Spring 5-17-2013

Innovation in Ship Design

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Innovation in Ship Design

A Dissertation

To Be Submitted to the Graduate Faculty of the
University of New Orleans
In partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
In
Engineering and Applied Science
Naval Architecture and Marine Engineering

By

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May, 2013

Dedication

This work is dedicated to Dr. Paris Genalis, 1942-2008.

Dr. Genalis was a native of Athens Greece and graduated in 1963 from the University of Michigan, where he studied naval architecture and marine engineering. He also received master's degrees in those subjects, as well as mechanical engineering, at Michigan. He received a doctorate in naval architecture and marine engineering from the University of Michigan in 1970.

Dr. Genalis spent much of his career in research and development for the Department of the Navy. He formerly was the Under Secretary of Defense (Acquisition, Technology & Logistics) and Chair of the National Defense University. In retirement he was a consultant to Office of Naval Research.

In 2008 he proposed to the author the pursuit of the present dissertation.

Acknowledgement

This work would never have been completed without the assistance of numerous people, but most important among them is the enthusiastic support of Program Officer Ms. Kelly Cooper of the Office of Naval Research.

Foreword

"Imagine that you enter a parlor. You come late. When you arrive, others have long preceded you, and they are engaged in a heated discussion, a discussion too heated for them to pause and tell you exactly what it is about. In fact, the discussion had already begun long before any of them got there, so that no one present is qualified to retrace for you all the steps that had gone before. You listen for a while, until you decide that you have caught the tenor of the argument; then you put in your oar. Someone answers; you answer him; another comes to your defense; another aligns himself against you, to either the embarrassment or gratification of your opponent, depending upon the quality of your ally's assistance. However, the discussion is interminable. The hour grows late, you must depart. And you do depart, with the discussion still vigorously in progress."

Kenneth Burke, The Philosophy of Literary Form

It is in the spirit of this image that I respectfully raise my hand and offer the following remarks, in this long-standing academic conversation.

Chris B. McKesson

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Abstract

What is innovation in ship design? Is it a capability that is inherent in all naval architects? Is it the result of the application of a certain set of tools, or of operation within a certain organizational structure? Can innovation be taught?

Innovation is a creative act that results in a new and game-changing product. The emergence of an innovative product creates an asymmetric market. The emergence of an innovative weapon creates an asymmetric battlefield. It is clearly in the economic and military interest of the United States to be able to develop and deploy innovative products, including innovative ships.

But the process of ship design is usually one of incremental development and slow evolution. Engineers are taught to develop their product by paying close attention to previous developments. This approach is viewed by some people as anti-innovative. And yet the author has made a career of innovation in ship design. How has this been possible?

This dissertation will answer the four questions posed above. It will show what innovation in ship design is, and where innovative naval architecture[1] lies in the taxonomy of human creative endeavor. It will then describe those human attributes which have been found to be essential to successful innovation. It will also describe some of the many tools that innovators use. Some of those tools are used unconsciously. Some of those tools are formal products supported by research institutes and teaching academies.

Finally, given the fact that innovation in ship design is a component of engineering – which is a subject taught in Universities – and that it is facilitated by the use of tools – and tool use can be taught – the author will conclude that innovation itself can be taught.

Whether it can be mastered will depend upon the individual, just as with most other creative skills.

KEYWORDS: Ship Design, Naval Architecture, Innovation, TRIZ, Synectics, KAI, MBTI, Problem Solving

[1] "Ship design" and "naval architecture" are used as synonyms throughout this dissertation. In reality naval architecture includes many other components, most notably a broad array of engineering analyses that are not necessarily part of ship design. The author knows this.

1: Introduction & background[2]

There has for some long time been an academic conversation on the nature of design, creativity, innovation, and invention. This conversation has embraced many technical disciplines and has been formative of many important practical contributions to engineering.

I have listened to this conversation for many years, throughout my career as a naval architect, and the time has now come for me to respectfully raise my hand and offer a contribution. This dissertation is that contribution.

This work was provoked by Dr. Paris Genalis, former Under Secretary of Defense, now deceased. Paris asked me: “What is innovation in naval architecture, and can it be taught?” After five years of study and contemplation I can now offer an answer to this question:

- Innovation is not the same as invention, in that it is focused on fielding a product
- Innovation is a subset of Design, which is a subset of Creativity
- Innovation requires expertise: there is a subtle connection between the Metaphysics of Innovation and the Metaphysics of Quality
- Innovation requires specialized skills and aptitudes
- Innovation is facilitated by the use of certain tools
- The use of those tools does not guarantee innovation - tools don’t make the artisan, they only help him
- The practice of using innovation tools can result in developing innovation skills

This summary sounds simple when distilled to this level, but then again Fermat’s last theorem is structurally simple too…and like Fermat, a margin is not large enough to hold my proof. I hope in this dissertation to properly expand and support the answers I have just given.

In order to present my results, I will first recap the background of the conversation, for the benefit of the reader who has not been in the room as long as I. This will include establishing a set of definitions of terms, and boundaries for the present work.

I next observe that many people have put forward techniques or algorithms for innovation. I observe that all of these techniques share a common architecture, and it is not clear to me that this

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[2] Footnote: This introduction follows the architecture commonly called the Heilmeier Catechism. Dr. George Heilmeier was a former director of DARPA, and is known for a set of structured questions he posed to persons proposing research in his presentation "Some Reflections on Innovation and Invention," Founders Award Lecture, National Academy of Engineering, Washington, D.C., Sept. 1992.

The full catechism is:

- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What's new in your approach and why do you think it will be successful?
- Who cares?
- If you're successful, what difference will it make?
- What are the risks and the payoffs?
- How much will it cost?
- How long will it take?
- What are the midterm and final "exams" to check for success?

commonality is apparent to their creators. My first contribution is to note this common architecture, and reduce it to a morphology.

Armed with this morphology, my second contribution is to use this framework to create a superset of the previously-published innovation algorithms, putting each one's components in the appropriate niche of the morphological framework. The superset is thus an inclusive generic or omnibus innovation algorithm, which embraces all of its forerunners.

My third contribution is to return to my roots and show the application of this set of tools to the specific challenges of ship design.

It is my sincere desire that this contribution will assist other participants in the conversation in realizing the common threads that seem to permeate so many of the tools in this discipline. Armed with this realization, this dissertation may then serve as an example or paradigm for demonstrating the application of formulaic innovation to other specific design disciplines.

Of course, I also hope that this will be a reference work for naval architects faced with a certain class of problems.

Innovation in naval architecture is today accomplished haphazardly or *ad hoc*. When innovation is needed in a design project, project managers will look for a known-successful innovator to join the project team. I, the author of this dissertation, have made a successful career as one of these in-demand individuals. But while this has been professionally and personally rewarding, it is not an ideally efficient model for including innovation in engineering design.

This *ad hoc* or individual-based model means that innovation cannot be systematically applied. It is relegated to something close to good luck in hiring.

As will be seen below, innovation does require people with particular attributes, but now (as a result of this dissertation) we are able to identify those attributes without waiting for the individual's career to manifest itself. We also have tools that we can give to those individuals to increase their innovativeness, tools which were not issued to me. Indeed, if I may be permitted the first of many metaphors in this dissertation, I will liken this research to the difference between formal education and The School of Hard Knocks. Today we teach engineers, in a four year intensive process, many topics, rules and laws that took years to discover in centuries gone past. In the same way I hope that with this dissertation we can teach engineers the topics, rules, and tools of innovation, rather than hoping that they discover them for themselves.

This approach is unprecedented in naval architecture. There is a slowly emerging science of design which is beginning to be taught in the naval architecture curriculum, but this author knows of zero examples of where such teaching includes specific instruction on innovation in ship design.

Engineering creativity is a subject receiving a substantial amount of attention today. Figure 1 shows the number of publications, by year, found in the COMPENDEX database (http://www.engineeringvillage.org) for the search string "innovation AND engineering." The graph clearly shows the exponential growth of this subject, with approximately 40 new papers per day in the last year.

This research was funded by the Office of Naval Research under grant N00014-09-1-0145. I greatly appreciate the support and encouragement of ONR, and I sincerely hope that this dissertation will be a contribution of national value.

What is it about this subject that warrants the use of public monies for this study? The answer is that innovation is a powerful naval force multiplier. The Computer Science Department of the Naval Postgraduate School have on their website (NPS-CS, 2012) a description of the importance of innovation to military effectiveness:

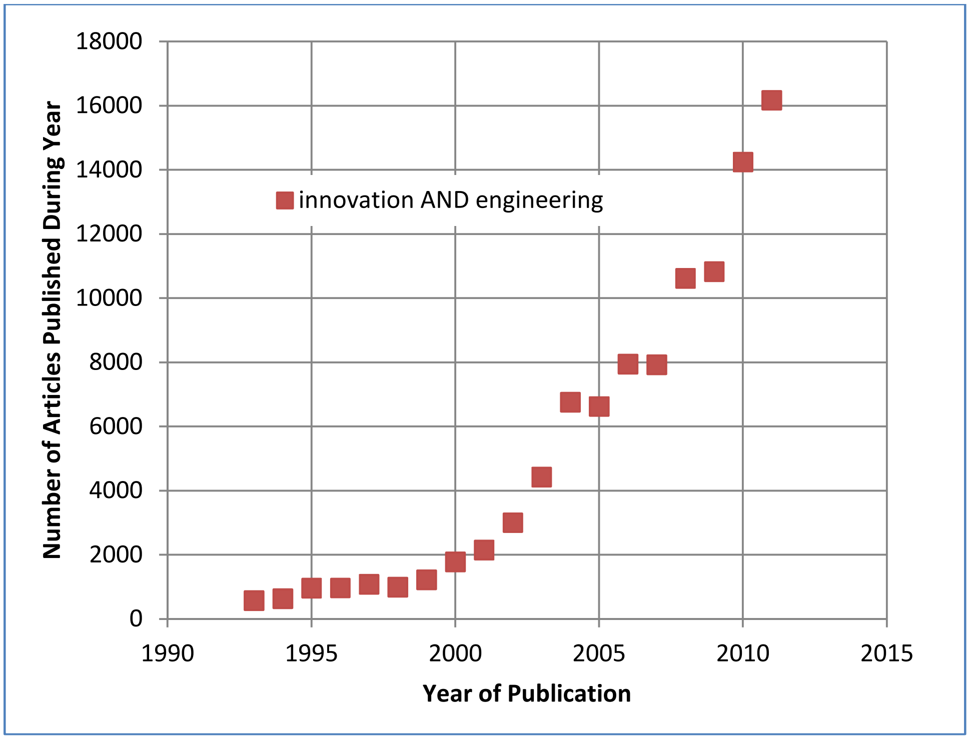

Figure 1 - Graph of number of technical papers returned in Compendex database search for search string "innovation AND engineering" as of 16 August 2012

"Our graduates will deal constantly with two kinds of innovation in the world: sustaining and disruptive. Most of the technologies they will work with go through extended periods of continuous, incremental improvements -- a process of sustaining innovation. Armored battleships, for example, became prevalent in the 1870s and underwent continuous improvement for well over a century. Aviation appeared in the early 1900s and underwent continuous incremental improvements, maturing into an air transportation industry used by 700 million people each year. Each of these sustained periods produced enormous cumulative improvements.

"Sooner or later, these sustained periods of incremental improvements are disrupted by completely new technologies based on different principles and requiring new ways of thinking. For example, in the early 1920s aerial bombing proved devastating to the most heavily armored ships, leading to the innovation of naval air fleets and eventually to the aircraft carrier. Terrorists disrupted air travel by exploiting Internet technology to coordinate suicide terror operations that eluded US intelligence.

"The point of the distinction is that sustaining and disruptive innovations require different approaches. Sustaining innovations "improve the system". Disruptive innovations "change the system"; they occur when something external changes the system or forces people to move to a new system. Our graduates will meet both cases in their work. Our curriculum and research support both. "

Former United States Ambassador to the United Nations John Bolton said that he believed America should "never be in a fair fight" (Bolton, 2012). This is the philosophy that motivates finding and exploring innovations in naval design. Breakthrough, disruptive, game-changing innovations in naval engineering are force multipliers that enhance the deterrent power of a naval force. They do this by increasing the asymmetry in a naval engagement. Even the perception of that asymmetry should be a deterrent to foreign aggression.

The value of innovation is recognized by non-naval branches of DOD as well, as witness the fact that the Department of the Army funded Hughes' study of alignment between Meyers-Briggs types and Kirton Adaptor/Innovator scores (Hughes, 1994.) This is yet another indication of the military relevance of an understanding of innovation generally.

This paper is not intended to be an essay on military policy, but it nevertheless seems clear to this author that innovation in naval engineering has a significant place in defense policy.

The present dissertation is a milestone in innovation in ship design, but it is neither the last work on the subject, nor without risks. For example, below I will develop the hypothesis that innovation is a specialized cognitive skill that can be learned by certain types of engineers. One risk is that based on this I will unfairly restrict the types of people who can learn innovation, by wrongly claiming that a certain attribute is needed. But my claim will be explicit, so a following researcher is welcome to challenge it.

Another risk is that I will overlook some extremely powerful tool, and thus do a relatively poor job of "teaching innovation" to my students. Again, my list of tools will be explicit, and following researchers are invited to expand upon them as new tools are developed and as existing tools are improved.

What is the payoff of an attempt to teach innovation? My reply is to ask what is the payoff of any attempt to formalize education? It is said "An Engineer is a man who can do for a dime what any fool can do for a dollar." In this spirit I hope by this work to be able to teach innovation, rather than waiting for it to grow by luck.

This research has grown across several intermediate checkpoints, which in Heielmeier's metaphor might be considered "homework assignments." These assignments culminated in the thesis that formalized innovation methods exist, and can be applied to naval architecture. This idea was developed and defended as a dissertation proposal at the University of New Orleans in 2011. The proposal defense might be considered a sort of mid-term exam.

Following approval of the dissertation proposal, the author had one more major checkpoint during the summer of 2012 when the ideas contained herein were tested during a summer fellowship at the US Navy's Center for Innovation in Ship Design, in Washington DC. (ref: ONR fellowship reference...) This checkpoint modified some details of the work and provided valuable validation insights. The work was then revised in subsequent semesters.

The present dissertation represents the "final exam" for this research.

2: Where does innovation fall within the activities of ship design?

2.1: Definition of terms

To frame the conversation we need a standard terminology. My topic is "innovation in ship design" but this begs for the definition of many terms. Permit me to start with that which seems the simplest: “Design.”

2.1.1: Design

I define 'Design' as the creative component of engineering - by which I mean that component in which a new thing is created. A possible synonym for design is 'synthesis' as distinct from 'analysis.' In engineering analysis a system is described, and the system's performance is estimated or calculated by the application of engineering principles. By contrast, in synthesis - or by my definition in 'Design' - the system's performance is described (via the requirements) and it is the system characteristics that are determined by the engineer. Design thus means the engineering discipline of assembling the functional elements of the system into a coherent whole, to meet some set of performance requirements.

In some communities (yacht design and industrial design, in particular) the word 'Design' refers to the aesthetic or styling aspect of creation. While I do not wish to denigrate this aspect, this is not the meaning of Design in this study.

Design is also a uniquely anthropomorphic activity: Design requires a designer, the act of design is an act of the human, and not a feature of the product being designed. To this end I am attracted to Lamb's (SD&C, 2003) definition of design which is summarized as "design is decision-making." This definition succinctly captures the creative element, or the human input. Decisions are by their nature the product of something external to the design process - they are the actions of a Designer, not attributes of the design. To me this has parallel connotations to the word 'create', which similarly requires a creator.

2.1.2: Innovation

Further, I define 'Innovation' to mean something close to "Design which has no forebears." Much engineering design is derivative. Indeed, my own teaching of design in Naval Architecture begins with a major unit on how to establish trends of best practice by studying other ships, and then developing your ship so that it lies within those trend lines. This approach is an inherently derivative or incremental improvement approach. By 'Innovation' then I mean something that is in some sense opposite: A design that does *not* follow where others have gone before. This definition is not perfect, because we will see that one of the techniques of formalized innovation is to simply broaden our set of candidate forebears, and return to the practice of derivative design while drawing on a more distant set of parents, but for purposes of this discussion this definition is sufficient to allow our conversation to proceed.

There exist myriad other attempts to define innovation, each sufficient for the work of each author. Examples may be found in Rowe (1974), Dewar (1986), Rogers (1983), Utterback (1994), Afuah (1998), Fischer (2001), Garcia (2002), McDermott (2002), Pedersen (2004), Frascati (2004). Afuah (1998) refers to innovation as new knowledge incorporated in products, processes, and services. Bers and Dismukes (Bers, 2007) define innovation from a performance, rather than process, point of view, calling a product 'radically innovative' if it has a previously unknown functionality, or a fivefold increase in performance, or a 30-percent reduction in cost. While this appears to be a very different definition than the one I have offered, I submit that it is actually very similar: Bers and Dismukes are saying "level of *performance* which has no forebears," and the similarity to my own definition thus becomes obvious.

2.1.3: Innovation versus Invention

Within the innovation and invention community there is a rising clarity of the difference between the terms "innovation" and "invention." Consider the following from Popadiuk, (2006) .

"In the research literature, the definition of innovation includes the concepts of novelty, commercialization and/or implementation. In other words, if an idea has not been developed and transformed into a product, process or service, or it has not been commercialized, then it would not be classified as an innovation."

The Wikipedia entry for "Innovation" may be taken as a form of popular or usage-driven definition. In this case it states: "Innovation differs from invention in that innovation refers to the use of a new idea or method, whereas invention refers more directly to the creation of the idea or method itself."

In light of this emphasis upon the commercial aspect of innovation, we draw the line of discrimination at the point where the product development is complete, and the product is ready to be fielded.

Within ship design this then begs the question of what the product is: Is it the ship, or is the design a product in its own right? I believe that the ship design is a product in its own right, and that the " commercialization" of a design is the act of sending the design to the shipyard for construction. In similar manner a Concept Design may be innovative, if it 'commercialized' to the point where it can be transitioned to the next phase, commonly "Preliminary Design."

The crux of this matter is that the creative product (the design) is developed to the point where it is finished to the point where it can be used. In the case of a consumer product this may mean "used by the end customer." In the case of an engineering concept design it may mean "used by the follow-on design team." But in either event the product is fully completed and ready for "deployment" into the inventory of its user community.

Sign studies that are not intended to be instantiated in ships – albeit after further development – are not the subject of this dissertation. The topic of this dissertation is innovation, meaning a ship that is intended to be created - delivered - the naval equivalent of commercialized.

An invention may be essential to innovation, but it is not equivalent to it.

2.1.4: Sustaining versus Disruptive

As mentioned earlier, innovations are sometimes divided into two classes; "Sustaining" and "Disruptive." Christensen (2003) provides a helpful discussion of the difference between these two types of innovation, by reference to a case history in the disk drive industry. In this case the sustaining innovations involved technologies yielding ever-increasing data storage density in the then-existing 5-inch disk format. The disruptive innovation was the introduction of the 3-inch disk drive, which made laptop computers feasible.

A sustaining innovation helps an industry sustain a rate of growth despite the maturity of its constituent technologies. Most technologies follow an S-curve of development (see Figure 2), wherein there is a low-growth tail during the item's nascent phase, and a high-growth boom during which the technology rockets into prominence. After some period of time however the technology will begin to 'plateau' as its own development rate diminishes.

The challenge is that the system, of which this item is a component, may wish to sustain a growth rate closer to the component's 'boom' rate. And it is here that the concept of sustaining innovation comes into play.

If several S-Curves are overlaid, each subsequent one shifted slightly to the right of the one before it, it may be possible to build layer upon layer of innovation such that the envelope of the these curves resembles a straight line with high slope, running from one 'boom' to the next 'boom' *ad infinitum.* See Figure 3. In this situation these technology innovations are called 'sustaining.'

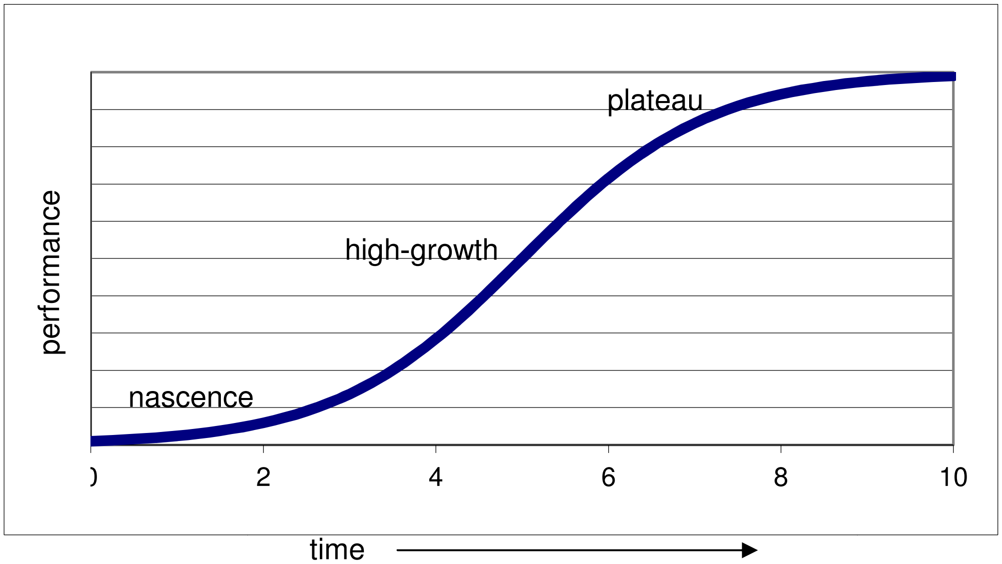

Figure 2 - The Technology Development S-Curve[3]

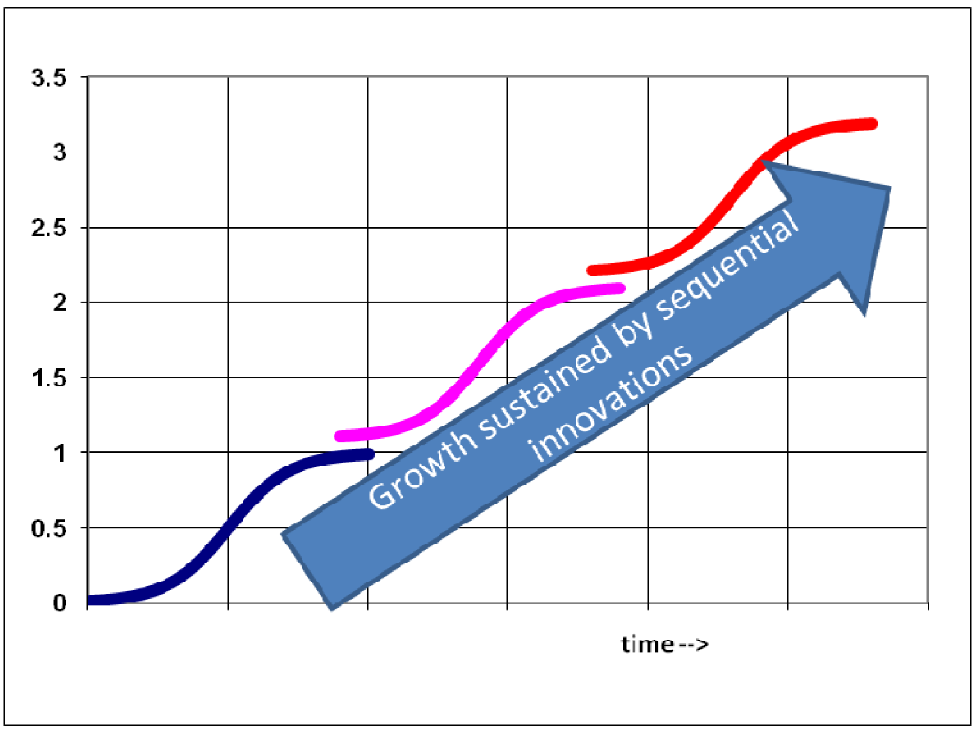

Figure 3 - Sustaining Innovation - Overlaying multiple S-curves to sustain a composite growth rate

[3] The technology S-Curve can be described mathematically as:

$$performance\ (\in 0{,}1) = \frac{10^{\left(\frac{4*time}{time_{max}}-2\right)}}{\left(1+10^{\left(\frac{4*time}{time_{max}}-2\right)}\right)}$$

Where: $time\ \in (0\ ,\ time_{max})$

By contrast, a disruptive innovation may be thought of as one which creates a whole new market, even perhaps eliminating the market which came before. Certainly the motorcar was a disruptive technology to the proverbial buggy-whip maker.

