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Patterns from Nature

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Abstract

We are facing increasingly complex and far-reaching environmental challenges. In addition to solving specific problems, designers and engineers are being called upon to consider how their solutions affect the long-term viability of environmental, social and economic systems. Practitioners often lack the skills, experience and knowledge to effectively deal with interlocking issues such as the implications of specific materials and manufacturing processes, product and service use, and the impact of final disposal. Research in industrial ecology suggests truly sustainable design "is about designing human ecological-economic systems which fit in with natural ecological systems" [29], to preserve the well being, resiliency and adaptability of both systems. Kay proposes "a new branch of engineering ... (that) will bring together the disciplines of ecology, economics, engineering design, systems theory, and thermodynamics". To deal with these complex issues, practitioners will need tools and methods supporting interdisciplinary collaboration.

Many students are eager for information relating to environmental issues and sustainability. A number of courses successfully integrate biological and engineering concepts, fostering a more fundamental understanding of both fields. Students seem excited with the freshness of this approach as well as the ability to relate their field of study to current events. Educators could benefit from tools that help them organize and communicate information about natural systems, in a way that is relevant to their specific disciplines.

This paper will describe a project to explore a 'pattern language' based on knowledge about ecosystems as well as robust human designs. Alexander [1, 2] developed the concept of 'pattern languages' in the late 1970s as a means of capturing and communicating recurrent problems and solutions in architecture. Successful pattern languages provide a framework that structures information so that practitioners can gain a deeper insight into specific problems and develop solutions that 'fit'. By using terminology that is not discipline-specific, pattern languages have the potential to facilitate interdisciplinary communication and simplify the transfer of knowledge between diverse fields, such as biology and engineering. Pattern languages also contain information on how problems and solutions relate to each other at different levels, helping practitioners deal with multiple perspectives and different temporal/spatial scales.

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1. Challenges

As environmental concerns and sustainability have entered the mainstream, popular demand for innovative solutions has also grown. These solutions must not only reduce our impact on the environment but also help to restore and regenerate it. Environmental problems are often complex and transcend fields of expertise, requiring multi-disciplinary collaboration. At the same time, the burden of keeping up with the 'information explosion' has led to greater specialization in both the research and design disciplines, possibly inhibiting communication amongst professionals and making it difficult to access existing solutions in diverse fields.

Sustainable or restorative design challenges often require a systems approach, taking into account complex networks of relationships that span natural and human contexts. This has the potential to further complicate the design process. Systems thinking requires a balance of breadth and depth - neither a focus on the trees nor on the forest is sufficient. Collaboration may often be the best way to gain the mix of skills required to address the challenges of spanning diverse fields of inquiry.

Effective communication and collaboration across disciplines requires tools to help bridge differences in discipline-specific language, analysis methods and implementation approaches. To be effective, these tools must counteract psychological inertia that can result from years of success in a field: the words we use to define problems, the initial images and solutions that appear in response to familiar ideas, and the comfortable security of the 'tried and true'. In order to empower collaboration, these tools must deliver insightful and useful content that is easily accessible to practitioners from a wide range of fields.

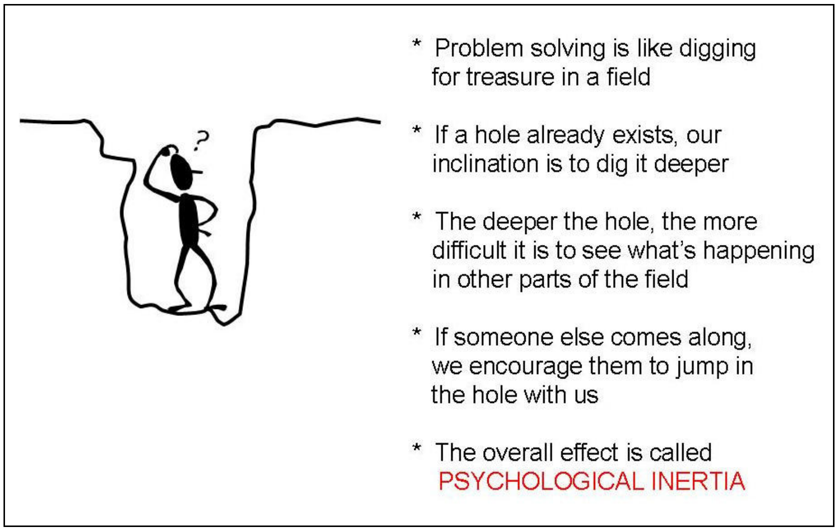

Figure 1 Psychological Inertia (Mann) [20]

2. Framework

2.1 Objective

The *Patterns from Nature* project began as an attempt to capture recurrent solutions from nature which would be valuable to designers engaged in developing efficient, effective and sustainable products or services. It was considered important to package the information in a form easily accessible and understandable to all designers. Although originally intended as a means of transferring knowledge from biology to design, the project goals evolved to study and incorporate insights from appropriate human designs.

2.2 Patterns

The concept of a 'pattern language' was chosen as the framework for the project. Alexander [1, 2] described a set of 253 patterns he believed captured the key aspects of buildings that were 'alive', in the sense that they directly enhanced the psychological experience of people interacting with the building. Many of the concepts came from an analysis of 'vernacular' architecture that was not obviously designed (in the modern sense), but grew organically over a period of time in response to the changing needs of users.

The term ‘pattern’ as used by Alexander [1, 2] builds on common usage as ‘a model or original used as an archetype’ or ‘a plan, diagram or model to be followed in making things’. According to Salustri [3], *"A pattern is a natural-language, context-dependent description of a solution to a class of problems, that is both generative and descriptive."* A pattern explains the steps required to solve a specific problem in sufficient detail so that users can develop similar solutions adapted to their specific needs. At the same time, the pattern provides insights into the problem, such as the situations in which the problem is likely to appear as well as the forces or drivers that cause the problem to occur.

