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TOWARDS BIOMIMETIC CONCEPT GENERATION

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ABSTRACT

This paper describes efforts towards generalizing biomimetic concept generation in engineering design. Biomimetic design fully or partially imitates or evokes some biological phenomenon. Nature has often inspired solutions to engineering problems. While biological phenomena hold a vast amount of ideas, a method for finding and using these ideas would make biomimetic innovation faster, easier and more accessible. The paper begins with a brief review of related research, recognition of engineering ideas in biological phenomena and advantages of the natural brand. Next presented are strategies for finding potential analogies in biological phenomena, including searching functionally across multiple levels of organization, from the molecule to the biosphere. Initial efforts at finding appropriate analogies are documented using an example in design for remanufacture.

Keywords: biomimicry, analogy, function, remanufacture

NOMENCLATURE

- Biomimetic design: Design that, fully or partially, imitates or evokes some biological phenomenon.
- Biological phenomenon: Any natural phenomenon pertaining to the biological sciences – the term "biological phenomena" includes all levels of organization pertaining to the biological sciences (see Table 1).

INTRODUCTION

Nature has often inspired solutions to engineering problems. For example, the Wright brothers devised their breakthrough flight control system after studying the flight movements of vultures. Biomimetic design has spawned innovation in design as well as pointed to ways of improving existing designs. Biological phenomena hold a vast amount of ideas. A method for finding and using these ideas would make biomimetic innovation faster, easier and more accessible.

The main components of the paper include:

- A brief review of related research.
- Recognition of engineering ideas in biological phenomena and advantages of the natural brand.
- Strategies for biomimetic concept generation.
- Documentation of initial efforts towards generalizing biomimetic concept generation using an example in design for remanufacture.

RELATED WORK

Offner (1995) offers excellent case studies of biomimetic design and discusses the biomechanics of systems found in a number of animals, some plants, and the cell. He outlines a course designed for engineering students and dedicates a chapter to a discussion of techniques for the development of creativity.

New modes of propulsion based on animal locomotion have been explored for robotic locomotion. For example, MIT's RoboTuna is an underwater autonomous vehicle that uses oscillating-foil propulsion based on that of the blue fin tuna (Machine Design 1995). The ornithopter is a flapping-wing aircraft, imitating bird or bat flight. The University of Toronto's Institute for Aerospace Studies made its first successful remote-piloted ornithopter flight in 1991.

Sfakiotakis *et al.* (1999) presented an overview of fish swimming mechanisms. With recent developments in oscillating-foil, underwater locomotion, the authors aimed to introduce engineers to the existing literature on fish swimming. This type of research provides a useful reference for engineers who are using a specific biological model.

Vincent (1992, 1994) raised awareness of biomimetic design in the area of materials engineering. Materials engineers have been studying biological tissues and creating new composites with exceptional new properties. They have also been studying biological synthesizing methods for their ability to function under low-control conditions (Bond *et al.* 1995).

A cheaper and more efficient solar cell was created that functions on a principle similar to photosynthesis, the conversion of solar energy to chemical energy carried out by green plants (Freemantle 1998).

Computer engineers have been studying and simulating human thought with artificial intelligence. Specifically using neural networks, more powerful computers and computer architectures have been created by studying the structure of neurons in the brain (Happel and Murre 1994).

Genetic algorithms simulate the evolution of populations and have been used to find optimal design solutions by evolving populations of possible solutions (Goldberg 1989).

This paper focuses on the process of finding useful biological models for the creation of engineering systems. We discuss how to find the broadest range of options for biological models by considering all organizational levels from molecule to biosphere and document preliminary efforts using an example in design for remanufacture.

DESIGN IN NATURE

Many books on the problem solving abilities of nature (e.g., Hertel 1966, Thomson 1971, Paturi 1976, French 1994, Benyus 1997, Vogel 1998) present novel ways by which organisms and other biological phenomena have adapted to their environments through evolution by natural selection.

Advantages of Natural Designs

Observed are the following characteristics about solutions that currently exist in nature.