In naval parlance a disruptive technology is called a “game changer”, and the advent of the submarine and aircraft carrier are two obvious examples of disruptive platform technologies. One may imagine others, taken from the realm of science fiction: An impenetrable missile shield, such that one could be the aggressor without fear of counter-attack, would be a disruptive technology.

2.1.5: Incremental versus Radical

Almost the same as the definitions of "Sustaining" and "Disruptive" innovations are the twin concepts of "Incremental" and "Radical" innovation.

An incremental innovation is one which improves some component of the existing system, while leaving the system architecture and functionality basically unchanged. Thus, to create an example in ship design, the invention of the controllable-pitch propeller is an incremental innovation in improving ship propulsive efficiency and performance.

By contrast a radical innovation is one which results in, not an improvement of an existing capability, but a whole new capability. Again from the field of ship design the innovation of the hovercraft, with its amphibious capability, is a radical innovation in ship design.

2.1.6: Architectural Innovation

In Henderson, (1990) Henderson and Clark argue that a third type of innovation needs to be defined: Architectural innovation. This refers to an innovation that does not require any new fundamental technology, but instead assembles existing technologies in a new way.

The crux of Henderson & Clark's formulation is to distinguish between the system and the system's components. They state *"Successful product development requires two types of knowledge. First it requires component knowledge, or knowledge about each of the core design concepts and the way in which they are implemented in a particular component. Second, it requires architectural knowledge or knowledge about the ways in which the components are integrated and linked together into a coherent whole."*

This comment of theirs touches upon the subject addressed later in this dissertation of the need for expert knowledge in order to make inventions. It is my opinion that there is also a need for expert architectural knowledge, required to make an architectural innovation.

Henderson *et al* use Figure 4 to illustrate the result of their amplification. In this figure the horizontal axis represents the spectrum from incremental to radical innovation, while the vertical axis indicates which part of the system that innovation applies to. Thus, for example, innovations that apply to the components of the system, and leave the architecture of the system unchanged, occupy the top row of the graphic. Innovations that apply to the architecture rather than to the components, are grouped in the bottom row of the graphic.

This results in dividing the innovation landscape into four quadrants: Incremental innovations are those that are applied to the system's components, while leaving the core concept architecture unchanged. A Radical innovation, in their parlance, is one that employs a novel architecture and novel core concepts - a complete departure at the system and component level from the previous system. (A flat panel television in the palm of your hand (e.g. an iPhone) is such an innovation, when compared to a 1960s era CRT television set. Their components are extremely different, and their architecture is extremely different.)

Two new classes of innovation result from the Henderson and Clark definition. One is Modular innovation. Modular innovation applies to the use of a whole new core concept for some or all components of the system, while still assembling those components in the traditional architecture. Thus the invention of solid-state circuitry for televisions, to replace vacuum tube circuits, represents a modular innovation.

An architectural innovation then is one in which only the architecture is changed, while the components still represent the original fundamental concepts. An example the authors use is that of a room fan: The *status quo ante* involves a motor with a fan blade attached via a shaft. An architectural innovation would replace this with a rim-drive motor - it is still an electric motor and fan blade, but they are assembled in a completely different relationship.

2.2: Creativity

Having defined some key terms, let us now turn our hand to fitting innovation into that larger activity which is "ship design." To do this we will construct a map which shows where innovation in ship design fits within the spectrum of human creativity.

The highest level of a creativity taxonomy is simply creativity itself. This level embraces all of the creative acts, whether these be artistic, philosophical, intellectual, or technical. While I do not intend to dwell very long upon the subject of creativity generally, I will in the section that follows present some informative background on attempts to compose a general model of human creativity. This superset includes creation in art, music, literature, etc., as well as encompassing creativity in the mechanical arts. Since this is a superset and not the main focus of the work, it will only receive a very light touch, but it provides an essential foundation for the study, which will drill down from general to particular.

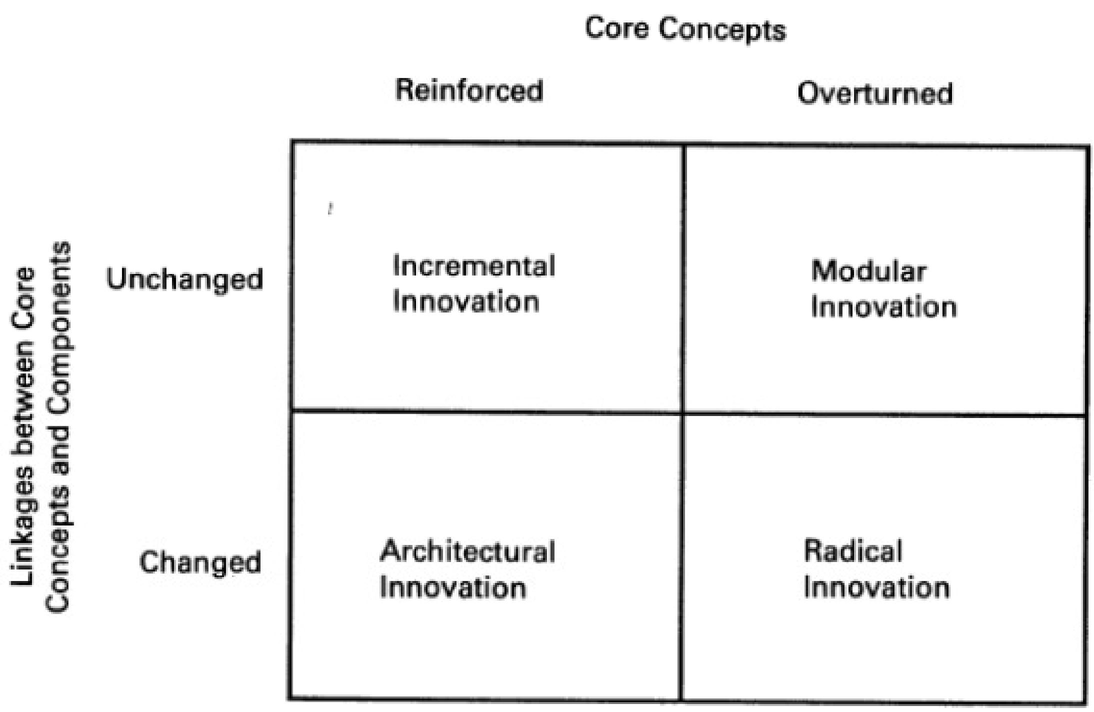

Figure 4 - Henderson and Clark's illustration used to define Architectural Innovation (Henderson, 1990). Note that although this is depicted as a distinct categorization, in actuality each axis is continuous.

Figure 5 attempts to depict the entire creative taxonomy. Under creativity we find engineering design or product development, including ship design. This is a specific class of creativity focused upon the creation of tangible objects or processes, under the constraints of physical laws, and in service of some purpose.

Let us begin the discussion at the topmost level: What is Creativity? This question seems simple, but it has given rise to a vast body of literature. The literature of creativity is remarkable for the number of attempts simply to define this "I know it when I see it" term. I define creativity as follows:

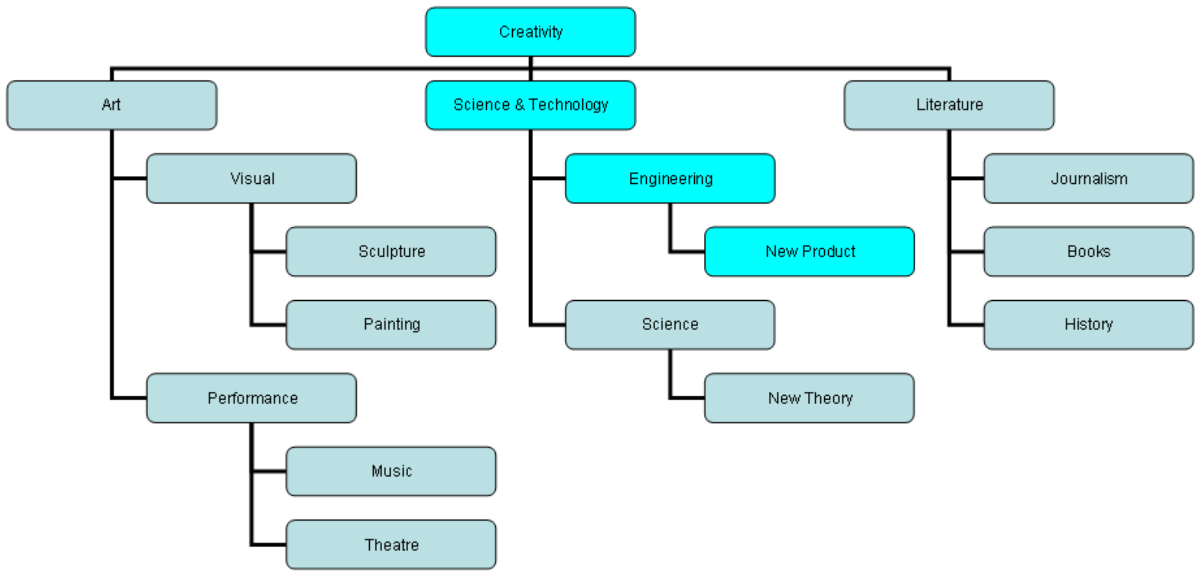

Figure 5 - The Author's attempt to depict the taxonomic 'Family Tree' of Creativity

A creative act is the conscious (purpose-driven) invention of a new work, with the goal of this work being better in some sense than the works that went before.

This definition hinges upon three attributes:

- Purpose
- Novelty
- Quality

Let us observe the development of this definition:

2.2.1: Stahl's Overview

Professor Robert Stahl provides an interesting summary of definitions of creativity, drawn from publications in the education industry, which is understandably interested in identifying and encouraging creativity. In Stahl, (1980) he describes the development of many alternative definitions of creativity, with particular emphasis on student creativity in the classroom – an emphasis that is not far removed from engineering creativity.

Professor Stahl provides a list of possible definitions of creativity, supported by a separate list of possible descriptions of the steps taken in the creative process. Let us begin by considering his summary list of definitions, as follows:

Creativity is:

i) Any activity which leads to the production of something new, whether it be a new technical invention, a new discovery in science, or a new artistic performance (DeHaan, 1957).
ii) Anything produced by a person which is new or unusual to him/her (Vance, 1976).
iii) A process of becoming sensitive to problems, deficiencies, gaps in knowledge, missing knowledge, missing elements, or disharmonies (Torrance,1966).
iv) The forming of associative elements into new combinations which either meet specified requirements or are in some way useful (Mednick, 1962).
v) An activity which possesses four types of response properties or features:
   (1) Unusualness (i.e., the relative frequency of the product among all possible products);
   (2) Appropriateness (i.e., the relation of the product to the demands of the situation);
   (3) Transformation (i.e:, the development of new forms that involve overcoming the constraints of reality);
   (4) Condensation (i.e., the degree to which the product manifests a unified and coherent relationship between simplicity and complexity) (Cronbach, 1968).
vi) The power of the imagination to break away from a perceptual set so as to restructure new ideas, thoughts, and feelings into novel and meaningful bonds (Khatena and Torrance, 1973).
vii) The intellectual operations relative to divergent thinking and re-definition abilities which are set in motion by a sensitivity to problems (Guilford, 1973).
viii) Thinking that includes some quality control of newly generated ideas including appropriateness (Crockenberg, 1972).
ix) The intentionally entered into process whose final product is unknown with its originality or uniqueness providing the peak experience response (Gallagher, 1975) the display of an openness to new or unusual ideas, a rich sense of humor, an ability to come up with unique solutions to problems (GTGEA,1978)

These definitions bring the following parameters as possible conditions for creativity. I overlook here the distinction of whether the particular condition is claimed to be necessary or sufficient or both.

The parameters listed are:

• Novelty	i, ii, v(1, 3, 4), viii, ix
• Adherence to a process	iii, iv, vi(?), vii
• The presence of requirements or a goal	iv, v(2), viii
• Extreme quality	ix

Of these parameters the reader will observe that I have accepted three of them in my chosen definition of creativity, eschewing only the concept that creativity is the result of adherence to a certain process. Let me present some more authors' discussions of creativity, to amplify this choice.

2.2.2: Rhodes' 4P model

Rhodes (1961) put forward a model of creativity that described creativity as a four-dimensional construct involving 'Person' 'Process' 'Product' and 'Press.' ('Press' is Rhodes' attempt to find a P-word to describe the climate or environment in which the creativity is expressed. The other four terms are straightforward.) Thus Person underscores the human constituent, the need for a Creator. Process is where the aspect of novelty comes in. Product indicates that creativity produces something - whether it be an art form or an object.

Rhodes' verbatim definition is: "*The word creativity is a noun naming the phenomenon in which a person communicates a new concept (which is the product). Mental activity (or mental process) is implicit in the definition, and of course no one could conceive of a person living or operating in a vacuum, so the term press is also implicit. The definition begs the questions as to how new the concept must be and to whom it must be new.*"

These same elements are present in engineering design. As stated earlier, design requires a designer, hence 'Person.' Design also produces a 'Product.' Design, engineering design properly executed, most certainly follows a 'Process', indeed it is a process that is steeped in and governed by the laws of physics, and is composed largely of a variety of engineering analyses. Finally, engineering design occurs within the framework of an industrial and economic infrastructure, which is Rhodes' 'Press.'

Rhodes stopped short, however, of defining the details of these four components. He discusses a couple of different proposed processes for creativity, he presents some interesting discussions of the characteristics of the creative person, and similarly for process and product. But he does not conclude by saying which of these processes, characteristics, etc., are mandatory for creativity. Instead, he leaves the door open to the possibility that there may be several right answers.

2.2.3: Lopez' 4P+N Model

Lopez, (2006) expanded upon the Rhodes model to add a fifth dimension, 'N' for client needs. This is a helpful addition as it adds the crucial element of requirements pull, which is extremely relevant in naval ship design.

More importantly, let us note that Lopez felt it necessary to add this fifth parameter. She felt that creativity was not sufficiently defined if it was not required to be directed toward some goal. Here we hear a thought that we will re-encounter later - the need to close the door to random undirected effort as "creativity." And yet this door-closing must not inadvertently also eliminate the possibility of the intuitive creative leap of "A Ha!" We will tread with care.

2.2.4: The Cognitive Network Model

Santanen et al, (Santanen, 2002) pick up the 4-P model of creativity and use it as a basis for modeling problem-solving. Santanen et al focus their discussion upon the solution-generation phase of engineering problem solving, and later in this dissertation the present author will also focus upon this aspect. These authors also develop a thesis that more research is needed into the cognitive processes associated with creativity. They state: *"The above perspectives of creativity offer tremendous insights into creative problem solving. Many of the prescriptions for enhancing creativity (for example, following stage models, employing group support systems, creating a specific environment, or gathering people with certain abilities) are demonstrably effective and have yielded vastly useful insights drawn from extensive experiences. However, these prescriptions tend to imply a cause-and-effect relationship without addressing what actually causes the effect or explaining why the results obtained matter to creativity. Given this discussion, it is difficult to explain why one may be creative at some times and not at others, or why one person is more creative than another is. Without this causal explanation, it is difficult to know what parts of the various prescriptions are effective and which are superstitions."*

Again, the present author will return to this topic when discussing the characteristics of the creative individual, below.

The Cognitive Network Model (CNM) developed by these authors is founded upon simple principles which have a ring of empirical truth in the present author's experience. I can do no better than to submit a lengthy quote from the authors: (* Embedded citations have been removed)

"The Cognitive Network Model of creativity ... attempts to answer the research question "What is the configuration of a basic cognitive mechanism that is responsible for producing creative solutions to a problem?" This model derives from a synthesis of concepts from three bodies of research: organization of memory and knowledge, the role of cognition and knowledge in problem solving, and creativity.

"The CNM begins with the assumptions that human memory is organized into bundles of related knowledge. The most basic of these bundles is generally referred to as the concept that comprises semantic memory. Several models that account for the structure of concepts have been proposed. While various strengths and weaknesses exist for each of these structures that are hypothesized to represent our knowledge, each model proposes that memory is organized into concepts that contain related knowledge. Thus, human memory is not atomic in nature; rather, knowledge is represented by collections of related entities.

"The second major premise of the CNM asserts that the concepts which comprise human knowledge are highly associative in nature. That is, concepts are interconnected such that they form vast networks representing our knowledge and experiences. The concept models of memory introduced above serve primarily to help us classify and deal with object concepts (like cats, dogs, and chairs). However, human knowledge is clearly organized according to more sophisticated entities than objects alone. There are also relational concepts that indicate how the different objects interact with one another through temporal relations. Accordingly, researchers have proposed more complex and abstract forms of memory organization. Prevailing constructs used to account for the relational structure of knowledge include schemata and frames. A frame can thus be thought of as a network of nodes (concepts) and the relationships among them. Similarly, schemata are packages that represent all types of knowledge as well as information about how this knowledge is used. For example, schemata represent concepts stored in memory such as objects, situations, events, and sequences of events. Therefore, the CNM assumes that human memory exists as a complex network structure where frames interconnect with one another by associations (links).

"The two previous sections argue that human memory is organized into frames (bundles) that are highly associative in nature. This section considers the third major premise that underlies the CNM: when any particular frame becomes activated (for example, when we think about cats, dogs, or chairs), subsequent activation spreads to other frames which are closely related to the originally activated frame (for example, thinking about 'cat' may lead someone to think about their pet). The spreading activation model asserts that activation of one node activates the next most strongly associated node, which in turn activates the next most strongly associated node to that one. As activation spreads out in this fashion, the relative strength of activation for each successive frame decreases. Patterns of activation among associated frames involve two components. The first is an automatic spreading activation that is fast acting and occurs without intention or conscious awareness, while the second involves a limited- capacity processing mechanism that cannot operate without intention and conscious processing. Evidence for spreading activation derives predominantly from priming experiments. In the simplest case, priming occurs when people that are shown the same stimulus on two separate occasions are faster to identify the stimulus on the second occasion due to "residual" activation. This repetition priming effect occurs even when there is no conscious awareness that the stimulus was previously presented.

"Together, the presentations in this and the previous two sections draw upon a vast body of research which concerns the organization of memory and knowledge. These findings represent major components of the foundation for the CNM. "

Based on this model of cognition, these authors then build a model of the creative process via a set of eight fundamental "Propositions" of the CNM, as follows. I have inserted attempts to show naval architecture applications of the Propositions.

- Proposition 1: Conditions that increase the likelihood of forming new associations between distant frames from our knowledge network also increase the production of creative solutions.

This suggests that exposure to a wide variety of vessel types, including understanding of the design forces that lead to their development, will increase the likelihood of a naval architect producing an innovative vessel himself as the solution to a particular design task.

- Proposition 2: As the associative distance between salient frames increases, so too does the likelihood of forming new associations between those frames. The distance between the frame "shipboard electronics" and the frame "hull form" is large. Thus it is unlikely that a naval architect will establish a single well-worn pathway between these two frames, instead he is far more likely to have many different such pathways (my term for associations) and to quickly and easily develop new ones. By contrast the associative distance between hull form and hull structure is much shorter, and a much smaller set of associations will exist, and they will be less prone to change.
- Proposition 3: As cognitive load increases, the likelihood of forming new associations between distant salient frames decreases. In a highly complex design situation, or even in one in which non-engineering demands are driving up the architect's mental burden (cognitive load), it is less likely that the engineer will conceive an innovation. In a word, he is too busy.
- Proposition 4: As the number of stimuli we are exposed to per unit of time increases, our corresponding level of cognitive load also increases. In an almost banal explanation of this Proposition, it seems to me that this says that if the engineer is interrupted frequently his innovation productivity will go down.[4]
- Proposition 5: As the associative distance between salient frames increases, our corresponding level of cognitive load also increases. To construct a link between shipboard electronics and hull form is hard work, and this will lead to all the other consequences of high cognitive load.
- Proposition 6: As the degree to which we are able to chunk salient frames increases, our corresponding level of cognitive load decreases. This Proposition is very interesting, given my (McKesson's) predilection for Very Simple Models (VSMs) in engineering (ref McKesson, 2011). The VSM is a tool for chunking of information. Thus the use of a VSM reduces the cognitive load and (via Propositions 3 – 5) increases the ability to produce new associations and thus innovations.
- Proposition 7: As the diversity of stimuli we are exposed to increases, the associative distance between salient frames also increases. This suggests that possessing a great detail of knowledge about a particular frame has the effect of "expanding" that frame such that it occupies a greater "distance." This may mean that the naval architect with detailed expertise in, say, hull structure, will experience himself to be far removed from the discipline of, say, hull form design, with implications already discussed.
- Proposition 8: As the diversity of stimuli we are exposed to increases, the degree to which we are able to chunk salient frames decreases. Under Proposition 6 I suggested that VSMs are tools for increasing the ability to form new associations, and that reducing – in the example of McKesson 2011 – the ship's propulsion plant to two parameters, and her hydrodynamics to one, can lead to powerful innovations in total ship design. Proposition 8 then suggests that marine engineers will resist the chunking of their discipline, as will hydrodynamicists resist the chunking of theirs. This could be taken to suggest that increasing expertise serves to construct barriers to innovation – an intriguing implication.

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[4] An interesting educational implication may be drawn from Propositions 4 & 5, applicable to naval architectural education as well as any other: It may be deduced from these propositions that a student with a high course load, and thus heavy cognitive load, is actually *less* adept at learning, if we accept that learning is the result of formation of new associations.

From these propositions it is easy to see implications for the definition of creativity itself. We might define creativity as a personality trait in which the mind is able to associate previously dissociated frames of knowledge, and allow this association to create new knowledge. It is not clear to me whether the authors require this associative effort to be conscious or if it can be unconscious. In my own experience as an innovator (and thus creator) I find much of my own association to be unconscious.

Santanen et al have therefore not provided us so much with a definition of creativity, but of a sketch of the creative process, and of the creative mind. These sketches will be useful to us later.

2.2.6: Other Process-Driven Definitions of Creativity

The Cognitive Network Model has introduced us to the idea of defining creativity as the result of a process. Santanen *et al* are not alone in offering definitions of this sort. Stahl (1980) cites several models of creativity which are process-dependent. Three such models are sufficient:

(a) the phases proposed by DeHaan , (1957):

1-period of increasing sensitivity to a problem,

2-period of searching,

3-plateau stage,

4-moment of 'creative' insight, and

5-period of confirmation.

