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Good Practices of Biomimicry in Education

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INNOVATION IN SCHOOLS

INSPIRED BY NATURE SOLUTIONS

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1. Introduction

1.1. What is biomimicry

Biomimicry or biomimetics is the examination of nature, its models, systems, processes and elements to emulate or take inspiration from in order to solve human problems [INT.1,2]. The term biomimicry and biomimetics come from the Greek words bios, meaning life, and mimesis, meaning to imitate.

Biomimicry (literally: imitation of the living) aims to take inspiration from natural selection solutions adopted by nature and translate the principles to human engineering. The biomimicry approach aims to favor “choices” tested by nature which had millions of years to understand what works best and what doesn’t. Designs following biometrics will ultimately allow human productions to be more efficient, resilient and sustainable [INT1.2].

Biomimicry is learning from and then emulating natural forms, processes, and ecosystems to create more sustainable designs. The core idea is that nature has already solved many of the problems that we are facing: pollution, energy, food production, climate control, benign chemistry, transportation, collaboration, etc. Mimicking these natural designs can help humans develop solutions that save energy and work as a system to create conditions conducive to life. Biomimicry is a way of looking for sustainable solutions by imitating life’s blueprints, recipes, and ecosystem strategies. Finally, it brings us into a harmonic relation with the rest of the natural world.

The central idea is that nature has already fixed many problems society is facing. Animals, plants, and microorganisms are experienced engineers. They know what works, what’s appropriate, and most importantly, what lasts on Earth. The main belief of the biomimicry approach is that after 3,8 billion years of research and development, what did not work is now a fossil and what is around us is the secret to survival.

1.2. Principles and characteristics

Biomimicry is a technological-oriented approach focused on putting nature’s lessons into practice [INT1.2]. According to Janine Benyus, biomimicry sees nature as:

- A model. It studies nature’s models and imitates them or uses them as inspiration for designs or processes with the goal of solving human problems
- A measure. It uses ecological standards to judge the rightness of human innovations
- A mentor. It is a new way of observing, assessing and valuing nature

In 1960, the term “bionics” was coined by psychiatrist and engineer Jack Steele to mean “the science of systems which have some function copied from Nature.” However, the word’s later misuse in connection with electronically-operated artificial body parts and the 1974 television series The Six Million Dollar Man led to it being dropped by the scientific community. Otto Schmitt, an American academic and inventor, coined the term “biomimetics” to describe the transfer of ideas from biology to technology and it first appeared in the Websters Dictionary in

1974. The term “biomimicry” appeared as early as 1982 but was popularized by scientist and author Janine Benyus in her 1997 book Biomimicry: Innovation Inspired by Nature. Benyus suggests looking to Nature as a “Model, Measure, and Mentor” and emphasizes sustainability as an objective of biomimicry [INT1.3].

The ten principles of biomimicry were developed by Janine Benyus. They include:

1. building from the bottom up
2. self-assembling
3. optimizing rather than maximizing
4. using free energy
5. cross-pollinating
6. embracing diversity
7. adapting and evolving
8. using life-friendly materials and processes
9. engaging in symbiotic relationships
10. enhancing the bio-sphere

The main characteristics of biomimicry-inspired optimum systems design include:

- form fits function
- resilience
- decentralization
- effectiveness and good performance
- abundance (using what’s at hand)
- bottom-up design
- cooperation and collaboration
- the whole is greater than the sum of its parts

1.3. Levels of biomimicry

According to Janine M. Benyus (Biomimicry 3.8), there are three distinct levels of Biomimicry [INT1.3]:

The first level of biomimicry is the mimicking of natural form. For instance, you may mimic the hooks and barbules of an owl’s feather to create a fabric that opens anywhere along its surface. Or you can imitate the frayed edges that grant the owl its silent flight. Copying feather design is just the beginning, because it may or may not yield something sustainable.

Deeper biomimicry adds a second level, which is the mimicking of natural process, or how a thing is made. The owl feather self-assembles at body temperature without toxins or high pressures, by way of nature's chemistry. The unfurling field of green chemistry attempts to mimic these benign recipes.

At the third level is the mimicking of natural ecosystems. The owl feather is gracefully nested—it's part of an owl that is part of a forest that is part of a biome that is part of a sustaining biosphere. In the same way, our owl-inspired fabric must be part of a larger economy that works to restore rather than deplete the earth and its people. If you make a bio-inspired fabric using green chemistry, but you have workers weaving it in a sweatshop, loading it onto pollution-spewing trucks, and shipping it long distances, you've missed the point.

1.4. Biomimicry in education

Biomimicry today is not just influencing design, it's also revolutionizing education – offering teachers a compelling way to teach biology, STEM subjects, creative problem-solving, and systems thinking. Biomimicry in education can provide:

1. A compelling way to present science, technology, engineering, and math subjects.
2. An interdisciplinary platform to connect subjects to one another, and to the real world beyond classroom walls.
3. A tool to enhance creativity and problem-solving skills through design and project-based activities.
4. A new way for young people to view and value the natural world; to see nature not just as something to learn about, but as something to learn from.
5. A unique and powerful way to think and learn about sustainability.

One of the first examples of biomimicry is the study of birds to enable human flight. Although never successful in creating a "flying machine," Leonardo da Vinci was a keen observer of the anatomy and flight of birds and made numerous notes and sketches on his observations as well as sketches of various "flying machines." Accordingly, the Wright Brothers, who finally did succeed in creating the first airplane in 1903, apparently gained inspiration for their airplane from observations of pigeons in flight. Modern biomimicry research has inspired glue from mussels, solar cells made like leaves, fabric that emulates shark skin, harvesting water from fog like a beetle, and more. The fastening marvel called Velcro inspired by the tiny hooks found on the surface of burs, carbon-sequestering cement inspired by corals, and energy efficient wind turbines inspired by schooling fish are other examples of biomimicry being used to create better products in the modern world. In fact, the green building sector has enthusiastically embraced biomimicry as an interdisciplinary way to investigate the design of buildings that move beyond current definitions of sustainability towards regenerative and restorative.

Incorporating biomimicry in education would suggest that education should be decentralized, self-regulating, co-operative, resourceful, always adapting and shifting in response to new information and changing conditions, active and always in motion, with built-in feedback mechanisms.

2. Methodology

In order to collect and assess examples of good practices regarding biomimicry in different contexts, the InNature partnership has developed a template which consisted of:

Title

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Description

………

………

………

Keywords

………

Subject Domain

………

………

Objectives

………

………

Partnership opportunities

Family	.
Teachers	
Universities or technology companies	
Researchers	

In total, 22 cases were selected, as listed below:

- Solar panel and the eye of the moth
- The structure of a cactus and a water collector.
- The lithium-ion batteries model after pomegranates

- The Burr and the Invention of Velcro
- Sequester carbon with cement by studying coral
- Beaver Dams
- Whales & Wind Turbines
- Spiders & Protective Glass
- Sharks & Aquatic Vehicles
- Butterflies & Solar Power - leaf & photosynthesis
- Kingfisher & The Shinkansen Train
- Gecko Gloves
- Canine Scent Receptors
- Armadillo Backpack
- Cat's Eyes Safety Markers
- Optimal Transportation Network
- The collection of water using a natural leaf design
- Inspiring engineering - from nature to community
- Mound facilitates gas exchange.
- The proboscis of the mosquito inserts painlessly in the skin.
- Permaculture
- Cleaning of water using ecosystem plants

After close inspection and analysis, 8 good practices finally were selected and are presented in detail in the following chapter.

3. Good Practices

3.1. Sequester carbon with cement by studying coral

Researchers at Stanford University have developed a novel way to create a new form of carbon neutral cement by studying the formation of coral reefs and applying the principles at work. Coral takes in minerals and CO2 and then secretes calcium carbonate to build its hard exoskeleton. Inspired by this construction process, Stanford scientist Brent Constanz has developed a way to capture CO2 and dissolve it in seawater to form calcium carbonate, which has properties suitable for use in construction and could replace Portland cement (which is responsible for more than a ton of CO2 for every ton of product created). This new technology could reduce the environmental impact of construction in a big way by capturing and sequestering CO2 emissions while creating a durable building material.

The animals that make up corals are anthozoans, a class of invertebrate within the phylum Cnidaria, which includes a diverse assortment of creatures like jellies, hydroids, and sea anemones. In this mostly marine and entirely carnivorous club you can either float or anchor yourself to a surface, and many do both within their lifespan.

When corals anchor themselves, they do so as attached polyps in large colonies, and they do it by using calcium carbonate, or lime, as a cement. The Great Barrier Reef along Australia's northeastern coast is a huge collection of these colonies, built on the 10,000-year-old ruins of their ancestors' exoskeletons. Their method for building their homes is worlds away from the way humans have been making cement and concrete, but one company has developed an innovative method for using seawater (which corals also utilize to make calcium) to both make cement and sequester carbon dioxide. But first, we'll look at how corals make their homes.

