also regulate ionic and molecular traffic into and out of the cell.
222. Two Ways to Regulate a Metabolic Pathway: feedback from the end product can block enzyme activity, or it can stop the transcription of genes that code for the enzyme.
223. Many species of birds and mammals use regulated hypothermia as a means of surviving periods of cold and food scarcity. Some become hypothermic on a daily basis.
224. Roots anchor the plant in place, and their extreme branching and high surface area-to-volume ratio adapt them to absorb water and mineral nutrients from the soil. Each of the vegetative organs can best be understood in terms of its function and its structure.
225. Alterations in pH can change the pattern of ionization of carboxyl and amino groups in the R groups of amino acids, thus disrupting the pattern of ionic attractions and repulsions that contributes to normal tertiary structure. The loss of normal tertiary structure is called denaturation, and it is always accompanied by a loss of the normal biological function of the protein (Figure 3).
226. Plant cells communicate by plasmodesmata. Plasmodesmata are not merely passive channels, but can be regulated. Plant viruses may infect cells at one location, then spread rapidly through a plant organ by plasmodesmata until they reach the plant's vascular tissue (circulatory system).
227. Allosteric enzymes have interacting subunits (Note that not all allosteric enzymes have multiple subunits; there are some single-chain enzymes that are allosterically regulated.) The activity of allosteric enzymes is controlled by molecules called effectors, which may have no structural similarity either to the reactants or to the products of the reaction being catalyzed.
228. The Release of Melatonin Regulates Seasonal Changes. Melatonin is released in the dark and inhibited by light exposure. The duration of daily melatonin release thus changes as the day length (photoperiod) changes, inducing dramatic seasonal physiological changes in some animals, such as these Siberian hamsters.

229. The enzymes act on the food, reducing it to nutrient molecules that can be absorbed by the cells lining the cavity. Only after they are absorbed by the cells are the nutrients within the body of the animal.
230. Instead, the opening and closing of channels and the action of membrane pumps regulate levels of the ion in a cellular compartment.
231. Insects are attracted into the pitchers either by bright colors or by scent and are prevented from getting out again by stiff, downward-pointing hairs.
232. Lysozyme ruptures some of the bacteria that live in the foregut, releasing nutrients, which the mammal absorbs. How many changes were incorporated into the lysozyme molecule to allow it to function amid the digestive enzymes and acidic conditions of the mammalian foregut? To answer this question, molecular evolutionists compared the amino acid sequences of lysozyme in foregut fermenters and in several of their nonfermenting relatives.
233. Males compete for these limited nest sites; males that hold the best sites, near the tips of branches where they are safe from predators, attract the most females. Males spend their time attempting to attract additional mates rather than helping to rear the offspring they already have, which explains the evolution of brighter plumage among males.
234. One of two things happens: The molecule returns to the ground state, emitting much of the absorbed energy as fluorescence. The molecule passes some of the absorbed energy to another pigment molecule.
235. Microfilaments form the backbone of the microvilli that increase the surface area of some cells, such as intestinal cells that absorb nutrients. Actin microfilaments, along with ankyrin and spectrin proteins, support the "doughnut" shape of red blood cells.
236. The proteasome controls the longevity of proteins after translation. We have considered how gene expression may be regulated by the control of transcription, RNA processing, and translation. However, the story does not end here, because most gene products-proteins-are modified after translation.
237. In addition, eukaryotic cells have "cells within cells"-interior compartments surrounded by membranes that regulate what enters or leaves that compartment.
238. Catabolism and anabolism are integrated. The cell regulates the enzymes of catabolism and anabolism so as to maintain a balance. This metabolic homeostasis gets upset only in unusual circumstances.
239. Insulin and glucagon regulate blood glucose. Before the 1920s, diabetes mellitus was a fatal disease, characterized by weakness, lethargy, and body wasting.
240. A rhodopsin molecule consists of a protein, opsin (which by itself does not absorb light), and a light-absorbing prosthetic group, 11-cis-retinal. The light-

absorbing group is cradled in the center of the opsin and the entire rhodopsin molecule sits within the plasma membrane of a photoreceptor cell (Figure 45).

241. Metabolic pathways are often compartmentalized and are highly regulated. When glucose burns, energy is released as heat and light: C6H12O6 + 6 O2 ? 6 CO2 + 6 H2O + energy. The same equation applies to the metabolism of glucose by cells, but the reaction is accomplished in many separate steps so that the energy can be captured as ATP.

242. In damaged or infected tissue, complement proteins and other chemical signals attract phagocytes-neutrophils first, and then monocytes, which become macrophages.

243. Photoperiodic plants regulate their flowering by measuring the length of light and dark periods. Short-day plants flower when the days are shorter than a species-specific critical day length; long-day plants flower when the days are longer than a critical day length.

244. The courtship displays of a male, for example, benefit the male if they attract females, and they benefit the female if they allow her to assess whether the male is of the right species and whether he is strong, vigorous, and has other attributes that will make him a good father.

245. Predators may be attracted to regions where densities of their prey have increased. If predators are able to capture a larger proportion of the prey than they did when prey were scarce, the per capita death rate of the prey rises.

246. Companion cells retain all their organelles and may, through the activities of their nuclei, regulate the performance of the sieve tube members. All these kinds of plant cells play important roles.

247. Because heat always moves from a warmer to a cooler object, any change in the temperature of the environment causes a change in the temperature of an organism in that environment-unless the organism does something to regulate its temperature.

248. Such accessory pigments, in collaboration with the chlorophylls, constitute an energy- absorbing antenna system covering much of the visible spectrum.

249. A population whose dynamics are influenced primarily by density-dependent factors is said to be regulated. Factors that change per capita birth and death rates in a population independent of its density are said to be density-independent.

250. These opsin molecules differ in the wavelengths of light they absorb best. Although the same 11-cis-retinal group is the light absorber, its molecular interactions with opsin tune the spectral sensitivity of the rhodopsin molecule as a whole.

251. The stability of mRNA can be regulated. DNA, as the genetic material, must remain stable, and there are elaborate mechanisms for repairing it if it becomes damaged.

252. An important way to regulate the action of a protein in a cell is to regulate its lifetime in the cell. Proteins involved in cell division.
253. A driver uses information and control mechanisms to regulate the speed of the car.
254. Other oligosaccharins may regulate aspects of cell differentiation. Three other hormones-jasmonates, salicylic acid, and systemin-serve as important signals in plant defenses.
255. The result is a brief, weak attraction. Although each such interaction is brief and weak at any one site, the summation of many such interactions over the entire span of a large nonpolar molecule can produce substantial attraction.
256. Arterial pressure is controlled and regulated by hormonal and neural mechanisms. The same smooth muscle of arteries and arterioles that responds to autoregulatory stimuli also responds to signals from the endocrine and central nervous systems.
257. Calcitonin and parathormone help regulate blood calcium levels. Bone can be a source (site of production) or a sink (site of utilization or storage) for calcium.
258. The lizard apparently cannot regulate its body temperature or metabolism independently of environmental temperature. The mouse, however, regulates its body temperature by increasing its metabolic rate, which increases its production of body heat.
259. Photosystem II absorbs photons, sending electrons from P680 to pheophytin-I-the first carrier in the redox chain-and causing P680 to become oxidized to P680+.
260. Phytochromes mediate the effects of red and far-red light. They are blue because they absorb red and far-red light and transmit other light. In the cytosol of plants are two interconvertible forms of phytochromes.
261. Colorful pigments stored in the chromoplasts of flowers like this begonia may help attract pollinating insects. Leucoplasts in the cells of a potato are filled with white starch grains.
262. If a substantial amount of lactose remains unabsorbed and passes into the large intestine, its metabolism by bacteria in the large intestine causes abdominal cramps, gas, and diarrhea.
263. Some animal pollinators such as this lesser long-nosed bat are attracted by rewards of nectar or pollen.
264. Both marine and terrestrial vertebrates must conserve water. The fish handle these salt loads by simply not absorbing some ions (such as Mg^{2+} or SO_4^{2-}) from their guts and by actively excreting others (such as Na^+ and Cl^-) from the gill membranes and from the renal tubules.
265. Light absorbed by photoreceptors affects this time-measuring process. Once a leaf has determined that it is time for the plant to flower, that information must be transported as a signal to the places where flowers will form.

266. Multicellular organisms cannot achieve their adult shapes or function effectively unless their growth is carefully regulated. Uncontrolled growth-one example of which is cancer-ultimately destroys life. A vital characteristic of living organisms is regulated growth.
267. Mendel's second law says that alleles of different genes assort independently. Were such results to be obtained, there might be no reason to suppose that seed shape and seed color were regulated by two different genes, because spherical seeds would always be yellow, and wrinkled ones always green.
268. They also use song to attract females, which suggests that the females know the song of their species even if they do not sing.
269. Membranes also regulate ionic and molecular traffic into and out of the cell. This selective permeability, which we describe in this chapter, is an important characteristic of life.
270. There are many ways to regulate the presence of mature mRNA in a cell even after a precursor has been transcribed. As we saw earlier, pre-mRNA can be processed by cutting out the introns and splicing the exons together.
271. Now let's complete the sexual life cycle by considering the transition from the vegetative to the flowering state, and how this transition is regulated.
272. It is also important to remember that ions with opposite charges attract each other. With these basics of bioelectricity in mind, we can ask how the resting potential of the neuronal plasma membrane is created, and how the flow of ions through membrane channels is turned on and off to generate action potentials.
273. When the 11-cis-retinal absorbs a photon of light energy, its shape changes into a different isomer of retinal-all-trans-retinal.
274. The bile that emulsifies the fats is not absorbed along with the monoglycerides and the fatty acids, but shuttles back and forth between the gut contents and the microvilli.
275. Its binding changes both its own shape and that of the DNA, presenting a new surface that attracts the binding of other transcription factors. RNA polymerase II does not bind until several other proteins have already bound to this complex.
276. Most materials are digested and absorbed in the midgut. Specialized glands secrete some digestive enzymes into the intestine, and the gut wall itself secretes other digestive enzymes.
277. Phenotypic plasticity of leaf shapes benefits a tree because deeply lobed leaves offer less resistance to wind, absorb less sunlight, lose heat more rapidly by convection, and allow more sunlight to pass to lower leaves.