Alexandrian patterns have a defined structure which expresses the relationship between a problem, a context and a solution. The authors used a simplified ‘Therefore-But’ pattern template [3] containing the following sections:

1. **Pattern Name:** A short, descriptive name that quickly conveys the intent of the pattern.
2. **Problem Statement:** A concise statement of the problem, including the context in which the pattern can be applied and the forces or drivers that create the problem and that must be resolved to obtain a successful solution.
3. **Therefore:** The solution (including any required tasks), how the outcome is used, why the solution works, and relationships to other patterns. The solution resolves the forces or drivers, moving the system from an undesirable to a more preferred state. Examples from different fields can demonstrate that the problem/solution set is recurrent and broadly relevant.
4. **But:** The consequences of implementing the solution, to help avoid 'surprises'. Can also show how the solution changes the context of the problem, either by eliminating contradictions between forces/drivers or by working at a different level than the original problem (sub-system or super-system).
5. **See Also:** Pointers to related patterns not mentioned in other sections of the pattern.

An example of a developed pattern is the *Variable Fluid Mixer* example reproduced in Appendix 1. It describes the problem in rich detail so that the reader can not only determine whether the pattern is relevant to the reader's circumstances, but also gain insight into the underlying causes of the problem and the implications of applying the solution.

Patterns may incorporate information derived from theories, principles and strategies, but must express that information in pragmatic and practical terms. According to Appleton [4], "*A pattern is where theory and practice meet to reinforce and complement one another, by showing that the structure it describes is useful, usable, and used!*" Appleton has identified the following characteristics of a successful pattern [4]:

- *"**It solves a problem**: Patterns capture solutions, not just abstract principles or strategies."*
- *"**It is a proven concept**: Patterns capture solutions with a track record, not … speculation."*
- *"**The solution is not obvious**: ... The best patterns generate a solution to a problem indirectly -- a necessary approach for the most difficult problems of design."*
- *"**It describes a relationship**: Patterns don't just describe modules, but describe deeper system structures and mechanisms."*

2.3 Pattern Language

Patterns do not stand on their own - they exist in a context of patterns that occur at a similar level, a higher (encompassing) level, and a lower (component) level. Alexander [1, 2] calls this network of patterns a ‘Pattern Language’, which incorporates both the individual patterns and a 'grammar' that ties the patterns together in a logical fashion that *"... reveals the inherent structures and relationships of its constituent parts ..."* [4].

Robust pattern languages contain a number of levels. Each level generally contains a complete set of patterns that enable the user to fully visualize the design at that level. It is important that no gaps exist and that no unnecessary patterns are included, and that all the forces or drivers contributing to the problems have been resolved.

Specific levels may be associated with different design scales or design disciplines. Regardless of the level or scale initially chosen to begin the design process, the designer can explore levels above and below to gain insights on the larger system as well as more detailed components required to complete the solution. In addition to improving the overall completeness and 'fit' of a specific design, the ability of pattern languages to address problems at multiple scales can facilitate communication and collaboration in an interdisciplinary setting, especially when a consistent language is used throughout the pattern language.

A pattern language describes the relationship between many patterns that make up a system, allowing the user to solve larger problems that cannot be handled by individual patterns. According to Appleton [4], *"... a pattern language is a collective of such* [recurring] *solutions which, at every level of scale, work together to resolve a complex problem into an orderly solution according to a pre-defined goal."*

Like patterns, pattern languages also help generate solutions, but at a systems level. *"Patterns encapsulate related forces so you can focus on local trade-offs using local thinking; pattern languages are about emergent behavior in systems"* [5]. It is through the interaction between individual patterns that dynamic, adaptive and robust systems can result.

Patterns and the relationships between patterns ideally capture knowledge about a domain in a comprehensive and accessible fashion. Salustri [3] states *"A group of tightly integrated patterns covering entirely a domain of interest is a pattern language ... Alexander's pattern language* [1] *ostensibly describes solutions for every kind of problem faced by architects ranging from locating urban/suburban regions to the positioning of photographs and other decorations on the wall of rooms."*

Alexander did not attempt to depict his entire architectural Pattern Language [2] graphically. Individual sections were rendered using network diagrams for illustrative purposes [1]. One example where the relationship between patterns has been explicitly documented is the Conservation Economy Pattern Language [13] illustrated in Figure 2. This structure is intended to guide but not necessarily constrain the user. Designers should select patterns that make sense for the problem they are trying to solve. They may link patterns in novel ways that reveal insights and lead to innovative solutions. It is the interaction of the designer with the pattern language that can ultimately lead to a unique solution which solves a larger system problem in an efficient, effective and robust manner.