- Efficient use of materials and energy: biological organisms usually use the minimum amount of energy and materials needed for survival (Paturi 1976). The less they need, the easier it is to survive.
- High tolerance: Living systems can operate in a wide range of conditions relative to man-made systems (Affholter and Arnold 1999, David 1999). Tolerance relates to an organism's ability to adapt to variation of its environment.
- Adaptable: Either through learning, evolution, or succession, biological systems adapt to their situation. Adaptability to changing conditions is the key to survival (Galbraith *et al.* 1989).
- Environmentally sustainable: Biological systems like natural ecosystems survive by recycling materials and energy (Benyus 1997).
- Independent, self-regulating: Organisms and cells have brains and are self-controlled. "Intelligent" organisms can react to external stress by way of sensors. Organisms maintain internal functions through homeostasis—the maintenance of steady levels of metabolism, chemicals and temperature (Galbraith *et al.* 1989). Communities and ecosystems maintain themselves through feedback loops. For example, if there is a drop in the mineral content of an aquatic ecosystem, algae will become scarce. Fish will then die. Bacteria will decompose the large number of dead bodies and thus increase the amount of minerals in the water (laws of ecology).
- Precise: Biological synthesis is very precise (Paturi 1976) even though they require minimal energy, machinery and control relative to most man-made synthesizing methods (Bond *et al.* 1995).
- Diverse: The biological world offers a huge scope of solutions and adaptations. It is still largely undocumented.
- Suitable: Biological systems are always well suited to the given environment (Paturi 1976).
- Self-Assembling: Through mechanisms like synthesis, reproduction, and succession, biological systems automatically create and re-create tissues (Bond *et al.* 1995), organisms and ecosystems, respectively.

STRATEGIES FOR BIOMIMETIC CONCEPT GENERATION

To find design ideas in nature, one must first define the requirements of the artificial system and then find a system in nature that performs a similar function. The search process is the challenge. Nature is a vast, largely undocumented field. The approach described below facilitates the search while seeking the broadest range of possibilities.

Flow versus Function

Some of the best parallel solutions in nature may not be obviously analogous to the engineering problem under study. For example, one may not think of plants as very mobile organisms, but the mechanisms they use to disperse seeds can provide ideas for new types of transportation devices (Paturi 1976). For example, the dandelion exploits wind power to disperse its seeds. To avoid overlooking useful biological models, it is important to consider all levels of organization. In the example given, the biological model exists at the organ system level (the plant's reproductive system). The parallel is less apparent when considering the entire organism, the plant. The engineer can find additional analogous systems by disregarding the flow used in the biological system and focusing on the required function. For example Whitlock (1961) studied parasite epidemics in sheep using engineering analysis tools and found that the biological system was an ideal subject on which to test new mathematical engineering models. In this case, the parasite population patterns stood in for electrical feedback systems. The flow of parasites was analogous to the flow of electrons.

Function Extraction

An approach to biomimetic concept generation would be to first abstract the system by indicating its essential functions, and then find a biological system, to be used as a model, that performs similar functions.

Models of conceptual design (e.g., Pahl and Beitz, 1996) require, first, abstracting an engineering problem to obtain a clear statement of the overall function of the required system. Next, the overall function is broken into less complex sub-functions. Then follows a "search for working principles to fulfill the sub-functions," or, a search for the means by which the sub-functions may be fulfilled.

Biomimetic design only requires modeling one or more working principles of the system on some biological phenomenon. Finding the best parallels between natural and artificial systems can be difficult. The following questions may help identify suitable analogies:

- **What does the system do?** What does the same thing, or something similar in nature?
- **How is the system unique?** What functions must be maximized? What performs these functions best in nature at each level of organization? For example, when researchers at MIT decided to build a more efficient propulsion system, they modeled their design on that of the blue fin tuna since it is the most efficient swimmer (Machine Design 1995).
- **How does the system carry out its function or functions?** What kinds of biological processes carry out the same functions? Again, the function must be the same but the flow may be totally different.
- **Under what conditions does the system operate?** Systems that live in biomes with similar characteristics as the operating conditions may be suitable models. For example, research at NASA is modeling planetary explorers after animals and plants that live in harsh environments on earth to give them a better chance to withstand the harsh climates on other planets (David 1999).
- **What kinds of relationships exist between the functional requirements?** Organizational levels that involve much interaction, like ecosystems and organ systems, may be examined. Also of potential interest are symbiotic relationships between organisms, as well as the emergent properties of organizational levels.
- **What compromises are required?** Multi-function systems like organisms and organ systems may be suitable models. Organisms must perform multiple functions while using minimal energy. Certain functions are compromised to benefit others (Sfakiotakis *et al.* 1999) while not sacrificing the integrity of the organism.