278. The phosphate functional group has a negative electric charge, so this portion of the molecule is hydrophilic, attracting polar water molecules. But the two fatty acids are hydrophobic, so they aggregate away from water.
279. "Like attracts like" is an old saying, and nowhere is it more true than in polar and nonpolar molecules, which tend to interact with their own kind.
280. First the root releases flavonoids and other chemical signals that attract the Rhizobium to the vicinity of the root.
281. Homeostasis depends on the ability to regulate the functions of the organs and organ systems to counteract influences that would change the physical or chemical composition of the internal environment.
282. Environmental factors, hormones, and photoreceptors regulate the first stages of plant growth.
283. The food of herbivores is often low in energy and hard to digest. Yet the koala's gut can digest and detoxify the leaves and absorb all the nutrients the animal needs from this highly specialized and formidable diet.
284. The courtship displays of a male, for example, benefit the male if they attract females, and they benefit the female if they allow her to assess whether the male is of the right species and whether he is strong, vigorous, and has other attributes that will make him a good father.
285. Saprobes (also called saprotrophs or decomposers) are mostly protists and fungi that absorb nutrients from dead organic matter. Detritivores, such as earthworms and crabs, actively feed on dead organic material.
286. The two morphogens regulate the expression of the gap genes, although in different ways.
287. The first, aequorin, absorbs light and transmits some of its excitation energy to a second protein, green fluorescent protein (GFP).
288. In sum, noncyclic electron flow uses a molecule of water, four photons (two each absorbed by photosystems I and II), one molecule each of NADP+ and ADP, and one Pi. From these ingredients it produces one molecule each of NADPH + H+ and ATP, and half a molecule of oxygen (1/2 O2).
289. Cytokines may also attract phagocytic cells to the site of injury and initiates a specific immune response to the pathogen.
290. A very good example of a long-term process regulated primarily by hormones is animal reproduction, the topic of the next chapter. Endocrine cells secrete chemical messages called hormones, which bind to receptors on or in target cells.
291. The phycobilins (phycocyanin and phycoerythrin), which are found in red algae and in cyanobacteria (contributing to their respective colors), absorb various yellow-green, yellow, and orange wavelengths. Such accessory pigments, in collaboration with the chlorophylls, constitute an energy-absorbing antenna system covering much of the visible spectrum.

292. The atmosphere regulates temperatures close to Earth's surface. Ozone (O3) in the stratosphere absorbs most incoming short-wavelength ultraviolet radiation, shielding organisms from its damaging effects.
293. The binding of the substrate to the active site depends on the same kinds of forces that maintain the tertiary structure of the enzyme: hydrogen bonds, the attraction and repulsion of electrically charged groups, and hydrophobic interactions (see Chapter 3).
294. However, when ions are dispersed in water, the distance between them can be large; the strength of their attraction is thus greatly reduced. Under the conditions that exist in the cell, an ionic attraction is less than one-tenth as strong as a covalent bond that shares electrons equally (see Table 2).
295. They reduced the UV reflectance of some males by applying to their blue patches a mixture of fat from the glands the birds use to oil their own feathers and UV- absorbing sunblock. Control males received the fat coating with no sunblock. Although the two groups of males looked the same to human observers, female bluethroats could distinguish them.
296. For example, if a pigment absorbs both blue and red light-as chlorophyll does-what we see is the remaining light-primarily green.
297. In addition, eukaryotic cells have "cells within cells"-interior compartments surrounded by membranes that regulate what enters or leaves that compartment. The membranes ensure that conditions inside the compartment are different from those in the surrounding cytoplasm.
298. Molecules that absorb visible or near ultraviolet light-called chromophores-are likely to have been components of the lipid membranes of some protobionts.
299. Abscisic acid also regulates gas and water vapor exchange between leaves and the atmosphere through its effects on the guard cells of the leaf stomata (see Chapter 35).
300. If leaves were thicker than they are, the outer layers of cells would absorb so much of the light that the interior layers would be too dark and would be unable to photosynthesize.
301. Ions form bonds by electrical attraction. When one interacting atom is much more electronegative than the other, a complete transfer of one or more electrons may take place.
302. Rhodopsin changes its conformation when it absorbs light.
303. The products of fat digestion are absorbed by intestinal mucosal cells, where they are resynthesized into triglycerides and exported to lymphatic vessels.
304. Our conclusion must be that the lizard can regulate its body temperature quite well by behavioral mechanisms rather than by internal metabolic mechanisms.

305. The mechanisms by which the cells lining the intestine absorb nutrient molecules and inorganic ions are diverse and not completely understood. Many inorganic ions are actively transported into the cells.
306. Thermostats regulate temperature. The thermostat that is part of the heating-cooling system of a house is a regulatory system.
307. Without water to act as a solvent for biochemicals, to receive wastes, to absorb heat, and to participate directly in chemical reactions, life would not exist as we know it. With strong recent evidence that there was once flowing water on Mars, and that Europa (one of Jupiter's moons) may have a thin crust of ice with liquid water below it, there is great excitement about the possibility of life on nearby extraterrestrial bodies.
308. The chromoplasts have no known chemical function in the cell, but the colors they give to some petals and fruits probably help attract animals that assist in pollination or seed dispersal.
309. Density-Dependent Factors Regulate Population Size. The densities of all populations fluctuate, but they tend to return to equilibrium value if either birth rate and or rate are density-dependent.
310. If leaves were thicker than they are, the outer layers of cells would absorb so much of the light that the interior layers would be too dark and would be unable to photosynthesize.
311. Sodium cotransport is a common mechanism for actively absorbing nutrient molecules and ions. Fats are absorbed mostly as monoglycerides and fatty acids, which are the product of lipase action on triglycerides in food.
312. As a result, bacteria using this pigment can grow in water beneath fairly dense layers of algae, using light of wavelengths that are not appreciably absorbed by the algae (Figure 26.8b). Photoheterotrophs use light as their source of energy, but must obtain their carbon atoms from organic compounds made by other organisms.
313. Like the genes of prokaryotes that code for proteins, eukaryotic genes are flanked by noncoding sequences that regulate their transcription. These include the promoter region, where RNA polymerase binds to begin transcription.
314. We have just seen that proteins regulate the movement of ions across membranes. We shall now see that even water movement itself is regulated by proteins.
315. How do eukaryotic cells coordinate the regulation of several genes whose transcription must be turned on at the same time? In prokaryotes, in which related genes are linked together in an operon, the mechanism is clear: A single regulatory system can regulate several adjacent genes. But in eukaryotes, the several genes whose regulation requires coordination may be on different chromosomes.

316. Development consists of growth, differentiation, and morphogenesis. In plants and animals alike, differentiation and morphogenesis result ultimately from the regulated activities of genes and their products, as well as the interplay of extracellular signals and their transduction in target cells.
317. The circulatory system is controlled and regulated by neural and hormonal mechanisms at both the local and systemic levels. Every tissue requires an adequate supply of blood that is saturated with oxygen, carries essential nutrients, and is relatively free of waste products.
318. The kidneys help regulate acid-base balance. Besides salt and water balance and nitrogen excretion, the kidneys have another important role in regulating the hydrogen ion concentration (the pH) of the blood.
319. The reaction center for photosystem I contains a chlorophyll a molecule in a form called P700 because it can best absorb light of wavelength 700 nm. The reaction center for photosystem II contains a chlorophyll a molecule in a form called P680 because it absorbs light maximally at 680 nm. The reaction center for photosystem II contains a chlorophyll a molecule in a form called P680 because it absorbs light maximally at 680 nm. Thus photosystem II requires photons that are somewhat more energetic.
320. These cells also produce the enzymes maltase, lactase, and sucrase, which cleave the common disaccharides into their constituent, absorbable monosaccharides-glucose, galactose, and fructose. Many humans stop producing the enzyme lactase around the age of 4 years and thereafter have difficulty digesting lactose, which is the sugar in milk.
321. When a molecule absorbs the energy of a photon, it is raised from a ground state to an excited state. In the excited state, one of the molecule's electrons is boosted to a higher orbital, where it is held less firmly by the molecule.
322. All animals that thermo regulate, both vertebrate and invertebrate, must have regulatory systems, but here we will focus on the vertebrate thermostat.
323. Some ectotherms produce heat. Honeybees regulate temperature as a group. They live in large colonies consisting mostly of female worker bees that maintain the hive and rear the offspring of the single queen bee.
324. Unlike charges (+/-) attract each other; like charges (+/+ or -/-) repel each other. The neutron, as its name suggests, is electrically neutral, so its charge is 0 unit.
325. Photosynthesis uses most of the visible spectrum because the participating pigments absorb photons most strongly at different wavelengths.
326. Fuel metabolism is controlled by hormones. During the absorptive period, blood glucose levels are high as carbohydrates are digested and absorbed . During this time, the liver takes up glucose from the blood and converts it to glycogen and fat, fat cells take up glucose from the blood and convert it to

stored fat, and the cells of the body preferentially use glucose as their metabolic fuel.

327. The selectively permeable plasma membranes of the cells control access to the symplast, so movement of water and dissolved substances into the symplast is tightly regulated. Water and minerals can pass from the soil solution through the apoplast as far as the endodermis, the innermost layer of the cortex.