Coral reef communities in general, and coral polyps in particular, exhibit that characteristic so common in these crowded, diverse environments: interdependence. When real estate is expensive, you find a way to make a living (ask any of my fellow Californians). Stiff competition makes for some pretty creative methods, however, and often they include the mutually beneficial relationship called symbiosis.

The carnivorous corals can't go it alone so they have co-evolved with an algae boarder, a paying house guest who supplies most of their energy needs through photosynthesis. The algae are there for the same reason as everyone else: clear, calm and relatively warm water. For their tithing of sugars they receive the shelter and protection of the corals' limestone fortress. They also receive a daily nutritious dose of nitrates and phosphates from the corals' waste. While this mutualism is beneficial to both parties, it isn't entirely unforced. The corals excrete a digestive solution that causes the algae cell walls to leak their precious food. It's estimated that 80 percent of the algae's sugars go to the corals. An entire ecosystem is based on this relationship that translates the energy of the sun into the building of a massive underwater world.

Corals are extremely sensitive to small changes in the magic formula that makes up their habitat. Even slight changes in temperature, salinity, light and nitrogen can kill them outright. It has been estimated that half of the world's reefs could die out within 50 years. How we reduce and reverse the air pollution that is causing climate change will be critical to the survival of these shallow seas ecosystems. Ironically, the corals themselves may provide part of the answer for us.

Unlike their human counterparts, anthozoans don't make their cementitious homes by mining fossil rock. They don't grind it up, cook it to over 1,450 degrees C and then pound the baked material back into a pulverized dust. No, they just take in plain seawater, and precipitate out calcium and magnesium at normal temperatures and pressure. The calcium is turned into a crystal form of carbonate called aragonite. They secrete this lime out a little at a time while they are multi-tasking with other things like gathering food and having sex.

We could use some pointers from our salty friends, especially since cement production is the third largest source of GHG emissions in the U.S., according to the U.S. Environmental Protection Agency. The $11.9 billion industry produced approximately 110.3 million metric tons of cement in 2007, from 116 plants in 36 states. Yearly global production of cement dwarfs this figure: it is reckoned by the Portland Cement Association to be approximately 1.25 billion metric tons, with much of it spurred by development in China and India. Sobering indeed, when you consider that every ton of cement produced is matched by another ton of carbon dioxide (CO2) put into our atmosphere. Happily, there are some companies that are developing ways to make cement production more like the coral's methods.

The Calera Corporation operates a small facility on the central California coast that is testing some of these biomimetic processes [GP1.1]. Located next to the Moss Landing Power Plant, the facility has been making small batches of cement by processing CO2 gas through seawater to make first carbonic acid and then carbonates [GP1.2]. Their process is proprietary and in patent development, but, if successful, could revolutionize how we make cement and, perhaps more importantly, how we capture and sequester carbon. It is an elegant scheme: Take a waste product, CO2, that is so damaging but ubiquitous that governments like the state of California are forced to regulate its reduction. Use this waste as a feedstock, process it through the most abundant substance on earth, seawater, and produce a material that not only can be used for building but permanently entombs the offending carbon. To power part of your processing use the free waste heat from the power plant itself. When you are done, return the unheated, unpoisoned seawater back safely, or pass it on as a pretreated (and money saving) stock for desalinization.

As an example, the Moss Landing plant is a gas-fired electricity generating facility that produces about 1,000 megawatts of power. While it is doing this it is also pumping out about 30,000 parts per million of CO2 into the air. Calera claims that it can capture most of this carbon and sequester a half-ton of carbon for every ton of cement that it makes. Company officials are currently describing their product as a supplementary cementitious material admixture, rather than as a replacement for Portland cement. It is being promoted as a replacement for fly ash, which can be increasingly hard to obtain, and as a better performing portion of a greener concrete mix when 50 percent recycled materials are specified.

The eventual possibilities sound a lot like the interdependent material cycling in coral colonies that we have just discussed, and the industrial ecology practiced in Kalundborg, Denmark [GP1.3]. There, for instance, the city's power plant shunts several by-products to waiting, intentionally located industries, including “waste” heat, fly ash, heated seawater, and gypsum (another ingredient, by the way, in Portland cement). A similar symbiotic arrangement of power plant, carbon capture cement plant and desalinization plant seems worthy of study.

This process holds even greater promise for what the U.N. Intergovernmental Panel on Climate Change considers a critical option for reducing climate-changing air pollution: Carbon capture and sequestration [GP1.4]. Most any power plant will do as a source of stock; in fact, the dirtier the better. We have a wealth of this waste-turned-resource in the United States. Approximately 2.5 billion metric tons of CO2 were produced in 2006, by 2,775 power plants. Of these, 600 were coal-fired plants that spewed 5 times more pollution (or should we say grey gold?) than the Moss Landing operation. The Calera process would take sequestration one step further by recycling the carbon into a very useable and worthwhile product.

Since Calera potentially provides at least three benefits, pollution abatement, seawater treatment and cement production, the company seems to have the opportunity to engage in several separate markets. This may offer the chance to be as innovative at the business table as at the manufacturing plant. Indeed, a recent article in the Harvard Business Review noted that the company was considering giving the cement away for free while making its income from carbon capture [GP1.4]. Whatever their eventual business model, for sure the anthozoans will be pleased at their success [GP1.5].

3.2. Butterflies & Solar Power - leaf & photosynthesis

Sed aliquet sapien lectus, quis luctus quam consequat eu. Etiam a pretium nulla. Curabitur a consequat neque. Aenean fringilla augue at mi tristique, ut gravida est pretium.

The wings of a butterfly have inspired a new type of solar cell that can harvest light twice as efficiently as before and could one day improve our solar panels.

Solar panels are usually made of thick solar cells, and are positioned at an angle to get the most amount of light from the sun as it moves throughout the day. Thin film solar cells, which can be only nanometers thick, have a lot of potential [GP2.1]. These are cheaper and lighter, but because they're less efficient, we usually use them only in watches and calculators, instead of solar panels. Scientists studied the black wings of the rose butterfly, and copied the structure to create thin solar cells that are more efficient [GP22.2]. Unlike other types of cells, these can absorb a lot of light regardless of the angle, and are also easy to make. The results were published in the journal *Science Advances* [GP2.3].

The rose butterfly is native to Southeast Asia. Because it is cold-blooded and needs sunlight to fly, its black wings have evolved to be very good at absorbing energy. "The really interesting thing is that the butterflies, which have evolved these complex structures as a result of selection over millions of years, are still way outperforming our engineering," YaleNUS College biology professor Vinod Saranathan told *The Verge* in an email. (Saranathan was not involved in the study.) [GP2.4]

To figure out why these butterflies are so efficient, scientists led by Radwanul Siddique, a bioengineer at the California Institute of Technology, looked at wings under an electron microscope and created a 3D model of the wings' nanostructures [GP2.5]. The wings are built from tiny scales that are covered in randomly spaced holes. The holes are less than a millionth of a meter wide, and they help scatter the light and help the butterfly absorb heat.

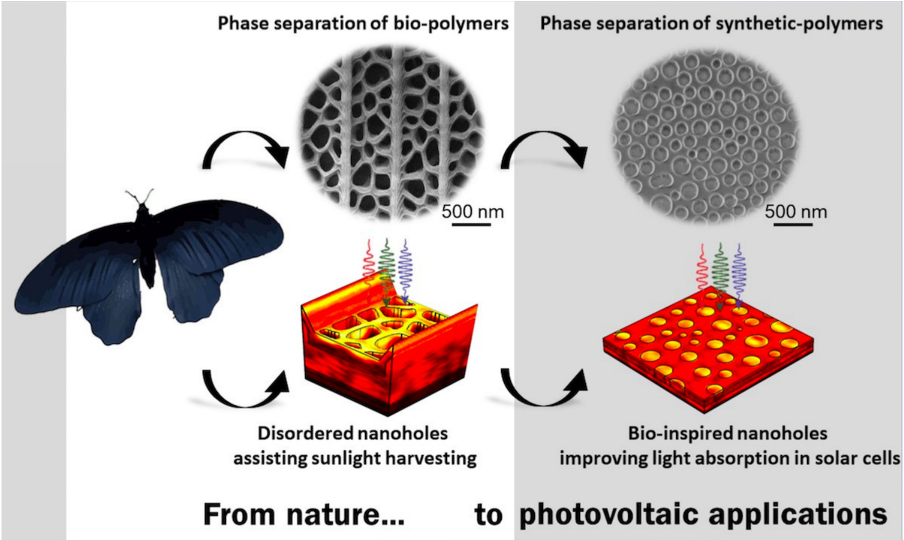

Figure 1: From nature to photovoltaic applications (source Radwanul Hasan Siddique, KIT/Caltech)

The holes are random in size, distribution, and shape, says Siddique. Using computer models, the team figured out that the position and order are important for absorbing light, but the shape doesn't matter. Next, they created a similar structure using extremely thin sheets of hydrogenated amorphous silicon that have the same type of holes.