(b)the phases proposed by Wallas (1926) and Gallagher (1964):

1-preparation,

2-incubation,

3-illumination, and

4-verification

(c) the phases proposed by Torrance (1966):

1-identifying the difficulty or problem,

2-searching for solutions,

3-making guesses or formulating hypotheses,

4-testing and retesting these hypotheses,

5-verifying and consolidating these hypotheses, and

6-communicating the findings or results

The models are interesting, because they constitute time-domain definitions. That is to say, the authors claim that if the steps are not followed then the act is not creative. Stahl rejects these models as definitions rather summarily, by noting that creativity is tested in timed tests. *" If creativity requires the several prerequisite phases listed earlier, then true creative thinking probably never has occurred nor ever will actually occur during the course of a short, timed test of creativity."*

This leads us to our next conundrum: If creativity is not defined by its process, then perhaps its entire definition is contained in its product? I am much closer to accepting this alternative, but it still has problems.

2.2.7: Creativity versus Novelty

A wind-fallen log may be used as a boat. And depending upon its geometry it might exhibit excellent directional stability, say, or other naval architectural feature. Does this random act then mark it as creative? I am reminded of an old joke, in which a city-dweller buys a work of art in the country, after being amazed to learn that this modern free-form sculpture was produced by the artist entirely by using her tongue. The aged farmer in the story then shakes his head at the city-slicker buying a cow's salt-lick.

Is creativity necessarily the result of a specified cognitive pattern - a certain 'algorithm' for thinking? Or does the entire definition lie in the product, with the result that any product that is "novel" is necessarily and by definition, "creative?" I reject both of these alternatives, in favor of Rhodes' inclusion of "Purpose."

This aspect of purposefulness is important, because otherwise the cow's salt-lick gets labeled "creative." If the only litmus for creativity is novelty, then randomness is creative. And, indeed, if we consider the role of randomness in genetic evolution (including man-made genetic algorithms) then randomness is an element of the creative act. But while novelty is a necessary condition for creativity, it is not a sufficient one.

Stahl (1980) tackles this thesis as well. He takes the approach that the problem with a product-only definition is that a wrong answer may possess novelty, but we do not want to admit 'wrong' answers into the pool of creative answers. And yet clearly creativity *does* depend upon novelty, and so the question now becomes 'novelty from who's perspective?'

"Stahl (1977) has argued that many behaviors and/or products are labeled "creative" merely because they represent something which is "personally different" from the perspective/experiences of the individual observer. Hence, people are likely to use the "creative" label to describe behaviors or products which are unique to their own thinking, experiences, expectations, or perceptual orientation. This labeling occurs regardless of the degree of actual originality or the intent which went into the behavior or product itself.

"A response which attracts the attention of and lies outside the personal experiences and/or capabilities of the teacher are very likely to be called "creative". A vivid example of this phenomenon is a doodled monster a second grade pupil drew for an art teacher. Upon seeing the monster the teacher immediately pointed it out as a beautiful example of a creative drawing. Later the teacher was disappointed by the news that a monster nearly identical to that doodled was observed by the child two days earlier on a Saturday morning cartoon show. Without that knowledge, the teacher to this day would still believe that that doodled monster was a result of creative thinking and behavior. Many an English composition has been labeled creative because the students used language (e.g., metaphors) in ways different from the teacher's expectations. In both cases the products are labeled "creative" merely because they appeared to be quite original and were out-side the frames of reference the teachers had for that situation and those students at that time (i.e., they were personally different experiences for these teachers). Interestingly, students who are more clever than their teachers are very likely to be identified as being the most creative students in the class - providing of course their cleverness is routed in positive directions."

What we see in this is that creativity lies often in the eye of the beholder. It is in fact possible that some of the world's most creative works are actually 'routine' to their creators, they are only 'creative' to you and I. I am not seriously advancing this as a thesis – merely acknowledging the possibility, in the mathematical sense.

In my own work I have often been asked to review the "creative" concepts produced by various non-naval architects. Indeed, this task formed a significant fraction of my workload at Navy Headquarters, because these ideas would be sent to members of Congress by constituents, and these letters would then end up at my desk for review and response back to the Congressperson.

In that situation I am clearly “the beholder,” and it is my judgment that establishes the degree of creativity expressed. And, as discussed above, it was very common for my reply to the Congress to be along the lines: “Your constituent has re-invented an idea that was tried some years ago…”

2.2.8: Creativity Defined

In summary of the above, creativity for our purposes has the following attributes:

- It is a purposeful human act, not a randomly occurring one
- It may be described algorithmically, but the algorithms are only sufficient, not necessary
- It results in novelty, but the novelty is in the eye of the receiver, not necessarily of the producer.

2.3: Design

Design is a subset of creation, but which subset? What are the discriminators that distinguish design from other creative acts? One might suggest that design is different from creation in the fact that design is constrained by physical laws or technological limitations, but then we note that music is constrained by the physics of sound and mechanics of the instruments, and that book writing is constrained by the limitations of typesetting and the laws of language (James Joyce's "*Finnegan's Wake*" notwithstanding.) So perhaps the distinction between creation in art and creation in engineering lies only in the author's definition of his sphere of endeavour? Is a physics-compliant science fiction author engaging in design or fantasy?

I believe that the answer is straight-forward: Design is an element of creation. A composer or a novelist may design their works even as they sit down to write them. A painter designs his painting - but he calls it composition. Design is the intelligent arrangement of the subcomponents as required to bring about the whole, which is the vision of the creator.

A science fiction novelist probably designs his book, but he doesn't design the spaceships and laser cannons within the book. This is because I choose to define 'design' as meaning 'establishing all the steps and components (at an appropriate level of detail) to bring the creation into existence.' In this way he does in fact design his book, but he does not design his fantasy inventions - that step is left to some future engineer.

There are many formalized methods for design, such as Lang, (1968), Eder, (2009), and Hubka, (1967). A comprehensive review of these models would be a dissertation in itself, and in the present work I subjugate this important set of models to the supporting role of foundation, touching upon enough of them to further outfit our mental furniture for the subsequent discussion of innovation. In addition, I restrict myself to those models which claim relevance to naval architecture. If design must by definition lead to instantiation, then this also limits some of the candidate models of the design process, because some of these models do not lead all the way to completion.

2.3.1: The Design Spiral

The most venerable model of ship design is the design spiral. One illustration of the design spiral (taken from SD&C, 2003) is reproduced in Figure 6. The design spiral models design as an essentially iterative process, with increasing level of detail and convergence at each iteration. The process is implied to be linear within a single iteration, that is to say it flows steadily from Step A to Step B to Step C.

There are many variations of the design spiral to be found in the literature, but their differences are matters of which order various modules come in - whether one should do structures before hull form, or vice versa. These differences in detail do not constitute different models of the process. In fact, the number of different versions of the design spiral may be taken as an endorsement that this model does indeed appear to capture the reality of design - at least to naval architects.

So if it is accurate, then in what way is it accurate? There are, as mentioned, two key attributes:

The process is iterative or repetitive. Calculations performed once may be expected to be repeated, because other subsequent calculations will change the input conditions to calculations already performed.

The process converges. The spiral depicts convergence as the radius decreases with time. Indeed, this is such a common belief that naval architecture jargon describes a failed design as "the spiral blows up." This means that convergence did NOT occur, but rather each subsequent iteration got progressively further away, rather than nearer.

The above description of the design spiral will ring true with many naval architects, but it lacks one key element of design: It does not explicitly contain decision making and creativity. The words that I have used above suggest that design is a sequence of calculations, which could as well be performed by a machine as by a man. (And there are many attempts to build such a machine.)

However the key to convergence lies in the human element and the aspect of decision making. The design spiral only converges because a human is able to look at the implications of subsequent turns of the spiral and can make decisions during the next turn that will help the results of that turn be convergent and not divergent. And indeed those cases where the spiral blows up can very usefully be blamed on poor decision making, in the form of poor design leadership[5].

The design spiral won't converge by itself. It converges because clever people make clever decisions.

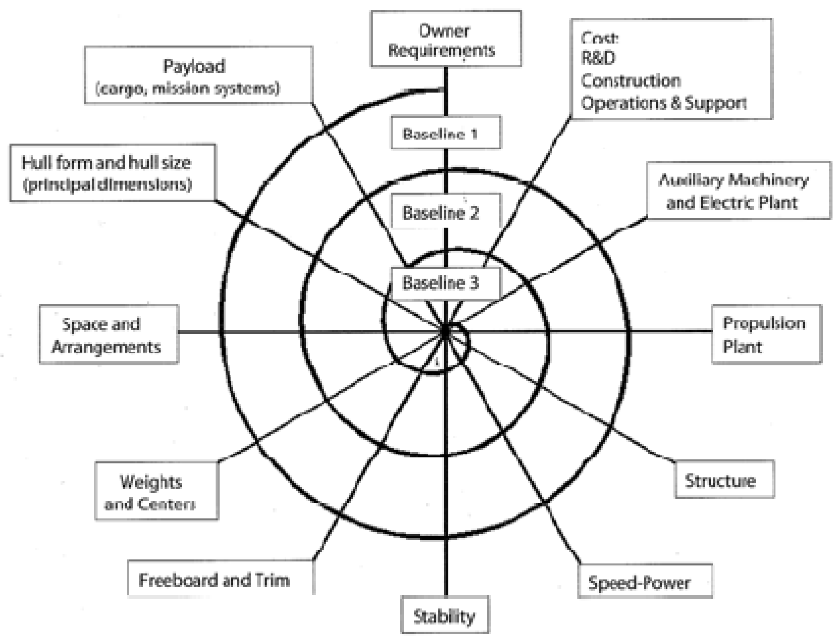

Figure 6 - The Ship Design Spiral, an illustration of one model of the design process (from SD&C, (2003)

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[5] There are several computer programs that attempt to capture the decision making as well, and thus reduce the entire ship design process to the execution of an algorithm, once a sufficient set of input guidance is given. Some of these programs work very well, and each of them is useful to the naval architect. But we will find nobody in the industry, including the inventors of those programs, who will claim that "the program designs the ship." Even the most powerful of the programs must be guided by a human mind.

2.3.2: Dr. Tyson Browning

Browning, (2010) has written on modeling of the design process, and it is interesting to note that he begins by responding to an apparent criticism that having a model of design will stifle a designer's creativity. If this were true for "design" as I have used the term, then it would certainly be even more damning for innovation. However Browning's response is that a design process model is not only "not a hindrance" but is in fact essential to establishing a design capability. Browning quotes W. Edwards Deming to the effect "If you can't define what you do as a process, you don't know what your job is."

A major thrust of Browning's work is that the most important aspect of the design process to model is the interaction component. In other words the critical feature is usually not what happens within each node of the design process, but rather the interactions that occur between the nodes.

This insight is valuable and should inform more of our courses in naval architecture, because our coursework in the engineering sciences already teaches the content in the particular nodes, it is our coursework in "design" that should capture the interactions between those nodes.

We will also see that this focus upon interaction is reflected in several of the innovation techniques we will encounter below.

There is another interaction between Browning's process modeling work and my own innovation modeling research. Browning rightly notes that the use of a process model can be an important step toward ensuring that knowledge is captured and stored. This takes the form of "lessons learned" on the best and worst ways to do things, and the interactions that resulted in more work, less work, more quality, less cost, more reliability, and so forth.

In Browning's work we also find an echo of the cognitive network model and its attention to associative distance and interactions between concepts. In fact, it would be interesting to apply Browning's philosophy by actively studying, not concepts, but the associations between concepts, explicitly. We may think of this as studying adjectives instead of nouns. Some naval architects will recognize this type of thinking in the following example: Contrast the difference between characterizing ships by hull form (a noun) versus by speed or seakeeping (adjectives.) The former characterization will have discrete classes such as "monohull," "catamaran," "trimaran," etc. By contrast the speed and seakeeping axes are necessarily continuous and will lead to different types of insight.

In practice, of course, both types of characterization may be important.

2.3.3: C-K Theory

C-K design theory or concept-knowledge theory is another model of the design process, and here again we will see the same thoughts as were encountered in Browning's focus on interactions, and in Santanen's focus on associative distances.

C-K theory defines the design process as a structured system of expansion processes, *i.e.* an algorithm that organizes the generation of previously unknown objects. The name of the theory is based on its central premises: the distinction between two spaces, a space of concepts "C", and a space of knowledge "K".

The process of design is defined as a *double expansion* of the C and K spaces through the application of four types of operators: C→C, C→K, K→C, K→K

C-K theory was a response to three perceived limitations of existing design theories, which it claims to have overcome:

- Design theory did not account for innovative aspects of design.

- Classic design theories were tailored to specific knowledge bases and contexts. Without a unified design theory these fields experience difficulties over cooperation in real design situations.
- Design theories and creativity theories have been developed as separate fields of research. But design theory should include the creative, surprising and serendipitous aspects of design; while creativity theories have been unable to account for intentional inventive processes common in design fields.

Note in particular that the third point echoes our foregoing discussion of the need for there to be purpose, or requirements, in the engineering innovation process.

C-K theory has a specialized terminology. A "brief" is defined as an incomplete description of objects that do not exist yet and are still partly unknown. The first step in C-K theory is to define a brief as a concept, through the introduction of a formal distinction between concept and knowledge spaces; the second step is to characterize the operators that are needed between these two spaces.

The knowledge space (K-Space) is a set of propositions with a logical status, according to the knowledge available to the designer or the group of designers. The K-Space describes all objects and truths that are established from the point of view of the designer. The process of design affects the K-Space - it is constantly changing, expanding as new truths appear as a result of the design process. Conversely, the structure and properties of the K-Space have a major influence on the design process itself. Thus in ship design there is a large body of knowledge touching upon, say, hull form, stability, and hydrodynamics, and the status or values of each of these items affect the values of the others, and the status of value of these items will also affect the ship design process. When stated in naval architectural terms this seems clear – the stability status of the ship design affects the steps that must be taken next in the design process.

A concept is then defined as a proposition without a logical status in the K-Space. A central finding of C-K theory is that concepts are the necessary departure point of a design process. Without concepts, design reduces to standard optimization of problem solving, which is essentially analytic and not synthetic. Concepts assert the existence of an unknown object that presents some properties desired by the designer. In ship design the concept might be a hull having a specified metacentric height and a specified resistance.

Building on these premises, C-K theory shows the design process as the result of four operators: C→K, K→C, C→C, K→K.

The initial concept is partitioned using propositions from K: K→C The laws of hydrodynamics add certain implications from the concept's stability.

These partitions add new properties to the concepts and create new concepts: C→C The concept (ship) takes on form and / or spawns variants.

Thanks to a conjunction C→K this expansion of C may in return provoke the expansion of the K space: K→K The generation of some variants, say for example a multihull, will require additional knowledge of the laws of stability and resistance.

The mappings in C-K theory might also be called a full factorial expansion. And, as with many such combinations of design variable, not all of the combinations are reasonable. In C-K language the unreasonable concepts are referred to as crazy concepts. Crazy concepts are concepts that seem absurd as an exploration path in a design process. Both C-K theory and practical applications have shown that crazy concepts can benefit the global design process by adding extra knowledge, not to be used to pursue that "crazy concept" design path, but to be used to further define a more "sensible concept" and lead to its eventual conjunction.

C-K Theory also claims to aid design creativity. The creative aspect of Design results from two distinct expansions: C-expansions which may be seen as "new ideas", and K-expansions which are necessary to validate these ideas or to expand them towards successful designs. Again using the C-expansion of the multihull ship, this requires a K-expansion in the fields of resistance and structural loads.

What we see here is an attempt to model design as the interaction between these two spaces. Again, as with the previous definitions the focus is upon the process, or the dynamic, or other similar action, and not upon the content or the product. In my parlance I say that these definitions emphasize the verb, rather than the noun.

2.3.4: Design Defined

Based on the foregoing, I define "design" in engineering as a subset of creativity as follows:

- Engineering design is the application by people of engineering principles, via some process, to create a specific new product, having therefore a specific purpose.

Note that this definition of design is very similar to Rhodes' 4P model of creativity, with the addition that the creative "tool" used is "engineering principles."

2.4: Innovation

We are now positioned to answer the first question of this dissertation: What is innovation, especially engineering innovation in ship design?

Starting from the top: Creativity is a purposeful human act that results in novelty in the eye of the beholder. Design is a subset of creativity relying on engineering principles and devoted to the creation of a purposeful product.

What, then, is innovation? The answer emerges clearly:

- Innovation is engineering development toward commercial deployment of a new product.
- The new engineering product may be either a new architecture, or a new component within the existing architecture.
- Innovation may be sustaining or disruptive, synonymous with "incremental or radical." The difference is not the magnitude of the innovation, but rather the 'location' of the innovation within the product definition.

Innovation can now be placed on the family tree of creativity (Figure 5) as illustrated in Figure 7.

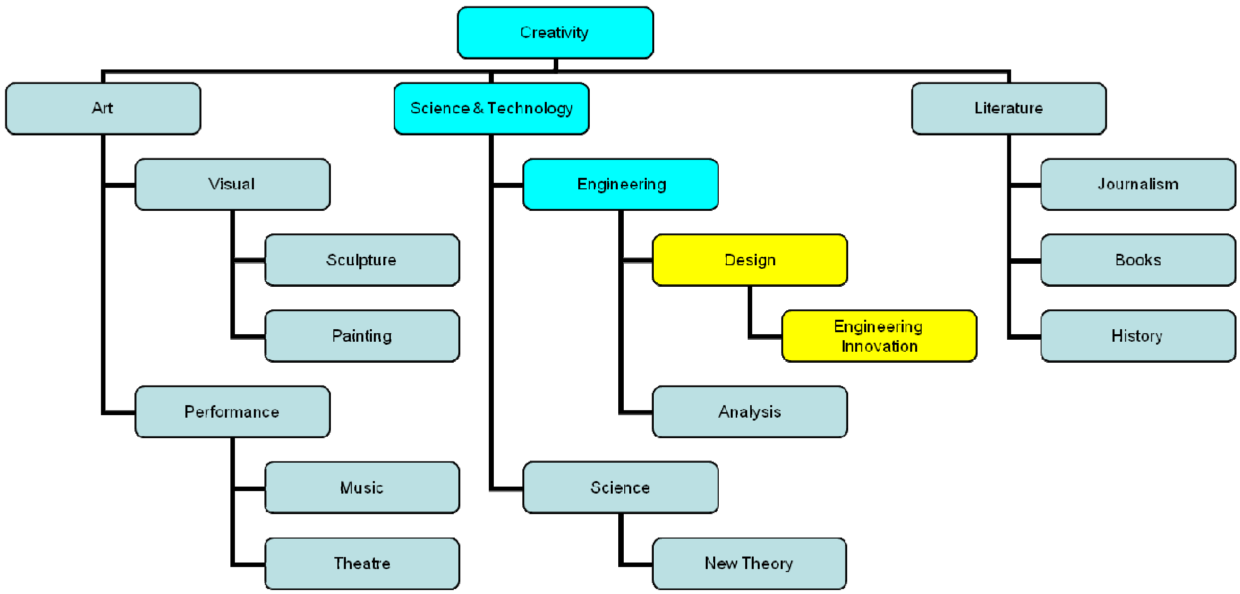

Figure 7 - The taxonomy of creativity, (Figure 5), edited to show engineering design innovation

3: What are the tools of ship design innovation?

The second question for this thesis is "What are the tools of ship design innovation?"

There are many published (and no doubt many unpublished) tools for innovation. A set of about a dozen tools is summarized in Appendix C of this dissertation. This appendix provides working descriptions of those tools gleaned from publicly available sources. Some of the tools summarized in the appendix have formal certification or credentialing programs associated with them, and it should be admitted that the author does not possess these third-party certification. Thus the summaries in Appendix C should be taken as indicative, rather than definitive.

Some of the innovation tools are extremely formalized, proprietary (copyrighted), and / or supported by formal research and teaching institutions. The poster child for this set may be "TRIZ." Others of the tools are unstructured, and have taken on the position of generic tools within the popular culture. The poster child for this set may be "Brainstorming."

I have studied a number of these tools of both classes, and it is my observation that they all follow the same algorithmic structure or morphology, but this shared structure is not recognized across developers. In this section I will present this overarching morphology, and then I will show the mapping of several innovation algorithms into this common structure. I shall attempt to weave a consistent thread of ship design through this section, by using the example of the design of a ship's rudder. Rudder design was indeed one of my early areas of expertise in ship design, I designed the rudders of the Navy DDG 51 class warships. At the time rudder design was a simple application of derivative design: I looked at previous successful ships (e.g. the DD 963 class) and scaled my rudders in the same proportion of LxT.

Let us now see what rudder design could look like, if viewed as an application of the innovation process.

3.1: Overview of the Innovation Algorithm Morphology

A morphology is a system for describing the structure or form of an entity, by dividing it into common components. Thus in entomology all insects have a common morphology of head, thorax, abdomen, etc. – see Figure 8. This is different from a taxonomy, where the taxonomy is a hierarchical or family-tree type structure, which is used for classifying and differentiating between members of a set. Perhaps our most familiar introduction to taxonomy is in biology, where organisms are classed according to Kingdom, Phylum, Class, Order, Family, Genus, and Species – see Figure 9.

Both morphologies and taxonomies are important for myriad purposes. Bloom (1956) and Krathwohl (2002) cite the value of a taxonomic system as an aid to measurement, and also for establishing a common language about the subject, and for finding congruence among different elements of the group being classified. In the case of Bloom and Krathwohl the items being classified are educational objectives, and not animals, but this is an apt paradigm for my use of a combined morphological and taxonomic system to classify invention algorithms, and for suggesting that this act of classification will have value both as a means for understanding those various algorithms, but also as a means for comparing and contrasting them, and finding their points of commonality or congruence.

The morphology of innovation algorithms is as follows (illustrated for convenience in Figure 10.):

- Define Problem
- Generalize Problem
- Search for solutions
- Apply Solutions
- Implement Application
- Learn

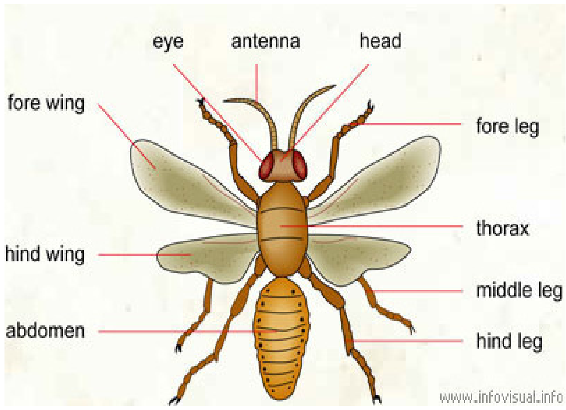

Figure 8 - The morphology of a flying insect. (Infovisual, 2012)

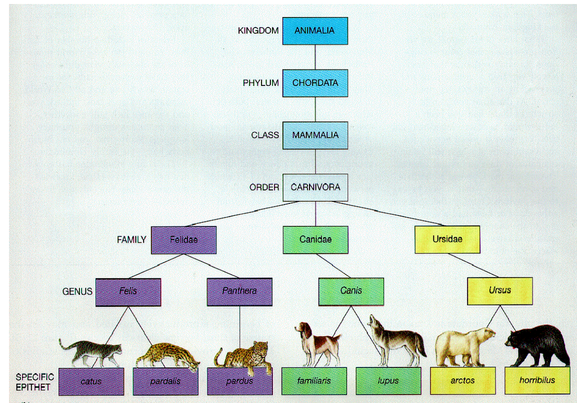

Figure 9 - The taxonomy of some carnivorous mammals (Biologicalexceptions, 2012)

3.2: Step 1 - Define problem

The first step in the morphology - the first common component in the innovation methodologies - is the problem statement. Problem definition is, in naval engineering terms, approximately equivalent to stating design requirements.