328. Several lines of evidence, especially details of their structure and development, indicate that protective spines, tendrils, and brightly colored structures that attract pollinators (Figure 23.4) are all modified leaves; they are homologs of one another even though they do not resemble one another closely.

329. Set points and feedback information are required for regulation. You can regulate the speed of a car only if you know the speed at which you are traveling and the speed you wish to maintain.

330. The mechanism that senses room temperature provides negative feedback that is used to regulate both the air conditioner and the furnace. Negative feedback is a stabilizing influence in physiological regulatory systems.

331. A substantial fraction of the light energy absorbed in noncyclic electron flow is lost as heat, but another significant fraction is trapped in ATP and NADPH + H+.

332. Food provides carbon skeletons for biosynthesis. Humans obtain amino acids by breaking down proteins from food and absorbing the resulting amino acids. Another source of amino acids is the breakdown of existing body proteins, which are in constant turnover as the tissues of the body undergo normal remodeling and renewal.

333. The corolla and calyx, which can be quite showy, often play roles in attracting animal pollinators to the flower. The calyx more commonly protects the immature flower in bud.

334. Noncyclic electron flow produces ATP and NADPH. These molecules are associated with two different photosystems, each of which consists of many chlorophyll molecules and accessory pigments in separate energy- absorbing antennas (Figure 8.12): •Photosystem I uses light energy to reduce NADP+ to NADPH + H+. •Photosystem II uses light energy to oxidize water molecules, producing electrons, protons (H+), and O2.

335. Tubular guts have an opening at each end. A mouth takes in food; molecules are digested and absorbed throughout the length of the gut; and solid digestive wastes are excreted through an anus. Different regions in the tubular gut are specialized for particular functions (Figure 50).

336. The vertebrate retina receives and processes visual information. A curious feature of the anatomy of the retina is that the light-absorbing outer segments of the photoreceptor cells are all the way at the back of the retina. Light must

pass through all the layers of retinal cells before reaching the place where photons are captured by rhodopsin.

337. The lizard's body temperature is dependent on environmental heat, but it can regulate its temperature by moving between different environments.

338. How do eukaryotic cells coordinate the regulation of several genes whose transcription must be turned on at the same time? In prokaryotes, in which related genes are linked together in an operon, the mechanism is clear: A single regulatory system can regulate several adjacent genes.

339. This part of the viral genome contains the promoter sequence that attracts host RNA polymerase. The early genes often include proteins that shut down host transcription, stimulate viral genome replication, and stimulate late gene transcription.

340. The form that absorbs principally red light is called Pr. Upon absorption of a photon of red light, a molecule of Pr is converted into Pfr.

341. The jasmonates, in turn, trigger the formation of the volatile compounds that attract the "helper" insects. In some cases, splicing in a gene may confer insect resistance Wild and domesticated common beans (Phaseolus vulgaris) differ in their resistance to attack by two species of bean weevils.

342. An important way to regulate the action of a protein in a cell is to regulate its lifetime in the cell.

343. Weight is the measure of the Earth's gravitational attraction for mass; on another planet, the same quantity of mass would have a different weight. On Earth, however, the term "weight" is often used as a measure of mass, and in biology one encounters the terms "weight" and "atomic weight" more frequently than "mass" and "atomic mass"; therefore, we will use "weight" for the remainder of this book.

344. Solar energy inputs drive global climates. In addition, when the sun is low in the sky, sunlight must pass through more of Earth's atmosphere, with the result that more of its energy is absorbed and reflected before it reaches the ground. At high latitudes (closer to the poles), there is more variation in both day length and the angle of arriving solar energy over the course of a year than at latitudes closer to the equator.

345. Even animals that osmoconform over a wide range of environmental osmolarities must osmoregulate in extreme environments. An excellent example is the brine shrimp Artemia (Figure 51.1a), which lives in environments of almost any salinity.

346. However, all photosynthetic organisms possess accessory pigments, which absorb photons intermediate in energy between the red and the blue wavelengths, then transfer a portion of that energy to the chlorophylls.

347. Some hyphae grow into the living plant cells, absorbing the nutrients within the cells. Eventually fruiting bodies form, either within the plant body or on its surface.
348. Finally, we present the mechanisms that control and regulate salt and water balance in mammals, giving the vampire bat and other species their remarkable abilities to exploit unusual diets and extreme environments.
349. These include: The binding of oxygen to hemoglobin, which shows a sigmoid relationship and cooperativity, The binding of a hormone to its cellular receptor protein, which causes the protein to change shape and provides the signal to initiate reactions within the cell (Chapter 15) The binding of an inducer to a protein that regulates DNA expression (Chapter 12).
350. Other scientists-such as those working in agriculture, conservation, or medicine-wish to manage species to raise (in the case of crop plants, aesthetically attractive species, or threatened or endangered species) or lower (in the case of agricultural pests and disease organisms) their densities.
351. Ionic bonds are bonds formed by electrical attractions between ions bearing opposite charges. In sodium chloride-familiar to us as table salt-cations and anions are held together by ionic bonds.
352. Leaf fall (abscission) is regulated by an interplay of the hormones ethylene and auxin. Finally, the entire plant senesces and dies.
353. Chordin and sog are among the many genes that appear to regulate similar functions in very different organisms. There are several almost universal animal genes that help transform a single-celled egg into a multicellular adult.
354. Some plants produce chemical defenses or attractants Plants attract, resist, and inhibit other organisms often by producing special chemicals known as secondary products.
355. Hydrogen bonds may form between molecules. (Remember, negative charges attract positive charges.) The bond resulting from this attraction is called a hydrogen bond. Hydrogen bonds are not restricted to water molecules.
356. In fishes, such as salmon, that migrate between salt water and fresh water to breed, prolactin regulates the mechanisms that maintain osmotic balance with the changing environment. In all of these cases prolactin is involved in reproductive processes, but as those processes have changed through evolution, so has the information signaled by the hormone.
357. Allosteric effects regulate metabolism. Metabolic pathways typically involve a starting material, various intermediates, and a product, which is used for some purpose by the cell.
358. Ionic bonds are electrical attractions between oppositely charged ions. Ionic bonds are strong in solids, but weaker when the ions are separated from one another in solution.

359. Like the genes of prokaryotes that code for proteins, eukaryotic genes are flanked by noncoding sequences that regulate their transcription.
360. Mycorrhizae, associations of fungi with plant roots, enhance the ability of the roots to absorb water and nutrients. Lichens, mutualistic combinations of a fungus with a cyanobacterium or a green alga, are found in some of the most inhospitable environments on the planet.
361. Because opposite charges attract, the DNA moves toward the positive end of the field. Since the porous gel acts as a sieve, the smaller molecules move faster than the larger ones.
362. If the hypothalamus of a mammal's brain is damaged, the animal loses its ability to regulate its body temperature, which then rises in warm environments and falls in cold ones.
363. Vitamin D regulates the absorption of calcium from the intestines. It is necessary for the proper deposition of calcium in bones; a deficiency of vitamin D can lead to rickets, a bone-softening disease.
364. Phytochromes help to regulate a seedling's early growth.
365. Some of them absorbed their food directly from the environment. Others were photosynthetic. Still others fed on smaller prokaryotes by engulfing them.
366. In damaged or infected tissue, complement proteins and other chemical signals attract phagocytes-neutrophils first, and then monocytes, which become macrophages. The macrophages engulf the invaders and debris, and are responsible for most of the healing associated with inflammation.
367. Gibberellins and other hormones regulate the growth of fruits. It has long been known that seedless grapes (an inbred strain) form smaller fruit than their seeded relatives.
368. The cells that erode or reabsorb bone are the osteoclasts. They are derived from the same cell lineage that produces the white blood cells.
369. They also use song to attract females, which suggests that the females know the song of their species even if they do not sing.
370. The three kinds of cone cells contain slightly different opsin molecules, which absorb different wavelengths of light.
371. The difference in energy between the excited state and the ground state is precisely equal to the energy of the absorbed photon. The increase in energy boosts one of the electrons in the molecule into an orbital farther from the nucleus; this electron is now held less firmly by the molecule (Figure 8).
372. A similar antagonistic relationship is true of hormones of the pancreas, which regulate blood glucose levels.
373. The leaf then absorbs the products of digestion, especially amino acids, and uses them as a nutritional supplement.

374. In bright sunlight, red wavelengths are absorbed by a receptor protein called phytochrome. We will say more about this important receptor later in the book, but for now it is important to note that it is activated by red light.
375. Sperm of one species may not be attracted to the eggs of another species because the eggs do not release the appropriate attractive chemicals, or the sperm may be unable to penetrate the egg because it is chemically incompatible.
376. Complement proteins activate the inflammatory response and attract phagocytes to sites of infection. Complement proteins, acting with antibodies, lyse (burst) invading cells such as bacteria.
377. Digestion involves the breakdown of complex food molecules into monomers that can be absorbed and utilized by cells. In most animals, digestion is extracellular and external to the body, taking place in a tubular gut that has different regions specialized for different digestive functions.
378. To avoid loss of homeostasis, the activities of organs must be controlled and regulated in response to changes in both the external and the internal environments. Control and regulation require information; hence the organ systems of information-the endocrine and nervous systems-must be included in our discussions of every physiological function.
379. Naturally occurring inhibitors regulate metabolism; artificial ones can be used to treat disease, to kill pests, or in the laboratory to study how enzymes work.
380. Blood pressure and osmotic attraction (both expressed as millimeters of mercury, mm HG) control the exchange of fluids between blood vessels and intercellular space.
381. Metabolic pathways in organisms are regulated by the activities of a few enzymes.
382. Cryptochromes are yellow photoreceptor pigments that absorb blue and ultraviolet light. They affect some of the same developmental processes, including seedling development and flowering, as do phytochromes.