"I think what's interesting is the excellent approach of looking at the underlying physiological concepts and then taking these concepts and emulating them in a structure that doesn't look quite look like how a butterfly looks but does the same physics," says Mathias Kolle, a professor of engineering at the Massachusetts Institute of Technology [GP2.6]. He added that the design will need to be scaled, but the fabrication techniques discussed in the paper were relatively simple. (Siddique says it took only about 10 minutes to make these sheets.)

Figure 2: Rose butterfly (source Radwanul Hasan Siddique, KIT/Caltech)

Most solar panels are positioned at an angle, which means they generate lots of power for a few hours and then not much the rest of the time. Solar panels using Siddique's technique could produce more power throughout the day. Though Siddique is now at CalTech, he did this research as part of his doctoral work in Germany, and some members of his old lab have already received funding from the German Research Foundation to work on solar cells and LEDs [GP2.7].

3.3. Cat's Eyes Safety Markers

One of the most valuable devices in driving safety over the past century has been the cat's eye—yet, most people don't even know what it is or that it bears that name. If you've driven down a dark, rural stretch of road through the countryside, you've seen periodic glimpses of light flashing up at you from the median. If you've gotten close enough to inspect these devices embedded in the pavement, you've realized that they're not light projectors—they're light reflectors. They're called cat's eyes [GP3.1].

English inventor Percy Shaw created many gadgets, but he's most widely recognized for his contribution to road safety: the cat's eye. He developed this reflective road stud in 1934 to help driver's follow the road in the dark or fog. He was inspired by how vehicle headlights reflected on road signs. Eventually, the device caught on and became mandatory on British roads, well before reflective paint was widely used to mark medians and shoulders.

The device used glass encased in rubber and metal to precisely reflect light rays from vehicle headlamps back at the driver. Over time, the stud was simplified and refined into a rubber block with abrasion-resistant glass (how most of the markers in America are).

Today, cat's eyes are becoming more high-tech. They're gradually being replaced with solar-powered LED versions, which can be seen 10 times further than reflective cat's eyes and can run for days on a single charge. These high-tech replacements are supposed to last three times as long and cost three times as much.

3.4. Optimal Transportation Network

In this good practice the goal is to find the best way to go from place to other places in order to e.g. deliver goods, put tunnels, put bridges, irrigation network, through the shorter route and in more ecological way. This good practice is related to biomimicry, mathematics, physics, but also to sustanaibility and chemistry [GP4.1].

Figure 3: Example map of places (source https://portal.opendiscoveryspace.eu/en/osos-project/optimal-transportation-network-855963)

Subjects that are addressed in this good practice include the following:

- Geography: cruises on the sea, shipping container, putting bridges and tunnels, water network, real time trafic optimization (GPS, trafic jam)
- Economy: Goods or mail delivery for carriers, distribution centres, Hyperloop, modifying the public transport or the circulation (jams, pollution, accessibility), optical fiber network.
- Mathematics: measures, geometry (GIS), scales, combinatorics, graph theory, optimization.
- Computer science: algorithmic, coding.
- Physics: surface tension, water properties, soap elasticity,
- Chemistry: soap molecules.
- Technology: models production.
- Life and Earth Science: Irrigation in agriculture, minimal surfaces in biology (DNA, cells).

During the educational activity of this practice students learn and familiarize with various scientific topics like the surface tension of a liquid, features of bubbles, physical principle of bubble spread. They are also educated about environmental issues, problems, challenges and optimal ecological/economical solutions. In addition, students work in groups and collaborate throughout the project.

The project addresses the problem of building a net connecting different places e.g. travel, railways, short tunnels, irrigation pipes. The main question is to find the optimal, in space and time, and ecological solutions to do that. The project can be divided in the following steps:

Figure 4: Example map of main cities to connect (source https://portal.opendiscoveryspace.eu/en/osos-project/optimal-transportation-network-855963)

- Put the students into small groups. Give them maps and let them find a solution by themselves first by doing measures.
- Numerate some solutions.
- Search for an automatic solution (e.g. by using a computer).
- Observe the behavior of soap bubbles.
- Deduce a solution.
- Create a model of your neighborhood or the given area as it is illustrated in the images below.
- Create a soap solution by dilution of some quantity of soap in a basin.

Figure 5: Example map of country (source https://portal.opendiscoveryspace.eu/en/osos-project/optimal-transportation-network-855963)

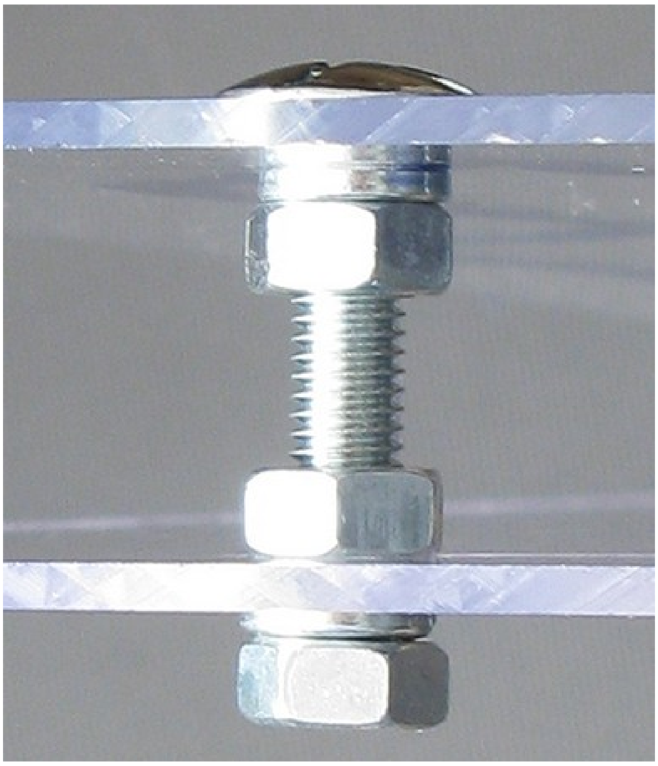

Figure 6: Construction of two flat layers
(source https://portal.opendiscoveryspace.eu/en/osos-project/optimal-transportation-network-855963)

Then put the model in the soap basin and remove it. A soap film appears betwin the 2 layers of the model. This film will connect the different points on the map. The length of the film is optimal since the soap has an elastic property and get always the minimal position. The solution is not unique. Student can compare after that the minimal solution among the optimal solutions.

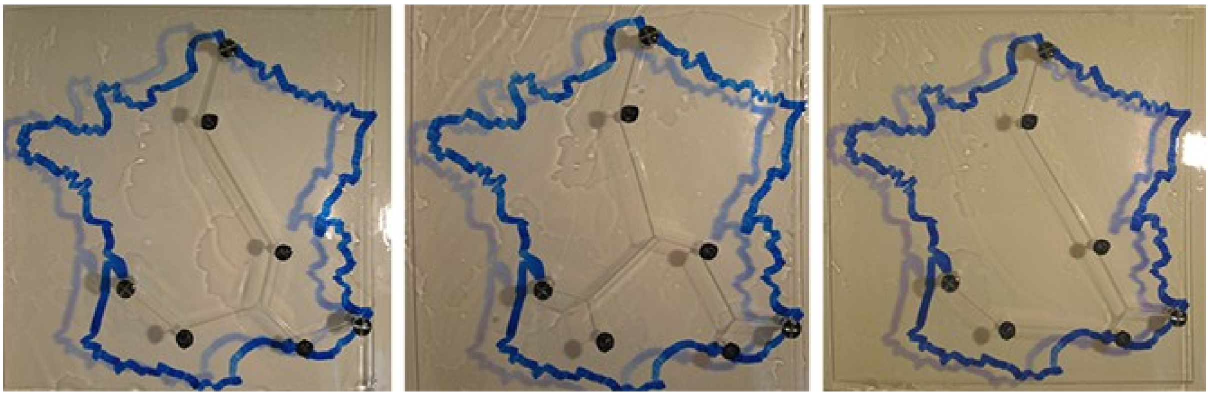

Figure 7: Examples of minimal solutions
(source https://fr.science-questions.org/experiences/79/Optimiser_les_transports_avec_un_film_de_savon/pics_o/Plaques_empilees.jpg)

3.5. The collection of water using a natural leaf design

The leaves and root of the desert rhubarb maximize water collection by directing rainwater to the plant's base and absorbing water from saturated ground. The desert rhubarb grows in the arid mountains of Jordan and Israel, where average annual rainfall is only 75 millimeters. In an average rainfall episode, up to two thirds of rainwater can evaporate before penetrating the soil. Because of this, most desert plants have shallow roots that collect the remaining surface water before it evaporates further.