First, there are well known guides for stating requirements. The most important of these is that the requirements should be stated in a manner that describes a function or relationship, and not in a manner that describes a solution. Thus if we state the problem as "staple the two pieces of paper together" we have already specified the solution (staples) and closed the door to a range of innovative solutions, including glue, straight pins, paper-clips, and the like. If the problem were formulated as "fix the two pieces of paper together" then these choices would be available.

In my rudder design example this is a straightforward principle, and we shall see it again later: We could state the requirement as “Design a spade rudder similar to the DD 963.” This is a constraining requirement that presupposes the solution[6].

If the design team had wished to solicit innovation in rudder design, then the requirement would better have been stated as “Design a rudder system adequate to steer the ship.” This then opens the door to study of how much control is “adequate” and what type of rudder will produce this degree of control.

Next, note that requirements may be stated in one of two ways - as component requirements or as architectural requirements, and thus we introduce a taxonomy for problem definition – see Figure 11.

Equivalent to “component” versus “architectural” we may say “functional requirements” vice “relational requirements.” Architectural requirements are relational requirements that describe the ways in which system components must interact. Thus, in a house-architecture example, the garage must be accessible directly from the kitchen. A naval engineering example might describe interactions of systems on the ship, or it might describe interactions between the ship and the super-system of which the ship is a part. Such an example would be "shall operate as an element of the Carrier Battle Group." The super-system or external architectural requirements are frequently of very great importance in naval design.

[6] And in fact this is the way the DDG 51 rudder design requirement was stated, because arguably there is no need for innovation in ship rudder design.

Figure 10 - The author's common morphology of innovation algorithms

Component requirements are functional requirements imposed upon all or part of the ship. Thus a component requirement would be a statement of the requirement for maneuverability, or firefighting, or other similar performance aspect. Generally the whole-ship functional requirements are actually stated as a large number of smaller component requirements. My rudder design task is an example of a functional requirement.

Of course, in many cases requirements are (badly) stated as both - e.g. "The requirement is for a missile armed patrol vessel." In this case we say that the requirement is badly stated because it has been posed in the form of a solution, rather than as a problem. But notice that this statement includes both a functional requirement (that the vessel “patrol”) and a component requirement (that it be “missile armed.”)

The proper statement of the problem, or requirements, is important. I have already spoken of the need to state requirements without positing their solution. Another aspect is the breakdown of the problem into chunks. Von Hippel (1990) discusses the way that the problem is broken down, and the role that this breakdown architecture can have upon the invention / innovation outcome. Von Hippel is discussing innovation in an industrial context, wherein the innovation task is of necessity broken down into subtasks and distributed across the enterprise. The nature of the breakdown will open and close certain doors to innovation, by the simple act of defining the boundaries of inquiry of those tasks.

He uses “task interdependence” as the metric of whether problem solving in one task will require a complementary effort in another task. He then posits that the innovation will be more successful if the interdependence among tasks is minimized, and goes on to give guidance for how to specify tasks to minimize their interdependence, and also to reduce the cost of unavoidable interdependence.

In terms of facilitating innovation, von Hippel is saying that component requirements should avoid interdependence, and that this independence should also be reflected in the make-up of the design team to whom the task is assigned.

Let me construct an example of this principle, drawing on my rudder design task: As this dissertation progresses I will conceive some radical solutions to the rudder task. In fact, I will at one point suggest that the ship might be steered by manipulating her firemain. What von Hippel is saying here is that this particular innovation – firemain steering – is less likely to be successful specifically because it crosses boundaries and creates an interdependence.

This principle has two interesting implications for naval design: On the one hand we find here the scientific explanation of the well-known inventor’s principle of “make only one innovation at a time.” And innovation that requires extensive interdisciplinary tendrils is one that is less likely to be successful. But if that principle is accepted, then it gives rise to another possible implication: Based on von Hippel we may consider that specialists working on one part of a design problem don't actually need the full capability of the interfacing tasks, but might be able to get away with using relatively simple surrogate models for those tasks. Thus for example does the hull form designer really need to know the characteristics of the propeller, or is it sufficient to know merely the diameter? As one can see by this example, the interface between design tasks would be streamlined in accordance with this philosophy. This also reflects the idea of “chunking” found in the Cognitive Network Model discussed earlier. The reader may recall that chunking was a technique that could reduce the cognitive load, and thus increase the ability to innovate.

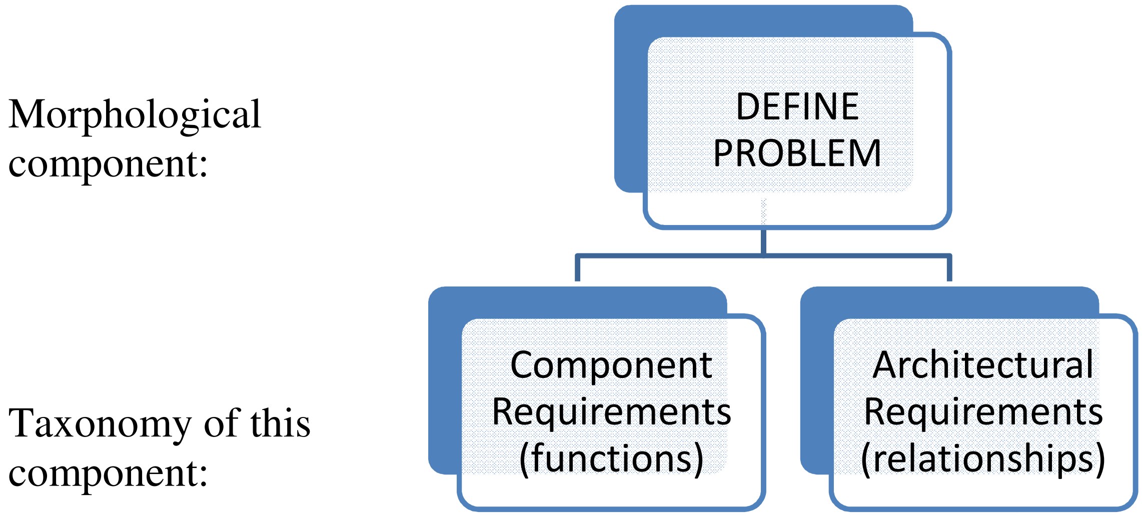

Figure 11 - The two taxonomic options for the Problem Definition element

Von Hippel then focuses upon this task partitioning aspect, and seeks out tools and models in a manner similar to the present author's search for tools and models of innovation. As a tool for stating requirements in an independent manner von Hippel mentions QFD (Quality Function Deployment – see Akao, 1994). It is interesting to read von Hippel's discovery of the QFD method, and to listen to the similarity with the TRIZ concept of "contradiction." von Hippel:

"QFD encourages the placing of customer requirements, engineering requirements and manufacturing requirements with respect to a proposed project onto a common matrix, so that interactions and possible conflicts can be identified and discussed by project team members at an early stage. Thus, the method might highlight the following interaction: "The better an auto door is at tightly sealing out noise and dirt (a desirable characteristic), the harder it is to close (an undesirable characteristic) given that conventional sealing technology is applied". Such information can be used as an aid to improving task partitioning. Thus, if project specifications require improvements in door closing or door sealing, the presence of the interaction with respect to these two matters suggests that arranging task partitions so that both are included in a single "improve door closing and door sealing" task would reduce task problem-solving interdependence in this instance."

There are myriad naval architectural examples of this type of interface between tasks. Staying with the ship's stern gear we may consider the interaction between rudder, propeller, shaft brackets, and stern tube. Clearly, before any one of those items is changed the architect should consider it's impact upon the others. What von Hippel suggests is that if innovation is sought, then this entire suite of components ought to be treated as a system: The most innovative rudder might turn out to be a modification of the stern tube or shaft brackets…or a steerable propeller as in today's electric drive pods.

Up to this point von Hippel has been arguing that one should state problems in terms of their interactions, and perhaps in terms of their contradictions. Finally, in addition to careful problem definition, von Hippel states:

"A second approach to managing task problem-solving interdependence involves reducing the cost of engaging in problem-solving across task boundaries. This approach is complementary to the one discussed above: It regards existing task partitions as given, and seeks ways to minimize the costs of any associated cross-boundary problem-solving. Therefore, both approaches can be applied simultaneously when attempting to manage the effects of task problem-solving interdependence."

This suggests that classic project management disciplines of communication, integration, gatekeeping, and so forth are all contributors to innovation success, and that careful design of the technical skills included in the design team, will be a necessary concomitant of team success.

What we see in von Hippel then is that we are enjoined to carefully define the problem, and we are invited to do so in a language of interface and contradiction. Further, we are shown that any single problem can be decomposed into subsidiary interface or contradiction problems. We are then offered some tools to manage those problems that can't be separated from their interdependencies - such as the whole set of architectural requirements. We are also taught to populate our design team with expertise in all the interfacing technologies, but only with those skills.

From the foregoing we can assemble a list of "best practices" for the problem definition step, where "best practice" should be understood in the sense of "most likely to permit successful innovation."

- Divide requirements into functional and architectural groups
- State requirements without stating solutions
- Consider using relationship-capturing tools such as QFD for requirement definition
- Explicitly define requirements interactions and conflicts
- Chunk requirements to avoid task interdependence
- Populate the design team with expertise in the interdependent technologies

With this as a foundation, let us now see what the innovation algorithms provide as tools for this step of the process. The reader may wish to refer to Appendix C frequently for descriptions of the algorithms discussed.

3.2.1: Problem Definition using Brainstorming

Brainstorming takes the problem statement for granted, and dives straight into ideation. But the grand tenet of brainstorming - to withhold judgment - has the effect of constantly exposing the problem to reformulation or restatement.

In a brainstorming session it is common for a participant to say "But wait, what if instead of pushing, we were to pull?" Ideas such as this are back-handed ways of restating the problem. In the push/pull example the proposer is actually starting down the path of restating the requirements at a higher level of abstraction. Reformulation of this sort, as opposed to restatement, properly belongs below in the discussion of "generalize the problem."

3.2.2: Problem Definition using Mathematical Problem Solving

Martin Gardner's algorithm for solving mathematical puzzles contains another element in the problem definition. He begins "Are there aspects of the problem that are actually irrelevant for the solution, and whose presence in the [statement] serves only to misdirect you?" (Gardner, 1978)

This might be considered an element in the generalization of the problem, but I prefer to see in it the same philosophy as we found in von Hippel, in the injunction to minimize task interrelationships.

3.2.3: Problem Definition using Muda

The technique of Muda elimination falls in similar category. Muda calls for us to eliminate "that for which there is no customer." This is very similar to Gardner's "distractions and irrelevancies." If the real goal is to cool one space and heat another, then why go through the steps in Figure 12? Who are the customers for the intermediate products? Can we not "short circuit" around the Muda in a fashion similar to Figure 13?

To use my rudder example, an obvious piece of Muda in a ship rudder is the drag of the rudder. We have no actual customer for this resistance – can we produce lift without drag? Alternatively, can we use the drag itself to steer the ship? I have seen catamaran concepts where only the rudder on one side is used at a time, and always the side that is 'inside' to the turn. This is because the drag of the rudder, given the wide beam of the catamaran, will actually help to turn the ship, converting "Muda" into something useful, finding a "customer" for the drag of the rudder.[7]

To return to solely the level of "Problem Definition," we may see that in these examples we are redefining the problem as "exert a turning force" while eschewing the specification that this must be a *lift* force.

3.2.4: Problem Definition using the Osborn Parnes Creative Problem Solving Process

The Osborn-Parnes Creative Problem Solving Process was developed by Alex Osborn (the inventor of brainstorming) and Dr. Sidney J. Parnes in the 1950s (Reali, 2012). CPS is a structured method for generating novel and useful solutions to problems. CPS follows three process stages, which match a person's natural creative process, and six explicit steps – See Table 1.

Table 1 - The Osborn-Parnes Creative Problem Solving Process

Process Stage	Steps
Explore the Challenge	Mess-Finding (identify the goal, wish or challenge)
	Fact-Finding (gather the relevant data)
	Problem-Finding (clarify the problems that need to be solved in order to achieve the goal)
Generate Ideas	Idea-Finding (generate ideas to solve the identified problem)
Prepare for Action	Solution-Finding (move from idea to implementable solution)
	Acceptance-Finding (plan for action)

As may be seen, the CPS stages are very similar to the present author's morphology. I find it interesting that CPS includes a step of actively seeking out problems – so-called "Mess Finding." The Mess-Finding step is one in which the practitioner is invited to imagine things that could be better. The examples in the literature are generally lofty in concept, such as "imagine a world without war."

I have not included this "Mess Finding" step in the present morphology because in most of engineering the "mess" is provided by the client. Instead, my morphology begins with the element of "Problem Definition" which lies at the end of CPS' first stage – "Explore the Challenge." Sower, (2006) provides an interesting list (attributed to Van Grundy) of amplifying questions for this part of the process:

[7] A clever extension of this is the "plunging rudder" used on some early west coast catamarans. The rudders were fixed in angle of attack, but their actuation was to raise and lower them from the water. When the inside rudder was "plunged" into the water it would exert turning moment, due to both lift and drag. When retracted as for straight-ahead operation it had no drag at all – a complete elimination of the drag Muda.

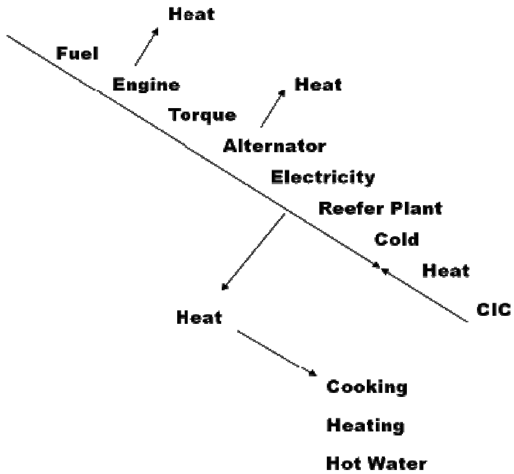

Figure 12 - The steps involved in cooling a ship's CIC, while producing heat for domestic consumption

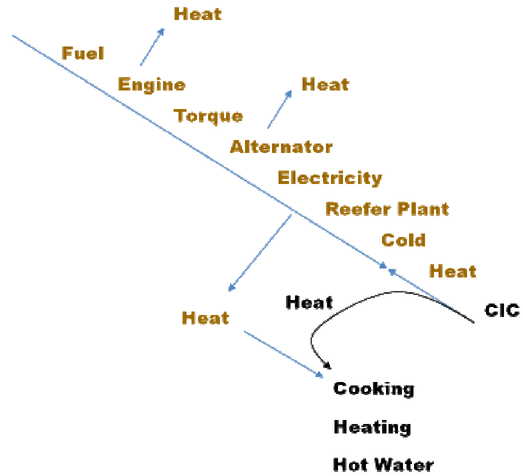

Figure 13 - The steps involved in cooling a ship's CIC, while producing heat for domestic consumption, streamlined to eliminate Muda

- What do you know about the situation?
- What would be better if you resolved this situation? What would be worse?
- What is the major obstacle facing you in dealing with this situation?
- What parts of the situation are related?
- When is the situation likely to get worse? Get better?

Notice in Sower's list a language of contradiction and interrelationship. This is the same concept that we have seen in von Hippel and will see below in TRIZ. The picture emerges that we have many authors, all saying nearly the same thing.

3.2.5: Problem Definition using TRIZ[8]

The step of "Problem Definition" is recognized within TRIZ as an extremely important component. Within classical TRIZ, the key element of the problem definition itself is the identification of the inherent 'contradiction' that gives rise to the problem. We have already seen this in von Hippel's example of a door seal: The contradiction is that a tight seal is necessary when the door is closed, but a tight seal makes it harder to open the door – there is a contradiction between "need it tight when closed, need it not-tight to open."

The TRIZ method standardizes the definition of contradiction. There are 39 standard terms which encompass all possible desired features of a system. The full list is given in Table 2, but a few examples are the producibility of the system (feature 32) contrasted with the complexity of the system (feature 36).

It takes some training for a practitioner to be able to map conventional requirements into the 39 standardized terms in TRIZ, but once this is done it is then possible to employ the rest of the TRIZ method for restating the requirements in the language of contradiction. Thus for example, the

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[8] TRIZ is a Russian acronym for "Theory of Inventive Problem Solving"(теория решения изобретательских задач.) See Appendix C.

producibility of the object may be made worse by the fact that the object is very complex, thus features 32 and 36 are in contradiction.

We will later see how this use of standard contradictions – potentially 39 x 39 of them – open the door to the use of a similar list of standard interventions to solve the contradiction.

Table 2 - TRIZ's 39 "features" which apply to all invented systems (Domb, 1998)

No.	Title	Explanation
1	Weight of moving object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension.
2	Weight of stationary object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
3	Length of moving object	Any one linear dimension, not necessarily the longest, is considered a length.
4	Length of stationary object	Same.
5	Area of moving object	A geometrical characteristic described by the part of a plane enclosed by a line. The part of a surface occupied by the object. OR the square measure of the surface, either internal or external, of an object.
6	Area of stationary object	Same
7	Volume of moving object	The cubic measure of space occupied by the object. Length x width x height for a rectangular object, height x area for a cylinder, etc.
8	Volume of stationary object	Same
9	Speed	The velocity of an object; the rate of a process or action in time.
10	Force	Force measures the interaction between systems. In Newtonian physics, force = mass X acceleration. In TRIZ, force is any interaction that is intended to change an object's condition.
11	Stress or pressure	Force per unit area. Also, tension.
12	Shape	The external contours, appearance of a system.
13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.
13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.

Table 2 – Continued

13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.
14	Strength	The extent to which the object is able to resist changing in response to force. Resistance to breaking .
15	Duration of action by a moving object	The time that the object can perform the action. Service life. Mean time between failure is a measure of the duration of action. Also, durability.
16	Duration of action by a stationary object	Same.
17	Temperature	The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
18	Illumination intensity	Light flux per unit area, also any other illumination characteristics of the system such as brightness, light quality, etc..
19	Use of energy by moving object	The measure of the object's capacity for doing work. In classical mechanics, Energy is the product of force times distance. This includes the use of energy provided by the super-system (such as electrical energy or heat.) Energy required to do a particular job.
20	Use of energy by stationary object	same
21	Power	The time rate at which work is performed. The rate of use of energy.
22	Loss of Energy	Use of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
23	Loss of substance	Partial or complete, permanent or temporary, loss of some of a system's materials, substances, parts, or subsystems.
24	Loss of Information	Partial or complete, permanent or temporary, loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, etc.
25	Loss of Time	Time is the duration of an activity. Improving the loss of time means reducing the time taken for the activity. "Cycle time reduction" is a common term.
26	Quantity of substance/the matter	The number or amount of a system's materials, substances, parts or subsystems which might be changed fully or partially, permanently or temporarily.

Table 2 – Continued

27	Reliability	A system's ability to perform its intended functions in predictable ways and conditions.
28	Measurement accuracy	The closeness of the measured value to the actual value of a property of a system. Reducing the error in a measurement increases the accuracy of the measurement.
29	Manufacturing precision	The extent to which the actual characteristics of the system or object match the specified or required characteristics.
30	External harm affects the object	Susceptibility of a system to externally generated (harmful) effects.
31	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These harmful effects are generated by the object or system, as part of its operation.
32	Ease of manufacture	The degree of facility, comfort or effortlessness in manufacturing or fabricating the object/system.
33	Ease of operation	Simplicity: The process is NOT easy if it requires a large number of people, large number of steps in the operation, needs special tools, etc. "Hard" processes have low yield and "easy" process have high yield; they are easy to do right.
34	Ease of repair	Quality characteristics such as convenience, comfort, simplicity, and time to repair faults, failures, or defects in a system.
35	Adaptability or versatility	The extent to which a system/object positively responds to external changes. Also, a system that can be used in multiple ways for under a variety of circumstances.
36	Device complexity	The number and diversity of elements and element interrelationships within a system. The user may be an element of the system that increases the complexity. The difficulty of mastering the system is a measure of its complexity.
37	Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labor to set up and use, or that have complex relationships between components or components that interfere with each other all demonstrate "difficulty of detecting and measuring." Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring.
38	Extent of automation	The extent to which a system or object performs its functions without human interface. The lowest level of automation is the use of a manually operated tool. For the highest level, the machine senses the operation needed, programs itself, and monitors its own operations.
39	Productivity	The number of functions or operations performed by a system per unit time. The time for a unit function or operation. The output per unit time, or the cost per unit output.

3.2.6: Problem Definition using Design by Analogy

Problem definition is key to any of the design by analogy methods, because the statement of the problem will guide the search for analogs. If the requirement is for a warship then we might be motivated to look at predators in the animal kingdom. If the requirement is for efficiency then a lexical search will emphasize words that are synonyms (or antonyms) for efficiency. In all such cases it will be necessary for the practitioner to grasp the nature of his challenge, the problems that are inherent in his assigned requirement, in order to pursue analogs from the visual, lexical, or biological realms.

3.2.7: Summary: Problem Definition

At the beginning of this section we created a list of "best practices" for the problem definition step. We can now add to that list some specific tools for innovation in the problem definition process, and put forward an omnibus summary:

- The statement of the problem constrains the opportunity for innovation
- Requirements should be divided into functional and architectural groups
- Requirements should be stated without stating solutions
- Expanding the problem statement "teleologically upward" expands the solution space, thus opening the door to innovation
- The problem must be stated in a scope that is within the technical domain of the design team
- The problem statement can identify distractions, irrelevancies, and Muda
- The problem statement is an opportunity to define the problem by analogy
- Related problems may be combined to allow multitasking.
- Consider using tools such as QFD for requirement definition
- Explicitly define requirements interactions and conflicts
- Chunk requirements to avoid task interdependence
- Populate the design team with expertise in the interdependent technologies

3.3: Step 2 - Generalize problem

The second step in the morphology is to generalize the problem. Problem statements are usually given in situation-specific language. In order to open the door to innovative solutions, it is necessary to study the problem more closely to – in some sense – take it apart and find the "real" problem.

The clearest example we have seen thus far in this essay is in TRIZ, where the 39 features constitute means of restating a problem in language that is not specific to a given technical domain. Let us explore other such techniques.

3.3.1: Problem Generalization using Brainstorming

As mentioned earlier, the brainstorming process has the effect of constantly exposing the problem to reformulation. A brainstorming session on rudder design has led to ideas far away from the simple derivative rudder. Examples proposed (and remember the principle of suspending judgment) include:

- Instead of designing a rudder, we just need to steer. And we can:
    - Steer with a rudder
    - Steer with an air rudder
    - Steer with a bow rudder
    - Steer by bending the ship
- Instead of steering the ship, why not use another ship to steer our ship?
    - Steer using tugboats

- Why steer at all? Can we simply aim the ship in the right direction once she passes the sea buoy? We do this with ballistic weapons.