383. The development of a plant-the series of progressive changes that take place throughout its life-is regulated in complex ways. Four factors take part in this regulation: The plant senses and responds to environmental cues.
384. Gene expression can be regulated at three levels: at transcription, at translation, or after translation.
385. The attractive force that an atom exerts on electrons is its electronegativity. It depends on how many positive charges a nucleus has (nuclei with more protons are more positive and thus more attractive to electrons) and how far away the electrons are from the nucleus (closer means more electronegativity).
386. Blood pressure and osmolarity are regulated by ADH. When you lose blood volume, your blood pressure tends to fall. Besides activating the kidney

autoregulatory mechanisms described in the previous section, a drop in blood pressure decreases the activity of the stretch sensors in the walls of the aorta and the carotid arteries (see Chapter 49).

387. The underground portion could anchor the plant firmly, and even in this primitive condition it could absorb water and minerals. The subsequent discovery of fossil plants from the Devonian period, all having horizontal stems (rhizomes) with both underground and aerial branches, supported Lignier's hypothesis.

388. Variation in skills, competitive abilities, and attractiveness to potential mates is often associated with these size differences. An almost universal cost associated with group living is higher exposure to diseases and parasites.

389. Testosterone and the estrogens are steroid hormones that regulate sexual development in vertebrates.

390. Negative feedback loops help to regulate testis functions. The Leydig cells are stimulated by LH to produce testosterone. The rise in the level of testosterone in the prepubertal male causes the development of secondary sexual characteristics and the pubertal growth spurt, promotes increased muscle mass, and stimulates growth and maturation of the testes.

391. Eventually clouds of matter collapsed through gravitational attraction, forming the galaxies-great clusters of hundreds of billions of stars. Somewhat less than 5 billion years ago, toward the outer edge of our galaxy (the Milky Way), our solar system (the Sun, Earth, and our sister planets) took form.

392. Photosensitivity depends on the capture of photons of light by rhodopsin, a photoreceptor molecule that consists of a protein called opsin and a light-absorbing prosthetic group called retinal. Absorption of light by retinal is the first step in a cascade of intracellular events leading to a change in the receptor potential of the photoreceptor cell.

393. There are many other chlorophyll a molecules in the antenna, but all of them absorb light at shorter wavelengths than does the molecule in the reaction center.

394. Plants produce molecules such as sugars that attract pathogens. But the presence of a pathogen stimulates the plant to produce defensive molecules that can work in many different ways.

395. In order to sense environmental cues, the plant uses receptors, such as photoreceptors that absorb light. Chemical messages, or hormones, mediate the effects of the environmental cues sensed by the receptors.

396. Three classes of segmentation genesact, one after the other, to regulate finer and finer details of the segmentation pattern.

397. The carotenoids are a family of light- absorbing pigments found in plants and animals. Beta-carotene ((-carotene) is one of the pigments that traps light energy in leaves during photosynthesis.

398. All of these etiolation phenomena (lack of chlorophyll, rapid shoot elongation, production of an apical hook, delayed leaf expansion) are regulated by the phytochromes. In a seedling that has never been exposed to light, all the phytochrome is in the red-absorbing (Pr) form.
399. In liquid water, the negatively charged oxygen ((-) atom of one water molecule is attracted to the positively charged hydrogen ((+) atoms of another water molecule. (Remember, negative charges attract positive charges.
400. Multiple feedback loops regulate the chain of command from hypothalamus to anterior pituitary to endocrine glands.
401. The mechanisms by which the cells lining the intestine absorb nutrient molecules and inorganic ions are diverse and not completely understood.
402. During winter, honeybee workers combine their individual heat-producing abilities to regulate the temperature of the brood. They cluster around the brood and adjust their joint metabolic heat production and density of clustering so that the brood temperature remains remarkably constant, at about 34°C, even as the outside air temperature drops below freezing.
403. Parasitic species that absorb digested food from their hosts do not have a digestive tract. The flatworms probably most similar to the ancestral forms are the turbellarians (class Turbellaria), which are small, free-living marine and freshwater animals (a few live in moist terrestrial habitats).
404. Water and ions are absorbed in the large intestine. Peristalsis gradually pushes the contents of the small intestine into the large intestine, or colon.
405. Ectotherms and endotherms use behavior to regulate body temperature. As its skin absorbs solar radiation, its body temperature rises considerably above the air temperature. By altering its exposure to the sun, the lizard maintains its body temperature around 35°C all morning.
406. Both marine and terrestrial vertebrates must conserve water. Marine bony fishes cannot produce urine more concentrated than their tissue fluid, but unlike most marine animals, they osmoregulate their tissue fluid to only one-fourth to one-third the solute potential of seawater. They prevent excessive loss of water by producing very little urine.
407. Each positively charged nucleus exerts some attraction on the other atom's unpaired electron, but this attraction is balanced by each electron's attraction to its own nucleus. So the two unpaired electrons become shared by both atoms, filling the outer shells of both of them.
408. The composition of tissue fluids can be regulated. Osmoconformers can be ionic conformers, allowing the ionic composition, as well as the osmolarity, of their tissue fluids to match that of the environment.
409. Europeans traditionally used pigs to find truffles because some truffles secrete a substance that has an odor similar to a pig's sex attractant. Unfortunately, pigs also eat truffles, so dogs are now the usual truffle hunters.

Penicillium is a genus of green molds, of which some species produce the antibiotic penicillin, presumably for defense against competing bacteria.

410. The translation of mRNA into protein can also be regulated. Finally, once the protein itself is made, its structure can be modified, or it can be broken down and destroyed.

411. A given type of molecule can absorb radiant energy of only certain wavelengths. If we plot a compound's absorption of light as a function of the wavelengths of the light, the result is an absorption spectrum (Figure 8).

412. However, males with artificially elongated tails attracted about four times more females than males with shortened tails (Figure 53.3). Why do females prefer males with long tails? Probably because the ability to grow and maintain a long tail, which probably carries energetic costs, indicates that the male is vigorous and healthy.

413. However, all photosynthetic organisms possess accessory pigments, which absorb photons intermediate in energy between the red and the blue wavelengths, then transfer a portion of that energy to the chlorophylls.

414. A DNA sequence can move to a new location to activate transcription. In some instances, gene expression is regulated by the movement of a gene to a new location on the chromosome. An example of this mechanism is found in the yeast Saccharomyces cerevisiae.

415. Most animals avoid these problems by digesting food proteins extracellularly and then absorbing the resulting amino acids into the body, where they synthesize new proteins that will function correctly and be recognized as "self" by the immune system.

416. The simplest liverwort gametophytes, however, are flat plates of cells, a centimeter or so long, that produce antheridia or archegonia on their upper surfaces and water- absorbing filaments called rhizoids on the lower. Liverwort sporophytes are shorter than those of mosses and hornworts, rarely exceeding a few millimeters.

417. A given type of molecule can absorb radiant energy of only certain wavelengths.

418. Companion cells retain all their organelles and may, through the activities of their nuclei, regulate the performance of the sieve tube members.

419. Nonhalophytes accumulate relatively little sodium, even when placed in a saline environment; of the sodium that is absorbed by their roots, very little is transported to the shoot. In halophytes, the increased salt concentration makes their water potential more negative, so they can take up water from the saline environment.

420. Successful competitors for resources may gain exclusive access to mates that are attracted to the resources they control. Traits that improve success in

courtship may evolve as a result of mating preferences by individuals of the opposite sex.

421. Rotifers are small but structurally complex. When rain falls, they absorb water and become motile, feeding in the films of water that temporarily cover the plants. Most rotifers live no longer than 1 or 2 weeks.

422. There are mechanisms to alter the rate at which some enzymes catalyze reactions, making enzymes the target points at which entire sequences of chemical reactions can be regulated. Finally, we examine how the environment-namely, temperature and pH-affects enzyme activity.

423. Unassisted, the root hairs of such plants do not absorb enough water or minerals to sustain maximum growth. However, the roots usually become infected with fungi, forming an association called a mycorrhiza (Figure 30).

424. Homeostasis depends on the ability to control and regulate the functions of organs and organ systems. Cells that have a similar structure and function make up a tissue.

425. It may become possible to regulate plasmodesmata in crop plants. Epidermal cells protect against excess water loss.

426. Since most normal cells do not have this ability, telomerase is an attractive target for drugs designed to attack tumors specifically. There is also interest in telomerase and aging.

427. The existence and heritability of mutations in bacteria attracted the attention of geneticists to these microbes. But if there were no form of exchange of genetic information between individuals, bacteria would not be useful for genetic analysis.

428. The eukaryotic genome is larger and more complex than the prokaryotic genome. It takes a million to make several thousand different proteins and regulate their synthesis. Humans have considerably more genes and regulators: nearly 6 billion bp (2 meters of DNA) are crammed into each human cell.

429. Deficiency diseases can also result from an inability to absorb or process an essential nutrient even if it is present in the diet. Vitamin B12 (cobalamin), for example, is present in all foods of animal origin.

430. The excitation passes from one pigment molecule in the antenna to another, moving from pigments that absorb shorter wavelengths (higher energies) to pigments that absorb longer wavelengths (lower energies) of light.

431. Electrons from the oxidation of water are passed to P680+, reducing it once again to P680, which can absorb more photons. The electron from photosystem II passes through a series of exergonic reactions in the redox chain, which are coupled to proton pumping.

432. Light (an environmental cue) acts directly on photoreceptors, which in turn regulate processes such as the many changes accompanying the growth of a young plant out of the soil and into the light.