The desert rhubarb sets itself apart by having a sophisticated water collection system that transports and absorbs water deep in the ground. First, rain water collects on the surface of the rhubarb's leaves. The rhubarb has one to four meter long leaves with a series of successively wider, hydrophobic (meaning "water-fearing") grooves embedded into its sides. In a sleek system, the grooves funnel rain water down the leaf similar to a system of rivers and creeks down a mountain.

Next, the collected rainwater pools on the soil at the base of the plant. This small area of soil becomes saturated, allowing water to seep deeper into the soil. In an average rainfall, water penetrates desert soil between one to three centimeters. Pooling around the rhubarb, however, helps water to penetrate over ten centimeters into the ground. This is a comparatively high volume of water collected. In addition, the deeper the water penetrates the soil, the less exposed it is to the sun's heat, and the less it will evaporate.

Lastly, the water is absorbed. The rhubarb has a single, long root that extends down into the desert ground. Compared to the thin shallow root system of its neighbors, the rhubarb root absorbs up to three times as much rainwater. While the single root is still technically collecting surface water, the pooling enabled by the grooved leaves has already brought the water much deeper into the soil.

The project looked at using the structure of leafs found in nature to capture water vapor from the air and transport it for use in a domestic dwelling. Our problem was then to transfer the water from the walls of the building into a storage reservoir once more we reverted to nature.

To understand biomimicry our group went outside to observe and get feel for nature in the great tradition of Leonardo da Vinci. This leaf provoked a conversation and inspired memories of leaves that are able to gather moisture directly from the atmosphere . We discussed the idea of converting this nature process into a function which could convert air vapor into water and be placed on the side of a building in hot climates. In order to develop a system for the transfer of water we fist looked at non succulent leaf structure. The leaf structure was not very useful for our purposes. In looking again at nature we found a tree that was both wet and dry to the touch in different areas. We observed that through a type of capillary action water was being moved through the tree we formed a hypothesis that by combining our two observed phenomena we could gather and move water via methods inspired by nature.

3.6. The proboscis of the mosquito inserts painlessly in the skin

The mouthparts of female mosquitoes have evolved to form a special proboscis, a natural biomicroelectromechanical system (BMEMS), which is used for painlessly penetrating human skin and sucking blood. Scanning electron microscope observations show that the mosquito proboscis consists of a small bundle of long, tapering, and feeding stylets that are collectively called the fascicle, and a large scaly outer lower lip called the labium. During blood feeding, only the fascicle penetrates into the skin while the labium buckles back to remain on the surface of the skin. The mosquito uses the two maxillas as variable frequency microsaws with nanosharp teeth to advance into the skin tissue. This elegant BMEMS enables the mosquito to insert its feeding fascicle into human skin using an exceedingly small force.

Figure 8: Mosquito amd its proboscis
(source https://news.osu.edu/news/2018/06/25/painless-microneedle/)

Engineers at Ohio State University’s biomimicry laboratory rigorously researched all existing literature on how a mosquito pierces its victim and then draws blood. 'We used our engineering backgrounds to figure out the mechanism used by mosquitoes to puncture victims painlessly,' says researcher Bharat Bhushan in a message from Ohio State University about the painless microneedle. In addition, the engineers carried out their own research on the extended proboscis of a common mosquito species, using nanoindentation to determine the hardness of its various parts.

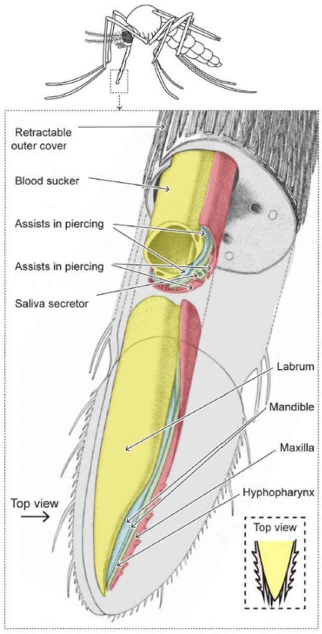

Figure 9: An artful device
(source https://news.osu.edu/news/2018/06/25/painless-microneedle/)

A mosquito's proboscis turns out to be an artful device. It is relatively soft at the tip and on the side, hardening in parts more towards the inside and closer to the head of the mosquito. According to Bhushan, 'The skin clearly suffers less pain from the soft part.'

The mosquito first uses the tip to find a suitable place to pierce the skin, and then inserts a tube with a serrated exterior design. The mosquito vibrates this tube at a frequency of about 15 Hz, with a movement of less than a 0.1 mm. Sawing the skin sounds painful, but the vibration actually makes penetrating the skin easier. The pressure needed by the mosquito to pierce the skin is a third of that needed by an injection needle. Less pressure on the skin means that it deforms less, and the skin nerves emit fewer pain reactions.

Once the proboscis is inserted in the skin, the mosquito applies a numbing agent, a substance with proteins that eases pain. Only then does the mosquito search for the nearest blood vessel with the soft tip of its proboscis. After finding a blood vessel, the mosquito again uses a vibrating motion to penetrate the vessel with the softer tip, but this time at a much lower frequency of up to 5 Hz. Once in the skin, the mosquito has to overcome greater resistance. Rapid vibration is therefore not possible, but neither is it necessary, because the wall of the blood vessel is much softer than the outside of the skin. Once the tip of the proboscis is in the blood vessel, the mosquito begins to draw blood.

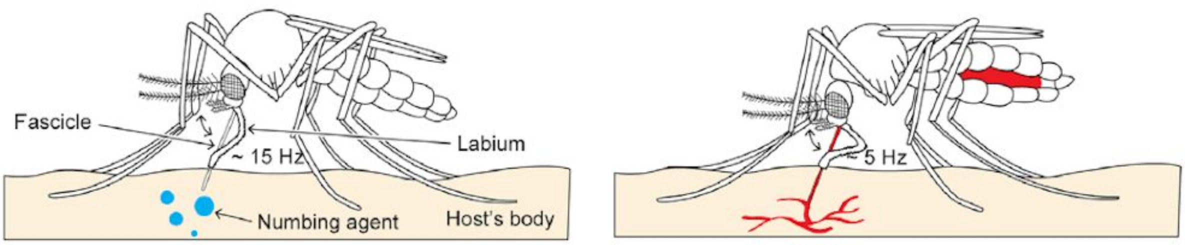

Figure 10: The mosquito first injects a numbing agent before penetrating the flesh to reach a blood vessel
(source https://news.osu.edu/news/2018/06/25/painless-microneedle/)

So, what does this all mean for the design of a microneedle? How can we design of a microneedle imitating the mosquito model? The researchers are in favour of a double needle. One needle pierces the skin and administers the drug or draws blood, the other administers a light anaesthetic. Like the mosquito's proboscis, the first needle is softer at the tip, while the outside immediately surrounding it is serrated. It pierces the skin using a vibrating action. The next step now is to actually make the needle according to this design. The objectives are reduced pain for injecting or drawing blood samples or to make very small biomedical devices, that for instance are used in diabetic patients to monitor blood-glucose levels.

3.7. Permaculture

Permaculture is an innovative framework for creating sustainable ways of living. It is a practical method of developing ecologically harmonious, efficient and productive systems that can be used by anyone, anywhere. By thinking carefully about the way we use our resources - food, energy, shelter and other material and non-material needs - it is possible to get much more out of life by using less. We can be more productive for less effort, reaping benefits for our environment and ourselves, for now and for generations to come. This is the essence of permaculture - the design of an ecologically sound way of living - in our households, gardens, communities and businesses. It is created by cooperating with nature and caring for the earth and its people.

Permaculture is not exclusive - its principles and practices can be used by anyone, anywhere. For example in:

- City flats, yards and window boxes
- Suburban and country houses/garden
- Allotments and smallholdings
- Community spaces
- Farms and estates
- Countryside and conservation areas
- Commercial and industrial premises
- Educational establishments
- Waste ground

Permaculture encourages us to be resourceful and self-reliant. It is not a dogma or a religion but an ecological design system which helps us find solutions to the many problems facing us - both locally and globally. Writer Emma Chapman defines it as: "Permaculture, originally 'Permanent Agriculture', is often viewed as a set of gardening techniques, but it has in fact developed into a whole design philosophy, and for some people a philosophy for life. Its central theme is the creation of human systems which provide for human needs, but using many natural elements and drawing inspiration from natural ecosystems. Its goals and priorities coincide with what many people see as the core requirements for sustainability." Permaculture tackles how to grow food, build houses and create communities, and minimise environmental impact at the same time. Its principles are being constantly developed and refined by people throughout the world in very different climates and cultural circumstances.

