01: BIOLOGICAL Hierarchy

(Ref: Korn RW, 2005. The Emergence Principle in Biological Hierarchies, Biology and Philosophy (2005) 20:137–151)

(Biological hierarchies are integrated. Each hierarchy constrains members at lower level. Structure and function are correlated at all levels of biological organization. The function is achieved by a coordinated action. Novel properties appear at each levels of hierarchy. Life is sustained by survival and reproduction)

Solar system is familiar to all of us. We know that the sun and a planet impose equal gravitational pull on each other. It is the mass difference makes them distinct so that one orbits the other. Hence a planet with small mass is restrained more by the sun. This is also true for planet and its moon. What we can infer from this **integration** is that an entity at a level **constrains** members at a lower level. The strength of constraints becoming progressively weaker as we descend in the organization.

In living systems, cells are held together by a greater density of covalent and hydrogen bonds of tissue features than these tissue features are held together by organ features and organ features are held together by organismal features. Thus a **hierarchical model** defines several levels of complexity

A simple biological hierarchy is represented below

Hierarchical Unit	**Description**	**Example**
Molecules	Groups of atoms, smallest unit of most chemical compounds	Carbohydrate, Protein, DNA
Cell	Basic biological unit	Epidermal cell, Parenchyma cell, Blood cell
Tissue	A group of similar cells	Muscle tissue, Nerve tissue

Organ	A structure that is composed of different tissues	Liver, leaf, eye
System	Functional unit made up of correlated and semi-independent parts	Digestive system, Photosynthetic system
Organism	Any living thing	Animal, Plant or a microbe
Population or Colony	Similar individual organisms (species) in a specific locality	Asiatic Lion population in Gir forests of Gujarat, India; E. coli population in the mouth
Biome	Major regional community of organisms defined by the habitat and determined by the interaction of the substrate, climate, flora and fauna	Grassland biome, Desert biome, Ocean biome
Ecosystem	A collection that includes all the biotic organisms and abiotic components of the total environment	Marine ecosystem, Himalayan ecosystem
Biosphere	The part of earth that contains all the ecosystems	All ecosystems of Earth

In a hierarchical relationships in the living systems, we can observe many features or characters. They are summarized below:

1. The principal feature of a biological hierarchy is that the **constraints imparted by each of the component**
2. Biological hierarchies **can undergo decomposition** like that of a solar system. Applying a little perturbation energy removes the top levels and as the amount of energy is increased, progressively lower levels are uncoupled
3. A hierarchy can be of two types **structural and functional**. Structural hierarchy is simpler and can be explained by the forces operating within the system (E.g. Cells are organized into tissues, Structure of proteins). We feel energetic when we have a soft drink. This is a **functional hierarchy**, cells are influenced by the sugar supply from outside. An animal

cell or plant cell responding to a hormone secreted from outside is another example. Functional hierarchy is also constrained by the mental state regulated by the nervous system. Based on these facts functional hierarchies are more complex to explain. Hence **structure and function are correlated at all levels of biological organization**

4. Living hierarchies are **composed of sub-hierarchies**: E.g. Atoms are built into macromolecules like enzymes. These enzymes are indeed a sub-hierarchy *i.e.* a chemical sub-hierarchy [Other examples: macromolecules self-assemble into cells (cellular sub-hierarchy), cells differentiate into organisms (specialization sub-hierarchy) and organisms form populations by mating patterns (evolution sub-hierarchy).]
5. A pendulum clock simply explains a hierarchical concept. None of its parts can tell time, but a clock as a whole can. Similarly is the living system**. The coordinated actions of constrained parts** fitting together toward a complex goal. Thus it is it is obvious that the whole is greater than the sum of its parts.
6. A painter begins a part of his whole painting. Later the painting work is elaborated according to the relative size and orientation of the first part. Novel properties that appear at each level of the biological hierarchy as a result of interactions among components at the lower levels. After finishing, the paint dries into the final constrained system. Now the painter assumes that the painting is sufficient to stand by itself as a novel one. Similarly **novel properties that appear at each level of the biological hierarchy as a result of interactions among components at the lower levels.**