433. Water and ions pass to the xylem by way of the apoplast and symplast. Movement of materials through the apoplast is thus unregulated. The remainder of the plant body is the symplast (from the Greek for "together with living material").
434. Ground tissue functions primarily in storage, support, photosynthesis, and the production of defensive and attractive substances. In the discussions that follow, we'll examine how the tissue systems are organized in the different organs of a flowering plant.
435. The Origin of Life on Earth began 520 billion years ago by gravitational attraction of rocks of various sizes. As Earth grew by this process, the weight of the outer layers compressed the interior of the planet.
436. The stability of mRNA in the cytoplasm can be regulated by the binding of proteins. Translational repressors can inhibit the translation of mRNA.
437. One nucleus may exert a greater attractive force on the electron pair than the other nucleus, and so the pair tends to be closer to that atom.
438. The growing fungus absorbs organic and inorganic nutrients from the ant's body, eventually killing it, after which the fruiting body produces a new crop of spores.
439. Molecules that absorb wavelengths in the visible region of the spectrum are called pigments.
440. Lactose is a disaccharide and cannot be absorbed without being cleaved into its constituent units, glucose and galactose. If a substantial amount of lactose remains unabsorbed and passes into the large intestine, its metabolism by bacteria in the large intestine causes abdominal cramps, gas, and diarrhea.
441. Photosynthesis uses chlorophylls and accessory pigments, which absorb photons in the blue and blue-green wavelengths and appear deep yellow. The phycobilins (phycocyanin and phycoerythrin), which are found in red algae and in cyanobacteria (contributing to their respective colors), absorb various yellow-green, yellow, and orange wavelengths.
442. The requirement for these proteins affords a way to regulate the transcription of particular genes.
443. To osmoregulate in fresh water, animals must excrete water and conserve solutes; hence they produce large amounts of dilute urine.
444. Insulin and glucagon regulate blood glucose. After a meal, the concentration of glucose in the blood rises as glucose is absorbed from the food in the gut. This increase stimulates the pancreas to release insulin. Insulin stimulates cells to use glucose as fuel and to convert it into storage products such as glycogen and fat.
445. Bacteriochlorophyll absorbs light of longer wavelengths than the chlorophyll used by all other photosynthesizing organisms does.

446. The jasmonates, in turn, trigger the formation of the volatile compounds that attract the "helper" insects.
447. The five amino acids that have electrically charged side chains attract water and oppositely charged ions of all sorts.
448. The final digestion of proteins and carbohydrates that produces these absorbable products takes place among the microvilli. The mucosal cells with microvilli produce peptidases, which cleave larger peptides into tripeptides, dipeptides, and individual amino acids that the cells can absorb.
449. A chemical bond is an attractive force that links two atoms to form a molecule. There are several kinds of chemical bonds.
450. Na+ ions would diffuse into the cell because of their higher concentration on the outside, and they would also be attracted into the cell by the negative membrane potential. As a result of the entry of Na+ ions, the inside of the cell would tend to become less negative.
451. Then we learn how the body regulates its traffic in metabolic fuels, and return to the quandaries we have just posed about the regulation of food intake and body mass .
452. Hydrogen bonds are weak electrical attractions that form between a (+ hydrogen atom in one molecule and a (- nitrogen or oxygen atom in another molecule or in another part of a large molecule.
453. Nonpolar molecules are attracted to each other by very weak bonds called van der Waals forces. In chemical reactions, substances change their atomic compositions and properties.
454. Arthropods use chemical signals to attract mates. These signals, called pheromones, demonstrate the sensitivity of chemosensory systems.
455. The nutritious pulp of fruits are attractive to many birds, such as this cedar waxwing.
456. Through its effects on stomatal opening, it also regulates gas and water exchange between leaves and the atmosphere. Oligosaccharins are hormones released by the cell wall in response to an attack by a pathogen.
457. The filamentous hyphae give fungi a large surface area-to-volume ratio, enhancing their ability to absorb nutrients. The hyphae usually have incomplete partitions (septa) that do not divide them into separate cells.
458. Should a fish in the deep ocean, where the temperature changes very little, be called a homeotherm? Should a hibernating mammal that allows its body temperature to drop to nearly the temperature of its environment be called a poikilotherm? The problem posed by the hibernator has been solved by creating a third category: the heterotherm, an animal that regulates its body temperature at a constant level some of the time. Another set of terms classifies animals on the basis of the sources of heat that determine their body temperatures.

459. Only the smallest products of digestion can be absorbed through the mucosa of the small intestine and passed on to the blood and lymphatic vessels that lie in the submucosa.
460. When food is being absorbed from the gut, the liver takes up and stores fats and carbohydrates, converting monosaccharides to glycogen or fat.
461. Most of the chapter is devoted to how food is digested and absorbed. Then we learn how the body regulates its traffic in metabolic fuels, and return to the quandaries we have just posed about the regulation of food intake and body mass .
462. Townsend's males are more aggressive than hermit males toward stuffed males of the other species placed in their territories, and they are better at attracting mates than hermit warbler males.
463. Photosensitivity depends on the ability of rhodopsins to absorb photons of light and to undergo a change in conformation.
464. The light energy absorbed by the antenna system is transferred from one pigment molecule to another as an electron. When this happens, the second molecule is reduced by the first.
465. Initiation of transcription requires a promoter and an RNA polymerase. The requirement for these proteins affords a way to regulate the transcription of particular genes.

APPENDIX B

PILOT DESIGN STUDY SCRIPT

Design Experiment Instructions

Pilot Study

Background:

- The experiment must be conducted in an uninterrupted two hour period
- There is one problem in the experiment:
    - The geoengineering (managing incoming sunlight) problem
- The participants will be given two hours to work on this problem
- The participants must be split into three groups
    - All students will be working silently and alone, but there are three different packets per experiment

Instructions:

1. Briefly explain that the students are participating in a design research experiment.
2. Next, hand out the packets – MAKE SURE YOU GIVE AN EQUAL NUMBER OF EACH TYPE OF PACKET. Tell them to keep the packets closed until instructed.
    i. It might help if you divide the students into three groups, or stack the packets so that the three categories are alternating (primary, spatial, and control). These are the three categories. It is very important that they be distributed equally.
3. Ask the students to read the Scenario and Design Problem.
4. Next, ask them if they have any questions.
    i. Most will probably ask for clarification; just tell them that they should read the sentences and formulate an idea to solve the design problem based on these passages.
5. After all questions are answered, remind them again that they will have two hours, and let them open their packets and start.
6. At the end of the hour, collect the packets.
7. At the end of the two hours, collect the packets and hand out the feedback form.
    i. Tell them they can leave when they have completed this form
8. Collect the feedback forms as students leave and thank them for participating.

APPENDIX C

PILOT DESIGN STUDY SAMPLE PACKET: CONTROL

Bioinspired Design Experiment

Scenario:

You are an entry-level engineer at a large consulting firm, and you have been asked to solve an engineering problem using nature. Your manager has given you one hour to read fifty passages from a biology textbook and come up with solutions based on what you read. To test your creativity, and thus job performance, he has forbidden the use of reference texts to help translate any unfamiliar scientific terms. Your manager would like to see complete, good solutions to the design problem for each passage.

Design Problem:

Your task is to design a way to prevent incoming sunlight from warming the earth.

- Use the text passages to formulate your ideas
- Write your ideas clearly below each passage
- Your idea must address the incoming sunlight

1. Chemical reactions do not create or destroy energy, but changes in energy usually accompany chemical reactions.
2. An exoskeleton, or cuticle, covers all the outer surfaces of the arthropod's body and all its appendages.
3. The podocytes wrap around the capillaries so that their fingerlike projections interdigitate and cover the capillaries completely.
4. Their mechanisms of action take advantage of the roles of estrogens and progesterone as negative feedback signals that work on both the hypothalamus and the pituitary to inhibit gonadotropin release.
5. Because these spermicides inhibit dynein, the sperm cannot swim toward the egg, and fertilization cannot occur.
6. The body wall surrounding each segment has two muscle layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise
7. In the human genome, some genes act as oncogenes, which act as the "gas pedal" to stimulate cell division, and some as tumor suppressor genes, which "put the brake on" to inhibit it.
8. An extremely hard material called enamel, composed principally of calcium phosphate, covers the crown of the tooth.
9. Such accessory pigments, in collaboration with the chlorophylls, constitute an energy-absorbing antenna system covering much of the visible spectrum.
10. The virion, the basic unit of a virus, consists of a central core of either DNA or RNA (but not both) surrounded by a capsid, or coat, composed of one or more proteins.
11. As a tree grows in diameter, the xylem toward the center becomes clogged with water-insoluble substances and ceases to conduct water and minerals; this is heartwood and appears darker in color.
12. When stretched, these receptors send impulses to the medulla that inhibit the inhalation neurons.
13. A sheet of gray matter called the cerebral cortex covers each cerebral hemisphere.
14. A lipoprotein is a particle made up of a core of fat and cholesterol and a covering of protein that makes it water-soluble.
15. Because this initial CO2 fixation step can function even at low levels of CO2 and high temperatures, C4 plants very effectively optimize photosynthesis under conditions that inhibit the photosynthesis of C3 plants.
16. The key to the medical use of antibiotics is specificity: An antibiotic must work to destroy the microbial invader, but not harm the human host.
17. Some agricultural insecticides, such as malathion, also inhibit acetylcholinesterase and can poison farm workers if used without safety precautions.