Table 1: Possible Applications by Organizational Level

Level	Intermediate Levels	Possible Applications	Characteristics
Molecule		Chemical processes, Catalysis, Nanosystems	Complexity ↓ Variability ↑
	Protein		
Organelle One of several formed bodies with specialized functions suspended in the cytoplasm found in eukaryotic cells.		Components, Single function systems, Microsystems	
	Virus		
Cell The lowest level of organization where all the properties of life appear.		Microsystems	
Tissue An integrated group of cells with a common structure and function.		Materials, Composites, Smart materials	
Organ A specialized center of body function composed of several different types of tissues.		Single function systems, Sub-systems	
Organ System An organized group of organs that carries out one or more body functions.		Multi-function systems, Information systems	
Organism A complete living being composed of one or more cells.		Autonomous systems, Multi-function systems	
	Family Unit		
Population A group of individuals of one species that live in a particular geographic area.	**Host-Parasite Symbiosis**	Self organizing systems	
Community All the organisms that inhabit a particular area; an assemblage of populations of different species living close enough together for potential interaction.		Competing systems, Co-operative systems	
Ecosystem A level of ecological study that includes all the organisms in a given area along with the abiotic factors with which they interact; a community and its physical environment.		Complex systems, Macrosystems	
	Biome		
Biosphere The entire portion of the earth that is inhabited by life. The sum of all the planet's ecosystems.		Macrosystems, Isolated systems	

INITIAL EFFORTS TOWARDS GENERALIZING BIOMIMETIC CONCEPT GENERATION

While the previous section described strategies that may be used to guide a search for suitable biological analogies, many engineers may not have the background in biology to be able to think of analogies that are relevant to their design. Therefore, next explored is what may be involved in generalizing and automating biomimetic concept generation. This section documents our process for finding suitable analogies for an example problem, with the goal of identifying obstacles in the process, how these obstacles were handled, as well as limitations of these initial efforts.

When designers seek solutions to functions and subfunctions, the obvious starting point is to search by function. Biological information however, is not indexed by function. Therefore, the steps followed to find suitable analogies include:

1. Select initial information source of biological phenomena.
2. Identify synonyms for engineering functional keywords.
3. Identify suitable bridge between engineering functional keywords and synonyms and biological phenomena.
4. Search for keywords and synonyms in bridge.
5. Identify and find more detail on relevant biological phenomena.

The example with which we illustrate our initial efforts for finding suitable analogies comes from the corresponding author's research on how to design products for ease of remanufacture (Shu and Flowers, 1999). Remanufacture is a production-batch process of product disassembly, cleaning, assessment, replacement and or repair of parts, and reassembly at a product's end-of-life. Product design that facilitates any aspect of the remanufacture process, e.g., disassembly, cleaning, reassembly, etc., facilitates remanufacture. However, the most essential aspect of remanufacture is that parts can be reused. Many parts fail and require refurbishment. Refurbishment processes can be capital and or labor intensive and may not be performed for economic reasons. An alternative during design is to make regions that are prone to failure separable so that they can be more easily replaced during remanufacture. However, making parts separable runs counter to design-for-assembly principles, resulting in higher part count and more assembly steps during first manufacture. Therefore, needed is a design solution that addresses both the needs of manufacture and remanufacture.

1. Select initial information source of biological phenomena

As a starting point for our search, we chose Purves *et al.* (1998), the reference text for BIO 150Y, the introductory year-long course in biology at the University of Toronto. This text was chosen because of its general nature, covering many of the organizational levels in biology, from the molecular to the biosphere level.

2. Identify synonyms for engineering functional keywords

The first attempt consisted of searching the index of the text for terms such as remanufacture and refurbish. Not surprisingly, no references were found. A few synonyms for the keywords were generated using an online thesaurus (www.m-w.com/home.htm), but these terms were also not contained in the index. It was noted that the index contained biological terms, yet their relationships to functions useful to engineering needs were not apparent to those without prior knowledge of the biological terms.