Permaculture Ethics

Permaculture is primarily a thinking tool for designing low carbon, highly productive systems but its influence can be very pervasive! What can start as a journey towards living a more ecologically balanced lifestyle can go far deeper, even transforming our worldview and radically altering behaviour. This is the inspirational nature of permaculture, it is a means of connecting each of us more deeply to nature's patterns and wisdom and of practically applying that understanding in our daily lives.

The discipline of permaculture design is based on observing what makes natural systems endure; establishing simple yet effective principles, and using them to mirror nature in whatever we choose to design. This can be gardens, farms, buildings, woodlands, communities, businesses, even towns and cities. Permaculture is essentially about creating beneficial relationships between individual elements and making sure energy is captured in, rather than lost from, a system. Its application is only as limited as our imaginations.

Permaculture is not just a green way of living or a guiding system of ethics, it is a way of designing using nature's principles as a model; 'bending' them as much as possible to create fertile, self-reliant, productive landscapes and communities. This is what defines permaculture and it is uniquely effective and powerful. Where permaculture stands out from the crowd as a design system is in its capacity to integrate the intellect with ethics. It can teach us to 'think' with the heart and respond with the head. By combining pragmatism with philosophy, we can create a greater synthesis.

The three ethics are: Earth Care, People Care and Fair Shares. They are not exclusive to permaculture and were derived from the commonalities of many worldviews and beliefs. They are therefore shared by many throughout the world. What permaculture does is it makes them explicit within a design process; removing them from the realms of philosophy and practically rooting them in everybody's lives. This transforms thinking into doing. It is their combined presence within a design that has a radical capacity for ecological and social transformation.

Earth Care

Imagine the originators of permaculture, Bill Mollison and David Holmgren, in the 1970s, seeing the devastat-ing effects of a temperate European agriculture on the fragile soils of an ancient Antipodean landscape [GP7.1,2]. Like the dust bowls of Oklahoma in the 1930s, an alien agriculture has the capacity to turn a delicately balanced ecology into desert. Their initial response was to design a permanent agriculture with tree crops and other perennials inhabiting all the niches, from the canopy to the ground cover and below. The soil is left untilled to establish its own robust micro-ecology. Key to this is that the land must be biodiverse and stable for future generations.

This ethic of Earth Care was the basis of permaculture design, but it was bound to grow and pervade all aspects of permaculture... How can we have an organic agriculture or horticulture and manage our landscapes to sustain themselves over gener-ations on one hand, then consume goods from industries managed in ecologically damaging ways on the other? It's pointless designing an organic garden and then buying a gas guzzling car or building a house from concrete and steel, when we can use local materials with less embodied energy.

The original vision of care for all living and non living things has grown to embrace a deep and comprehensive understanding of Earth Care that involves many decisions; from the clothes we wear and the goods we buy to the materials we use for DIY projects. Though we can't all build our own house or grow all our own food, we can make choices about what and how we consume and conserve. Key to this is the understanding that up to one third of our ecological footprint is taken up by the food we buy, so even growing a small amount in a city allotment or container gar-den can make a difference. Permaculture is all about making a difference.

People Care

Fundamental to permaculture is the concept of Permanent Culture. How can we develop a permaculture if our people are expendable, uncared for, excluded? People Care asks that our basic needs for food, shelter, education, employment and healthy social relationships are met. Genuine People Care can-not be exclusive in a tribal sense; there can be no elites here: no plutocracies or oligarchies, all members of the community must be taken into account. It is a global ethic of Fairtrade and intelligent support amongst all people, both at home and abroad.

At the core of People Care is an understanding of the power of community. If we can change our lives as individuals and make incremental differences: think what we can do as a community! The permaculture designers who helped initiate Cuba's post oil urban agriculture are a good example. They mobilised a whole country to become self-reliant. Ecovillages and cohousing communities who can significantly reduce their ecological footprint by sharing resources are other good examples.

In smaller ways; in our cities, towns and villages, we can all benefit from deepening community links. I may not have all the skills to grow all my food or eco-renovate my house, for example, but by developing good networks I can expand my capacity to live more sustainably and become more self-reliant. This is a decentralised, democratic vision of social transformation where grass-roots initiatives like the Transition Towns movement can begin to plan for a low carbon 'energy descent' on a community level. There is no time to wait for central government to act, or eventually to react.

Fair Shares

The last ethic synthesises the first two. It acknowledges that we only have one earth and we have to share it with all living things and future generations. There is no point in designing a sustainable family unit, community, or nation whilst others languish without clean water, clean air, food, shelter, meaningful employment, and social contact. Since the industrialised North uses the resources of at least three earths, and much of the global South languishes in poverty, Fair Shares is an acknowledgement of this terrible imbalance and a call to limit consumption (especially of natural resources) in the North.

Permaculture fundamentally rejects the industrial growth model of the global North at the core of its ethics, and aspires to design fairer, more equitable systems that take into account the limits of the planet's resources and the needs of all living beings. Whilst these permaculture ethics are more like moral values or codes of behaviour, they are not enough on their own.

We need the principles of permaculture to provide a set of universally applicable guidelines that can be used in designing sustainable systems. Otherwise, permaculture becomes merely a lifestyle choice within an existing unsustainable system. These principles can be inherent in any perma-culture design, in any climate, and on any scale. They have been derived from the thoughtful observation of nature, and from earlier work by ecologists, landscape designers and environmental science.

Permaculture Principles

The 12 permaculture design principles are thinking tools, that when used together, allow us to creatively re-design our environment and our behaviour in a world of less energy and resources. These principles are seen as universal, although the methods used to express them will vary greatly according to the place and situation. Theycan be applied to our personal, economic, social and political reorganisation and the ethical foundation of permaculture guides the use of these design tools, ensuring that they are used in appropriate ways.

Each principle can be thought of as a door that opens into a whole system of thinking, providing a different perspective that can be understood at varying levels of depth and application. David Holmgren, the co-originator of permaculture, redefined permaculture principles in his seminal book, *Permaculture: Principles and Pathways Beyond Sustainability* [GP7.2]. When I started giving talks about permaculture to all sorts of different audiences, I decided to write my own explanations and apply the principle not only to designing gardens and farms but to business, society and culture. Every principle comes with David's 'proverb' and is followed by my explanation.

1. OBSERVE & INTERACT "Beauty is in the eye of the beholder."

For me this element of stillness and observation forms the key of permaculture design. In a world of instant makeovers, of 'fast' every-thing, having the capacity to observe the seasons, watch the changing microclimates on a patch of land, understand how the patterns of wind, weather and slope affect the frost pockets and plant growth, is an opportunity to begin to learn the deeper aspects of Earth Care. It also makes us more capable of making wise decisions about how we design or eco-renovate our houses and plan our gardens and farms.

2. CATCH & STORE ENERGY "Make hay while the sun shines."

Intimately connected to observation is the art of capturing energy in a design,?so that we minimise the need to seek resources from the outside. In a garden this is about avoiding planting tender seedlings in frost pockets in spring or maximising solar gain by siting a greenhouse/conservatory on the south side of a building so that we can both extend the season and heat a house with passive solar gain. We are attempting to capture water, sunlight, heat, soil, biomass and fertility whenever we can in order to become more self-resilient.

3. OBTAIN A YIELD "You can't work on an empty stomach."

Food can account for as much as one third of our ecological footprint so it makes sense to grow as much as we can, even if this is limited to tasty sprouted grains on the windowsill of a flat. So a permaculture garden is by default an edible landscape with good floral companions to attract beneficial insects, and a building is a potential heat store and structure for solar panels. But the concept of 'yields' is not merely about renewable energy or veggies; a yield can be about social capital. At PM, to see people changing their lives for the better, building community links and reducing their carbon after reading our books or magazines is the ultimate positive yield for a publisher.

4. APPLY SELF-REGULATION & ACCEPT FEEDBACK "The sins of the fathers are visited on the children of the seventh generation."

When we burn fossil fuels we release CO_2 into the atmosphere, trapping heat and increasing temperatures. This causes ice to melt which leads to loss of reflective surfaces, leading to more absorption of sunlight and even higher temperatures. We must accept responsibility for our actions.

5. USE & VALUE RENEWABLE RESOURCES & SERVICES "Let nature take its course."

Whenever possible, permaculture seeks to use resources that can be renewed. This naturally applies to energy but also to ecological building, coppicing, soil conservation, and the planting of perennial food crops, as well as annuals with seed saving. The dangers of relying on non-renewables, technological fixes and speculative money are becoming ever more evident.

6. PRODUCE NO WASTE "Waste not, want not. A stitch in time saves nine."

In the UK, we throw away the equivalent of 24 bags of sugar per household per week: 14.1 kg. That's 29 million tonnes (55% of that is household) per year. I have a favourite saying that the landfill of today will be the 'mine' of tomorrow. At PM we have no waste collection and our business is designed on permaculture principles. We reuse first and recycle all possible materials: ?paper, cardboard, textiles, glass ?and compost all organic materials, from kitchen waste to shredded paper. The subsequent compost feeds the edible container garden outside our office and provides a medium for growing plants for other projects at the Sustainability Centre.