What we see in this discussion is that the proposer is actually starting down the path of restating the requirements at a higher level of abstraction, and recognizing that the real problem is to exert a force or to get an object to move.

This type of restatement is explicitly the goal of the method called teleological decomposition.

3.3.2: Problem Generalization using Teleological Decomposition

One of the casual ways of referring to teleological decomposition was discovered written on a conference room white board. In what appeared to be graffiti was written:

> Begin by asking "why?"
>
> Then ask "why?" again.
>
> Then ask "why?" again.
>
> Then ask "why?" again.
>
> Then ask "why?" again.

Is it not obvious what the point of this is? Each statement of a requirement begs to be restated as the solution to a requirement one level higher. Even a military mission can be restated as a cascade from a level such as "enforce the political will of the nation."

And each time a statement of requirement is thus elevated, it introduces entirely new branches of a solution tree, and entirely new opportunities for game-changing innovation. Of course, this is the danger with this approach, in that it can create a factorial explosion of the amount of work required, due to the factorial expansion of the size of the solution investigation universe. So in response the practitioner may wish to expand the teleological tree quite far, but then prune the branches of that tree back to those perceived to be likely to bear fruit. Thus this step of the morphology includes a divergent / convergent form in itself.

Of course, based on this methodology alone there is no empirical basis for that perception, and it becomes the result of the creativity and open-mindedness of the practitioner.

One last comment is appropriate in this section: One of the fruits of the teleological approach is that it can lead to insights about the anti-problem. For example, consider the case where the problem is “the ship isn’t fast enough, put more power in her.” By decomposing teleologically we realize that “put more power in her” is not the real task, the real task is “the ship isn’t fast enough.” When we reach the ideation stage, this higher-level problem statement will help us realize that a solution is, not “put more power” but “reduce her drag.” Thus we have moved from the problem of “more power” to the anti-problem of “less drag.”

3.3.3: Problem Generalization using Synectics

Synectics attempts to force this same teleological expansion by creating metaphors for the original problem. If we then take the metaphor into the foreground, separating it from its origin, this can be a tool for the principle "make the familiar strange, make the strange familiar." Simply put: See in a new way. This emphasizes the divergent thinking aspect of problem generalization.

3.3.4: Problem Generalization using Quintilian's Seven Questions

Quintilian was a teacher of rhetoric and oratory in the first century CE. His seven questions have given rise to large body of literature. They are introduced in Appendix C, but their brevity permits them to be listed here as well:

- Who?
- What?
- Where?
- With what?
- Why?
- How?
- When?

The seven questions are powerful tools for all types of thinking, including engineering innovation. "See in a new way" is language that might be expected of Quintilian. The seven ancient questions can easily be described as tools to help observer "see anew."

One is reminded of Sherlock Holmes' oft-repeated statement to Dr. Watson "You see, but you do not observe." (Doyle, 1892) Had Watson methodically applied Quintilian's seven questions, his observation might have been greatly increased. Again what we find is that these questions may be used as tools for provoking divergent thinking.

3.3.5: Problem Generalization using Mathematical Problem Solving

Holmes' wisdom is also found in Martin Gardner's algorithm for solving mathematical puzzles. Gardner's second step was "Can the problem be transformed to an isomorphic one that is easier to solve?" (Gardner, 1978)

Clearly, this is a step of generalizing a specific problem – with unknown solution – into some other problem having known solutions. Gardner provides a similar injunction in his "Can the problem be reduced to a simpler case?" In fact, in derivative design this is what we do: We know the solution to steering the DD 963, let's simply apply that to the DDG 51.

But what if we didn't have a predecessor vessel? In most cases in innovation the task is not necessarily to transform into a known solution, but simply by the act of transforming the problem to open the door to numerous new avenues for solution. In later steps in the morphology we will meet techniques for finding those alternative avenues.

Note also that Gardner here does not speak only of the divergent step. Instead he encourages us to diverge, but only to diverge to *a problem with known solution.* Thus he incorporates the convergent thinking directly into this step.

The other methodologies discussed above do not provide guidance for the reconvergence of the problem.

3.3.6: Problem Generalization using the Osborn Parnes Creative Problem Solving Process

The Osborn-Parnes Creative Problem Solving Process (CPS) includes problem generalization within "Problem Finding." Immediately after the identification of the problem, as discussed above, the CPS user is enjoined to undertake divergent thinking in an effort to generalize the problem and generate solutions. CPS is also one of the few formalized methods to explicitly enjoin the use of divergent & convergent thinking, in pairs, at each step of the process.

Two key techniques in the CPS are "IWWMI" and "Five Whys." (Daupert, 1996) "IWWMI" stands for "In What Way Might I." Quoting from Daupert:

"Brainstorm a list of possible problem statements that begin with the sentence stem, "In what ways might I...?" This will prompt you to reorient your thinking from negative problem statements to positive ones. For example, a negative problem statement might be, "My problem is I don't have enough money." This statement leads the brain into a cul de sac by orienting its imagery and associations towards scarcity thinking. But stating the situation in a slightly different way leads to richer possibility thinking: "In what ways might I get more money?" The shift in thinking is subtle, yet profound. … Let's assume someone wants money to buy stereo equipment:

- *In what ways might I beg for money? (Panhandlers sometimes make a lot of money)*
- *In what ways might I borrow money? (Maybe my bank or Aunt Martha will help)*
- *In what ways might I steal money ? (A quick source of cash)*
- *In what ways might I find money? (Hmmm, I could look under the couch, check coin returns in vending machines and pay phones, or pick up soda bottles, or HEY! I just had an idea! Maybe I could put together found objects artistically and enter the art contest I just read about)*
- *In what ways might I win money? (Lottery, bingo at church, hold a raffle for my house)*
- *In what ways might I give away money? (Hmmm, this makes me think of becoming a fund raiser for worthwhile charities, and charging an ethical amount for my services)*
- *In what ways might I cough up money? (Ah-Ha! That triggered a memory of Uncle Fred. He sure coughs a lot. Haven't thought about him in a while. He always said if I ever needed help, come see him.)*
- *In what ways might I avoid the need for money? (Get a job at the stereo store so I can get the equipment I want at a discount. Hey! Maybe I can barter for it. Or maybe I can send an early Christmas list to my family and friends.)*
- *In what ways might I obtain resources? (Find some used equipment that they're throwing out, and learn to fix it.)*
- *In what ways might I get help? (Maybe if I get to know someone who works at the stereo store, or even get to know the owner, I can trade some work for some equipment.)"*

It is clear from the example that this technique results in a restatement of the problem at a teleologically higher level, and that it also starts the process of ideation. In fact, when we brainstormed the rudder design task, we identified several answers to "In what way might I steer the ship?" To reiterate:

- In what ways might I steer a ship?
    - Steer with a rudder
    - Steer with an air rudder
    - Steer with a bow rudder
    - Steer by bending the ship
    - Steer using tugboats
    - Why steer at all? Can we simply aim the ship in the right direction once she passes the sea buoy? We do this with ballistic weapons.

The "Five Whys" method is exactly what was previously discussed under teleological decomposition: Ask "why?" in answer to that question, then ask "Why?" again. Repeat through five "whys." Daupert: "*The outcome will be the distilled essence of your quest at a more abstract level of meaning, a higher point of view from which many more potential solutions can flow than you could have generated from the original problem definition."*

3.3.7: Problem Generalization using TRIZ

In TRIZ the problem definition and problem generalization steps are combined: The problem is to be defined in general terms at the outset. This is accomplished via the previously-supplied list of "standardized features," and identifying the contradictions between those features.

In our rudder design task, the contradiction is that we want the ship to be directionally stable – to go straight – except when want her not to go straight. In some sense we are looking for directional stability that we can switch on and off at will.

In the formality of TRIZ, the problem is explicitly generalized as the contradiction between two features, found in the 39 x 39 intersections of a square matrix.

Note that classical TRIZ in this way does not result in a factorial expansion of the problem. Instead the "real" problem is found to lie in one or two contradictions between one or two of the 39 features. By using the contradiction matrix a short list of less than a dozen inventive principles is found. The result is not a large expansion of the solution space but rather a focused statement of a handful of scientific investigations. These investigations can be assigned to appropriately-qualified members of the team in parallel, and without the "everybody should think about everything" chaos that is found in unstructured methods such as brainstorming.

3.3.8: Problem Generalization using Design by Analogy

The various design by analogy methods are mostly focused upon the ideation step of the morphology. However, the methods require that the problem definition be taken to a sufficiently generic level to permit the analogies to lead to innovative solutions, and not merely to parents for derivative design. Thus if we were to use design by analogy to find an innovative concept for a ship rudder, then we would need to state the problem as "steer" "guide" or "direct," rather than as "ship rudder." Analogs of a ship rudder will be rudders, analogs for "steer," "guide" and "direct" will be more thought-provoking, for example as shown in Figure 34 in Appendix C.

Thus it is my opinion that the innovation algorithms that are classed as "design by analogy" benefit from all of the problem definition tools listed above. We could investigate analogies based on the Five Whys. We could investigate analogies based on TRIZ's contradictions. We could search for analogies based on TRIZ's inventive principles.

It is noteworthy however that the WordTree method (Linsey, 2007) – which is a form of "design by lexical analogy" – does include an explicit problem generalization step. In Linsey's method the problem is decomposed by finding a cascading tree of related words. These words include the following elements:

- Key problem descriptors: Single-word action verbs which describe the problem. In a ship problem these might be: "Move," "Propel," "Steer," etc.
- Functional categories: Single word overall, Single word critical or difficult functions, single word customer needs. In the ship rudder example we might include: "Control" "Navigate"
- WordTrees: Armed with the one-word descriptors (which have much of the feeling of the TRIZ features and conflicts) the user then generates lexical analogs either manually (WordTrees on sticky notes) or automatically (WordTrees generated by WordNet thesaurus software.)

The resulting WordTree in this method has the same conceptual basis as the other methods discussed: To cause the user to see the problem in a new way (Synectics) by highlighting it's similarities to other problems (Gardner) and by highlighting the contrasts and conflicts inherent in the problem (TRIZ).

3.3.9: Summary: Problem Generalization

What we have seen is that there are various methods for problem generalization, but they may all be assigned into about three taxonomic categories (see Figure 14):

- Features and Contradictions: TRIZ, antonyms
- Teleological Expansion: We see the "5 Why's" repeated in CPS, and also in other forms in Brainstorming, Synectics, and Quintilian's seven questions.
- Transformation: Transformation is explicit in Martin Gardner's mathematical problem solving algorithm, and in the WordTree design by analogy method.

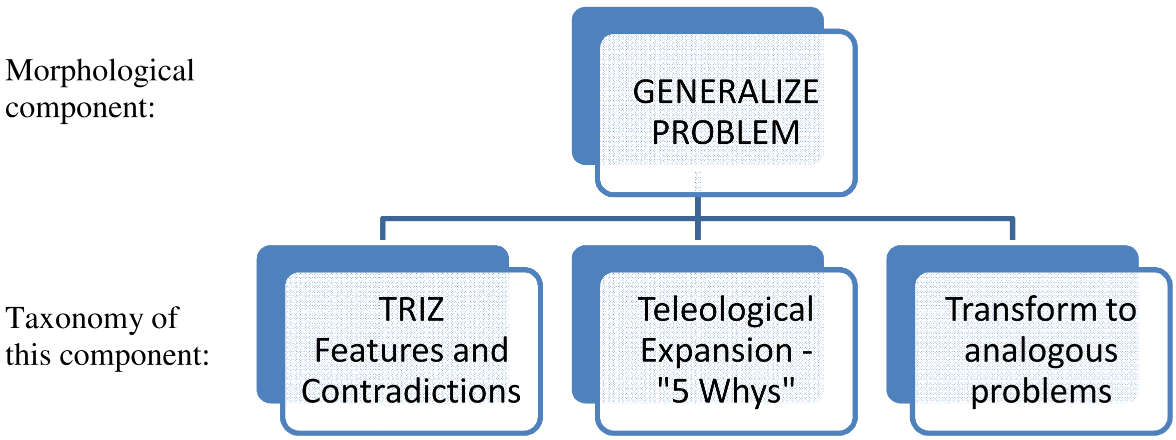

Figure 14 - The three taxonomic options for the Problem Generalization element

In all three types it is helpful to employ divergent thinking first, to expand the problem, followed by convergent thinking to collapse the re-stated problem to manageable size. As mentioned above, some of the formal methodologies provide tools for both components of this process.

3.4: Step 3 - Search for solutions

The search for solutions is in many ways the fun part of the innovation process. This is the stage formally called "ideation" – the generation of ideas. There are far more ideation methods than the few discussed in Appendix C, but the set given therein is sufficiently diverse to capture the main features of importance.

Ideation amounts to saying "taking the generalized problem as the 'real' problem, what are the possible solutions?"

Ironically, while the ideation step is a step replete with techniques, each technique can be summarized in only one or two sentences. In the majority of cases the technique's ideation protocol turns out to amount to either "look for solutions *here*" where "here" is a specified domain, or "look for solutions having *this* feature," (or both.) It is my finding that there are basically five types of ideation used:

- Ideation by Analogy
- Ideation by Contrast
- Ideation by Elimination
- Ideation by Combination
- Random (Unconscious) Ideation

3.4.1: The Search for Solutions using Quintilian's Seven Questions

Quintilian tells us to look in five places for solutions:

- Who – look for alternative people to produce alternative results. What if we used a plumber instead of a shipfitter? Would this lead to the idea of steering the ship by using the firemain to influence the boundary layer?

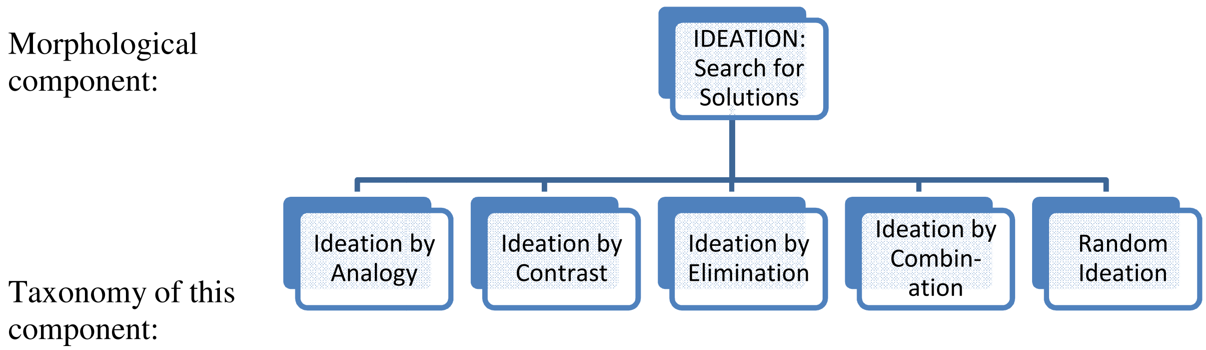

Figure 15 - The five taxonomic options for the Search for Solutions (Ideation) element

- What – look for alternative materials to produce alternative results: What if we used fabric instead of steel? Can we invent a sail-rudder?
- When – Look for alternative sequences to produce alternative results: What if we painted the ship before installing the systems? What if we design the rudder first?
- Where – Look for geometric alternatives to produce alternative results: What if the rudders were in the air instead of the water?
- With What – Look for alternative infrastructure to produce alternative results: Would we invent a different type of rudder if the ship had infinite electrical power?

In each case the question serves to provoke a new set of solution ideas, by changing some fundamental parameter of the problem. Changing the staffing, changing the powerplant, or changing the shipbuilding material will all lead to a different ship. In some cases that might be a better ship, in some way.

Given the manner in which I have worded a Quintilian-ideation process, I classify this as ideation by contrast: We are changing one element to a contrasting state, and seeing if that provokes an idea.

3.4.2: The Search for Solutions using Mathematical Problem Solving

Gardner's (1978) method for mathematical problem solving makes explicit reference to two ideation tools:

- Can you apply a theorem from another branch of mathematics?
- Can you invent a simple algorithm for solving the problem?

These are interesting as paradigms for ideation because of their substantial differences. The first case is clearly a case of ideation by analogy – we look for an analogous problem – but it is also an example of ideation by contrast because we seek out those analogs in a contrasting branch of mathematics. If we were to look not to mathematics but to another field of engineering, the naval architect might ask himself "How would a Civil Engineer solve this problem?"

The second method is very thought provoking. Gardner is talking about solving mathematical puzzles, and he suggests building an algorithm. I myself am not a talented mathematician, and I have often been faced with mathematical problems that I cannot solve explicitly. But I have found that I am quite good at constructing a numerical solution to the problem, and then manipulating the numerics (e.g. reducing the step size, etc.) so that the empirical solution is ever-closer approximated. This is not good math, but it can be powerful engineering.[9]

So then by extrapolation, is there a way that we can at least progressively approach a solution if we cannot solve our given design problem directly? If I need, say, flexible steel – steel cloth, if you will – then how can I approximate that? Well in one dimension a bicycle chain does exactly that. And in two dimensions old time chain mail accomplishes the same goal. These are in some sense 'approximations' of the desired state, by using small step sizes. As such I class them as exercises in ideation by analogy, because the purpose of the algorithm or approximation is to be analogous to the "real" problem, at least in its most-important essence.

3.4.4: The Search for Solutions using Osborn-Parnes Creative Problem Solving Process (CPS)

The Osborn-Parnes CPS has an explicit ideation step, named "Generate Ideas" or "Idea Finding (IF)." To the first order, the CPS IF step appears identical to brainstorming. This is not surprising, since both tools are the product of Alex Osborn. Indeed, it is my opinion that the primary way in which the CPS is an improvement upon its forerunner of Brainstorming, is that the CPS fits Brainstorming into a single cell of an overarching process.

Brainstorming as an ideation process is not formally structured, but it encourages divergent thinking in as broad a field as possible. As anybody knows who has participated in a brainstorming session, the ideas may be based on either similarities or differences (analogies or contrasts.) The range of ideas produced will depend upon the creativity of the participants (see Section 5) and upon the degree to which the problem has been generalized.

The danger with a brainstorming-based ideation method is that, if the problem is highly generalized and the team is highly creative, a huge matrix of ideas can result. The challenge of sorting them and applying convergent thinking to reduce the set to manageable size can be daunting. This is one reason that TRIZ says, in effect, "don't bother, the right solution will lie in one of these few tools…"

3.4.5: The Search for Solutions using TRIZ

TRIZ appears in some ways the least fun of the methods, because there is no obvious and freewheeling ideation process. Instead TRIZ has the matrix of contradictions and its 40 inventive principles (or in later developments the 76 standard solutions) to tell the engineer what to do. Of course, these solutions are given in very generic terms so we find that in fact plenty of ideation is required to come up with ways to exploit these principles. A classic TRIZ textbook example is the problem of cleaning up skeet targets after the skeet shoot, when the field is littered with shattered clay pigeons. The inventive principle is "exploit change of state." It takes then a fair bit of creativity to realize that this means to make the targets out of ice, and simply let the debris melt.

For this reason TRIZ is best learned via formal training and homework, just as engineering is learned. And indeed a philosophical fundamental in TRIZ is that innovation or inventive problem solving can be taught just as effectively as engineering can be taught in general.

[9] This is not meant to be a defense of poor math skills.

This is interesting to me personally. I find TRIZ a bit tedious, but then I am already a pretty good innovator. In consequence I am reluctant to take the time to slowly learn TRIZ, since I think it would only make me slightly better, not hugely better. In later sections I will discuss the personality characteristics of innovators. At this stage I merely state that it would be interesting to know what type of engineer "takes to" TRIZ the most easily – are these the linear algorithmic thinkers, or are they the wild hare creative ones? This might be a fruitful area for future research.

A few paragraphs above I said that TRIZ does not have a freewheeling ideation step. This fact is also one of the TRIZ advantages, because it means in turn that the range of divergent thinking in TRIZ is not so uncontrolled as it is in, say, CPS, and thus the re-convergent process is not so tedious. With TRIZ one does not have to pore over hundreds of bad ideas, just because we "suspend judgment" during our ideation. Instead our ideation is narrowly focused upon a few areas where conceptual "pay dirt" is likely to lie.

3.4.6: The Search for Solutions using Brainstorming

This has already been discussed under the heading above of the Osborn-Parnes CPS.

Let us consider here a discussion of one of the cardinal tenets of brainstorming – the suspension of criticism. Lehrer (2012), cited earlier, recounts the following:

"At the design firm IDEO, famous for developing the first Apple mouse, brainstorming is 'practically a religion,' according to the company's general manager. Employees are instructed to 'defer judgment' and 'go for quantity.'

"The underlying assumption of brainstorming is that if people are scared of saying the wrong thing, they'll end up saying nothing at all. The appeal of this idea is obvious: it's always nice to be saturated in positive feedback. Typically, participants leave a brainstorming session proud of their contribution. The whiteboard has been filled with free associations. Brainstorming seems like an ideal technique, a feel-good way to boost productivity. But there is a problem with brainstorming. It doesn't work.

"In 2003, Charlan Nemeth, a professor of psychology at the University of California at Berkeley, divided two hundred and sixty-five female undergraduates into teams of five. She gave all the teams the same problem—'How can traffic congestion be reduced in the San Francisco Bay Area?'—and assigned each team one of three conditions. The first set of teams got the standard brainstorming spiel, including the no-criticism ground rules. Other teams—assigned what Nemeth called the 'debate' condition—were told, 'Most research and advice suggest that the best way to come up with good solutions is to come up with many solutions. Freewheeling is welcome; don't be afraid to say anything that comes to mind. However, in addition, most studies suggest that you should debate and even criticize each other's ideas.' The rest received no further instructions, leaving them free to collaborate however they wanted. All the teams had twenty minutes to come up with as many good solutions as possible.

"The results were telling. The brainstorming groups slightly outperformed the groups given no instructions, but teams given the debate condition were the most creative by far. On average, they generated nearly twenty per cent more ideas. And, after the teams disbanded, another interesting result became apparent. Researchers asked each subject individually if she had any more ideas about traffic. The brainstormers and the people given no guidelines produced an average of three additional ideas; the debaters produced seven.

"Nemeth's studies suggest that the ineffectiveness of brainstorming stems from the very thing that Osborn thought was most important. As Nemeth puts it, 'While the instruction 'Do not criticize' is often cited as the important instruction in brainstorming, this appears to be a counterproductive strategy. Our findings show that debate and criticism do not inhibit ideas but, rather, stimulate them relative to every

other condition.' Osborn thought that imagination is inhibited by the merest hint of criticism, but Nemeth's work and a number of other studies have demonstrated that it can thrive on conflict."

It is my opinion productivity is increased because it allows the brainstorming team to do more of the steps of the full creative process. The morphology described in this dissertation includes "generate ideas" followed by "apply ideas" and "evaluate implementation." In effect the criticism step in modified brainstorm will result in attempts to apply and evaluate the idea, not merely generate them. Thus, in my opinion, rather than pursuing the asymptote on a single step of the process, it is more worthwhile to get the 80% solution to multiple steps of the process, i.e. to include the "apply" and "evaluate" steps.