3. Identify suitable bridge between engineering functional keywords and synonyms and biological phenomena

Since the text was only available to us in hardcopy form, a suitable bridge between biological and engineering terminology was required to avoid reading or searching the entirety of the text. The glossary for the text was identified as a suitable bridge. The glossary defines biological terms and often includes functional keywords or their synonyms. The glossary was scanned and converted into a searchable text format.

4. Search for keywords and synonyms in bridge

Searching the entirety of the glossary text for the original keywords, remanufacture and refurbish, was again not fruitful. No synonyms were found for remanufacture. Synonyms found for refurbish, including related words for one of the synonyms did result in matches in the glossary. Some of the matches occurred with part of the glossary term, but most of the matches occurred within the definition of the glossary term. The keywords, synonyms, as well as the references found in the glossary are shown in Table 2. The matched text is italicized in either the term or the definition.

5. Identify and find more detail on relevant biological phenomena

Table 2 shows that the majority of references located were related to *DNA replication*. There are two occurrences of both the terms *Excision repair* and *Mismatch repair*. Interestingly, some of the terms, *Negative feedback*, *Template* and *Error Signal*, are very familiar terms in engineering.

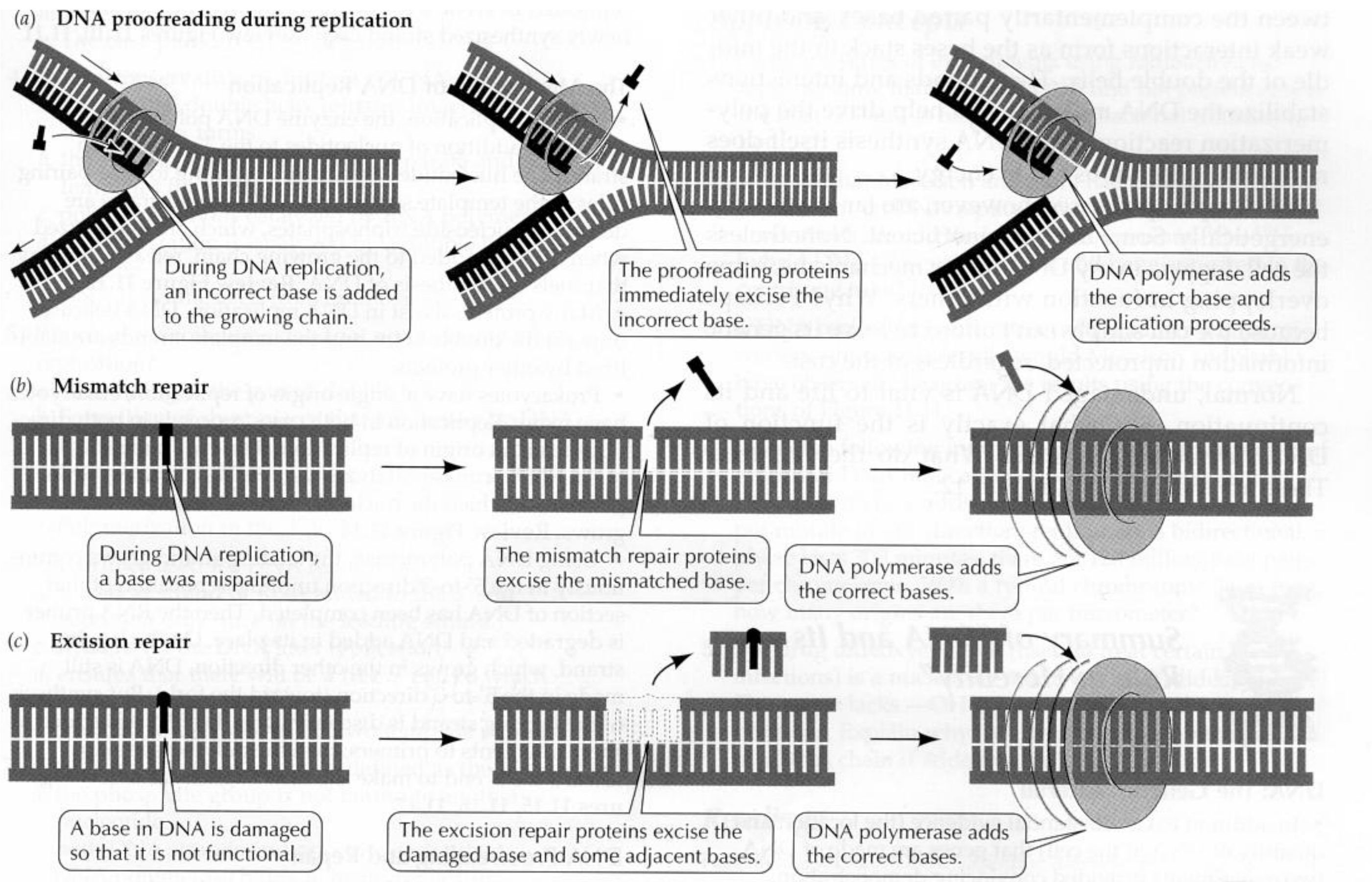
Based on the definitions of the glossary entries located, of direct interest are *Excision repair*, *Mismatch repair* and *Proofreading*, all of which occur during *DNA replication*. From the glossary, *DNA* (deoxyribonucleic acid) is "the fundamental hereditary material of all living organisms."