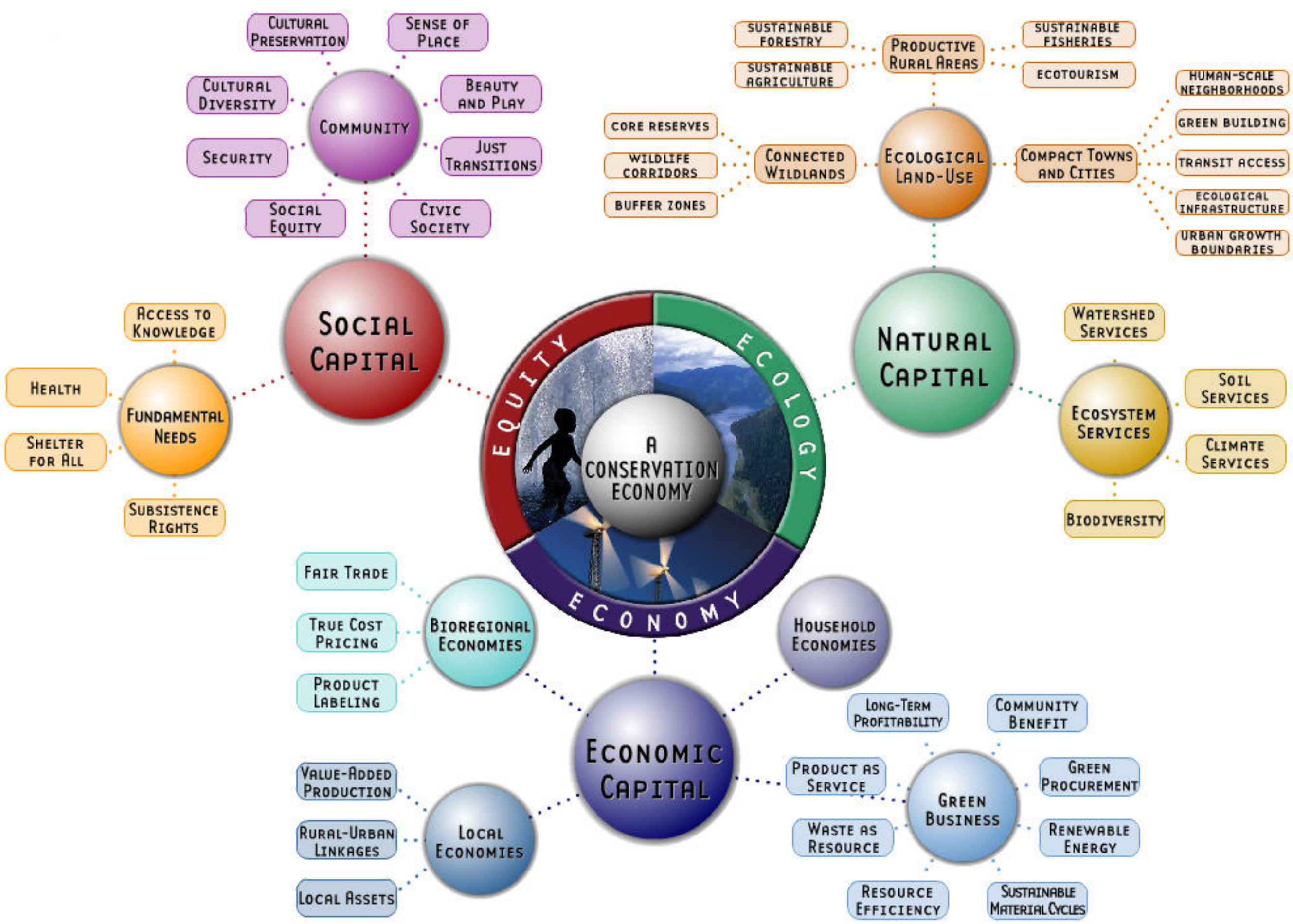

Figure 2 Conservation Economy Pattern Language (Cowan) [13]

2.4 Key Attributes

Patterns and pattern languages have a number of unique features that make them particularly useful to the field of design, especially when complex, inter-related problems are involved. Specifically, they:

- Clearly define the problem, the context, the solution and the consequences
- Describe the final solution and also guide the user in how that solution can be realized, by combining methodology with knowledge and systems relationships
- Use simple, concise and concrete language that can be communicated and shared with others
- Are practical and operational
- Are bottoms-up, solutions-based models
- Are a simple framework that helps make sense of the complexity and richness of real systems
- Are primarily qualitative but can also incorporate quantitative information
- Encourage organic, continuous and dynamic change, in contrast to traditional 'rip and replace' models
- Allow the user to develop their own insights as they tailor the pattern language to a specific task

2.5 Applications

The original pattern language developed by Alexander [2] is used by many architects as a way to communicate effectively with clients and other stakeholders and to facilitate collaborative design processes. An example is the *Community Open Space Initiative* at the University of Washington, Seattle, as demonstrated by Shaw [8]. This project captures how a pattern language can relate to the systems aspects of design by facilitating a design process involving diverse participants and guiding analysis through a focus on recurrent design issues.

> *"The next best option, then, is to have the community or individual work with the design professional to select and organize patterns into a coherent whole that supports the functions the community values. The important distinction between this and standard community involvement is that the community still designs, but with the help of a professional."* [8].

Pattern languages have become very popular in software development, starting with the 1987 work by Ward Cunningham and Kent Beck on Smalltalk. The work has been primarily in software architecture, design and re-use, with more recent attempts to explore, document and communicate software development processes [9]. A number of pedagogical patterns related to computer sciences have been developed by Bergin [10, 11, 12]. Bergin [10] includes another example where the pattern language network is graphically represented.

Cowan led a project at Ecotrust to develop a *Conservation Economy Pattern Language* [13]. Its *"fifty-seven patterns provide a framework for an ecologically restorative, socially just, and reliably prosperous society. They are adaptable to local ecosystems and cultures, yet universal in their applicability. ... Together, the patterns form a visual and conceptual framework that can be used to inspire innovation, focus planning efforts, and document emerging best practices."*

3. Approach

3.1 Background

The inspiration for the *Patterns from Nature* project came from interest in the field of biomimicry, described as *"a new science that studies nature's best ideas and then imitates these designs and processes to solve human problems"* [14]. Part of the biomimicry methodology [23] maps the problem statement to a set of biological challenges and habitat conditions, and then looks for species (often called 'champion adaptors') that are particularly well-adapted to solving these challenges. This can either lead to published information that can then be applied in the design process, or suggest opportunities for further research. This approach can be very fruitful, but currently requires access to experts in biology.