3.4.7: The Search for Solutions using Muda

Similar to TRIZ, Muda also saves us from a too-wide range of ideation. Since Muda is defined as "that for which there is no customer" then the solution-finding has only two branches:

- Find a customer for the item
- Get rid of the item

In ship design there are a number of opportunities to use a Muda-like approach to innovation and improvement. In the discussion of what Muda is, I already used the example of waste heat generation. There are many opportunities to convert waste-heat into a needed product. The simplest might be to simply arrange compartment adjacencies such that heat producing compartments are adjacent to heat consuming compartments. I have not seen this simple parameter recognized as a consideration in ship arrangement, or in, say, Intelligent Space Arrangement objective functions.

Another case of creating a customer for Muda lies in the design of engine resilient mounting systems. For some ships the machinery vibration requirements dictate that the engines be mounted on an intermediate mass approximately equal to the mass of the engine. In a classical example this intermediate raft is a steel frame ballasted with concrete. But why must this extra weight be so useless? Are there not myriad auxiliary systems, panels, pumps, switchgear, and tool lockers within the engine room, that could be used as the 'ballast' for this raft? In fact, we can easily image the entire engine room having a full-size floating floor, upon which everything is mounted. Surely this equipment would amount to a mass sufficient for the acoustic attenuation task required?

Indeed, this gives rise to an idea for an interesting naval architecture exercise in weight reduction: Go through a list of every system on the ship. For each system identify the goal of that system, the resources needed by that system, and also the Muda associated with the system. Thus, for example, the goal of the generating plant is to make electricity, the resources needed are fuel and conductors, the Muda is the waste heat, the exhaust gases, and the system weight. Upon compiling this list we then sort the entire ship set of "Muda" and "resources needed." I suspect that we might find a number of shipboard systems who are customers for some other system's Muda[10]. Exploiting this could result in weight saving, cost saving, or other advantage.

The other case is that we may find that some item is present on the ship despite being needed only rarely or only by a very small number of other systems. In an earlier example I suggested that for some line-haul merchant ships we might even find the crew to be such a system: In an age of pervasive broadband connectivity, we could design a remotely operated container ship that only picks up an on-board crew when within pilotage. Removing all the crew support functions in the ship design, and reducing these to "day boat" levels, would certainly result in a smaller, lighter, and less expensive ship.

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[10] Nearly the same idea has been presented under the heading of "multitasking." In the multitasking example I suggested the consideration of structural piping, or the use of the ship hull as return conductor for power. Both of these ideas exploit the Muda-fact that the ship structure is electrically conductive or that pipes may have strength beyond that needed for pressure resistance.

From these examples we see that the primary tools of Muda as an ideation method will lie in either elimination or combination.

3.4.8: The Search for Solutions using Multitasking

Multitasking is explicitly a method for seeking ideation by combination. We seek to combine two systems into one meta-system, hopefully simpler in total than the two separate systems were in sum. In order to use multitasking as an ideation tool, the user must determine "what other things could this system do?" My personal technique for this is to attempt to list the attributes of the system in question, and then identify tasks – currently performed by other systems – that need those attributes.

In my most classic example I note that the weight of steel in the containers on a container ship can easily exceed the weight of steel in the ship's structure. On the one hand this is testimony to the efficiency of ship structure, but it also raises an opportunity for multitasking. In my ideation method then, these facts would emerge when we listed the attributes of the cargo as including "100,000 tonnes of steel" and we set about to find other systems on the ship (i.e. the hull) that "consume" steel.

3.4.9: The Search for Solutions using Synectics

The ideation stage of Synectics emphasizes the use of divergent thinking. A synectics motto is "make the familiar strange and the strange familiar" or "trust things that are alien, and alienate things that are trusted." As an ideation tool, Synectics invented a technique called "springboarding" for beginning the ideation process. For the development of idea starting points, the method incorporates brainstorming and deepens and widens it with analogies; it also adds an important evaluation process for Idea Development, which takes new ideas that are attractive but not yet feasible and builds them into new courses of action which have the commitment of the people who will implement them.

3.4.10: The Search for Solutions using Design By Analogy

This class of techniques obviously promotes ideation by analogy, whether the analogies are found lexically, visually, or biomimetically. Indeed, to a large extent the design by analogy techniques are actually "ideation by analogy" methods.[11]

The challenge with these methods lies in the two flanking steps, of defining the generalized problem in order to seek out the analogies (step three of the morphology) or the task of finding means to apply the analogy to the task at hand (step four of the morphology). This will be discussed below, but at this time suffice it to consider the challenge in finding a way to apply the technique of gold panning to the task of designing a self-cleaning cat litter box (one of the WordTree examples.)

3.4.11: Summary: The Search for Solutions

In the foregoing paragraphs I have described how a group of innovation methodologies accomplish the task of ideation. What we see is that the process is generally one of divergent thinking, eschewing the conventional solution and seeking out new ones. We seek these new ones by looking in disparate venues for solutions to a problem that bears some resemblance to our problem. The different techniques then may address either or both of the topics of "where to look" or "what to look for."

Ironically, while the ideation step is a step replete with techniques, each technique can be summarized in only one or two sentences. In the majority of cases the technique's ideation protocol turns

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[11] I am sure that some of their proponents would object to this classification, because the authors of these methods have in fact paid attention to the other steps in the total innovation process. Nonetheless, the core concept of the design by analogy techniques is their use of ideation by analogy. This does not denigrate their efforts to include the other steps of innovation.

out to amount to “look for solutions *here*” where “here” is a specified domain. It is my finding as previously discussed that there are basically five types of ideation used:

- Ideation by Analogy: Analogous situations (venues) or analogous problems
- Ideation by Contrast: Contrasting situations, or contrasting problems
- Ideation by Elimination: Finding items that don’t belong
- Ideation by Combination: Finding items that are redundant
- Random (Unconscious) Ideation

3.5: Steps 4 & 5 - Apply and implement solutions

Note that I have identified two separate steps, being #4 Apply Solution and #5 Implement Application. These two sound very similar, and the difference between them is sufficiently subtle to demand re-emphasis:

In Step three of the morphology – Search for Solutions – we apply ideation techniques to stimulate thought. But the thoughts that are stimulated are not within our technical domain – on purpose! Thus the ideas generated may be as inchoate as:

- Use gold panning to separate cat litter[12]
- Change the phase of one of the materials used[13]
- Use a different type of person in the system[14]
- Find a customer for the waste[15]

How do we actually translate these ideas into actionable engineering solutions? That is step 4. Once translated, we will still have to actually engineer those applications in Step 5.

In my reading I find little attention given to this step. It appears that this step is considered to be “normal engineering” development with the implication that there are already sufficient tools in place.

In my own experience I find that this step actually requires just as much creativity as the idea generation step itself, and would be worth substantial expansion in the literature. As a starting point, or perhaps a “work around,” I suggest that the application step may be translated into a new innovation problem, and the innovation tools applied again. Thus the evolution might go something like this:

- Idea: Exploit phase change of a material
- New Problem: I don’t know which material to pursue
- Generalize new problem: List all materials and their phases, and the properties of those phases
- Ideation: What is the analogous process we are trying to find? Say that it’s leverage: In that case we look for which of the materials expands under the phase change.
- Result: The material has been identified.
- The new problem is how to get that material to undergo that change.

As may be seen from this example this process leads into a cascading spiral of innovations. Hopefully these spirals will eventually lead to a task with a simple and obvious solution, and not to an infinite series of spirals. It is not, however, mathematically obvious that this must be the result.

I opine that this step of the innovation morphology would be worthy of research expansion.

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[12] A WordTree example

[13] A TRIZ example

[14] An example from Quintilian’s seven questions

[15] An application of Muda

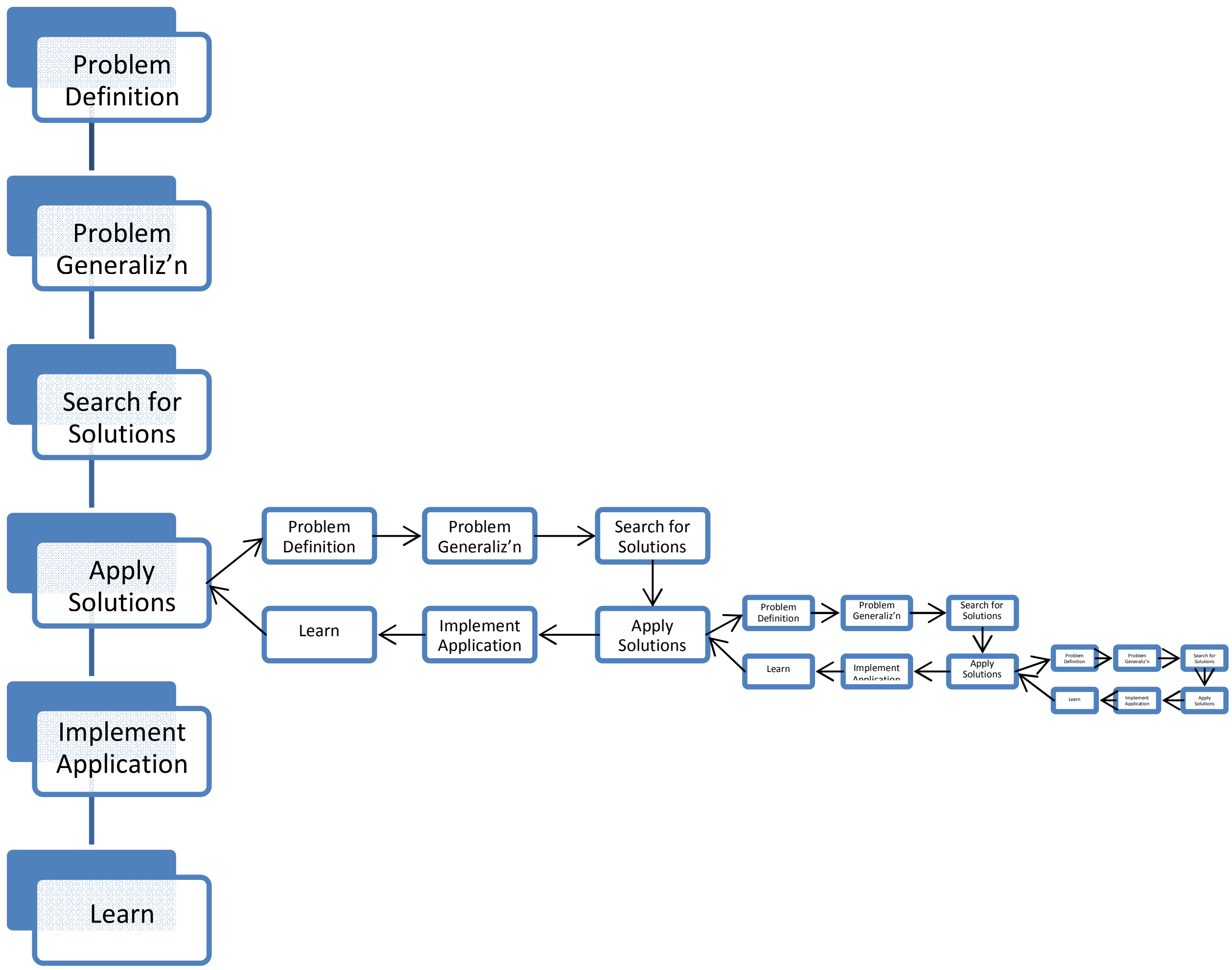

Figure 16 - An attempt to depict "Apply Solutions" as a nested iteration of the entire process

With the above as an overarching response, there are two cases of the innovation algorithms in which we can identify specific tools for applying the solution. These are Quintilian's seven questions, and Martin Gardner's mathematical problem solving.

3.5.1: Applying Solutions using Quintilian's Seven Questions

Quintilian's seven questions include one question that may be taken as the indicator of idea application: "How?"

In Quintilian we have used the first question – Why? – as the problem statement. This then leads to using five of the questions for ideation:

- Who?
- What?
- When?
- Where?
- With What?

The seventh question – How? – then becomes the "million dollar" question that leads to the engineering implementation. "How shall we actually do this?"

It is gratifying to see that this two thousand year old "algorithm" retains its completeness, but I must nevertheless admit that asking the question "how?" does not go a long way toward answering it. We are left to once again apply an engineering problem solving algorithm "in miniature" within this step.

3.5.2: Applying Solutions using Mathematical Problem Solving

Martin Gardner combines the steps of "application," "implementation," and "learning" into one seemingly simple statement: "Can you check the result with good examples and counterexamples?"

We will discuss this injunction further under the heading of "Learn," but at this step it seems appropriate to dwell on the upstream implications of this eventual testing phase. If we are going to test our innovation, either by positive or negative tests (Gardner's 'example or counterexample') then we will need to design those tests. And the time to design the tests is during the design of the solution itself, i.e. during the application of the innovative solution.

Many engineers will agree that the act of designing the test and / or test protocols has helped them to design the system that will eventually be tested.

3.6: Step 6 - Learn

Only Martin Gardner and TRIZ seem to have explicit "Learning" steps. Gardner's is the easiest to discuss: The step is "Can you check the result with good examples and counterexamples?" This action of checking the results will serve several learning functions, in addition to its basic purpose of validating the solution. These include casting new light upon the existing problem (because the example or counterexample will not be identical to the existing problem) and populating the problem-solver's mental inventory with additional fodder for future problems. This last is perhaps the most direct application of "learning," and it is paradigmatic for nearly all of the innovation algorithms: Solutions once found become parents for future tasks. Innovations once implemented become analogies for future problems.

TRIZ, unsurprisingly, takes an algorithmic approach to the Learning step. Bundled in the "Algorithm for Solution Verification" are the following elements: (Orloff, 2006)

ALGORITHM FOR THE SOLUTION VERIFICATION

1. Create a structural scheme of the object suggested
2. Define the components' functions at all levels
3. Define the streams of the most important resources using the structural scheme
4. Demonstrate the interdependencies of the functions of parameters. Define the qualitative and quantitative properties and functions.
5. Show newly introduced components.
6. Start with newly introduced components and follow the changes in every stream of resources for an evaluation of the changes in the functions of all levels up to and including the highest (main useful function of the object).
7. Check the character of changes in the functions of the pre-conflict, conflict, and post-conflict phase in the operative time with the old solution.
8. Check changes in the construction resources
9. Check the new positive functions and properties *(positive super effects).* Assess their influence on the values of the object's effectiveness.
10. Investigate the results of positive super effects. Create an overview of the (positive and negative) changes that result from servicing and usage around the object during its life cycle.
11. Examine the possibilities of improving the solution.

12. Check the new negative functions and properties *(negative super effects).* Assess their influence on the values of the object's effectiveness.
13. Investigate the results of negative super effects. Create an overview of the (positive and negative) changes that result in servicing and usage around the object during its life cycle.
14. Examine ways to remove insufficiencies that appear. If necessary, discard the solution, formulate new problems for inventions, and return to the search for new ideas.

Despite the obscure prose of the method, the image that it paints is one of teleological *re-*composition of the invention, checking at each step whether the teleological relationships are as desired. The various steps of "investigate" and "examine ways to remove" are again indicative of a nested spiral of innovation processes within the process, as was depicted in Figure 16.

3.7: Summary: The innovation morphology and methods

At this point we have constructed an over-arching morphology of the innovation process, and we have populated that architecture with specific techniques gleaned from a sample of published innovation methods.

The resulting super-set is depicted in Figure 17. Equipped with such a superset, we now gain an increased toolbox for innovation. Rather than necessarily pursuing a single algorithm to completion, we are now free to use components from other algorithms if we wish. In the section below I will show a small set of "test runs" of this sort of process.

										Design by Analogy		
McKesson Morphology	Brain- storming	Teleological Decom-position	Synectics	Quintillian	Gardner	Muda	Osborn-Parnes CPS	TRIZ	Multitasking	Visual Analogies	WordTree	Biomimetics (Inspiration from Nature)
Problem Definition	Unstructured process	Teleological Decomposition		Why?	Are there aspects of the problem that are actually irrelevant for the solution, and whose presence in the story serves to misdirect you?	Defines the anti-problem: What part of the existing system has no customer?	Objective Finding Fact Finding Problem Finding	Abstractize	Are there functions that are logically similar and could thus be combined into a single multitasked component or subsystem?	Unstructured process	Task is defined: "Develop a device to fold towels"	Define Function being performed
Problem Generalization	Unstructured process		Make the familiar strange, make the strange familiar		Can the problem be transformed to an isomorphic one that is easier to solve? Can the problem be reduced to a simpler case?			Define problem as a contradiction		Unstructured process	Problem is decomposed by finding cascading tree of related words 1. Key Problem Descriptors: Single word action verbs 2. Functional categories: Single word overall, Single word critical or difficult functions, single word customer needs 3. Sticky Note WordTrees 4. WordNet expanded WordTrees	Define Function being performed
Search for Solutions				Who? What? When? Where? With What?	Can you apply a theorem from another branch of mathematics? Can you invent a simple algorithm for solving the problem?	Can that part be eliminated? Can a customer be found for it?	Idea Finding	Investigate 39 Features, 40 inventive principles and 76 standards		Google image search?	Manual Analogy Generation Manual generation of Analogous Domains Search for application of Analogies: Google image search Search for applications in Analogous Domains: Patent searches	Is there a natural entity (animal) that does virtually the same thing? NB: Does not have to be the WHOLE animal - method applies at the component level Can I build a mechanical equivalent?
Apply Solutions				How?	Can you check the result with good examples and counterexamples?		Solution Finding	Apply solutions				
Implement Application					Can you check the result with good examples and counterexamples?		Prepare for Action	Concretize				
Learn					Can you check the result with good examples and counterexamples?							

Figure 17 - The alignment of the studied innovation algorithms against the innovation morphology

4: Applying the innovation morphology and methods

At this point we have constructed an over-arching morphology of the innovation process, and we have populated that morphology with tools from a variety of sources. I have claimed that this structure and tools can in fact be used in naval architecture, and I have included a few examples in the foregoing presentation. In this section I will make a more concerted and focused effort to demonstrate how the application of these tools might benefit a design project.

During the summer of 2012 I was given the opportunity to serve as ONR Summer Faculty in support of the Naval Research Enterprise Intern Program (NREIP). During this summer program eleven teams of student interns were presented with technological (design) challenges of real interest to the US Navy. My task during this time was to serve as a resource to all of the teams, including as a resource in ideation. I used this opportunity to explore the application of the various formalized invention methodologies, for application in naval architecture. Two of the student tasks required innovation, and these two teams were particularly encouraged to seek out my assistance.

In addition to these recent tasks involving third-party teams, I have also selected four projects from past professional activity which were highly innovation-centric. The collection of these several examples constitutes a demonstration of the present innovation morphology, and its component tools.

This collection of data is not a controlled experiment, but draws from many projects too large to be undertaken in a laboratory fashion (these were funded projects for real clients, with real deadlines). This is not unique to naval architecture: In many scientific processes we are not able to design and control experiments in the manner that we might wish, constructing nicely arranged grids of data along uniformly spaced intervals and the like. Instead, many studies must make do with naturally occurring data, that leaves gaps and questions. An example of this type of data would be any medical study that uses mortality data. We certainly do not intentionally kill patients in order to fill in a data space, no matter how mathematically appealing that might be. Thus in the present case the 'experiment' consists of ad hoc applications of the various invention methods found here, to an unstructured array of opportunities.

The innovation-related projects discussed below are:

- WTA Fuel Cell Ferry architecture (2002)
- Missile launcher re-arming at sea (NREIP 2012)
- UxV Ship Impact (NREIP 2012)
- EFV (NREIP 2012)

As mentioned above, I attempted to introduce multiple ideation methods at Carderock. One of the Carderock CISD conference rooms was equipped with a poster entitled "brainstorming" as depicted at the top of Figure 18. I added additional posters to this wall, as depicted in the rest of Figure 18, including the most important (in my opinion) of the ideation methods. [16]

4.1: WTA Fuel Cell Ferry architecture (2002)

I begin this section with a project from my professional history. This was a funded project completed while I was employed by John J McMullen Associates, Inc., of Arlington Virginia. The project was to develop a hydrogen fuel cell ferry for use on San Francisco Bay. The particular innovation challenge here was not so much finding a path to solution, but rather finding a means to select between the many emerging parallel technologies in this field. In 2001-2003 hydrogen fuel cell technology was growing very rapidly, and it was far from clear which technologies were going to be the "winners."

[16] Given that the Carderock CISD is the Center for Innovation in Ship Design, I found it interesting that the practitioners there did not know that there were formalized ideation methods other than brainstorming. I found this gratifying as it validated the naval need for the present foundational work.

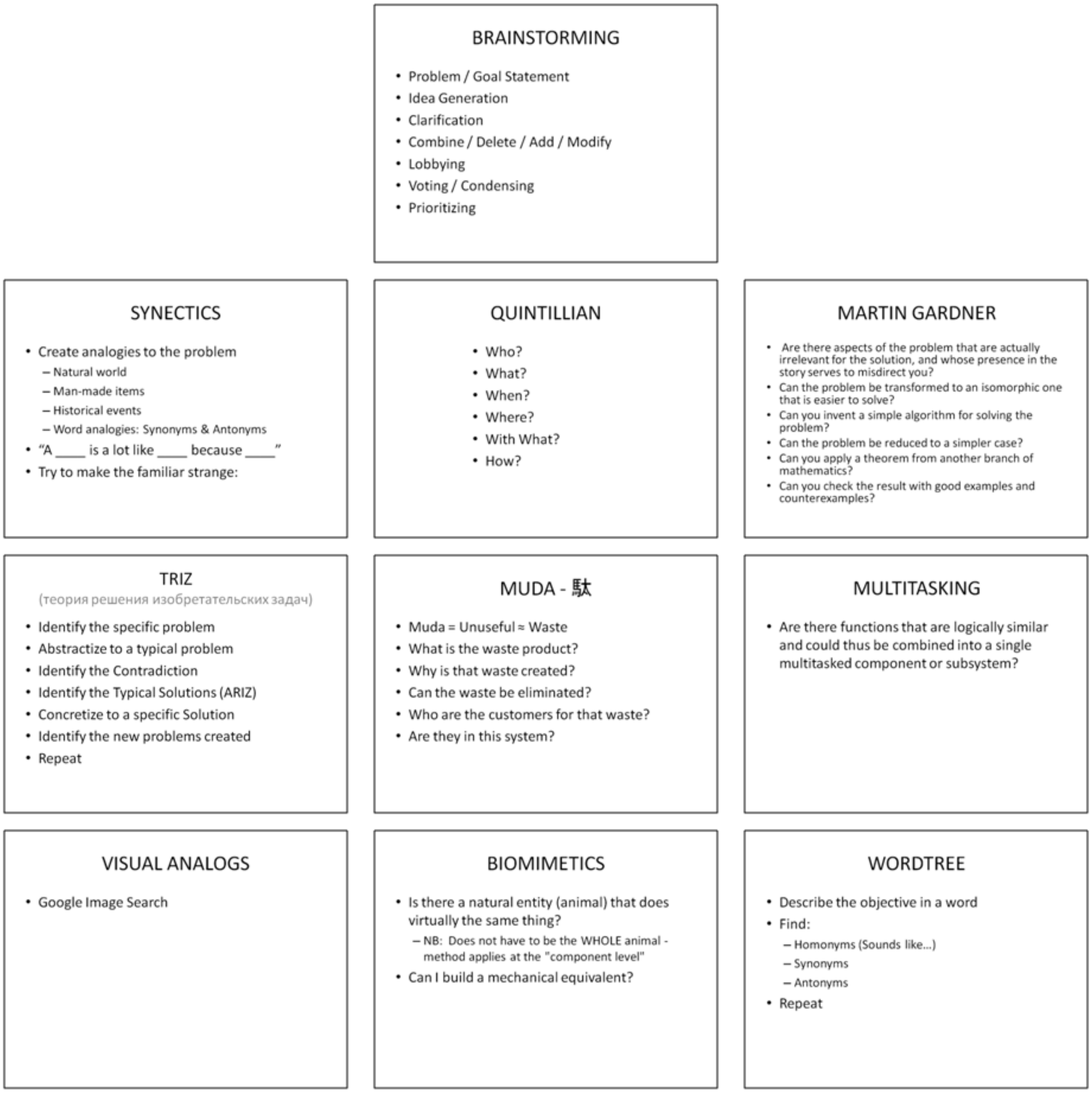

Figure 18 - A collage of ten ideation method posters displayed at the Center for Innovation in Ship Design, Summer 2012

At the time of this project I was not aware of the TRIZ methodology, nor had I formulated my morphology of innovation steps. But I find that I used these techniques perhaps unconsciously in resolving this problem.