The index of the Purves *et al.* (1998) text can now be used to find references to these phenomena to locate the following details.

DNA replication refers to the process of forming new DNA from old DNA, thereby passing on genetic material. "Yet, the replication of DNA is not perfectly accurate, and the DNA of nondividing cells is subject to damage by environmental agents." DNA repair mechanisms "include a 'proofreading' function that corrects errors as DNA polymerase makes them; a mismatch repair function that scans DNA after it has been made and corrects any base-pairing mismatches; and excision repair, in which abnormal bases that have formed because of chemical damage are removed and replaced with functional bases." (Purves *et al.* 1998)

Table 2: Keywords, Synonyms and Matches in Glossary of Purves *et al.* (1998)

Keywords	Synonyms	Matches	Definitions of glossary terms
Remanufacture	Remanufacture	None	
Refurbish	Refurbish	None	
	Renew	None	
	Modernize	None	
	Refresh	None	
	Rejuvenate	None	
	Renovate	None	
	Restore	Reversion	(genetic) A mutational event that *restore*s wild type phenotype to a mutant.
	Update	None	
Renew (Related words)	Make over	None	
	Remodel	None	
	Mend	DNA ligase	Enzyme that unites Okazaki fragments of the lagging strand during DNA replication; also *mend*s breaks in DNA strands. It connects pieces of a DNA strand and is used in recombinant DNA technology.
	Rebuild	None	
	Repair	Excision *repair*	The removal of damaged DNA and its replacement by the appropriate nucleotides. Often, several bases on either side of the damaged base are removed by the action of an endonuclease. Then a DNA polymerase adds the correct bases according to the template still present on the other strand of DNA. DNA ligase catalyzes the sealing up of the *repair*ed strand.
		Mismatch *repair*	When a single base in DNA is changed into a different base, or the wrong base inserted during DNA replication, there is a mismatch in base pairing with the base on the opposite strand. A *repair* system removes the incorrect base and inserts the proper one for pairing with the opposite strand.
	Correct	Excision repair	The removal of damaged DNA and its replacement by the appropriate nucleotides. Often, several bases on either side of the damaged base are removed by the action of an endonuclease. Then a DNA polymerase adds the *correct* bases according to the template still present on the other strand of DNA. DNA ligase catalyzes the sealing up of the repaired strand.
		Mismatch repair	When a single base in DNA is changed into a different base, or the wrong base inserted during DNA replication, there is a mismatch in base pairing with the base on the opposite strand. A repair system removes the in*correct* base and inserts the proper one for pairing with the opposite strand.
		Negative feedback	A pattern of regulation in which a change in a sensed variable results in a *correct*ion that opposes the change.
		Proofreading	The *correct*ion of an error in DNA replication just after an in*correct*ly paired base is added to the growing polynucleotide chain.
		Template	In biochemistry, a molecule or surface upon which another molecule is synthesized in complementary fashion, as in the replication of DNA. In the brain, a pattern that responds to a normal input but not to in*correct* inputs.
		Error signal	In physiology, the difference between a set point and a feedback signal that results in a *correct*ive response.
	Rectify	None	
	Reform	Telophase	(tee' lo phase) [Gr. telos: end] The final phase of mitosis or meiosis during which chromosomes became diffuse, nuclear envelopes *reform*, and nucleoli begin to reappear in the daughter nuclei.
	Revise	None	



11.18 DNA Repair Mechanisms The proteins of DNA replication also play roles in the life-preserving repair mechanisms, helping to ensure the exact replication of template DNA.