Principles of Biology

(Ref: Johnson, AT, 2011. Biology for engineers, CRC Press)

Biology is a very complex science, since living things are very complex. The study of biology requires inter-disciplinary approach. There are several things to imbibe for other branches of science including engineering. To study biology we need to understand what is happening inside at each hierarchical level. Apart from these we should also look into the surrounding physical, chemical and biological environment. We can develop the principles of biology at this context:

1. The primary goal of life is survival and reproduction [genetic material survives for next generation]
2. Living things are constantly changing [evolves gradually]

3. Long-term changes occur in a species only if there is a reproductive advantage [territorial establishment, mating with strongest and fit partner]
4. Life is redundant
5. Co-existence of species requires that each adapts to a different ecological niche [zebra and wild beast]
6. Attributes passed from one generation to the next require an information legacy [inheritance]
7. Each distinguishing biological trait is made valuable by its cost [species invests some energy in attracting a preferred mate e.g. Dancing of male peacock]
8. An individual is a product of both its genetic code and its environment [influence of environment – rabbit coloration]
9. Life is conservative [a species evolves from an existing one]
10. Living things use simple building blocks with complex interactions [polymers – proteins, polysaccharides and nucleic acids]
11. Extremes are not tolerated well by living things, nor do living things create extreme conditions. [Life will exploit its environment to the maximum extent as possible –E.g. bacteria in hot spring]

Life was considered only in terms of physics and chemistry till the recent past. Now it is known to have a third aspect of information that along with the descendant constraints in its hierarchical organization

03: SYMBIOSIS, COEVOLUTION, COMMUNAL BENEFIT, COMMENSALISM AND PARASITISM

[Ref: Reece at al., 2011. Campbell Biology, Pearson; Johnson, AT, 2011. Biology for engineers, CRC Press)

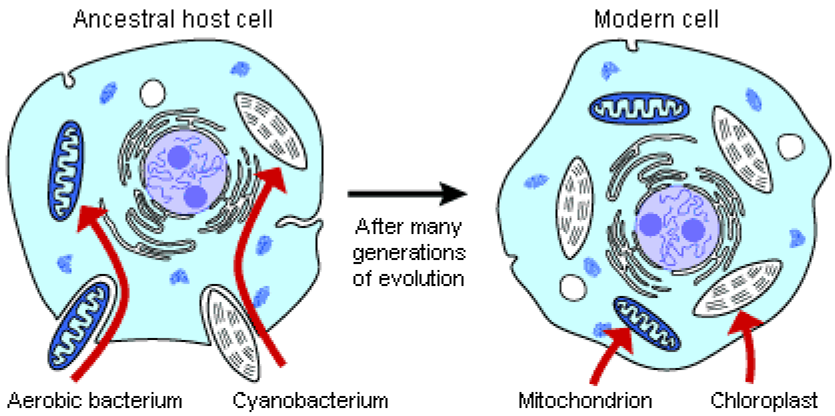
(Biological units cooperates resulting in an interaction and relationship. This has created different forms and levels of interaction for maximum exploitation of the resources. Organisms are benefited from a communal life style.)

Biological units **cooperate** with other biological units resulting in an **interaction and relationship**. This makes an effectively functioning whole organism. The gills gather oxygen, the heart circulates blood, the muscle locomote, the mouth ingests food, the gut digests food, the excretory system eliminates wastes and the liver processes biochemicals. In plants also the biological units cooperate. The root hairs absorb water and nutrients, the xylem and phloem transport materials, the leaves fixes energy from solar photons and cells at various locations emit chemicals for communication.