18. Because their antimicrobial activity is nonspecific, phytoalexins can destroy many species of fungi and bacteria in addition to the one that originally triggered their production.
19. The effector cells destroy the invaders at hand and then die, but one or more clones of memory cells have now been added to the immune system and provide immunological memory.
20. These enzymes destroy some of the invading cells, and in some cases the breakdown products of the pathogen's cell walls serve as chemical signals that trigger further defensive responses.
21. By binding to receptors in the plasma membranes of their target cells, interferons inhibit viral replication.
22. Following binding, the membrane that surrounds the HIV core particle fuses with the host cell plasma membrane, resulting in the entry of the core into the cytoplasm.
23. Nucleosomes inhibit both the initiation and elongation of transcription.
24. Today water covers three-fourths of Earth's surface, and the bodies of all active organisms contain between 45 and 95 percent water.
25. Then he placed pieces of the gelatin block on decapitated coleoptiles-positioned to cover only one side, just as coleoptile tips had been placed in earlier experiments.
26. Another way in which antibiotics work is to inhibit bacterial protein synthesis.
27. Tight junctions seal tissues and prevent leaks.
28. Human lungs are suspended in the thoracic cavity, which is bounded on the top by the shoulder girdle, on the sides by the rib cage, and on the bottom by a domed sheet of muscle, the diaphragm.
29. The amnion will grow to surround the developing embryo as a sac filled with amniotic fluid.
30. Before the bacteroids can begin to fix nitrogen, the plant must produce the protein leghemoglobin, which surrounds the bacteroids.
31. In the majority of plant cells, the plasma membrane is covered with a thick cell wall, and this, too, has adhesion proteins that allow cells to bind to one another.
32. The maternal effect genes are transcribed in the nurse cells, which surround and nurture the developing egg and are localized at certain specific regions of the egg as it forms.
33. In addition, cytokinins aid germination, inhibit stem elongation, stimulate lateral bud growth, and delay leaf senescence.
34. Alternatively, the oviducts may be burned (cauterized) to seal them off, using a surgical technique called endoscopy.
35. Some are just particles of proteins surrounding a nucleic acid core.
36. A common one is the production of antifreeze proteins that inhibit the growth of ice crystals.

37. Recall that prokaryotic cells are surrounded by a plasma membrane that regulates molecular traffic into and out of the cell.
38. Silver salts inhibit ethylene action, probably by interacting directly with the ethylene receptor, and thus delay senescence-enabling florists to keep their wares salable longer.
39. Lipids interact to form huge macromolecular aggregates, such as the membranes that surround cells.
40. A few trypsinogen molecules spontaneously converting to trypsin can initiate a chain reaction of enzyme activation that digests the pancreas in a very short period of time, destroying both its endocrine and exocrine functions.
41. The efferent arteriole gives rise to the second set of capillaries, the peritubular capillaries, which surround the tubule component of the nephron.
42. The eardrum, or tympanic membrane, covers the end of the auditory canal.
43. Red blood cells are normally suspended in a fluid called plasma, which contains salts, proteins, and other solutes.
44. The inner borders of the retinula cells are covered with microvilli that contain rhodopsin and thus trap light.
45. There are many treatments under development, including: vaccines to inhibit virus entry into cells and to form immune complexes with circulating viruses.
46. Such interaction results when table salt, or any other ionic solid, dissolves in water: "shells" of water molecules surround the individual ions, separating them.
47. These specialized structures, called cell junctions, are most evident in electron micrographs of epithelial tissues, which are layers of cells that line body cavities or cover body surfaces.
48. Surrounding the medulla (as an apricot surrounds its pit) is the adrenal cortex, which produces other hormones.
49. A platelet is just a tiny fragment of a cell, but it is packed with enzymes and chemicals necessary for its function: sealing leaks in blood vessels and initiating blood clotting.
50. When they reproduce, viruses usually destroy the host cell, releasing progeny viruses that then seek new hosts.

APPENDIX D

PILOT DESIGN STUDY SAMPLE PACKET: PRIMARY

Bioinspired Design Experiment

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20. These enzymes destroy some of the invading cells, and in some cases the breakdown products of the pathogen's cell walls serve as chemical signals that trigger further defensive responses.
21. By binding to receptors in the plasma membranes of their target cells, interferons inhibit viral replication.
22. Following binding, the membrane that surrounds the HIV core particle fuses with the host cell plasma membrane, resulting in the entry of the core into the cytoplasm.
23. Nucleosomes inhibit both the initiation and elongation of transcription.
24. Today water covers three-fourths of Earth's surface, and the bodies of all active organisms contain between 45 and 95 percent water.
25. Then he placed pieces of the gelatin block on decapitated coleoptiles-positioned to cover only one side, just as coleoptile tips had been placed in earlier experiments.
26. Another way in which antibiotics work is to inhibit bacterial protein synthesis.
27. Tight junctions seal tissues and prevent leaks.
28. Human lungs are suspended in the thoracic cavity, which is bounded on the top by the shoulder girdle, on the sides by the rib cage, and on the bottom by a domed sheet of muscle, the diaphragm.
29. The amnion will grow to surround the developing embryo as a sac filled with amniotic fluid.
30. Before the bacteroids can begin to fix nitrogen, the plant must produce the protein leghemoglobin, which surrounds the bacteroids.
31. In the majority of plant cells, the plasma membrane is covered with a thick cell wall, and this, too, has adhesion proteins that allow cells to bind to one another.
32. The maternal effect genes are transcribed in the nurse cells, which surround and nurture the developing egg and are localized at certain specific regions of the egg as it forms.
33. In addition, cytokinins aid germination, inhibit stem elongation, stimulate lateral bud growth, and delay leaf senescence.
34. Alternatively, the oviducts may be burned (cauterized) to seal them off, using a surgical technique called endoscopy.
35. Some are just particles of proteins surrounding a nucleic acid core.
36. A common one is the production of antifreeze proteins that inhibit the growth of ice crystals.

37. Recall that prokaryotic cells are surrounded by a plasma membrane that regulates molecular traffic into and out of the cell.
38. Silver salts inhibit ethylene action, probably by interacting directly with the ethylene receptor, and thus delay senescence-enabling florists to keep their wares salable longer.
39. Lipids interact to form huge macromolecular aggregates, such as the membranes that surround cells.
40. A few trypsinogen molecules spontaneously converting to trypsin can initiate a chain reaction of enzyme activation that digests the pancreas in a very short period of time, destroying both its endocrine and exocrine functions.
41. The efferent arteriole gives rise to the second set of capillaries, the peritubular capillaries, which surround the tubule component of the nephron.
42. The eardrum, or tympanic membrane, covers the end of the auditory canal.
43. Red blood cells are normally suspended in a fluid called plasma, which contains salts, proteins, and other solutes.
44. The inner borders of the retinula cells are covered with microvilli that contain rhodopsin and thus trap light.
45. There are many treatments under development, including: vaccines to inhibit virus entry into cells and to form immune complexes with circulating viruses.
46. Such interaction results when table salt, or any other ionic solid, dissolves in water: "shells" of water molecules surround the individual ions, separating them.
47. These specialized structures, called cell junctions, are most evident in electron micrographs of epithelial tissues, which are layers of cells that line body cavities or cover body surfaces.
48. Surrounding the medulla (as an apricot surrounds its pit) is the adrenal cortex, which produces other hormones.
49. A platelet is just a tiny fragment of a cell, but it is packed with enzymes and chemicals necessary for its function: sealing leaks in blood vessels and initiating blood clotting.
50. When they reproduce, viruses usually destroy the host cell, releasing progeny viruses that then seek new hosts.

APPENDIX E

PILOT DESIGN STUDY SAMPLE PACKET: SPATIAL

Bioinspired Design Experiment

Scenario:

You are an entry-level engineer at a large consulting firm, and you have been asked to solve an engineering problem using nature. Your manager has given you one hour to read fifty passages from a biology textbook and come up with solutions based on what you read. To test your creativity, and thus job performance, he has forbidden the use of reference texts to help translate any unfamiliar scientific terms. Your manager would like to see complete, good solutions to the design problem for each passage.

Design Problem:

Your task is to design a way to prevent incoming sunlight from warming the earth.

- Use the text passages to formulate your ideas
- Write your ideas clearly below each passage
- Your idea must address the incoming sunlight

1. Chemical reactions do not create or destroy energy, but changes in energy usually accompany chemical reactions.
2. An exoskeleton, or cuticle, covers all the outer surfaces of the arthropod's body and all its appendages.
3. The podocytes wrap around the capillaries so that their fingerlike projections interdigitate and cover the capillaries completely.
4. Their mechanisms of action take advantage of the roles of estrogens and progesterone as negative feedback signals that work on both the hypothalamus and the pituitary to inhibit gonadotropin release.
5. Because these spermicides inhibit dynein, the sperm cannot swim toward the egg, and fertilization cannot occur.
6. The body wall surrounding each segment has two muscle layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise
7. In the human genome, some genes act as oncogenes, which act as the "gas pedal" to stimulate cell division, and some as tumor suppressor genes, which "put the brake on" to inhibit it.
8. An extremely hard material called enamel, composed principally of calcium phosphate, covers the crown of the tooth.
9. Such accessory pigments, in collaboration with the chlorophylls, constitute an energy-absorbing antenna system covering much of the visible spectrum.
10. The virion, the basic unit of a virus, consists of a central core of either DNA or RNA (but not both) surrounded by a capsid, or coat, composed of one or more proteins.
11. As a tree grows in diameter, the xylem toward the center becomes clogged with water-insoluble substances and ceases to conduct water and minerals; this is heartwood and appears darker in color.
12. When stretched, these receptors send impulses to the medulla that inhibit the inhalation neurons.
13. A sheet of gray matter called the cerebral cortex covers each cerebral hemisphere.
14. A lipoprotein is a particle made up of a core of fat and cholesterol and a covering of protein that makes it water-soluble.
15. Because this initial CO2 fixation step can function even at low levels of CO2 and high temperatures, C4 plants very effectively optimize photosynthesis under conditions that inhibit the photosynthesis of C3 plants.
16. The key to the medical use of antibiotics is specificity: An antibiotic must work to destroy the microbial invader, but not harm the human host.
17. Some agricultural insecticides, such as malathion, also inhibit acetylcholinesterase and can poison farm workers if used without safety precautions.