The unique nature of 'champion adaptors' may reduce the ability to easily re-use information in a different context. Vincent [15] pointed out that *"every time we need to design a new technical system we have to start afresh, trying and testing various biological systems as potential prototypes and striving to make some adapted engineered version of the biomimetic device which we are trying to create*." A Biomimicry Portal is being developed by the Biomimicry Institute [21] to capture and structure biological information in categories such as challenges, strategies, organisms, people, citations and products. To date, its focus has been on architectural functions such as adhesion, color creation, protection and noise abatement.

The original intent of the *Patterns from Nature* project was to complement the biomimicry methodology by investigating and documenting recurrent natural solutions, structured in a form that could be made accessible to designers through the Biomimicry Portal. The information available through a pattern language could help to facilitate Reap's [16] goal of "*A holistic view of biomimicry* [that] *involves incorporation of life's general characteristics in design and application of these characteristics across multiple spatial, temporal and organizational scales of engineering influence."*

The authors initially incorporated solutions from human designs primarily as examples and counter-examples to help communicate the concepts to designers. This approach proved to be limiting, because it suggested a discontinuity between natural and human-designed systems, while our intent was to provide a smooth transfer of knowledge about nature to help solve human problems. This format also gave the impression that human solutions to design problems were an afterthought and not a significant source of ideas for patterns.

The authors recognized that human designs could be a source of ideas for patterns, and shifted to a general systems approach based on the following assumptions:

- There are really very few 'new' ideas. Innovation often involves building analogies between known or observed solutions and problems yet to be solved.
- Good designs are those that 'fit' well within a context. This ties the design to a specific 'place' and a larger system.
- Designs can deliver powerful and unexpected benefits when the larger system is considered.
- Systems of even moderate complexity often act in complex and unpredictable ways, due to iteration and interaction between components.
- Robust systems are likely based on a relatively small number of principles, where complexity is an emergent property.

These assumptions suggest a number of implications:

- Studying effective solutions from other fields (including nature and human design disciplines) can be an effective and efficient way to deliver innovation.
- Human-made and natural systems share common underlying principles. Knowledge learned from one domain can provide insights and suggest solutions in other domains. A common set of tools and measurements can be used to compare how systems function across domains.
- 'Good designs' may only reveal themselves over a period of time, due to the unpredictable and dynamic nature of systems. Solutions often need time to evolve. Even minor adjustments may significantly improve the 'fit'. Great designs build in feedback loops and adaptability.

This new approach shows promise in facilitating the two-way transfer of knowledge between the natural and human domains. It also opens up additional sources of input to develop patterns – human-designed systems can be analyzed for potential problems, drivers and solutions. Contradictions, paradoxes and 'lessons learned' from unsuccessful solutions can help reveal forces or drivers that underlie problems. Once resolved, these drivers sometimes seem to disappear, making reverse engineering difficult. Examples from human-made designs can also be more easily incorporated, helping designers identify and leverage previously implemented solution components from complementary disciplines.

3.2 Logistics

A call for volunteers in the September 2006 *BioInspired! Newsletter* and a posting to the Biomimetics listserver resulted in sixteen volunteers, of which the authors of this paper have been key contributors. Backgrounds include mechanical and civil engineering, molecular and microbiology, and various architectural and academic disciplines. The team members are geographically dispersed, across North America through to Europe and New Zealand. A Wiki website based on the MediaWiki platform was created to provide a way to created, share and edit content. Wikis simplify collaborative authoring and content linking (see Salustri [25] for more details).

A number of conference calls were scheduled to establish a common understanding of the project and to help build momentum. One of the team suggested that we start with the list of *Life's Principles* described by Benyus [17], in combination with additional ecosystem principles derived by a comparative study of knowledge about ecosystems from the disciplines of biomimicry, industrial ecology, ecology and ecological design. Although most pattern languages use a 'bottoms-up' approach by collecting large numbers of problem/solution sets, a 'top-down' approach can focus efforts and allow all participants to contribute early on.

One-on-one calls were scheduled with team members to explore the ecosystem principle of greatest interest to them. A Wiki template was built to guide the discussion and documentation of the pattern. This proved to help increase consistency. The rigor of the patterns approach has led to wide-ranging discussions on exactly what the ecosystem principles mean and how they can best be 'operationalized' so that a designer can apply the insights derived from the principles in problem analysis and solution development. Considerable time and effort is required to define terms, clearly articulate the problem and the underlying drivers, identify the right context, and document both the details of the solution and how it can be implemented.

4. Preliminary Results

4.1 Multi-Functional Materials 'Proto-Pattern'

One of the ecosystem principles refers to using materials effectively for multiple functions. Figure 3 contrasts material usage in beetle cuticle with that of candy wrappers, which may comprise up to seven layers of various materials. For example, a Luna Bar wrapper has been described as a *"75-gauge polypropylene/ink/adhesive/60 gauge metallized-oriented laminate"* [22]. In comparison, *"insect cuticle does all this in one material - a composite of polysaccharides whose functions are achieved by altering the shape of the polymers, their alignment, and how they are bonded together"* [22].