7. DESIGN FROM PATTERNS TO DETAILS "Can't see the wood for the trees."

When Tim Harland and I designed our house and garden, we read up on permaculture design, forest gardening, renewable energy, eco-architecture and eco-renovation as much as we could. We spent a year observing the land before we started planting and planned how best to make our house a happy, energy efficient place to live in. We observed the seasons, the climatic variations, the weather, the soil patterns, slope and our own human activities on the site as a family.

We also considered the 'edge' between house and garden and how we might make this both aesthetic and productive in terms of food crops and energy harvesting. In other words, we started off looking at the bigger picture, the pattern of what sustainable living might be, with examples from other places, and then we refined our exploration into the detail appropriate for our particular site. We didn't make a 'shopping list' of individual items or projects and try to mesh them together in a hotchpotch of what might be regarded as 'green'.

8. INTEGRATE RATHER THAN SEGREGATE "Many hands make light work."

We have a cultural tendency to separate veggie gardens from flower gardens and use hard edges to design our spaces. Companion gardeners will know however that the more integrated the orchard is with the wildflower meadow, or the vegetables are with flowers frequented by beneficial insects, the less pests will prevail. The same is true for people. Cultural diversity yeilds a robust and fertile culture, whereas a rigid monoculture of politics and religion can bring sterility, even social and political repression.

9. USE SMALL & SLOW SOLUTIONS "The bigger they are, the harder they fall."

Our society currently depends on vast inputs of fossil fuels, whilst our biosphere is over-loaded by their outputs. The more accessible and fixable our technology and chains of supply are, the more robust the system. This principle speaks of hand tools, of appropriate technology that can easily be fixed, and of relocalisation.

Currently we have a three day 'just in time' supply chain of supermarkets. If the fuel supply is interrupted, the super-market shelves will empty at an alarming rate. Better to build resilience into our systems by relocalising our essential needs as much as possible and having technological alternatives that we can fix.

10. USE & VALUE DIVERSITY "Don't put all your eggs in one basket."

Biodiversity creates healthy ecosystems. Diversity in terms of crops, energy sources, and employment, make for greater sustainability. Valuing diversity amongst people makes for a more peaceful, equitable society. Conflict and wars are the biggest slayers of sustainable development.

11. USE EDGES & VALUE THE MARGINAL "Don't think you are on the right track just because it is a well-beaten path."

Examples of 'edge' in nature are: where canopy meets clearing in the woodland, inviting in air and sunshine and a profusion of flowers; where sea and river meet land in the fertile interface of estuaries, full of invertebrates, fish and bird life; where the banks of streams meet the water's edge and fertility is built with deposited mud and sand in flood time, giving life to a riot of plant life; where plains and water meet, flooding and capturing alluvial soils...

Edge in nature is all about increasing diversity by the increase of inter-relationship between the elements: earth, air, fire (sun), and water. This phenomenon increases the opportunity for life in all of its marvellous fertility of forms. In human society, edge is where we have cultural diversity. It is the place where free thinkers and so-called 'alternative' people thrive. where new ideas are allowed to develop and ageless wisdom is given its rightful respect. Edge is suppressed in non-democratic states and countries that demand theological allegiance to one religion.

12. CREATIVELY USE & RESPOND TO CHANGE "Vision is not seeing things as they are but as they will be."

In nature, there is a process of succession. Bare soil is colonised by weeds that are in turn superseded by brambles. Then pioneers follow; like silver birch, alder and gorse which stabilise the soil. The latter two even fix nitrogen to create an environment that can host slow growing temperate climate species like oak, beech and yew. But nature is dynamic and succession can be interrupted by brow-sing animals, storms that fell trees and create clearings or a changing climate that is less hospitable for certain climax giants like oak and beech.

The challenge of a permaculture designer is to understand how all these factors interact with each other in a landscape or on a part-icular plot of land, and design accordingly. It is no good restoring coppice without fencing out deer, or planting trees if they will shade out the solar panel in a decades' time. Equally well, we need to appreciate how climate change will affect our agriculture, with higher summer temperatures, greater volumes of rain in winter and springtime, and more violent storms with higher wind speeds. Hotter summers may allow more vineyards on the gentle southern slopes of the chalk downland. They may also make English oaks less viable in the south. What then do we plant and how do we design in resilience to our settlements?

One example is to plant more shelterbelts for farmland as well as housing estates and forgo building on floodplains. The principle is deeper than this, however. It invites us to imagine a future world, a world without cheap oil, and a world that necessarily radically reduces its carbon load in the atmosphere. By doing this, we take the first steps towards creating it. We stand on the bedrock of permaculture ethics Earth Care, People Care and Fair Shares, and are empowered by a set of principles that can inform our planning and actions. Human beings can either be the destroyers or the self-elected stewards of our planet. We have the capacity to put our ethics into action, literally to 'walk our talk'.

With permaculture design, we create the potential for a powerful beneficial relationship with the Earth. We can become stewards for our world whilst still maintaining an openness and humility to accept nature as perhaps our most powerful and wisest of teachers. What a culture we could build if these two perspectives were the bedrock of our civilisation! I believe that as we awaken as human beings and our awareness grows, we turn away from designing our own private Eden and engage more fully with the rest of humanity and the biosphere. We cannot build ecological arks on a failing planet. We are part of an inter-dependent ecological system. There can be no 'them' and 'us' in ecology. Permaculture is about low carbon, eco-friendly, even abundant living. It is also an ethically based design system for people who want to not only transform their lives and the lives of the people around them, but also to play their part in bringing an ecologically balanced, equitable and kinder world into existence. That is our challenge.

Permaculture Design

Design is the *conscious assembly of concepts, materials, techniques and strategies for a particular purpose.* Yet seeing all the exciting possibilities that permaculture offers us, it's easy to forget this and just end up throwing together a collection of 'green' technologies and techniques, only to be disappointed by the result. There's now no shortage of these 'green options' for us to choose from and we've been given the impression that as long as we behave in certain ways and buy the right products, we're doing the best we can.

But permaculture and design is about more than just choosing the right things, it's also about *how we connect them together*. Nature abounds with examples of beneficial relationships, showing us the value of this strategy for long-term sustainability. So as permaculture designers, our role is to place components in the best places relative to each other, to create self-sustaining systems that also meet our needs. However, such relationships are often site-related, so we need to be able to *consciously design*; to become a 'permaculture chef', rather than simply learning to follow a recipe. While perfecting this can be a lifelong journey, it's also not so hard to learn the basics.

While it's easy to worry these days about our impact on the environment, it's perfectly natural for us to be shaping it to meet our needs, every species that lives here does just that. The important question that Biomimicry advocate Janine Benyus asks us is whether our choices are *well-adapted* ones. Permaculture gives us the tools to create systems that support not just ourselves, but future generations too and Life as a whole.

In *Permaculture: A Designer's Manual*, Bill Mollison suggests:

- That the systems we construct should last as long as possible, and take least maintenance.
- These systems, fuelled by the sun, should produce not only for their own needs, but the needs of the people creating or controlling them. Thus, they are sustainable, as they sustain both themselves and those who construct them.
- We can use energy to construct these systems, providing that in their lifetime, they store or conserve more energy than we use to construct them or to maintain them.

These design considerations provide us with clear criteria for how any permaculture design should perform. If we can design systems within these guidelines that meet our human needs, and at the same time support the eco-system as a whole, then we will be well on our way to a sustainable human society.

We should invest most time and energy in the establishment a good design, so inputs decrease as time goes on. Conversely, yields may start off small but then increase steadily. At a certain point, the total energy yielded from the site exceeds the total amount invested and the system goes 'into profit'. One more thing worth remembering is that biologically we're simply an eco-system living within a larger eco-system. And that whatever we do *has consequences*.

Ethics, Principles and Directives

Permaculture advises us that when we design to meet our needs, we should do so in a way that supports the ecosystem as a whole. The permaculture ethics, often abbreviated to *Earth Care, People Care, Fair Shares*, are our primary guidance in this process. Any ideas that don't fit with these ethics just aren't permaculture.

Bill Mollison and David Holmgren also provided us with a set of principles and directives, which have since been adapted and added to by others. The principles of ecology guide us in applying successful natural patterns to design gardens and farms. However, we can be even more creative and apply many of these same principles to people-based designs too. There are also principles that address how we think, helping us to see the gifts in every situation.

You'll find many more and different versions of these principles on your travels. It's not so much a matter of which ones are 'right', but rather which of them you find useful in your life.