The problem was to select components for the fuel cell ferry. The more accurate problem was that there were too many choices, with no clear winners and losers. If we locked in to any choice, then we were doing a disservice to the customer by narrowing their field of study.

This was the realization that offered a TRIZ-like resolution: The conflict was that we needed a choice (you can't design for non-specifics) but we also needed to keep the door open to revising that choice. The very statement of this conflict rapidly crystallized the solution: We postponed the selection, by dividing the system into logical parts and designing an interface between those parts, such that alternative choices could be swapped in and out in a plug-and-play architecture.

The components of the system, and their primary alternatives, were:

- Fuel storage module
  - Compressed hydrogen tanks
  - Liquid hydrogen tanks
  - Metal Hydride beds (Selected as baseline)
- Electricity Creation Module
  - Proton Exchange Memberane Fuel Cell (Selected as baseline)
  - Molten Carbonate Fuel Cell
  - Hydrogen-burning diesel engine
- Electricity Accumulator / Buffer Module
  - Lead-Acid Battery storage bank (Selected as baseline)
  - Super-Capacitor storage
  - Flywheel storage
- Power Conversion Module
  - A module of switchgear as needed to interface the chosen electricity creation and electricity storage modules
- Motor Controls
- Propulsion Motors

By adopting this "divide and conquer" paradigm we successfully resolved the issue of what technology to choose, by in effect kicking the decision down stream. We engineered a ship that accommodated all of the options listed above (with certain varying ship impacts, to be sure) and provided our customer with superior service in doing so.

The final ship design was a modular ship, including fuel storage module, electricity creation module, electricity accumulator module. The client choose to move forward with fuel storage in the form of compressed gas, electricity creation via a hydrogen-burning diesel engine, and electricity accumulation in lead-acid batteries. But the architecture of the vessel would allow switch-out of any of these modules for any of the other listed technologies.

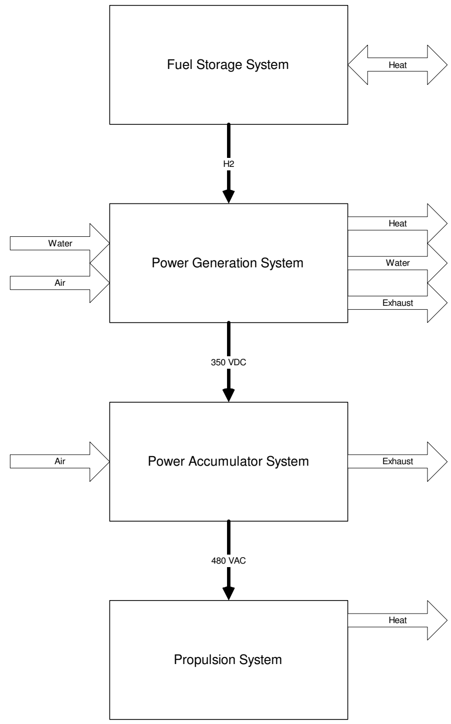

Figure 19 - Concept Block Diagram for the WTA Fuel Cell Ferry (WTA 2002)

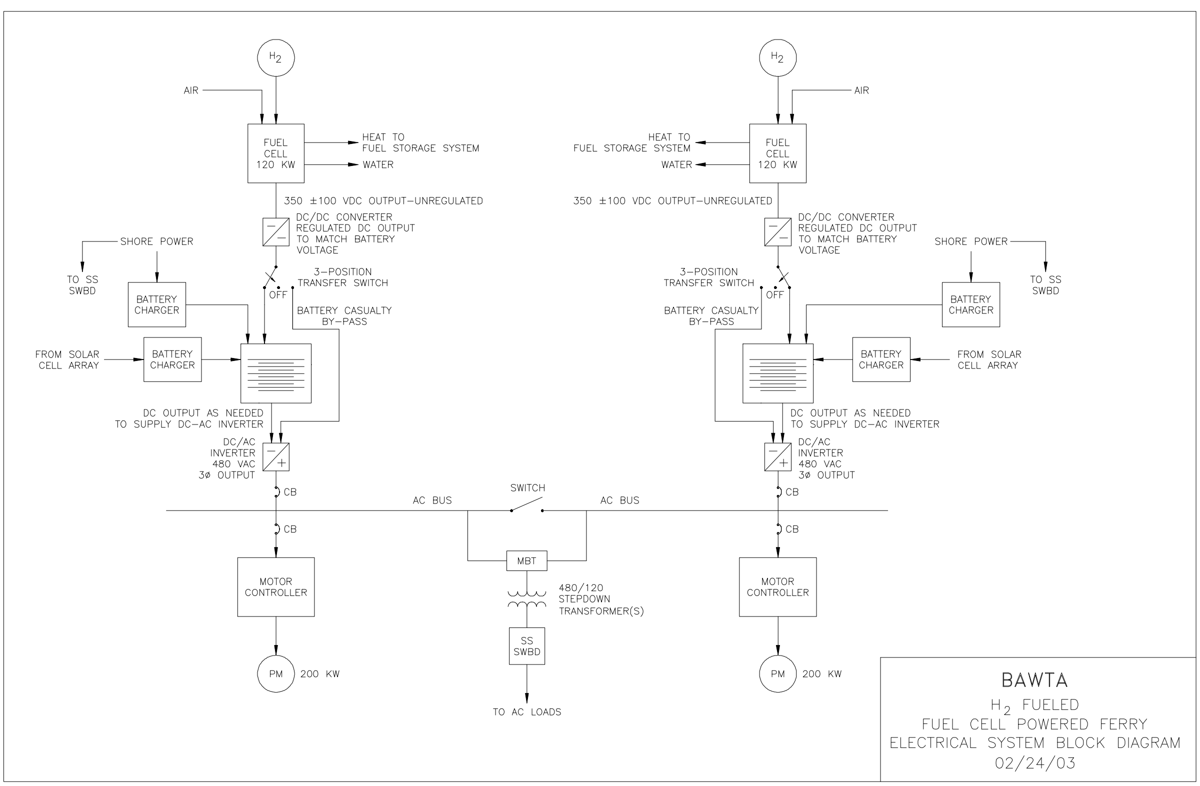

Figure 20 - Detailed Block Diagram for the WTA Fuel Cell Ferry (WTA 2002)

4.2: Missile re-arming at sea

The first of my CISD Summer 2012 project assignments was actually a very short and unstructured meeting. After an introduction to the task a team consisting of Mr. Jack Offutt (CISD), Dr. Colen Kennel (CISD), and myself spent about 30 minutes in ideation, after which the interns were released to proceed with engineering development. For our ideation session we were first equipped with a short menu of already-defined solution concepts, such as the use of various types of positive-control cranes, or the use of a rolling cart with an integrated payload-erector. We employed ideation to increase the size of the menu of solutions.

The first ideation technique applied was design by analogy. We identified one industrial analog - how are eggs loaded into a cardboard dozen box - but this avenue was not pursued. [17] We searched for processes that were analogous to the re-arming process, and quickly decided that re-arming the missile launcher might be analogous to re-loading a pistol, with options ranging from the one-bullet-at-a-time model for a revolver to a model including the concept of the plastic strip magazine reloader for an automatic. Note that the strip loader changes the nature of the rearming process at the launcher, but involves the baseline "one bullet at a time" process in order to prepare the loader.

TRIZ received a very brief attempt. We were able to get as far as the problem being defined as "should move / shouldn't move": The weapons are brought over on a crane (they move) but when they get to the combatant it is important that they should not move, so that the missile tube can be reloaded. This turned out to be a pretty good technique because Colen quickly came up with the idea of using an inflated bag to grab the missile and immobilize it. In this version we imagine a sort of inflatable donut or collar: The missile can be placed generally near the center, hanging (and moving) from its crane lift, and when the donut is then inflated it will firmly grip the missile and prevent further movement. The donut is then traversed as required to the missile launcher cell, and the missile gently released (by throttling the donut pressure) so that the weapon slides into the cell.

An untouched area was biomimetics. I still feel like there is probably a biomimetic parallel but we didn't find one (we didn't try, either.) Wordtree, visual analogs, and other techniques were not attempted.

4.3: UxV Launch & recovery

Another of the CISD teams was working on quantifying the ship impact of accommodating a future panoply of unmanned vehicles. These so-called UxVs may be air vehicles (UAVs), surface vehicles (USVs), or undersea vehicles (UUVs.) I was called upon by this team to assist in developing concepts for minimizing this ship impact, by in particular minimizing the impact of the launch and recovery operation. I applied the menu of innovation techniques to this problem, in a two-hour discussion with the three-person team.

4.3.1: The Problem Definition

The problem is to launch, recover, resupply, and maintain an unknown number of unknown types of UxVs. The problem lies in the unknown nature of the vehicles, and their thus-unknown infrastructure

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[17] I researched this many weeks later: Eggs are rolled in bulk through various washing processes. The rolling motion exploits the round shape of the egg. When it is necessary to place them in the carton – the analog to the missile launcher reload – the eggs are handled by suction-cup lifting devices, or by a clamshell device that looks something like a split funnel. The taper of the funnel holds the egg despite variations in size, and then the funnel opens clamshell-like to permit the egg to drop into the carton. The height of the drop is calculated to minimize breakage.

requirements. The problem becomes to know these unknowns, without constraining the future vehicles. This is a thorny challenge when presented in these terms.

4.3.2: The Problem Generalized

Given that our problem is to know the unknown, it is tempting to declare it unsolvable at the outset. But this of course overlooks the many things that we do know, that are simply found at a higher teleological level than has been stated in the problem.

The generalized problem is that of launching and recovering offboard vehicles, and that very statement contains a lot of information. We know that the vehicles will be in one of three types: Surface, Air, or Subsurface vehicles. We further know how to put offboard systems into the air (aircraft and missiles), into the water (from life rafts to small boats), and below the surface (torpedoes.) Thus we are already generating analogs to our UxV problem.

In the actual CISD team discussion we spent most time upon the recovery aspect, because this was perceived to be the thorniest problem. We did however generate one useful guidance for the launch problem, which will be documented (out of order) here:

Air, Surface, and subsurface vehicles may compete for different types of ship launch support infrastructure. Helicopter-like UAVs need a flight deck. Boat-like USVs need a boat ramp, davit, or other similar way to be put into the water.

In order to minimize ship impact, and maximize ship flexibility, we concluded with the recommendation that all types of UxVs should be configured for water take-off. This means that no matter whether the vehicle dives, swims, or flies, it would do so from an attitude of 'floating near the mother ship', and that the act of "launch" would – from the mother ship's point of view – consist only of putting the vehicle into the water in a satisfactory manner.

This act of partitioning the problem, similar to the WTA solution, allowed us to focus more intently upon the recovery task. We will see that our ideation regarding recovery did also generate additional ideas for launch – the division of the task was not taken as "permanent."

The recovery task can be generalized as to recover the vehicle from its native element, in a manner consistent with the vehicles sensitivity to, say, impact, wetness, personnel hazard, etc. To generalize this problem we called it "catching eggs."

4.3.3: Idea Generation

Note how even in the act of generalizing the problem, we begin to find analogs. The division between the steps of innovation is not hard and fast.

Again in this project as with the others, we attempted to apply the various innovation tools in the ideation step, as follows:

TRIZ: What is the inherent conflict in the project? It was somewhat difficult to state the challenge of UxV recovery in the words of a TRIZ contradiction, but we must recall that none of the participants are truly expert in TRIZ. The gist of the contradiction is that the unmanned vehicle is separate from the ship, by design and intention, and we need to make it not-separate from the ship, as the act of recovery.

QUINTILIAN'S SEVEN QUESTIONS: The seven questions did not generate solutions, but they did elucidate some easily overlooked constraints, as follows:

- Who? – Must be executable by ship's force
- When? - Time is a factor, in that we wish to not overly constrain the maneuverability of the mother ship

- Where? - The vehicle must be recovered in all types of environments, including sea and wind conditions that we couldn't launch in, but that arose after the vehicle had been deployed.
- With What? - Our goal is to minimize the space, weight, cost, and other impacts of the "with what." This also includes our inventory of recovery assets that already exist or may exist on the mother ship, such as davits, kingposts, cranes, flight decks, etc.

MARTIN GARDNER: Martin Gardner's method emphasizes simplifying the problem, and searching for solutions to the simpler problem. So in this case, what is the simpler problem that is equivalent to the UxV recovery problem? Would it be easier if the vehicle were stationary? In the actual event this line of thought did not lead to any innovative solutions, but it nags at me that there may be fruit down this path, if we had pursued it further.

BIOMIMETICS: The obvious biomimetic parent is a landing bird. We had a lengthy discussion about how birds land and take off. The key insight was that they like to drop from a perch, falling to flight speed. This suggests that rather than launching, throwing, sling-shotting a UAV, perhaps it should be hauled to the masthead and drop-launched.

Similarly, the birds like to flare up at their landing site, and drop the last millimeter to land. To do this they approach from below the landing spot and pull back on the stick in a controlled stall. By timing the approach exactly, the moment of complete loss of speed occurs just at the landing spot.

Contrast how gracefully some birds land on a perch, by flaring, with how ungainly the same bird is at landing on flat ground, where the flare up is constrained.

MULTITASKING: Are there any functions that are logically similar and could thus be combined into a single multitasked component or subsystem? We discussed the idea that the landing perch and stowage site might be one and the same thing, in a pattern something like the way that bats hang from the ceiling in their cave.

4.3.4: Applying The Solutions

The ideas above generated a few interesting recovery solutions. As we discussed the bird landing on an elevated perch, one of the ideas was to exploit the bird's self-control. The alternative is to ask the bird to take on a stationary attitude, and have the recovery asset scoop the bird out of the air like catching butterflies. This requires a shift of control to an active system on board the ship, but it doesn't reduce the need for active systems on the bird, since the bird still must fly and hover.[18]

As a result we conceived that it would be desirable to have a sort of perch on which the vehicle can land. At the present time this is how rotary-wing UAVs are recovered, with the ship's flight deck being the perch. To some extent this is also how stern-ramp boat operations are conducted. The problem with both of those cases lies in the motions of the mother ship, and the chance for a catastrophic conflict of velocities.

We conceived of one novel solution for sea-recovered vehicles. This was to tow a linear perch, which can be grabbed at any point along its length, reducing the need for precision in the approach.

This linear perch is nothing more than a tow rope, and the reader should envision a rope-tow ski lift, usually found only on the beginner slopes of a ski resort. Indeed, I recall learning to ski in my own boyhood, and how easy it was to use the rope tow, compared with how scary the "all or nothing" experience of the chair lift was.

[18] Note that when I speak of birds in this manner, the same logic may be applied to sea vehicles.

In the case of the UxV, the vehicle would be navigated over to encounter the rope, and it would then grab on. We envisioned that some sort of grab claw would have to be fitted to the vehicle – the skier's gloved hand, or the bird's talons – although we had the beginning of an exploration of means of shifting this function onto the rope itself.[19]

Once captured by the rope – which could take several passes – the rope is then winched into a conventional stern-ramp boat bay or UxV bay. We have eliminated the excitement of driving at high speed into the wall of a garage, and replaced it with a much safer maneuver conducted in open water.

4.4: EFV

The most thorough (but still not comprehensive) treatment of an innovation project took place regarding the perennial problem of providing decent hydrodynamics to an amphibious armored vehicle. Previous attempts at this lead to the "planing brick" of the AAAV / EFV – see Figure 21.

The EFV is an armored vehicle with the requirement to cross water at high speed. The geometry of the vehicle was highly constrained, and the result was the planing concept illustrated. The current task is for a more modest speed goal of only about 12 knots. However, early hydrodynamic studies suggest that 12 knots for a vehicle of this size is a very poor choice of Froude Number, and thus the wavemaking drag is high. The CISD team was investigating means of increasing the hydrodynamic length, in order to change the operational Froude Number.

I applied the first three steps of the innovation morphology to this problem, using a variety of techniques.

4.4.1: The Problem Definition

The problem is to make a vehicle like the EFV go 12 knots in water, on a minimum level of power, safely. The solution space is constrained that all solutions must be external to the vehicle, and that the solution must "go away" when the vehicle operates on land.

4.4.2: The Problem Generalized

The problem may be generalized in many ways, as follows:

TELEOLOGY: What is the purpose? The task is to turn the EFV into a 34.5 tonne 12 knot boat. What would such a boat be, if not an EFV? How much does this differ from the EFV? Can we make the EFV "look like" the boat defined above?

TRIZ: What is the inherent conflict in the project? The design team has taken length as the contradiction: That the craft "wants to be" twice as long as the EFV "wants to be." Presumably the EFV length is driven by transport and maneuverability requirements. The desired boat length is driven by hydrodynamics. The conflict thus is between two different lengths.

LEXICAL TECHNIQUES:

Keywords that are relevant:	Planing Brick
Synonyms:	Skipping stone
Antonyms:	Sink

These techniques did not return any obviously fruitful paths for investigation. Of course, this is only a superficial use of the technique.

[19] In this case we may imagine catching birds with a rope coated with birdlime or other sticky substance, or perhaps a boat-recovery rope made of industrial strength Velcro. It need only be hit in order for the UxV to be captured.

Figure 21 - The Expeditionary Fighting Vehicle (EFV) in planing mode. (DID, 2012)

MUDA: Similar to TRIZ's use of contradiction, can I define any aspect of the problem as "Muda" – as that for which I have no customer?

In this case one definition is of the length increment required: We need to make the craft longer as a boat, but then we need the length to 'go away' ashore, because we have no customer for length, once in land-vehicle mode.

QUINTILIAN'S SEVEN QUESTIONS:

- Who? - The fighting vehicle
- What? - Needs to cross water at 12 knots. To do this, we think it needs to be longer or at least more hydrodynamically shaped.
- When? - Time is manifest in the desired speed, 12 knots.
- Where? - must function in deep water
- With What? - Must only use systems or components that can be easily carried on the vehicle
- How? - TBD

MARTIN GARDNER:

Martin Gardner's method emphasizes simplifying the problem, and searching for solutions to the simpler problem. So in this case, what is the simpler problem that is equivalent to the EFV problem? Several possibilities exist:

- What if we didn't need it to go 12 knots, but only 10? or 8? or 2?
- What if we didn't need it to be self-propelled, but could instead be towed?
- What if it were designed as a boat first, and then made to be a land vehicle after?

Of these, note that the first two require the naval architect to challenge the requirements, and this is difficult in an organizational context. But in this case the goal is not really to challenge these requirements, but to see if by solving the problem in a simpler case, we can provoke a breakthrough that can be used in the “real” case. In other words, if the goal were only to go 2 knots, what would the solution be? Given that solution then, how hard would it be to jack that solution up in power such that we reach the 12 knot target? I will show an exploration of this below.

VISUAL ANALOGS:

I did not find any visual analogs, perhaps due to my inability to find suitable keywords to describe the problem in an image search. I did get many images in response to the phrase "skipping stone" and many of these images were interesting, but they were not directly provocative of solution ideas for this problem.

SYNECTICS:

In the divergent part of Synectics we seek to find unusual analogs to the EFV. The short list that I came up with was as follows (using a standard Synectics sentence structure.)

- “An EFV is like an Alligator because they are both amphibious."
- “An EFV is like a tug boat because they are both in unfavorable Froude Numbers."
- “An EFV is like a snow shovel because they both plow water."
- “An EFV is like a bull in a china shop, because it is blunt."
- “An EFV is like a half-tide rock, because the water flows around it much faster than one might wish."

BIOMIMETICS

The Synectic exercise above actually gave rise to the obvious biomimetic parent of an Alligator. The alligator has two separate forms of propulsion, but it does not attempt to move at high speed while waterborne, except in bursts. Is a burst speed an option for an EFV, or does it need 12 knots continuously?

MULTITASKING:

Are there any functions that are logically similar and could thus be combined into a single multitasked component or subsystem? I am unable to find any on this problem.

4.4.3: The Search for Solutions

Now that we have generalized the problem in a variety of terms, let us attempt to find concept level solutions in those same terms. First, we note that by applying *all* of the techniques we have created a much larger menu of choices than were generated by any single technique. We now take all of these thoughts and again apply them to the full range of innovation tools, but now at the third step of “search for solutions.”

The ideas are:

- What is a good 34.5 tonne / 12 knot boat? How much does this differ from the EFV? Can we make the EFV "look like" the boat defined above?
- What can we do to make length vary in the two modes land / sea?
- Is there a way to create a “customer” for increased length?
- What if the speed requirement were much lower?
- Does the speed need to be continuous?
- What if it were designed as a boat first, and then made to be a land vehicle after?

First, a quick look at the naval architectural task. The task is to build a 34.5 tonne 12 knot boat; how much does this differ from the EFV?

Applying McKesson's whole-ship method (McKesson 2011b) a good 12 knot 34.5 tonne boat will have an expected power demand of about 60 kW. It appears that at this speed the displacement / length ratio should lie in the range 1 to 3. This yields lengths of 22 to 32 meters, where the EFV is 10 meters. In fact, this quick look confirms that the team's current path is a reasonable one.

Now I investigate the effect of speed upon this solution. I am drawing here upon McKesson (2011b) for observed best attainable powering performance, and Saunders (1957) for recommended fatness ratio (Figure 22). The baseline EFV has a fatness ratio of 35, which is off the chart. However, we see that the desired fatness ratio decreases with increasing speed. Thus we can construct a range of "maximum acceptable fatness ratio" versus speed, and then apply the 34.5 tonne weight to translate this into "minimum acceptable length". The result is shown in Table 3. Again we see that the 12 knot speed "wants" a 20+ meter length, and that the present 10m length is too short for any speed at 34.5 tonnes displacement.

Note that we began this investigation by tackling the first bullet above: What kind of boat is implied by the EFV requirement? We have also investigated the fourth bullet – what is the effect of speed? We are now convinced that length holds a key, and the question becomes how much length?

The simplest solution, based on Table 3, is that we need a 15 meter extension to the vehicle, which will "go away" in land mode.

But now we consider bullet number three, and consider whether there is a customer for this extra length. In fact, we are talking about more than one EFV-length of extra length. What if we just coupled two EFVs?

Unfortunately the solution is not as simple as that, since coupling two EFVs does give us extra length, but it also doubles the weight. But does the benefit of length gain us ground faster than the penalty of weight loses it? The method above can be used to investigate this.