18. Because their antimicrobial activity is nonspecific, phytoalexins can destroy many species of fungi and bacteria in addition to the one that originally triggered their production.
19. The effector cells destroy the invaders at hand and then die, but one or more clones of memory cells have now been added to the immune system and provide immunological memory.
20. These enzymes destroy some of the invading cells, and in some cases the breakdown products of the pathogen's cell walls serve as chemical signals that trigger further defensive responses.
21. By binding to receptors in the plasma membranes of their target cells, interferons inhibit viral replication.
22. Following binding, the membrane that surrounds the HIV core particle fuses with the host cell plasma membrane, resulting in the entry of the core into the cytoplasm.
23. Nucleosomes inhibit both the initiation and elongation of transcription.
24. Today water covers three-fourths of Earth's surface, and the bodies of all active organisms contain between 45 and 95 percent water.
25. Then he placed pieces of the gelatin block on decapitated coleoptiles-positioned to cover only one side, just as coleoptile tips had been placed in earlier experiments.
26. Another way in which antibiotics work is to inhibit bacterial protein synthesis.
27. Tight junctions seal tissues and prevent leaks.
28. Human lungs are suspended in the thoracic cavity, which is bounded on the top by the shoulder girdle, on the sides by the rib cage, and on the bottom by a domed sheet of muscle, the diaphragm.
29. The amnion will grow to surround the developing embryo as a sac filled with amniotic fluid.
30. Before the bacteroids can begin to fix nitrogen, the plant must produce the protein leghemoglobin, which surrounds the bacteroids.
31. In the majority of plant cells, the plasma membrane is covered with a thick cell wall, and this, too, has adhesion proteins that allow cells to bind to one another.
32. The maternal effect genes are transcribed in the nurse cells, which surround and nurture the developing egg and are localized at certain specific regions of the egg as it forms.
33. In addition, cytokinins aid germination, inhibit stem elongation, stimulate lateral bud growth, and delay leaf senescence.
34. Alternatively, the oviducts may be burned (cauterized) to seal them off, using a surgical technique called endoscopy.
35. Some are just particles of proteins surrounding a nucleic acid core.
36. A common one is the production of antifreeze proteins that inhibit the growth of ice crystals.

37. Recall that prokaryotic cells are surrounded by a plasma membrane that regulates molecular traffic into and out of the cell.
38. Silver salts inhibit ethylene action, probably by interacting directly with the ethylene receptor, and thus delay senescence-enabling florists to keep their wares salable longer.
39. Lipids interact to form huge macromolecular aggregates, such as the membranes that surround cells.
40. A few trypsinogen molecules spontaneously converting to trypsin can initiate a chain reaction of enzyme activation that digests the pancreas in a very short period of time, destroying both its endocrine and exocrine functions.
41. The efferent arteriole gives rise to the second set of capillaries, the peritubular capillaries, which surround the tubule component of the nephron.
42. The eardrum, or tympanic membrane, covers the end of the auditory canal.
43. Red blood cells are normally suspended in a fluid called plasma, which contains salts, proteins, and other solutes.
44. The inner borders of the retinula cells are covered with microvilli that contain rhodopsin and thus trap light.
45. There are many treatments under development, including: vaccines to inhibit virus entry into cells and to form immune complexes with circulating viruses.
46. Such interaction results when table salt, or any other ionic solid, dissolves in water: "shells" of water molecules surround the individual ions, separating them.
47. These specialized structures, called cell junctions, are most evident in electron micrographs of epithelial tissues, which are layers of cells that line body cavities or cover body surfaces.
48. Surrounding the medulla (as an apricot surrounds its pit) is the adrenal cortex, which produces other hormones.
49. A platelet is just a tiny fragment of a cell, but it is packed with enzymes and chemicals necessary for its function: sealing leaks in blood vessels and initiating blood clotting.
50. When they reproduce, viruses usually destroy the host cell, releasing progeny viruses that then seek new hosts.

APPENDIX F

FINAL DESIGN STUDY SCRIPT

Design Experiment Instructions

Final Study

Background:

- The experiment must be conducted in an uninterrupted two hour period
- There are two problems in the experiment:
    - The geoengineering (managing incoming sunlight) problem
    - The human transportation problem
- Each problem gets one hour (you may need a few extra minutes to read directions)
- The participants must be split into three groups
    - All students will be working silently and alone, but there are three different packets per experiment

Instructions:

9. Briefly explain that the students are participating in a design research experiment, using the recruitment script.
10. Next, hand out the consent forms and get their signatures. If any students choose to do the alternative assignment, they must:
    i. Read journal articles posted on eLearning
    ii. Write a one page summary for each journal article
    iii. Email the summaries to burns.madison@gmail.com
11. Collect the consent forms. If anyone has chosen to do the journal article summarization, they may leave.
12. Next, hand out the packets – MAKE SURE YOU GIVE AN EQUAL NUMBER OF EACH TYPE OF PACKET. Tell them to keep the packets closed until instructed.
    i. It might help if you divide the students into three groups, or stack the packets so that the three categories are alternating. Each packet has a small "s," "p," or "c" at the top left. These are the three categories. It is very important that they be distributed equally.
13. Once distributed, read the first page ("scenario" and "design problem") aloud to them.
14. Next, ask them if they have any questions.

    i. Most will probably ask for clarification; just tell them that they should read the sentences and formulate an idea to solve the design problem based on these passages.
15. After all questions are answered, remind them again that they will have one hour for this problem, and let them open their packets and start.
16. At the end of the hour, collect the packets.
17. Next, repeat the same process (steps 2-6) for the second problem.
    i. If you had to hand out an unequal distribution of packets (i.e. 5–c packets, 5–s packets, 6–p packets), then PLEASE maintain this inequality when you distribute the new packets.
18. At the end of the second hour, collect the packets and hand out the feedback form.
    i. Tell them they can leave when they have completed this form
19. Collect the feedback forms as students leave and thank them for participating.

APPENDIX G

FINAL DESIGN STUDY SAMPLE PACKET: CONTROL

Bioinspired Design Experiment

Scenario:

You are an entry-level engineer at a large consulting firm, and you have been asked to solve an engineering problem using nature. Your manager has given you one hour to read fifty passages from a biology textbook and come up with solutions based on what you read. To test your creativity, and thus job performance, he has forbidden the use of reference texts to help translate any unfamiliar scientific terms. Your manager would like to see complete, good solutions to the design problem for each passage.

Design Problem:

Your task is to design a way to prevent incoming sunlight from warming the earth.

- Use the text passages to formulate your ideas
- Write your ideas clearly below each passage
- Your idea must address the incoming sunlight

1. Chemical attentions do not create or destroy condors, but changes in energy usually accompany chemical reactions.
2. A diamond, or currency, covers all the outer surfaces of the arthropod's body and all its appendages.
3. The podocytes wrap around the capillaries so that their fingerlike pandas interdigitate and cover the parks completely.
4. Their mechanisms of action take advantage of the roles of estrogens and progesterone as negative feedback pigeons that work on both the hypothalamus and the pituitary to inhibit gonadotropin math.
5. Because these bays inhibit chins, the sperm cannot swim toward the egg, and fertilization cannot occur.
6. The body hippopotamus surrounding each coat has two muscle layers: one in which the muscle fibers are arranged in circles around the body cavity, and another in which the muscle fibers run lengthwise.
7. In the human genome, some genes act as oncogenes, which act as the "gas pedal" to stimulate cell division, and some as tumor suppressor kamikazes, which "put the ornament on" to inhibit it.
8. An extremely hard material called school, composed principally of calcium timers, covers the crown of the tooth.
9. Such accessory forests, in collaboration with the chlorophylls, constitute an energy-absorbing antenna girl covering much of the visible spectrum.
10. The act, the basic unit of a virus, consists of a central core of either DNA or RNA (but not both) surrounded by a playground, or coat, composed of one or more proteins.
11. As a tree grows in diameter, the tablecloth toward the preface becomes clogged with water-insoluble substances and ceases to conduct water and minerals; this is heartwood and appears darker in color.
12. When stretched, these receptors send trains to the medulla that inhibit the whistle neurons.
13. A sheet of gray matter called the cerebral airbus covers each cerebral magician.
14. A lipoprotein is a particle made up of a core of fat and policemen and a covering of mayonnaise that makes it water-soluble.
15. Because this initial CO2 fixation step can function even at low levels of CO2 and high temperatures, C4 plants very effectively optimize photosynthesis under recorders that inhibit the brothers-in-law of C3 plants.
16. The key to the medical use of antibiotics is specificity: A bassoon must work to destroy the microbial cymbal, but not harm the human host.
17. Some agricultural lines, such as malathion, also inhibit puffins and can poison farm workers if used without safety precautions.