Design Frameworks

Permaculture has borrowed many useful thinking tools from different places, including several design frameworks from other disciplines. One commonly used is SADI, which comes from Landscape Architecture; the letters standing for Survey, Analysis, Design, Implementation. The value of a framework is that it can guide us through the process of design, reducing the chance that we might overlook something. While each of these stages can be quite detailed in themselves, for us the main things to remember are:

Survey ~ of both the needs of the client(s) and the landscape that will be meeting those needs. This might well include some mapping. The more focus given to this observation stage, the better a design is likely to be. Bill Mollison suggests observing a system for at least one whole cycle, which for a land-based design is a whole year. This shouldn't prevent us from making changes though, just don't, as Bill would say, do anything you might find difficult to reverse.

Analysis ~ this is the stage where we take all the information we have gathered and use the ethics, principles and appropriate design tools and methods to help us decide the best elements to choose and how best to connect them together into resilient low input, high output systems.

Design (or as I prefer to call this part *Decisions*, as the whole process is about design) ~ this is where we commit to our ideas, producing maps and lists that communicate our ideas to our client(s). While attractive maps are helpful at this stage, including your reasons for decisions can help illuminate the design process and increase the likelihood of the clients understanding the bigger picture of how it is intended to function. A design proposal should also include suggested implementation and maintenance plans.

Implement ~ at some point we have to take our ideas and put them into practice. However much time we take to deliberate, we'll still be surprised by some things that don't work as planned; so we shouldn't be afraid to take action. Only by implementing a design do we learn how well it performs in the real world. Mistakes are great opportunities to learn, but good attention to the survey and analysis stages should limit them to smallish ones.

Maintain / Monitor ~ this wasn't included in the original acronym, but maybe Landscape Architects just implement and walk away. Without knowing how to care for the system (and particularly unfamiliar technologies like composting toilets), it can fail to perform as intended and perhaps be abandoned as ineffective.

Design Tools and Methods

Throughout the design process we can make use of many different thinking tools and methods. These can for instance help us to make client interviews fully inclusive, especially when working with larger groups or community designs. They can help us with our decision making processes to ensure we create effective designs and also help us to produce a realistic implementation plan. Here are just a few examples from the many outlined in my book:

Permaculture is neither a specific recipe, nor an end point. Rather it is an ongoing process of harmonious adaptation to nature's changing conditions. The design process is a gift to us all that can help us to find and stay on our desired path.

3.8. Cleaning of water using ecosystem plants

The fight against the presence of emerging substances (pesticides, medication etc) and their derivatives which degrade water quality represents a veritable stake which is clearly reflected in regulatory evolutions. In effect, the European Union imposes that new pollutants (endocrine disruptors, pharmaceutical residues, hazardous substances…) must disappear from our water within the next 20 years. Currently, only between 30 and 80% of micro-pollutant flows, depending on substances, are stopped by treatment facilities.

These molecules appear in environments at an exponential rate and can disrupt elements from the trophic chain via accumulation or synergy, whilst we can detect them in water at very low concentrations which are often below detection limits. Whilst absorption treatments using activated carbon and ozone oxidation provide a treatment solution, other disposal routes must be developed, namely for smaller facilities.

Among them, we can mention the Artificial Wet Zones (Zones Humides Artificielles). The natural diversity of wet zones (biofilms, diatoms, plancton, microphytes, macrophytes, fauna) and root symbioses provide a wealth of complementarity to biological processes and standard treatment systems.

All of these reactions consequently ensure more refined water treatment. To resolve the problems of micro-pollutants, SUEZ has developed a new wet zone concept known as the Dragonfly Zone. The Dragonfly Zone is an artificial wet area able to be placed downstream of the wastewater treatment plant and in which the development of biodiversity contributes towards combatting micro-pollutants, limiting their diffusion into fresh or salt water sources.

The various successive zones (which among others include basins, phytoplancton, reed beds, damp pastures), based on the purification capacities of various aquatic eco-systems, are planted with locally selected plants. Thanks to a complex hydraulic run-off, the Dragonfly Zone protects the receiving environment whilst generating a better quality water at both a chemical and a bacteriological level. Faunal and plant dynamics also permit a particularly rich educational and recreational biodiversity support to be developed. The surface area of these wet zones can range from several hundred m^2 to several hectares depending on the flow reduction and local biodiversity development objectives.

Ecosystem Services - Water Purification

Purpose: To use the example of natural water purification to show students that healthy ecosystems provide services to people that are essential to life as we know it.

Context: This lesson was developed by Dr. Penny Firth, a scientist, as part of a set of interdisciplinary Science NetLinks lessons aimed at improved understanding of environmental phenomena and events. Some of the lessons integrate topics that cross biological, ecological, and physical concepts. Others involve elements of economics, history, anthropology, and art. Each lesson is framed by plain-language background information for the teacher, and includes a selection of instructional tips and activities in the boxes.

Ecosystem services are valuable for many reasons, including economic benefits, protection of human health and safety, and support of recreational or aesthetic enjoyment. Students should know that when ecosystems are not healthy, some or all of the services they provide to people may be lost. Replacing these services is often completely beyond current technology, and even when we can replace them, it is usually prohibitively expensive to do so.

Humanity came into being after most ecosystem services had been in operation for hundreds of millions of years. These services are so fundamental to life that they are easy to take for granted, and so large in scale that it is hard to imagine that human activities could irreparably disrupt them. Historically, however, the vital role of natural ecosystem services has not been given much attention. Because they are "free" these services are sometimes thought of as "without value." Nothing could be farther from the truth. Ecosystem services are essential to life as we know it.

In this interdisciplinary lesson, students explore the concept of ecosystem services by investigating natural water purification in their home watershed.

A few key points before getting started:

- Most water pollution is invisible. Trash in our waterways may look unsightly, but the really serious problems come from poisons, very fine sediments, and excess nutrients.
- Water runs downhill. If humans put it on the land, or in the air, it will likely end up in the water eventually.
- The worst problems with pollution in this country come not from industrial discharge pipes, but from "non-point sources" such as agricultural and urban runoff, and contaminated precipitation.

This lesson is about how ecosystems purify water and what kinds of things humans do that alter these processes. It also discusses the value of the natural water purification service to humans. The take-home message is that the key to maintaining water purification services is to protect and restore the ecosystems that provide these services.

Motivation: To begin this activity, ask students where their tap water comes from. Have students visit the EPA's Surf_Your_Watershed website and type in their zip code to find their watershed [GP8.1]. Have them click on the Index of Watershed Indicators and then the Impaired Water map to see the general condition of their watershed as well as what streams are healthy or unhealthy. Provide the zip codes of nearby urban, rural, suburban, and agricultural areas so that the students can see the differences in the watersheds.

Once all the students have had a chance to look at their watershed(s) online, have them discuss questions such as:

- What is the condition of streams in urban, suburban, agricultural or rural watersheds?
- What kinds of pollution could you expect in these different kinds of areas?
- Where would you expect the most nutrient pollution? The most pesticides and herbicides?
- What watersheds probably have the most sedimentation, heavy metal pollution, and thermal (heat) pollution?
- Where might you expect to find the most pathogens in the water?

Have students look at the USGS Water Watch site and judge whether or not their region is presently dry, wet, or average [GP8.2].

Ask them:

- What effect might a drought have on natural purification of waters? (Hint: Pollutants already in the water could be concentrated, but runoff from roads, lawns, and agricultural fields would likely be much lower).
- What effect might a flood have? (Hint: It depends on whether or not there are healthy ecosystems surrounding the water body).

Development:

Water purification occurs in nature in several different ways. Begin with a brainstorming session on how natural purification of water really works. Bring in a clear glass of muddy water (put it somewhere to settle), a sponge, and a coffee filter. Ask students what natural ecosystems could perform the functions of these items. (Hint: ponds, wetlands, and forests). It might be a little more challenging to mimic the functions of the living organisms that contribute so much to water purification. There are some websites below that will show students what these microbes look like. It's what they "do for a living" that makes them so important to this ecosystem service.

Water purification occurs when ecosystems slow the water down. Forests, woodlands, wetlands, and natural grasslands act as sponges to slow the movement of water from where it falls as precipitation to where it enters streams, lakes, and estuaries. This is important to natural purification because many of the processes by which the water is cleaned are biological processes—often performed by microbes like bacteria and fungi. The layer of bacteria, fungi, and algae that covers underwater surfaces has a technical name: "slime." Only kidding. Actually it is known as "periphyton" (which means "slime growing on underwater objects").

Biological processes take time, so the longer water takes to make its way across the landscape, the greater the chance that biological processes will clean the water. When humans replace natural vegetation with impervious surfaces such as paved roads and parking lots, water runs off the landscape very quickly and usually is not naturally purified much at all before it reaches the stream or lake. Unfortunately, these same impervious surfaces are usually a source of additional pollutants that come from cars, things people drop, things animals drop (!), and other wastes.