Symbiosis*:* This is a relationship between dissimilar organisms for the benefit of both the partners. Hence this is a **mutualism**. This is a +/+ interaction. We can see lot of examples from the environment

(1) The association between **hermit crab and sea anemone**. The anemone attaches to the crab's shell and obtains food scraps from the crab. In return, the crab is camouflaged by the anemone and defended by the stinging cells of anemone
(2) **Lichens**: This is a composite organism. The partners are green algae and fungus. The fungus gains oxygen and carbohydrates from the photosynthetic green alga. The alga gains water, carbon dioxide and mineral salts from the fungus. The fungus also provides protection from desiccation. Lichens are nature's bioindicators towards pollution.

(3) **Mitochondria and chloroplast**: It is believed that mitochondria and chloroplasts evolved from prokaryotes that became residents in a larger host cell in an attempt to exploit environment by few biochemical mechanisms.



(Image credit: http://evolution.berkeley.edu/evolibrary/article/history_24)

Coevolution: In this type of example two or more species have developed a mutual dependence that is very profound and essential.

Many species of flowering plants coevolved with specific pollinators. A perfect example can be seen in the case of the Madagascar orchid and its pollinator moth. The orchid produces nectar at the base of a foot long spur. When Charles Darwin saw this orchid for the first time, he predicted the existence of a moth with a proboscis (tongue) long enough to reach that nectar. Later this moth was discovered.

(Image credit: http://zooblogogy.tumblr.com/post/39029261422/during-his-trip-to-madagascar-charles-darwin)

Another example of coevolution is the *Trematolobelia singularis*, a flower found in Hawaii. The flowers are borne in clusters with distinct curve exactly fits the beak of Hawaiian nectar-eating bird called I’iwi.

Communal benefit:

Look at the following interaction in which when a single ant cannot bridge the gap between two leaves to be used in a nest, the worker ants arrange themselves in chains and pull together to close the gap. The entire community is benefited from this behavior.

(Image credit: https://www.catersnews.com/viewstory.php?id=1788)

Bacteria and their communal behavior: Biofilms are the complex, multilayered, multispecies consortia of microbes. These aggregations form sticky and persistent coatings on surfaces.

Biofilms are more resistant to some physical forces like a shear flow. It also well tolerates antimicrobial agents at concentrations much higher than an individual bacteria. Bacteria within biofilms may also be better adapted to withstand nutrient deprivation, pH changes, oxygen radicals, disinfectants and antibiotics than planktonic bacteria.

Biofilm formation is also a mechanism that enables bacteria to remain within a favorable environmental niche. By living together, they can specialize and divide the labor. Hence biofilms are interactive communities. They also provide an opportunity with higher rates of gene transfer. Therefore biofilm formation is a communal behavior of many bacteria

Surgical equipment and catheters are susceptible to biofilm formation by bacteria. This is a great threat. It will be more severe if the bacteria in the biofilm is drug resistant.

Commensalism: This is an interaction of +/o type. This is an interaction between species that benefits one of the species but neither harms nor helps the other. Cowbirds and cattle egrets feed on insects flushed out the grass by a grazing cattle. The birds increases their feeding rates by following an herbivore and clearly benefit from the association. On the other hand the cattle is unaffected or not benefited from the association. However, cattle may sometimes derive some benefit since the birds sometimes removes the ticks and mites from the cattle's body.

Parasitism: Parasitism is an interaction in which one organism is benefited, while the other is harmed. Therefore this is a +/- symbiotic interaction. The organism benefited is known as the parasite and the affected organism is called the host. The host is harmed in this process. Parasites can be endoparasites (E.g. Round worms) or ectoparasites (E.g. Ticks and Mites).

04: BIOINSPIRATION AND BIOMIMETICS

(Ref: National Geographic Magazine 2008 April Issue;

Flammang BE and Porter ME. Bioinspiration: Applying mechanical design to experimental biology. Integrative and comparative Biology 51:128-132.

Santaulli C and Langella C, 2011. Introducing students to bio-inspiration and biomimetic design: a workshop experience. Int J Technol Des Educ. 21:471-485.