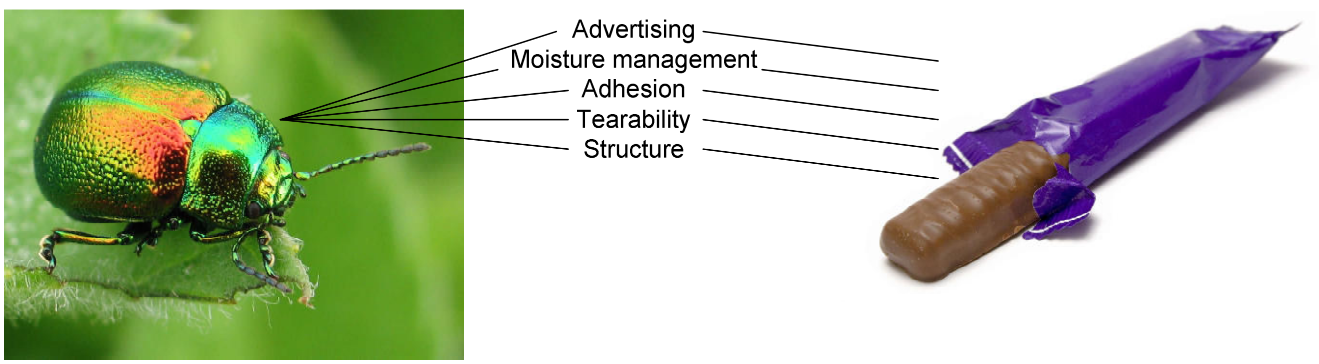

Figure 3 Beetle cuticle vs. candy wrapper [26, 27]

Problem or Challenge: Living systems tend to use single materials for multiple functions, whereas we employ chemistry to develop new materials for each desired performance characteristic or function. Vincent [15] describes various mechanisms that allow insect cuticle to be structurally stiff while allowing movement, storing energy, and providing controlled interaction with the outside environment (such as transmission of sensory information). In addition to exhibiting differences in geometry, orientation and cross-linking, layers can be porous or multiple layers can interact to deliver novel functions.

Multi-functionality in materials is related to structure (organization of the material), as well as information (usage, transformation or regulation). It is primarily found at the mid-spectrum level of tissue, organ or organism. At significantly smaller scales, the structural properties disappear, while at much larger scales, the impact of material structure is outweighed by other factors.

If multi-functional materials are of clear evolutionary value to most living things, why have we taken the path of ever-greater proliferation of new substances? The answer may lie in energy, possibly the most constrained resource on Earth. Vincent [31] estimates that "... *in technology, the manipulation of energy can account for up to 70% of the solutions to technical problems, whereas in biology energy never figures more than 5% of the time.*" For example, solar energy is wide-spread but diffuse. Although sunlight can be concentrated, organisms are limited in their ability to benefit from this path because of the limited temperature range at which proteins can function. Diamond quotes Goldstone [30]: "*Two problems faced all pre-industrial economies in regard to energy: amount and concentration.*" Industrialization and our ability to tap fossil fuels has allowed us to deploy energy when and where we need it, in the quantities we require.

Most organisms are limited to using carbon, hydrogen, oxygen and nitrogen as the key building blocks (along with calcium and other trace elements), arranged in a relatively small number of compounds. Fossil fuels have allowed us to invent new materials that are both energy intensive and able to withstand high energy levels, further feeding our ability to overshoot the limits imposed on other organisms. Vincent [31] writes: "*In technology we are outside the system. We destroy the information in the material (e.g. by processing, melting etc) then impose a new set of information (flow, moulding, casting) in order to end up with a product. This is making. In biology we are inside the system (at least the thing whose shape is being developed is inside the system) and the general scheme is to USE the information to generate the shapes / functions. This is becoming.*"

Therefore: We should analyze and utilize the inherent structural properties of materials. An existing, successful example is the JANO Dual Bike designed by Roland Kaufmann [32]. Kaufmann discovered that wood is significantly stiffer than fiberglass or even Kevlar/epoxy composites. By using wood veneer, Kaufmann was able mold wood into shapes that combined lateral stiffness with the shock absorption of carbon fiber and the responsiveness of steel.

Vincent [31] has challenged engineers to identify *"... what materials processing techniques there are in physics/chemistry/engineering which use and preserve the information at the molecular level. In biology this would be the order of amino acids and the secondary, tertiary, quarternary . . . structures which they drive. In engineering it would be LB [Langmuir-Blodgett] films, liquid crystals/thixotropy, followed by electrospinning, spinning, RP [Rapid Prototyping], etc . . . How much engineering can we do using only molecular rearrangements? Can we go all the way from nm to m without raising the temperature above (say) 100C?*"

Kay [29] emphasizes the importance of considering energy *quality* in addition to quantity. By fully exploiting the performance characteristics afforded by the structure of materials, we are similarly leveraging high quality information embedded in materials. The low value of most material 'waste' encourages recycling or 'down-cycling'. Retaining the structure of materials increases the end-of-life value of those materials, allowing us to apply the concept of 'waste as food'.

But: Our ability to mimic the benign, nano-manufacturing methods of organisms is limited, although new discoveries are closing the gap. Although tools exist to estimate the quality of energy (exergy), few tools exist to analyze quality measures of material flows.

See Also: Fully utilizing the inherent structure and quality of materials may significantly reduce the amount of energy we consume.

4.2 Conducive to Life 'Proto-Pattern'

Healthy ecosystems evolve into balanced, rich, diverse and vibrant communities of species, often displaying interdependent, cooperative or symbiotic behavior between individuals and species.

Problem or Challenge: Natural selection works at the level of organisms; there is no generally accepted theory of natural selection at the ecosystem level. 'Survival of the fit' suggests competition rather than cooperation and interdependence.