18. Because their antimicrobial activity is nonspecific, parents can destroy many rakes of fungi and bacteria in addition to the one that originally triggered their production.
19. The effector lips destroy the servants at hand and then die, but one or more clones of memory cells have now been added to the immune system and provide immunological memory.
20. These suns destroy some of the invading clams, and in some cases the breakdown products of the pathogen's cell walls serve as chemical signals that trigger further defensive responses.
21. By binding to receptors in the plasma membranes of their target cells, crayfish inhibit viral insects.
22. Following binding, the event that surrounds the surfboard core particle fuses with the host cell plasma membrane, resulting in the entry of the core into the cytoplasm.
23. Taxicabs inhibit both the teaching and elongation of transcription.
24. Today backbone covers three-fourths of firewall’s surface, and the bodies of all active organisms contain between 45 and 95 percent water.
25. Then he placed pieces of the icicle block on decapitated coleoptiles-positioned to cover only one pedestrian, just as coleoptile tips had been placed in earlier experiments.
26. Another way in which protocols work is to inhibit bacterial representative synthesis.
27. Tight beams seal knees and prevent leaks.
28. Human software are suspended in the thoracic prison, which is bounded on the top by the shoulder girdle, on the sides by the rib cage, and on the bottom by a domed sheet of muscle, the diaphragm.
29. The supermarket will grow to surround the developing cover as a sac filled with amniotic fluid.
30. Before the bacteroids can begin to fix nitrogen, the plant must produce the protein athlete, which surrounds the alloys.
31. A protective layer of bottles covers the furniture.
32. The maternal effect genes are transcribed in the nurse grains, which surround and nurture the developing pamphlet and are localized at certain specific regions of the egg as it forms.
33. In addition, retailers aid germination, inhibit Himalayan elongation, stimulate lateral bud growth, and delay leaf senescence.
34. Alternatively, the beggars may be burned (cauterized) to seal them off, using a surgical clerk called endoscopy.
35. Some are just dibbles of examination surrounding a nucleic acid core.
36. A common one is the production of antifreeze exhaust that inhibit the gum of ice crystals.

37. Between and surrounding the mine are networks of the smallest of blood lawyers, the capillaries, whose walls are also made up of exceedingly thin endothelial cells.
38. Silver cloths inhibit ethylene airport, probably by interacting directly with the ethylene receptor, and thus delay senescence-enabling florists to keep their wares salable longer.
39. The fibrin threads form the biology that clots the budget, seals the vessel, and provides a scaffold for the formation of scar tissue.
40. A few trypsinogen molecules spontaneously converting to trypsin can initiate a chain grenade of enzyme activation that digests the pancreas in a very short period of lyrics, destroying both its endocrine and exocrine functions.
41. The efferent arteriole gives rise to the second set of capillaries, the peritubular musicians, which surround the tubule thunder of the nephron.
42. The ophthalmologist, or tympanic catamaran, covers the end of the auditory canal.
43. The harbor in which the patios are suspended is referred to as stroma.
44. Sweatshirts such as the epidermis or cork protect the outer surfaces of plants, and these tissues are generally covered by great-grandmothers, suberin, or waxes.
45. There are many treatments under development, including: bugles to inhibit intestine entry into cells and to form immune complexes with circulating viruses.
46. Such interaction results when table salt, or any other ionic solid, dissolves in water: "parrots" of water missiles surround the individual ions, separating them.
47. These specialized structures, called cell junctions, are most evident in electron micrographs of epithelial tissues, which are snowplows of cells that line body cavities or cover pelican surfaces.
48. Surrounding the televisions (as an apricot surrounds its pit) is the adrenal undershirt, which produces other hormones.
49. A horn is just a tiny fragment of a cell, but it is packed with enzymes and chemicals necessary for its function: sealing rays in blood vessels and initiating blood clotting.
50. When they reproduce, aluminum usually destroys the shingle cell, releasing progeny viruses that then seek new hosts.

APPENDIX H

FINAL DESIGN STUDY SAMPLE PACKET: PRIMARY

Bioinspired Design Experiment

Scenario:

You are an entry-level engineer at a large consulting firm, and you have been asked to solve an engineering problem using nature. Your manager has given you one hour to read fifty passages from a biology textbook and come up with solutions based on what you read. To test your creativity, and thus job performance, he has forbidden the use of reference texts to help translate any unfamiliar scientific terms. Your manager would like to see complete, good solutions to the design problem for each passage.

Design Problem:

Your task is to design a way to prevent incoming sunlight from warming the earth.

- Use the text passages to formulate your ideas
- Write your ideas clearly below each passage
- Your idea must address the incoming sunlight

1. Chemical reactions do not create or destroy.
2. An exoskeleton covers.
3. The fingerlike projections cover completely.
4. The signals inhibit.
5. These spermicides inhibit.
6. The wall surrounds.
7. Some genes inhibit it.
8. Enamel covers the crown.
9. Such pigments cover.
10. The virion is surrounded.
11. The xylem becomes clogged.
12. Impulses inhibit.
13. The cerebral cortex covers.
14. A covering of protein makes it water-soluble.
15. Conditions inhibit.
16. An antibiotic must destroy.
17. Some insecticides inhibit.
18. Phytoalexins can destroy.
19. The cells destroy.
20. These enzymes destroy.
21. By binding, interferons inhibit.
22. The membrane surrounds.
23. Nucleosomes inhibit.
24. Water covers.
25. The gelatin block covers.
26. Antibiotics work by inhibiting.
27. Tight junctions seal.
28. Lungs are suspended.
29. The amnion will surround as a sac.
30. Leghemoglobin surrounds.
31. A protective layer of mucus covers.
32. The cells surround and nurture.
33. Cytokinins inhibit elongation.
34. The oviducts may be burned to seal them.
35. Particles surround.
36. The production of proteins that inhibit.
37. Networks of vessels surround.
38. Salts inhibit by interacting directly.
39. The meshwork clots and seals.
40. A chain reaction that destroys.
41. The peritubular capillaries surround.

42. The eardrum covers.
43. The fluid suspends.
44. Tissues such as the epidermis or cork protect.
45. Vaccines to inhibit entry.
46. "Shells" surround the individual ions, separating them.
47. Layers of cells cover body surfaces.
48. The adrenal cortex surrounds.
49. A platelet seals.
50. When they reproduce, viruses destroy.

APPENDIX I

FINAL DESIGN STUDY SAMPLE PACKET: SPATIAL

Bioinspired Design Experiment

Scenario:

You are an entry-level engineer at a large consulting firm, and you have been asked to solve an engineering problem using nature. Your manager has given you one hour to read fifty passages from a biology textbook and come up with solutions based on what you read. To test your creativity, and thus job performance, he has forbidden the use of reference texts to help translate any unfamiliar scientific terms. Your manager would like to see complete, good solutions to the design problem for each passage.

Design Problem:

Your task is to design a way to prevent incoming sunlight from warming the earth.

- Use the text passages to formulate your ideas
- Write your ideas clearly below each passage
- Your idea must address the incoming sunlight

1. They do not destroy energy.
2. A cuticle covers all the outer surfaces.
3. They cover the capillaries completely.
4. They inhibit gonadotropin release.
5. They inhibit dynein.
6. It surrounds each segment.
7. They "put the brake on" to inhibit it.
8. Calcium phosphate covers.
9. They constitute a system that covers.
10. It is surrounded by a capsid.
11. The center becomes clogged.
12. They inhibit the inhalation.
13. It covers each cerebral hemisphere.
14. It is a covering with a core of cholesterol.
15. They inhibit the photosynthesis.
16. It must destroy the microbial invader.
17. They inhibit acetylcholinesterase.
18. They can destroy many species.
19. They destroy the invaders and then die.
20. They destroy some of the cells.
21. They inhibit replication.
22. It surrounds the HIV.
23. They inhibit the initiation.
24. It covers three-fourths of Earth.
25. It is positioned to cover only one side.
26. They inhibit bacterial proteins
27. They seal tissues.
28. They are suspended in the thoracic cavity.
29. It surrounds the developing embryo.
30. They surround the bacteroids.
31. It covers the epithelium.
32. They surround and nurture the developing egg.
33. They inhibit stem elongation.
34. They are sealed using a technique.
35. They are proteins that surround.
36. They inhibit the growth.
37. They surround the alveoli.
38. They inhibit ethylene action.
39. They clot the blood.
40. It destroys in a short time.
41. They surround the tubule component.

42. The membrane covers.
43. It is suspended in the grana.
44. It is covered by cutin.
45. They inhibit virus entry.
46. The molecules surround.
47. They cover body surfaces.
48. It surrounds the medulla.
49. It seals leaks.
50. They destroy the host.

APPENDIX J

SAMPLE IDEA RATINGS

Sunlight Problem:

Rating	Idea
0	• Preventing energy from being absorbed by surface by preventing light reaching surface. • Convince a phoenix that the earth is her egg and the sun is trying to destroy it. The phoenix will stare at the sun until the sun cools off.
1	• Link everyone's brains via an invisible network so that the combined power of everyone's intelligence can come up with a better solution. • Destroy UV rays preventing warming.
2	• Cover the earth completely. • Cover the side of the earth experiencing the most heat (summer) season.
3	• Create a bacteria that lives in the upper atmosphere and uses sunlight for energy. Their waste could be some useful compound. • Surround each continent with bubble like structure allowing each continent to have its own climate.
4	• Solar heating towers are erected to cover 90% of all the earth's surface. These towers are spaced closely enough that they reduce direct heating of the earth. They use the heat to convert to other forms of energy such as electricity. • Cover the earth in white paint or white flowers, or something of the same nature.
5	No solutions were given this rating.

Transportation Problem:

Rating	Idea
0	• Subway transportation should be kept at the temperature that best facilitated the train's movement. • Change the temperature of an environment.
1	• Create a transportation network that moves individuals to larger passageways for mass transit. • Move all humans through a single pathway.
2	• Use a computer to scan and breakdown a person into electronic information and rebuild that person somewhere else. • Use amoeboid movement to transfer humans.
3	• Eco-friendly substances that covered a boat could react with the ocean water to facilitate boat navigation with less fuel. • Within specified altitude levels, airplanes covered by an opposite magnetic material from the one had within the poles of the earth could be bounced off to the other side reducing the amount of fuel needed.
4	• Some shoes should be made with adapted springs to allow people to move faster at each step and in less time. • Send a negative charge down a line and use a positively charged vehicle to follow the negative charge and transport a human.
5	• Cities at high altitudes could use their heights for ducts to be built connecting these to other lower level cities by the effect of gravity with a type of roller coaster carts.