Lenau T, 2008. Sensing in nature: using biomimetics for design of sensors. Sensor Review 28:311-316

Shimomura M, 2010. The New Trends in Next Generation Biomimetics Material

Technology: Learning from Biodiversity. Nistep Quarterly Review 37:53-75.)

<u>INTRODUCTION: Bioinspiration and biomimetics – creativity and innovation</u>

One of the earliest inspiration we got from nature is to fly. We tried several times to mimic it, many lost their life during this experiments.

The discovery of Velcro: Mimicking from dog's coat

Design by Nature led to the invention of Velcro. This is an example of **biomimetics** — the young science of **adapting designs from nature** to solve modern problems. The terms bionics, bionik (German) and biomimetics, are of a much more recent date. Biomimetics is a study involving copying, imitating and learning from nature.

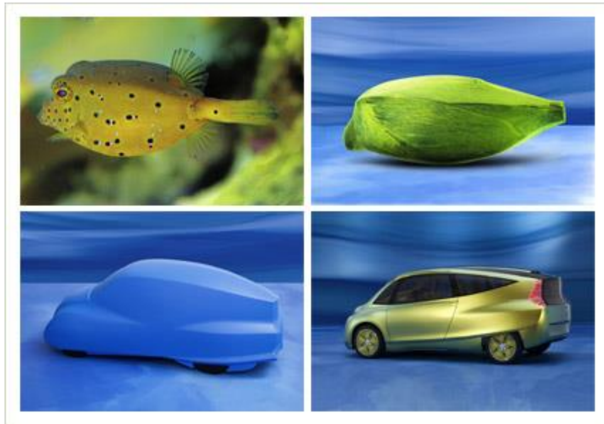
Examining burs plucked from his pants and dog's coat, Swiss engineer George de Mestral found their spines were tipped with tiny hooks—sparking his invention of Velcro. He was disappointed that fashion designers didn't rush to adopt his product [may be because of that ripping sound!] But Velcro found loftier applications "in the first artificial heart surgery and on trips into space." We will be surprised to know the fact that NASA was the one of the first user of Velcro tape sending Velcro to the moon on space boots and suits.

Biomimetics is the technique of imitating a biological material or function in the construction of artificial devices or systems. So the prototype is the living system and the artificial device is the copy.

Functionality in many of the tools and **artefacts** that we use in our daily life can be traced back to origins in nature.

First we will look into few examples.

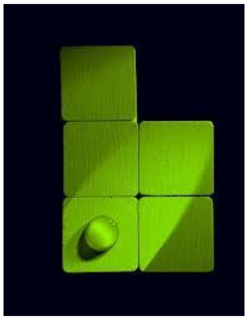
(1) Mercedes-Benz's bionic concept car



Behind the squared-off contours of the boxfish lies a lesson in sleek design. Low drag helps the fish swim up to six body lengths per second, stabilized by the keel-like edges of its carapace. The boxfish's surprisingly streamlined form inspired Mercedes-Benz's bionic concept car. Flowing vapors during wind-tunnel tests in a Stuttgart facility show off the car's aerodynamics, which helps boost its gas mileage to as high as 70 miles per gallon.

2. Australian Devil Lizard

Sipping through a foot, the thorny devil lizard of the arid Australian desert demonstrates its ability to wick water to its mouth via channels between its scales. Scientists hope to mimic the mechanism to develop water-capture technologies for dry regions.



(3) The Lotus effect

In 1982 botanist Wilhelm Barthlott of the University of Bonn in Germany discovered in the lotus leaf a naturally self-cleaning, water-repellent surface. The secret lies in waxy microstructures and nanostructures that, by their contact angle with water, cause it to bead and roll away like mercury, gathering dirt as it goes. Barthlott patented his discovery, calling it the Lotus Effect. It has found commercial application in products like the biomimetic paint Lotusan (on blocks above). Infused with microbumps, the paint is reputed to repel water and resist stains for decades.