Ecosystems do not lend themselves to analysis by reduction. Ecosystems are not machines with easily identified causes and effects. They:

- are comprised of complex arrangements of living and non-living entities
- are arranged in hierarchies of sub-systems and super-systems
- interact through a web of energy, material and information flows
- span a wide range of spatial scales, from cells to the entire biosphere
- span temporal scales due to iterative processes and feedback loops

Figure 4 Web of Life [49]
The Grinning Planet®
http://www.grinningplanet.com/

Therefore: New analysis methods and tools are required to understand the principles underlying ecosystems and allow designers to apply these principles in solving societal problems. Non-equilibrium dynamics and complexity theory [28, 29] suggest that under certain enabling conditions, open systems through which high quality energy flows will display emergent properties and spontaneously self-organize.

These systems build increasingly more organized processes that in turn build and maintain new structure. As a result these systems are able to capture, utilize and dissipate more energy; cycle resources more effectively; increase respiration and transpiration; add more biomass; and increase diversity. As energy flow increases, systems are pushed further and further from equilibrium until a critical point is reached where the system can no longer cope and behavior becomes chaotic. More than 80 years ago, Lotka [33] summarized his observations of biological and ecological systems in much the same way. He believed that evolution generates and selects living systems that maximize total energy flow per unit time subject to constraints.

Self-Organizing Hierarchical Open (SOHO) systems [29] may exhibit multiple stable states. Changes in the system's environmental conditions may appear to have no influence on the system, due to regulating feedback loops. However, at a critical threshold, even a small change may cause the system to switch to another stable state. The change may be very rapid, discontinuous, and from our perspective, unpredictable. The state at which a SOHO system finds itself is a matter of history - the concept of a 'correct' system state is a matter of human preference.

The principles of SOHO systems suggest a number of implications for the design process. The structure and processes of societal systems depend on resource flows from natural systems. Therefore societal systems must maintain the integrity of natural systems by protecting their health, ability to adapt, and ability to evolve. This requires not only a much deeper understanding of the structure and behavior of societal systems, but also that of related natural systems and the interaction between the two. Narratives or scenario analysis may better capture and represent the richness of information required by this process than reductionistic approaches and expert predictions within a discipline.

Kay [29] proposes four design principles:

- we must interact with natural systems recognizing their limited ability to provide energy and absorb waste
- large scale societal systems should be modeled on the behavior and structure of natural ecosystems
- where possible, natural subsystems should be leveraged to deliver the functionality required by societal systems
- non-renewable resources should be treated as capital expenditures as we switch to renewable resources

Kay [29] proposes two design strategies:

- adopt adaptive management: our designs must incorporate the ability to sense and adapt to change
- apply the precautionary principle: we must minimize our interaction with the natural system particularly in our use of resources such as energy, our production of waste, and our destruction of the natural environment

Kay emphasizes the importance of analyzing both the quantity and quality of flows, whether they involve energy, materials or information. In most cases, we focus on quantity by measuring efficiency. In contrast, quality is most closely related to effectiveness. Kay cites an example where electric radiant heat is 100% efficient, but is less effective than using natural gas. The high quality of electricity is more effectively leveraged in heat pumps or devices where heat is a secondary outcome. Emphasizing efficiency can also lead to optimization at the component level, on the oftentimes inaccurate assumption that this will make the entire system efficient. Effectiveness encourages optimization at the system level, accommodating non-linear interactions and feedback loops.

These concepts lead to a different approach to design. Rather than creating static 'solutions to a problem', design "*must be seen as setting in process the evolution of a built environment which evolves to meet the evolving needs of users and which adapt so as to fit into changing environmental conditions*." [29]

Vincent [31] estimates that "*... in technology, the manipulation of energy can account for up to 70% of the solutions to technical problems, whereas in biology energy never figures more than 5% of the time."* Our ability to tap into fossil fuels has allowed us to deploy large amounts of energy when and where we need it. Kay and

Gribbin describe how increased energy flow results in "period doubling", where the number of states and length of the state cycles increases dramatically until the behavior of the system becomes chaotic. However, they do not provide guidelines for predicting this transition. Are societal systems in the 'chaotic' range, where increasingly complex control mechanisms (driving even higher energy demands) are required to enforce stability? Would reducing our energy consumption allow inherently stable states to emerge?

Such questions command particular attention in light of recent findings concerning the mass-specific metabolic rates of organisms ranging from bacteria to whales. Makarieva and coauthors found that organisms spanning 20 orders of magnitude in body mass displayed specific basal metabolic rates from 1-10 W/kg [34] and average active rates in the range of 40 W/kg [35]. This finding led them to speculate that a universal specific metabolic rate might exist. Such a limit may also hold consequences for mankind's systems and behaviors [36]. Humans metabolize at the sluggish rate of primates, but when one considers the non-nutritional sources of energy they command, the situation changes dramatically (See Table 1). If a universal rate exists for organisms, does it mark the energetic constraint mentioned by Lotka and the chaotic boundary discussed by Kay and Gribbin? Does the developed world's energetic excursion beyond these potential limits portend darkly for global sustainability?

Country	Estimated Avg. Body Mass [kg]	Avg. Per Capita Energy Consump. Rate For '95-'04 [W]	Extended Metabolism [W/kg]
Brazil	67	1.6E+03	24
Canada	71	1.4E+04	195
China	61	1.1E+03	18
Czech Republic	78	5.5E+03	71
Denmark	74	5.6E+03	77
Finland	74	7.9E+03	107
France	70	6.1E+03	87
Germany	79	5.9E+03	74
Japan	60	5.8E+03	96
Netherlands	74	8.0E+03	108
Philippines	54	4.9E+02	9
Switzerland	70	5.8E+03	83
United Kingdom	78	5.5E+03	71
United States	82	1.2E+04	140

Table 1: Extended Specific Metabolic Rate for Selected Countries [37-48]

Box: Method for Estimating Average Body Mass by Country

1. Average body mass index (BMI) was calculated as a weighted average of the fraction of each country's population falling into the four international BMI classifications: underweight, normal weight, overweight and obese. The fractions were obtained by querying the World Health Organization's global BMI database [38]; only the most recent estimates were used.
2. Average heights for each country were obtained from a variety of sources [37,39-48].
3. Average BMI was multiplied by the square of average height to determine average body mass for each country.
4. In the cases of the U.S., U.K. and the Netherlands, measured body mass data was readily available. Body masses calculated following the previously described procedure were found to have < 2% error in these cases, lending confidence to the accuracy of body masses for other nations.