Figure 1. From Purves *et al.* (1998), DNA Repair Mechanisms

Figure 1 (Fig. 11.18 from Purves *et al.* 1998) shows three types of DNA repair mechanisms: DNA proofreading during replication, mismatch repair, and excision repair. Both the proofreading and mismatch repairs described refer to corrections of errors in assembly, i.e., an undamaged base in the wrong position. Excision repair targets damaged sections of a DNA molecule, including that which occurs during the life of the cell. This correlates more closely with damage that occurs to a product during its useful life, and is a more useful analogy for remanufacture. The text on excision repair from Purves *et al*. (1998) follows.

> For example, in excision repair, certain enzymes “inspect” the cell’s DNA. When they find mispaired bases, chemically modified bases, or points at which one strand has more bases than the other (with the result that one or more bases of one strand form an unpaired loop), these enzymes cut the defective strand. Another enzyme cuts away the bases adjacent to and including the offending base, and DNA polymerase and DNA ligase synthesize and seal up a new (usually correct) piece to replace the excised one.

While this additional information confirms the suitability of the analogy to the problem at hand, there is not enough detail to inspire a novel solution. Therefore, references that further describe excision repair were identified by a search for material at the University of Toronto libraries. While a search for subject or title on “excision repair” did not identify any matches, a more general search on “DNA repair” did. Publication date was used as one criterion to reduce the number of references found. References older than 10 years were rejected since much more detailed information has been obtained in the past decade. It should be noted however, that it is not critical that the analogical information is perfectly up-to-date or accurate, as long as it inspires some useful engineering solution. One of the remaining references (Friedberg *et al.* 1995) was commonly cited by the other references, and identified as a short-term loan item, indicating that it is a reference text used by students. Friedberg *et al.* (1995) contained the below figure with the following caption:

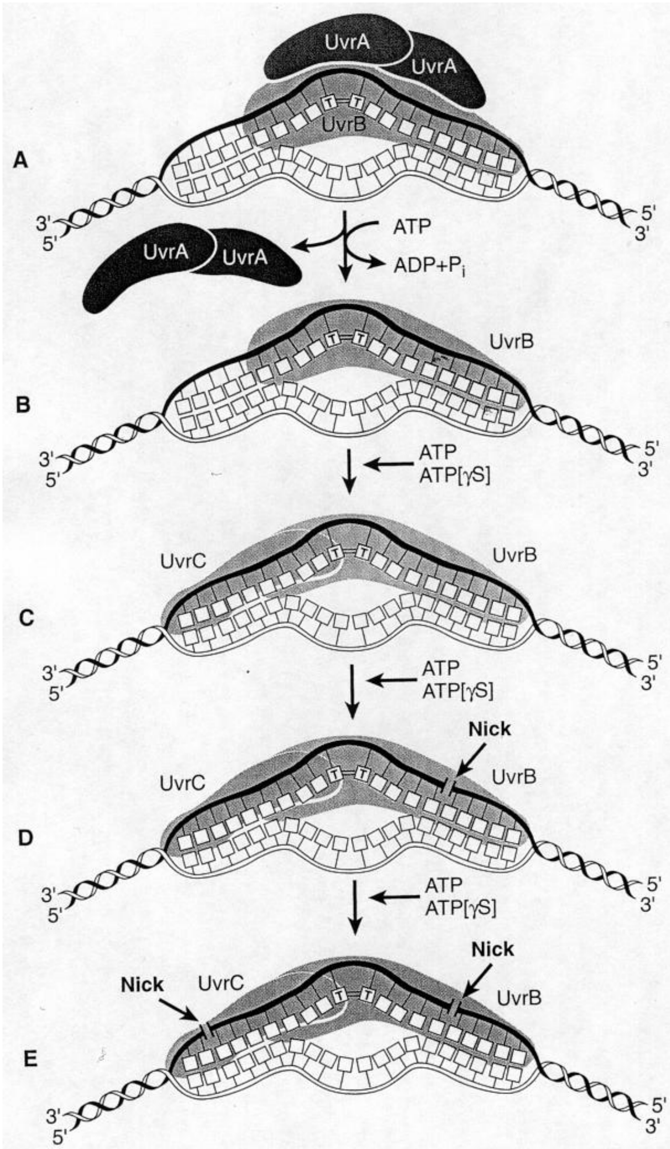


Figure 2. From Friedberg *et al.* (1995)