(4) Translating whale power into wind power

The whale's flippers scalloped edge helps it generate force in tightly banked turns. The whale-inspired blades are being tested at the Wind Energy Institute of Canada to see if they can make more power at slower speeds than conventional blades, and with less noise.

The significance of Bioinspiration/Biomemetics

The production of bioinspired and biomimetic constructs has fostered much collaboration between biologists and engineers. Biologists, engineers, and industrial designers differs in what will be the exact definition of this branch and how far we can copy a biological design/ This has resulted in a confusion regarding the level of integration and replication of biological principles. Innovative researchers with both biological and engineering backgrounds have found ways to use bioinspired models to explore the biomechanics of organisms from all kingdoms to answer a variety of different questions. Bringing together these biologists and engineers will hopefully result in an open discourse of techniques and fruitful collaborations for experimental and industrial endeavors.

Biomimetic vs. Bioinspired: The difference:

The terms **biomimetic** and **bioinspired** are often used almost interchangeably, because they do describe very similar concepts. In both cases, the idea is to replicate some property or function of a biological system.

The biomimetic approach most commonly strives to achieve this goal by reproducing some aspects of the biological system. An example we can found in early plane designs. Such early designs involved flapping wings, a biomimetics of birds.

In contrast, **bioinspired approach** aims to **discover and capture an essential idea** that underpins a biological system with an ultimate goal to use the same idea at the technological implementation level.

The two approaches are not mutually exclusive, i.e., in many cases a biomimetic solution can provide the best technological implementation of a bioinspired design, but a biomimetic solution is not always optimal from an engineering prospective. The modern technology of powered flight, for example, is dominated by designs that are bioinspired (by the idea of using a wing for flight), but distinctly *not* biomimetic. Fixed-wing aircraft turns out to be a more efficient solution for carrying cargo than are designs that replicate flapping wings of birds.

Application of Bioinspiration/Biomemtics

1. Biological Materials & Nanostructures : Starting from well-known biological structures, such as the complex structures with high toughness (biominerals like diatom and sponge silica, seashells and bone) and the structures with hierarchical organization and high mechanical strength (of organic fibers like spider silk), scientists and engineers develop the principles for design of novel nanomaterials with superior properties, using biomimetic nanotechnology.

2. Robotics: Animals exploit soft structures to move effectively in complex natural environments. These capabilities have inspired robotic engineers to incorporate soft technologies into their designs. The goal is to endow robots with new, bioinspired capabilities that permit adaptive, flexible interactions with unpredictable environments. Human-made manufacturing robots are mostly designed to be stiff. By contrast, in the animal world soft materials prevail. The vast majority of animals are soft bodied, and even animals with stiff exoskeletons such as insects have long-lived life stages wherein they are almost entirely soft (maggots, grubs, and caterpillars). Studying how animals use soft materials to move in complex, unpredictable environments can provide invaluable insights for emerging robotic applications in medicine, search and rescue, disaster response, and human assistance.

3. Sensing the Environment: Biosensors- Just recall that we discussed Lichens as bioindicators for pollution. In fact they are sensing the pollution and avoids polluted areas such as road sides, town and near-vicinity of a factory.

   Nature has developed, by many years' evolution processes, sensing organs and strategies. These natural sensors are being really difficult to achieve artificially by sensor technologists in versatility, performance, tolerance to saturation or sensitivity. The objectives of the system is to mimic animal senses to perform olfaction or tasting in hazard conditions, or in non-stop manner. This objective is followed by artificial olfaction or artificial taste researchers. But the same principle of using sets of sensors is being adapted to many other objectives for example a skin of pressure sensors to detect structural stress in vehicles or buildings.

4. Decision Making: Bioinspired algorithms and applications. The mystique of biologically inspired (or bioinspired) paradigms is their ability to describe and solve complex relationships from intrinsically very simple initial conditions and with little or no knowledge of the search space.
5. Bioinspiration in Architecture (Already discussed examples)