But: The mechanism of how systems self organize is unclear. We have only rudimentary tools to document, analyze, and make predictions about the complex structure and processes of self organizing systems. Although Network Thermodynamics and graph theoretic techniques allow us to capture the quantity and quality of energy flows, we lack similar tools to measure the quality of material or information flows.

Kay [29] points out that "*humans have a set of priorities which will cause them to find a different balance, between the need to make good use of resources while coping with a changing environment.*" In contrast to natural ecosystems, "*We value human life and try to minimize the 'hardships' felt by members of our species.*" We cannot blindly copy solutions from natural systems as though we do not exist or are isolated from those natural systems. Like beavers building dams, we influence and are influenced by the ecosystems in which we are embedded.

Approaching problems from a systems perspective often requires that the problem be re-stated or re-defined, introducing uncertainty into the design process. In addition, the emergent characteristics of self-organizing systems can result in potentially unacceptable unpredictability. Vincent [15] states that "*In general, we do not accept unpredictability in technical systems; indeed we avoid it.*" Yet we face this challenge with existing designs, *"... since nearly every technical system is actually a combination of a technical system in the narrow sense, and a living (usually human) system which is the operator of this technical system.*" Isolating the technical from the broader system "*... can lead to reduced effectiveness, ... technological catastrophes and/or social tension and unrest.*" However, without tools and methods to reduce this uncertainty, designers will continue to follow 'tried and true' methods that they are familiar with, but have detrimental systems consequences.

5. Insights

5.1 Theory

Patterns and pattern language are seductively simple concepts on the surface. It is only through trying to write patterns that the richness, depth and detail required to develop useful patterns become clear. Practical guidance on developing pattern languages proved difficult to find. Examples of pattern languages often take quite different approaches from the original Alexandrian Pattern Language, and the rationale for these differences is not always obvious. Most pattern languages are only presented in their final form. Significant time needs to be allocated so that all participants can fully understand the nuances of patterns and pattern language. 'Learning by doing' seems to have been the best approach in this context, along with frequent discussions to explore the finer details and to develop a consensus.

Good patterns are devilishly difficult to write. In hindsight, the scope of the project was far too broad and ambitious, given the information and resources available. Nevertheless, applying the rigor of the patterns process to deepen our understanding of ecosystem principles has already delivered worthwhile insights. One of the benefits of the patterns approach is that even preliminary results can be useful. For example, a team member has commented that the discussions on the ecosystem principles have helped her develop a more comprehensive and insightful model for a resource handbook she is developing.

5.2 Project Evolution

The team started looking at 'pattern language' as a tool or a method to solve a specific problem: how can we organize, communicate, and make biological information available to disciplines outside of biology? We recognized early in the project the importance of thinking in terms of systems, with natural and societal systems forming a continuum. We also questioned whether it was appropriate to talk about 'solutions to problems' - did it make more sense to talk about current and future states?

Developing patterns around the Life Principles taught us the value of treating patterns as a process to gain greater insight into what each Life Principle means and how this knowledge could be applied to the field of design. Kay [29] specifically argues for a close integration of societal and natural systems: natural systems provide key services and support for societal systems, while societal systems must maintain the integrity of natural systems.

The complexity and uncertainty of working with self organizing systems suggests pattern languages could be a useful tool to capture the current 'state of knowledge' as well as the gaps in that knowledge. This might help practitioners not only apply the knowledge but also set realistic expectations by increasing awareness of the limitations and boundaries of that knowledge. Such a framework could also drive research to close the gaps and act as a 'working document' to collect and communicate additional knowledge, tools and methods as they become available.

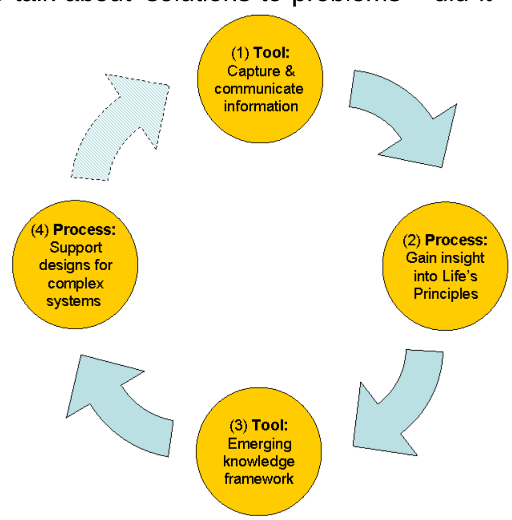

Figure 5: Project Evolution

A pattern language may also prove to be more amenable to the kind of dynamic design process that Kay [29] describes. Patterns encourage practitioners to think about the problem itself, rather than jumping immediately into finding a solution. The multi-scale aspect of pattern languages helps practitioners look at how their solutions 'fit' within the larger context, while the communication and collaboration aspects helps them work with multiple stakeholders.

5.3 Implications for the Design Process

At an abstract level, the existing design process is compatible with the concepts of systems thinking: designers will still identify goals, develop concepts, attempt to embody them and test prototypes, iterating the cycle as required. Applying principles from ecosystems will change and add to the list of goals that designers, developers and manufacturers set for their products and services. Designers will likely expand the bounds of the systems they analyze in the design phase and will take greater interest in hierarchical levels above and below the level occupied by the product or service.