Figure 5-8 Diagrammatic representation of bimodal damage-specific nicking of DNA by the E. coli UvrABC endonuclease. Following the formation of a stable (UvrB)ıdamaged-DNA complex (A and B) (see Fig. 5-7), UvrC protein binds at the site (C) <u>and induces a conformational change which enables bound UvrB protein to nick the DNA 4 nucleotides 3' to the site of damage</u> (D) (shown as a pyrimidine dimer). This reaction requires the binding of ATP (or ATP [γS]) by UvrB protein, but no ATP hydrolysis occurs at this step. Following the 3' incision, UvrC protein catalyzes nicking of the DNA 7 nucleotides 5' to the dimer (E).

The underlined portion of the above caption inspired the concept of failure-induced deformation in a product to facilitate removal of the defective zone, enabling easier replacement. Thus the failure-prone zone is not necessarily a separate part during original manufacture, but could be structured such that failure causes self-disassembly. For example, a wear-prone part could be designed such that the gradual thinning of a surface causes that surface to break away from the rest of the part. This seems to be a feasible practice, which to the authors' knowledge, has not been implemented in products to facilitate their repair during remanufacture.

Conclusions from Initial Efforts

The preceding example did very much so satisfy our desire for a biological analogy to inspire a novel idea. It is worthwhile to note that as a whole, the DNA replication process is a very good analogy to the remanufacture process. Both processes reuse old parts and add new parts where required. Both processes involve disassembly, assembly, and assessment of both existing parts and newly assembled parts.

Other observations are organized below according to the original steps of the process.

1. Select initial information source of biological phenomena.

Selection of an appropriate initial information source is crucial. Too specific of a source would have severely limited the search. However, given that our initial source was quite general, surprising was that an analogy was found only at the macromolecule level during this trial. It is not difficult for one to think of suitable examples at the other levels of organization, from the cellular to biosphere level, which were included in the introductory text, Purves *et al.* (1998).

2. Identify synonyms for engineering functional keywords.

The generation and use of synonyms greatly increased the chances of finding appropriate matches. One possible method to enable more matches in the glossary would be to generate synonyms for the biological terms in the glossary as well as the engineering functional keywords.

3. Identify suitable bridge between engineering functional keywords and synonyms and biological phenomena.

Identifying the glossary as a suitable bridge was critical to us because we did not have the entire text in a computer-searchable format. Regardless, having a bridge greatly reduces the time required for an initial search. Dictionaries of biological terms, e.g., genetics dictionaries, may serve as useful bridges to immense quantities of information.

4. Search for keywords and synonyms in bridge.

It is also possible that suitable analogies for our example at the other organizational levels involve more intuitive terminology, such as healing, regrowth, regeneration, etc., that are not included in a glossary. Limitation of our initial search for keywords and synonyms to the entirety of only the glossary, not the text, may not be necessary as more information becomes available in computer-searchable form.

5. Identify and find more detail on relevant biological phenomena.

For our example, in the transition from the introductory text, Purves *et al.* (1998) to Friedberg *et al.* (1995), the amount of background required to understand the material dramatically increased. It was difficult for a passage of more advanced text to inspire solutions since, for example, the structure of a protein is unfamiliar and cannot be visualized. Therefore, the diagrams in the advanced text were found to be the most useful when scanning for potentially enlightening details.

SUMMARY

Nature contains useful design ideas for engineers. Biomimetic concept generation has been used by engineers and inventors throughout history. The advantages of natural systems, such as efficiency and sustainability, are relevant to current needs. Useful to remember is that biological models exist at all levels of organization and that each level possesses special characteristics. When seeking a biological model, one should focus on a system's function. The checklist provided in this paper may be used to guide the search. Initial efforts towards generalizing the identification of biological analogies were illustrated by documenting an example in design for remanufacture. While the process did result in a novel solution to a problem, limitations in the preliminary process resulted in the location of an analogy at only one level of organization. Future work will be directed to finding analogies at multiple levels of organization as well as using more comprehensive sources of biological phenomena.

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