Once runoff water reaches a stream, natural woody debris dams become very important. Debris dams form when streamside trees die and fall into the water. Leaves and sticks catch on the wood, and the water is forced to slow down a bit as it moves through and over the dam. When the water is slowed by a debris dam, the periphyton organisms described above have more time to act, and thus a better chance of doing their job.

For a long time, people thought that debris dams were messy, and contributed to floods during high water. They were removed from many miles of streams and rivers by dredging. We now understand that they are very important to the retention, or slowing, of water and materials carried by the water. They are the sites of a lot of in-stream water purification. Along the shores of lakes, trees also fall into the water, and can be similarly important to water purification by providing surfaces for the microbes that do it. Incidentally, trees that fall into lakes are called "structure" by fishermen, and are usually great places to catch fish because of the habitat they provide.

Water purification occurs when ecosystems remove pollution from the water Wetlands and streamside (riparian) forests are particularly important for removing fine sediments from runoff. As sediment-laden water moves across and through these ecosystems, 80-90% of the fine particles settle to the bottom or are filtered out. Other pollutants such as organics, metals, and radionuclides (radioactive elements) are often adsorbed by (stuck onto) silt particles. Settling of the silt removes these pollutants from the water. Thus sediment deposition provides multiple benefits to downstream water quality.

Ranchers and watershed managers in the West are employing some of nature's own engineers for water quality improvement. Beaver-created impoundments (the "lakes" that form upstream of their dams) can be extremely useful in agricultural watersheds. They have been known to retain up to 1,000 times more nitrogen than streams without beaver dams. This has really opened the eyes of some water quality managers to ecosystem services.

There are many other stream animals that help filter the water. Many of the caddisflies construct nets that filter particles out of moving water. They clean their nets periodically, and eat some of the munchies that get stuck there. Black flies are also filter feeders, but their filtering devices are actually modified antennae that look kind of like giant Mickey Mouse ears sticking up from their heads.

Not all of the water purification services are provided by aquatic ecosystems, a lot happens on the land too. Precipitation moves into soil and is gradually released to plants, as well as to underground water (aquifers) and surface streams. Without soil and plants, as mentioned above, water runs off the land in flash floods. Plants shield the soil from the force of raindrops, which would otherwise quickly turn the soil into mud and wash much of it away. The amount of water that soaks into soil is determined by the soil organic matter content. Human disturbance, such as cultivation, reduces soil organic matter, makes soils more prone to erosion, and reduces their water-holding capacity. These changes, in turn, alter stream flow: increasing the frequency, severity, and unpredictability of floods. Floods tend to erode stream channels, lower water quality, and degrade aquatic habitat.

There is still much that we do not understand about how aquatic and terrestrial ecosystems perform the service of water purification. Factors such as location, size, type of soil and vegetation, water flow (patterns and extremes), and the landscape in which the ecosystem exists are all important. But predicting how much and what type of materials and pollutants can be "processed" within a natural ecosystem—without permanently harming the ecosystem—is very difficult.

Healthy microbial assemblages in soil and on surfaces in water change the form (and possibly the toxicity) of pesticides and they also remove heavy metals, such as mercury, that are harmful to life. Wetlands can remove 20-60% of heavy metals in the waters moving through them, and microbes in ecosystems can also change herbicides so that they are no longer toxic. The U.S. federal government spends more than $2 billion annually for clean water initiatives. This number might be hard for school children to conceive of. Just to give them an idea of how big a number 2 billion is, if you neatly piled up 2 billion pennies, they would occupy the same amount of space as 10 school buses. How much more might be spent if natural water purification was no longer working properly?

One way of estimating the value of an ecosystem service is to figure out what the replacement cost would be if the service was lost. In New York City, the replacement cost for the water purification services once provided "free" by its now-contaminated watershed was estimated at $6 to $8 billion to build a filtration plant (plus $300 million per year to operate it). Officials discovered that restoring the health of the watershed—and hence its water purification service—would cost only $1 billion. This was an easy decision for New York State. The restoration includes costs to purchase and halt development on land in the watershed, to compensate landowners for restrictions on development, and to improve septic systems.

Another way of estimating the value of natural water purification is to look at how humans try to mimic this ecosystem service in order to save money. Constructed wetlands are a good example. Wetlands are sometimes constructed as an alternative to wastewater treatment facilities. Water purification technology is costly, and in the case of drinking water, the more polluted the water, the more money is needed for disinfectants, such as chlorination, and the higher the energy, equipment, and labor costs. Constructed wetlands mimic the filtration and pollution-conversion functions of natural wetlands and are sometimes cost efficient for small communities that cannot afford wastewater treatment plants. Constructed wetlands are also used to treat agricultural runoff, suburban runoff, and other non-point sources of pollution.

Valuation of ecosystem services need not be limited to monetary notions. The value of the services can include aesthetic, biological, recreational, and health benefits. It is often difficult to give a monetary value to the services provided by natural ecosystems. There are many hidden benefits or tradeoffs that make it hard to evaluate and easy to underestimate the true value of any particular service. How much is your health worth? Sure, you can exercise and eat right, but what if the water you drink could make you sick?

The key to maintaining water purification services—and the value that they contribute to human life—is to protect and restore the ecosystems that provide these services. It makes economic sense for the present generation, and it makes sense to keep ecosystem services viable for generations yet to come.

Assessment:

Ask your students to develop a "river newspaper." These are some suggestions:

- Reporters (who could pretend that they are drops of water) could interview the trees and soil in the surrounding ecosystems for news stories on how they helped keep the river clean.

- Include a letter-to-the-editor from a wetland. For example, the letter could complain about invasive exotic species.
- Have a feature article written by a net-building caddisfly. For example, "Look what I got from my net last week."
- Include advertisements designed for woody debris dams from the local beaver colony.
- Have students come up with a song or rap about ecosystem services, and have "reporters" cover it on the Entertainment page.
- Have students write classified ads, and maybe even some personal ads.
- Include a lot of artwork (fallen trees in streams are beautiful too).

Then for real effect, invite a reporter from the local newspaper to visit the class and discuss with the students.

References & Resources

[INT.1] https://en.wikipedia.org/wiki/Biomimetics

[INT.2] https://biomimicry.org/what-is-biomimicry/

[INT.3] Benyus JM (2002). *Biomimicry: Innovation Inspired by Nature.* Perennial, New York

[GP1.1] http://www.calera.biz/

[GP1.2] https://en.wikipedia.org/wiki/Moss_Landing_Power_Plant

[GP1.3] http://www.symbiosis.dk/

[GP1.4] https://www.ipcc.ch/

[GP1.5] http://hbr.harvardbusiness.org/2009/09/why-sustainability-is-now-the-key-driver-of-innovation

[GP1.6] https://www.nationalgeographic.org/article/working-with-nature-to-slow-global-warming/

[GP2.1] https://en.wikipedia.org/wiki/Thin-film_solar_cell

[GP2.2] https://en.wikipedia.org/wiki/Pachliopta_aristolochiae

[GP2.3] Siddique R.H., Donie J., Gomard G., Yalamanchili S., Merdzhanova T., Lemmer U., Hölscher H. *Bioinspired phase-separated disordered nanostructures for thin photovoltaic absorbers.* http://advances.sciencemag.org/content/3/10/e1700232

[GP2.4] https://www.yale-nus.edu.sg/about/faculty/vinod-kumar-saranathan/

[GP2.5] https://directory.caltech.edu/personnel/rhs

[GP2.6] http://meche.mit.edu/people/faculty/MKOLLE@MIT.EDU

[GP2.7] http://www.dfg.de/foerderung/info_wissenschaft/info_wissenschaft_17_59/index.html

[GP3.1] https://en.wikipedia.org/wiki/Cat%27s_eye_(road)

[GP4.1] https://portal.opendiscoveryspace.eu/en/osos-project/optimal-transportation-network-855963

[GP5.1] https://portal.opendiscoveryspace.eu/en/osos-project/collection-water-using-natural-leaf-design-855952

[GP6.1] https://news.osu.edu/news/2018/06/25/painless-microneedle/

[GP6.2] https://asknature.org/strategy/needle-like-structure-inserts-painlessly/#.XjgYVGj7SHt

[GP6.3] https://asknature.org/idea/mosquito-inspired-microneedle/#.XjgZP2j7SHs

[GP6.4] https://www.deingenieur.nl/artikel/mosquito-bite-helps-create-the-ideal-injection-needle

[GP7.1] Mollison B. (1997). Permaculture: A Designers' Manual

[GP7.2] Holmgren D. (2002). *Permaculture: Principles and Pathways beyond Sustainability* http://www.green-shopping.co.uk/books/pp/david-holmgren-1/permaculture-principles-pathways.html

[GP8.1] http://cfpub1.epa.gov/surf/locate/index.cfm

[GP8.2] http://water.usgs.gov/waterwatch/

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