In practice, the changes will likely be more wide reaching. Kay [29] argues that "*We can no longer treat our designs as mechanical clock work edifices designed to withstand the test of time.*" Design is no longer seen as finding a 'right' solution to a problem, but rather a process for evolving the design to meet changing needs and conditions. Instead of static solutions, we need to design dynamic processes. The implication is that designers will remain involved with their designs beyond what is normally considered the end of a traditional design engagement.

Kay believes that designs must be more adaptive, which implies both gathering of information and acting upon that information. In architecture, Post-Occupancy Reviews are discovering that the interaction of facilities management, occupants and buildings can be dramatically different from design predictions. Buildings are now being designed with extensive monitoring capabilities. This information can be used to tune the building, provide additional information to the users, and review building design models.

Kay [29] argues that "*Central to the design process is the activity of making trade-offs. Choosing between alternatives usually comes down to people's values. ... ethics and values must be incorporated into any discussion, if for no other reason than trade-offs between sustainable livelihoods and ecological integrity will have to be made*." Just as designs need to fit within the natural ecosystem, they also need to fit within the societal ecosystem, with all of its stakeholders. Kay recommends that designers:

- identify the players and their issues
- build a systems description of the situation
- develop an ongoing adaptive management strategy
- implement a governance structure

The wider scope of the design process puts a greater emphasis on collaboration and communication. Designers will need to tap into diverse perspectives that approach the design challenge from different temporal and spatial scales. Designers may rely more extensively on narratives and scenarios to capture a richer range of possibilities that existing design tools can provide. Pattern languages can provide a powerful framework to help practitioners develop better and more sustainable designs by virtue of their simplicity, ability to capture complex ideas, capacity to handle both 'hard' and 'soft' information, and the combination of a flexible structure with a well defined process.

6. Next Steps

The project is still far from delivering a set of patterns that cover the key design strategies underlying robust and vibrant ecosystems, whether natural or man-made. Pattern development can take years of input, discussion and refinement before they achieve recognition as "useful, useable and used". In addition, further effort will be required to look for relationships between patterns that will allow a useful 'grammar' and a pattern language to emerge.

The team plans to continue exploring the ecosystem principles and re-casting them in the pattern format. The team will work closely with the Biomimicry Institute and Biomimicry Guild as these organizations research and document natural strategies, providing the basic input for a more traditional 'bottoms-up' approach to identifying recurrent sets of problems, contexts and solutions.

The team will also research additional potential clients for the project, to help focus our efforts on tangible deliverables. This will also help identify the right time and content to build a funding proposal for dedicated resources.

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Appendix 1 – Variable Fluid Mixer Pattern [3]

Problem: *design a system that mixes fluid (including powder) ingredients, controlling production rate and mix ratios.*

Sometimes, the same equipment may be used to mix different ingredients at different mix ratios to produce different products (EG: mixers for paint, fertilisers, or dry ingredients of baked goods). Although variability in mix ratio rarely affects production rate in such cases, even small mix ratio variations can lower product quality. Modular design suggests there are advantages to duplicating the ingredient delivery system identically for each ingredient (for example, having a separately driven pump for each ingredient) to get economies of scale in the subassemblies.

However, variation in the relative rates of the motors that drive the pumps can cause unacceptable variations in the mix ratio. The variation arises because the motors, though structurally separate from one another, are *functionally* coupled: the mix ratio is determined by *all* motor (and hence pump) speeds and their associated variations, which are additive.

Furthermore, many environments in which this situation can occur are *dirty*, i.e. there is an assortment of contaminants in the operating environment that can hinder relatively delicate control machinery or electronics.

Key drivers are:

- fine control of mix ratio is required
- delicate electronics should not be used because of dirty environment
- the mix ratio must be adjustable
- the mix ratio variability must be low
- reliability must be high
- capital, operating, and maintenance costs must be kept low

Therefore: design a *functionally* modular system**.**

Design the system to consist of independent *functional* modules. Assign one pump per ingredient, but use a single motor to drive all the pumps, and variable ratio gearboxes to vary the speeds of the pumps (and therefore the mix ratio). The variability arising from a single motor and a single gearbox will be transmitted proportionally to all pumps, effectively cancelling itself out or at least dramatically reducing it.

The solution is consistent with Axiomatic Design [24]. The functional requirements of this product are (a) it must produce the right amount of product, and (b) it must mix the ingredients correctly. If separate motors drive each pump, then the design parameters are the speed of each pump. This induces a fully coupled design, which is undesirable. Setting the speeds of the motors to achieve prescribed productivity and mix ratio values becomes an iterative process. Variation over time in the speeds of the motors requires active, dynamic control of the system.

However, if using a single motor and variable ratio gearboxes, the design parameters are the speed of the motor and the gearbox ratios; this design is decoupled, which is preferred. Setting the motor speed and gear ratios is not an iterative process and does not require active, dynamic control.

But: Selection of gears and calculation of tolerances must be done carefully, to minimise variability of the gearboxes.

Functional modularity introduces structural coupling here. One must pay attention to ensure that this coupling does not lower reliability in specific cases. Reliability Analysis and Failure Mode And Effect Analysis are recommended methods to assess this.

Structural modularity can be salvaged to a degree by designing the shafts and structural elements to facilitate replacement of gearboxes, pumps, the motor, and other major subsystems.

Furthermore, particular attention must be given to the gearbox design or specification. Backlash and other effects must be accounted for to ensure the gearbox prevents a quality loss similar to that of using multiple motors.