Table 4 shows the results of several hypothetical chains of EFVs, and we see that a chain of three-and-a half EFVs would be a satisfactory combination of weight and length for hydrodynamic purposes, with no "Muda" in the form of an ancillary component.

Of course, three-and-a-half is not a viable number, but in the implementation stage below we will see how this is overcome.

Separate from this idea of chains of EFVs, the team is focusing on a TRIZ-like resolution of the contradiction by pursuing the design of a variable-length vehicle. Their particular focus is on the implementation of the variable-length concept. They have developed several concepts, and the most fruitful is a form of telescoping structure that pushes out an inflatable ship's bow, but retracts (and deflates) for overland mode. This is a classic TRIZ transformation, so we can say that TRIZ is in effect being used by the existing design team.

Between these two extremes, of the retractable bow and the chain of EFVs, there are other hybrid solutions, for example marrying the Muda concept to the TRIZ concept: In this case one possible piece of Muda is of the length increment required: We need to make the craft longer as a boat, but then we need the length to 'go away' ashore - because we have no customer for length, once in land-vehicle mode. I can see two paths to study that might create customers for the extra length. Is there some gear that is needed ashore that can be brought by the EFV as "cargo" in the length-augment?

Table 3 - Preferred values of length for various speeds of a 34.5 tonne EFV

Froude Number (length)	Maximum Acceptable Fatness	Speed (knots)	Minimum Acceptable Length
0	11	0.0	14.5
0.1	8.8	2.4	15.6
0.2	6.8	5.0	17.0
0.3	4.4	8.1	19.7
0.4	2.2	12.1	24.8

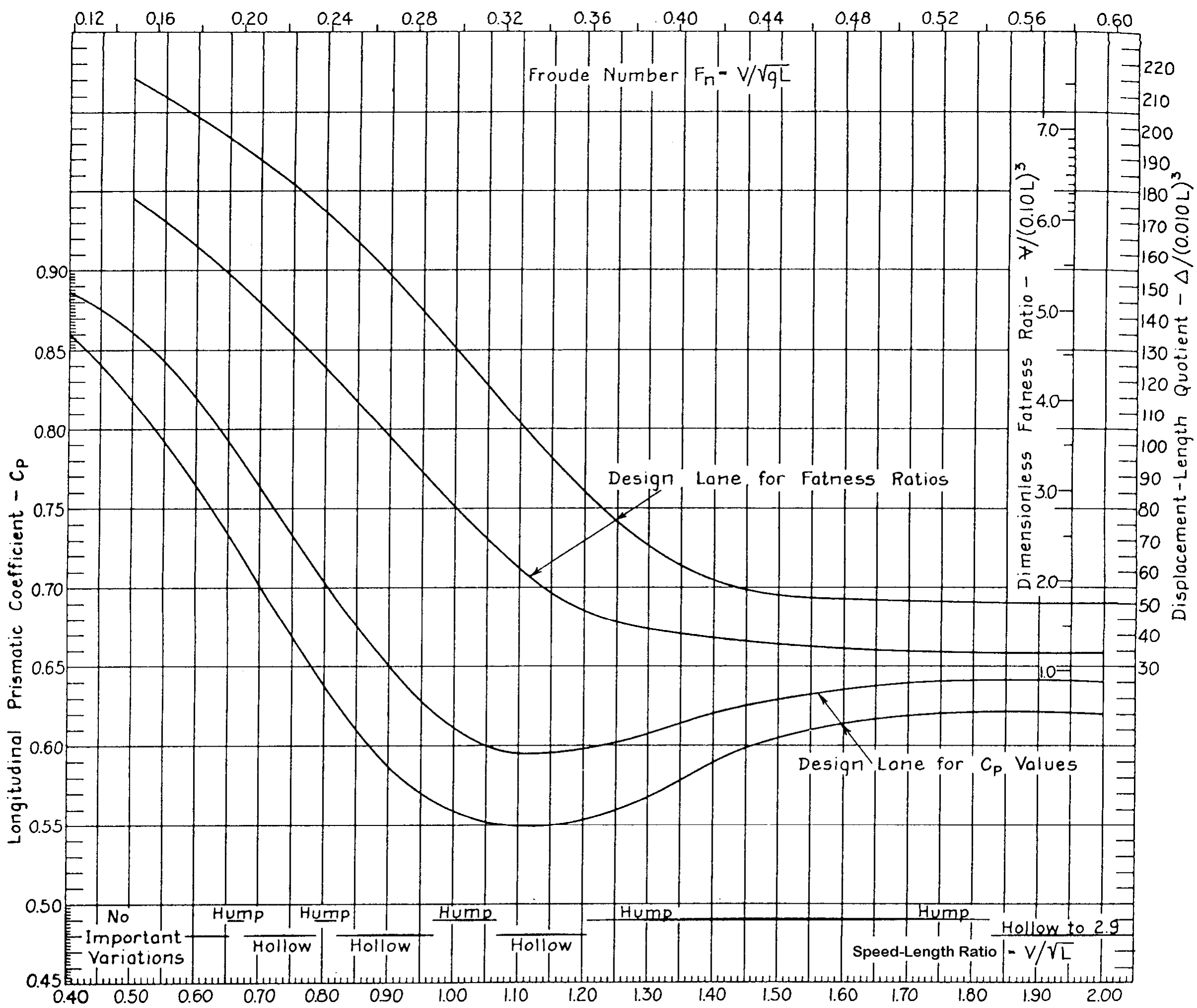

Figure 22 - CAPT Harold Saunders guidance for ship fatness ratio (Saunders, 1957)

Table 4 - Attained values of fatness ratios for various chains of EFVs, compared to recommended fatness ratios at 12 knots

Number of EFVs	Weight (tonnes)	Speed (knots)	Length total	Froude Number (length)	Attained Fatness	Maximum recommended Fatness	Minimum recommended Fatness
1	34.5	12	10	0.62	35.36	1.9	1.2
2	69	12	20	0.44	8.84	1.9	1.4
3	103.5	12	30	0.36	3.93	3.0	1.7
4	138	12	40	0.31	2.21	4.2	2.5
5	172.5	12	50	0.28	1.41	5.1	3.3
6	207	12	60	0.25	0.98	5.7	4.0

This requires discussion with the mission sponsor and this conversation has not taken place.

Finally, the last bullet in the idea list comes into its own when combined with the "chain of EFVs" idea. What if it were designed as a boat first, and then made to be a land vehicle after? There may be some merit to this idea. A 12 knot 34 tonne boat is about 33 meters long. Upon reaching the shore this boat could 'break apart' and become....what? An EFV plus three HMMVs?

Finally, the bullet asking "does the speed need to be continuous?" This question arose from the alligator analogy. It was noticed that the alligator is not fast in water, but does have a sprint capability - a burst speed. Would the EFV benefit in any way from a burst speed? Could this burst capability be used to justify a lower (and thus easier to attain) sustained speed?

Following the lizard analogy, I wonder if the EFV has to make more than one trip? If not, can the lizard drop its tail when it reaches shore?

4.4.4: Applying The Solutions

It is at this point that I "dropped out" of the task. Fortunately for this thesis, it is relatively easy to see how the solutions conceived above could be implemented:

First, the extensible bow is implemented by designing some sort of scissor mechanism that will extend a bow volume some 10+ meters forward of the craft. The bow volume is envisioned as an inflatable bag providing fixed buoyancy, and the extension mechanism also includes any necessary structure to provide a hull aft of that bow. (In the baseline concept at CISD, it is believed that the wake trench behind this bow will be sufficient to form a virtual hull, and no material hull is needed.)

Regarding the chain of EFVs solution, the investigation suggests that three EFVs could be coupled. And assuming that the coupling does require some length, we find that a truly optimal combination of length and weight can be hit with a coupling mechanism 1.3 meters long, i.e. a train of three EFVs comprising 103.5 tonnes and 34 meters.

We can now further improve the design by adopting the wake trench virtual-hull from the extensible bow solution, and determine that three EFVs 1.3meters apart need not have any actual gap-filling hull, they need only be fitted with a rapid break-away spacer between the vehicles. I opine that the engineering of this spacer assembly is at least as straightforward as is the engineering of the extensible bow.

4.5: Examples summarized

The foregoing four short stories are intended to illustrate a number of different ways that the formal methods and tools of innovation can be applied in ship design. To use a metaphor from the area of cuisine, we may consider them to be “appetizers” or samples of the sort of meals that can be prepared, by using the described morphology and its component tools.

Let us now turn our attention to the characteristics of the cook for those meals, that is “What are the characteristics of successful ship design innovators?”

5: What are the characteristics of successful ship design innovators?

We have seen what creativity is, and we have seen design through procedural and cognitive lenses. We have been introduced to some specific algorithms for innovation, and we have seen that these algorithms all share a common architecture or morphology.

Now let us turn our attention to the human actor, the innovator him- or herself. What are the kinds of people who are capable of creativity and / or innovation?

This turns out to be a very large field of study, which has given rise to much debate and is worthy of many dissertations in its own right. I will restrict the present discussion to engineering innovation, and will attempt to describe the overview of the types of individuals who show aptitude for creativity.

Many engineers remember a bifurcation of their personal universe which took place in their teen years, when they discovered that their friends didn't share their love for math and science. We each learned that not everybody could, or would, do math.

In the years that followed I have observed that even of those who can do math, not everybody can apply that math in the way that is needed for engineering analysis.

Continuing, it appears that there are a lot of excellent engineers, excellently skilled in engineering *analysis*, who can't do the problem backward and do engineering *synthesis*, which is what design is.

And of those who can do design, there are some who can't do the design-without-forebears that is innovation.

I hasten to state that this is not a value judgment, merely an observation. As an innovator myself, I am not a great mathematician. As an engineering designer myself, I greatly need good engineering analysts in my team. I am not saying that innovation is some sort of "higher" skill, just that it is a different skill.

My observation is that there exist individual differences in the aptitude for innovation, and this appears to be supported by the literature on this subject. Let me explore those that appear to me to be key, without making this into a dissertation on psychology.[20]

The topics of this exploration are as follows:

- What is the relationship between creativity and intelligence?
- What is the relationship between creativity and quality?
- What is the relationship between creativity and team work?
- Does creativity align with a certain psychological type?
- Can we learn to be more creative? (Separate from innovation methodologies.)

5.1: Creativity versus intelligence

I begin with the relationship between creativity and intelligence. Intuitively it seems that there ought to be such a relationship, but it turns out that this relationship cannot be described by the classic terms of necessary or sufficient.

Stahl, (1980) provides a discussion of this relationship when he analyzes student performance on a battery of creativity tests: *"According to the literature, the relationship between intelligence and creativity is not a direct one (Getzels, 1969; Ebel, 1974). The creativity-gifted person is seen as being different from the intellectually- or academically-gifted-person (Torrance, 1975). Torrance (1975) argues that to equate intellectual-giftedness with creativeness is to exclude nearly 3/4 of all highly creative*

[20] Which would be a valuable dissertation, but not one that I am qualified to undertake.

children. And, while creativity may be a factor of intellectual giftedness, it is certainly not a prerequisite (Torrance, 1963)."

Of course, some part of this result is due to the way that the question is framed. In this case the definition of creativity was "doing anything which is personally different and unique." This definition makes the result even more surprising:

"In view of the above, the finding that 70 percent of the children rated high in creativity would not have been selected as being intellectually-gifted should be perplexing to many educators. If creativity is loosely defined as "doing anything which is personally different and unique", then it is difficult to believe that 70 percent of the intellectually-gifted children do little that is new or unique. Furthermore, a liberal definition of creativity would require one to acknowledge that nearly three-fourths of the children who are highly creative are not very "smart". Both explanations seem somewhat absurd.

"In much the same vein, the relationship between intelligence (i.e., I.Q.) and creativity test scores is not a clear-cut one (Crockenberg, 1972; Torrance,1975; Ebel, 1974; Getzels, 1969). Low test scores and correlations provide no evidence that being intelligent disqualifies a person from being creative, or vice versa (Ebel, 1974). As long as I.Q. tests stress the measurement of convergent factual abilities and creativity tests are believed to reflect primarily divergent, non-factual recall responses, the controversy connected with the relationship between intelligence and creativity will continue."

If creativity is not the unavoidable concomitant of intelligence, then perhaps it is simply the result of the rote execution of some process? From an engineering point of view this would be wonderful, because it would mean that mechanistic execution of an innovation methodology (pick a comprehensive one, such as TRIZ) would replace a need for personal creativity. We have already rejected this hypothesis in our definition thus far, but Stahl is again helpful to us:

"It seems appropriate to examine some consequences of adhering to the position that creativity is caused by distinct creative thinking processes. If such processes actually do exist, then we must accept the fact that inherent creativity rather than developed ability, opportunity, effort, intentions, task or career requirements, or circumstances, accounts for the unique behaviors and products achieved by so-called creative people. Efforts to explain the creativity of individuals in such divergent areas as art, science, architecture, literature, directed at identifying a single "cause" of all these creative behaviors have not been successful (Berelson, 1964 and Taylor, 1975). Interesting, there has yet to be identified a distinct activity, attribute, or process that is commonly shared by all recognized 'creative', persons which sets them all significantly (and I don't mean in the statistically hallowed sense of .05) apart from less-creative people.

"That these distinctions do not exist is supported by a list of characteristics or distinguishing features and attributes of gifted and talented individuals published by the Council for Exceptional Children – Nazzaro, 1978). (See Figure 23) In reference to the "creative characteristics" of gifted/talented children, the CEC points out that these characteristics "constitute observable behaviors that can be thought of as clues to more specific behaviors" to identify the creative person. Even in Figure 23 there is an implied cause-effect relationship between a type of thinking (e.g., 'fluent', 'flexible') and the described behaviors which follows. Here again, even the research and literature review by the CEC did not identify clearly distinguishable characteristics of either creative behaviors or so-called creative thinking processes."

What Stahl is giving us is that creativity is not the unavoidable offspring of an algorithm, nor of intelligence, and even that creativity may be found in the not exceptionally intelligent. This is important, because it means that our innovative ship designer may not necessarily be found at the head of the class.

Creative Characteristics of the Gifted and Talented

Few gifted children will display all of these characteristics, while characteristics do not necessarily define who is a gifted child. They do constitute observable behaviors that can be thought of as clues to more specific behavior characteristics are signals to indicate that a particular student might warrant closer observation and could require specialized education & attention.

- They are fluent thinkers, able to produce a large quantity of possibilities, consequences, or related ideas.
- They are flexible thinkers, able to use many different alternatives and approaches to problem solving.
- They are original thinkers, seeking new unusual, or unconventional associations and combinations among items of information.They also have an ability to see relationships among seemingly unrelated objects, ideas, or facts.
- They are elaborative thinkers, producing new steps, responses, or other embellishments to a basic idea, problem, or situation.
- They show a willingness to entertain complexity and seem to thrive in problem situations.
- They are good guessers and can construct hypothesis or "what if" questions readily
- They often are aware of their own impulsiveness and the irrationality within themselves and show emotional sensitivity.
- They have a high level of curiosity about objects, ideas, situations, or events.
- They often display intellectual playfulness, fantasize, and imagine readily.
- They can be less intellectually inhibited than their peers, expressing opinions and ideas and often exhibiting spirited disagreement.
- They have a sensitivity to beauty and are attracted to aesthetic dimensions

Figure 23 - Creative Characteristics of the Gifted and Talented (Nazzaro, 1978)

5.2: Creativity and quality

Stahl argues that creativity is not intelligence. Does this mean that intelligence is not required for engineering innovation?

In my position as Section Head for the Advanced Vehicles Design Section at Navy headquarters[21] I was 'privileged' to receive a steady trickle of innovations from outside the naval engineering enterprise. Well-meaning constituents would have a 'great idea' that they would send to their congressman. The congressman would honestly reply "I have forwarded your idea to the Department of the Navy for review…"

In the vast majority of cases the ideas were, not unintelligent, but perhaps uneducated. There were violations of physics, or misapplications of fluid theory, etc.[22] In fact, in years of performing that sort of review I find that professional researchers operating within their field of expertise are far more likely to come up with useful innovations than any number of well-meaning outsiders.

But if that is not the result of intelligence, then what is it? I think that the answer is: Expertise.

Earlier I argued that creativity is more than novelty. But again if it is more than "mere" novelty, then what is the "delta"? What is the element that must be added to "novelty" to yield "creativity?" I opine that this element is "quality," the offspring of expertise. Quality is an essential component of creativity.

Consider again Stahl's discussion of creativity tests. He says:

"Crockenberg (1972) warns that educators too often (and all too rapidly) mistakenly equate the mere frequency of new and different responses or products with high levels of creativity. She strongly suggests that we avoid being heavily influenced by the mere multitude, elaborativeness, and/or attractiveness of so-called 'creative products' which so often have nothing to do with genuine creative thinking.

"Unless these ambiguities are clarified, then, carried to the extreme, class-room teachers, curriculum developers, and teacher educators will continue to believe that anything a person does in response to a problem or situation which is different, new and attractive, is to be judged 'creative'. If this loose definition is rejected, then some degree of correctness, accuracy, and/or quality is implied but rarely stated in most conceptualizations of creativity. If correctness or quality is involved, then there must exist a right or appropriate externally determined and measurable criteria for what is supposed to be a 'divergent' activity. Again, logic would suggest that creativity may be an extension or the next step beyond the convergent responses expected in the situation. This phenomenon may help to explain why many very new, "creative" responses are met by rapid acceptance by individuals on the brink of the same discovery.

"The fact that other people not only must recognize but also determine whether one's products are creative poses an interesting dilemma. It may well be that individuals have no problem whatsoever in generating new and unique behaviors and products. Rather, the problem arises when we find so little support and favor from others in connection with those novel things that we actually can do. As Ebel (1974) suggests, nearly all of our unique behaviors and products are ignored because few other people value them enough to mention them. Hence, built into the uniqueness must be externally demonstrable elements such as excellence, quality, appropriateness, and usefulness. The emphasis that promoters of creativity put on suspension of critical judgment, on complete openness to new ideas however bizarre; and mere numbers of novel alternatives, may need to be reconsidered in light of these external criteria."

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[21] Then NAVSEA 50141, a position I held beginning in 1991.

[22] There was, of course, a certain amount of lunacy as well. I remember one letter including "Please tell Warren Burger that *Philadelphia Freedom* is a much better song than *Hail to the Chief*."

If creativity requires quality, and it is built upon a foundation of intelligence, then it seems clear that expertise is included in the recipe as well. The final remark above pointed out that much of the creative quality requires recognition before it can be fruitful. Thus there is something more than expertise, it is *recognized* expertise.

This latter point was touched upon in UNO course ENMG 6401 “Seminar in Organizational Behavior” in a unit on the nature of power in an organization. In this unit students learn that innovation or novelty requires a certain amount of “swimming upstream", bucking the norms. How then does the innovator get the credibility to be listened to? One key is technical excellence. Whetten and Cameron (Whetten, 2011) tell the story of a non-conformist whose performance review includes the remark “he is so blasted smart we have no choice but to promote him.” This is how innovation succeeds within the corporate structure: Expertise trumps conformity (in some cases.)

Of course, there are a number of nuances to this, and I hope that no reader takes this thesis as a license to deviate will-he / nil-he. An aspect not mentioned in Whetten’s text is for the innovator to show that he does understand the corporate norms, but that he is suggesting to willfully and knowingly violate them, for some higher purpose – e.g. to solve the technical problem at hand in a “better” way.

Too often I see young innovators whose ideas may be good, but who by their brashness communicate that they disrespect the corporate norms. These folks rarely succeed while they work in this mode. By contrast the seasoned innovator shows that he does understand, but that we ought to put aside those norms this time, for this reason… Indeed, often this seasoned innovator understands those norms better than her colleagues, because she has pulled them out of the background and studied them explicitly. We will see this principle again, under the label "metacognition."

In Krathwohl (2002) there is proposed a two-dimensional taxonomy of learning, which embraces a Knowledge axis and a Cognition axis. Krathwohl posits that progress along the dimension of the axis is related to maturity or experience or expertise, each simpler category being prerequisite to the next more complex one.

The Krathwohl taxonomy may explain some of the fundamental skills needed for engineering innovation. As I have repeatedly stated "not everybody can do it." It seems to me – and this would be a fruitful avenue for future research – that one has to have progressed pretty far on the knowledge axis in the metacognitive realm, and pretty far along the Cognition axis into the Creative realm, for invention to be easy. This would be a fruitful topic for statistical study.

Kratwohl’s taxonomy is described in Table 5. The two dimensions, listed as two columns, are mutually orthogonal.

I think of the sector A-C & 1.0-3.0 as being “Technician grade” knowledge. This is knowledge of, say, what a nut and bolt are, how they relate to each other, how to apply their relationship (how to pick the right nut for the bolt).

An Engineering education touches upon elements 4.0 and 5.0: Given what we know about nuts and bolts, can we generalize, and understand the role that thread pitch has on the relationship between gripping force and bolt torque? Can we then use that analytical knowledge to evaluate which would be the best bolt for a given task?

I believe then that Innovation lies at step 5.0: Create, plus knowledge not only of the facts and procedures, but also of what we really know about those facts and procedures – knowledge about knowledge – so that we can generalize our knowledge, apply it in novel ways or novel sectors. And, as we recall the various innovation methodologies, we realize that many of them were attempts to force us to think about our knowledge, whether this was via the explicit step of “make the familiar strange” or via the biomimetic analogy of looking for ship rudders in Otter tails. In both cases (and many more) we are enjoined to diverge our knowledge, which we may also describe as “thinking about our thoughts.”

Table 5 - Krathwohl's Educational Taxonomy

Knowledge Dimension	Cognitive Process Dimension
A. Factual Knowledge - The basic elements that students must know to be acquainted with a discipline or solve problems in it. a. Knowledge of terminology b. Knowledge of specific details and elements B. Conceptual Knowledge - The interrelationships among the basic elements within a larger structure that enable them to function together. a. Knowledge of classifications and categories b. Knowledge of principles and generalizations c. Knowledge of theories, models, and structures C. Procedural Knowledge - How to do something; methods of inquiry, and criteria for using skills, algorithms, techniques, and methods. a. Knowledge of subject-specific skills and algorithms b. Knowledge of subject-specific techniques and methods c. Knowledge of criteria for determining when to use appropriate procedures D. Metacognitive Knowledge - Knowledge of cognition in general as well as awareness and knowledge of one's own cognition. a. Strategic knowledge b. Knowledge about cognitive tasks, including appropriate contextual and conditional knowledge c. Self-knowledge	1.0 Remember - Retrieving relevant knowledge from long-term memory. 1.1 Recognizing 1.2 Recalling 2.0 Understand - Determining the meaning of instructional messages, including oral, written, and graphic communication. 2.11nterpreting 2.2 Exemplifying 2.3 Classifying 2.4 Summarizing 2.5 Inferring 2.6 Comparing 2.7 Explaining 3.0 Apply - Carrying out or using a procedure in a given situation. 3.1 Executing 3.2 Implementing 4.0 Analyze - Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose. 4.1 Differentiating 4.2 Organizing 4.3 Attributing 5.0 Evaluate - Making judgments based on criteria and standards. 5.1 Checking 5.2 Critiquing 6.0 Create - Putting elements together to form a novel, coherent whole or make an original product. 6.1 Generating 6.2 Planning 6.3 Producing

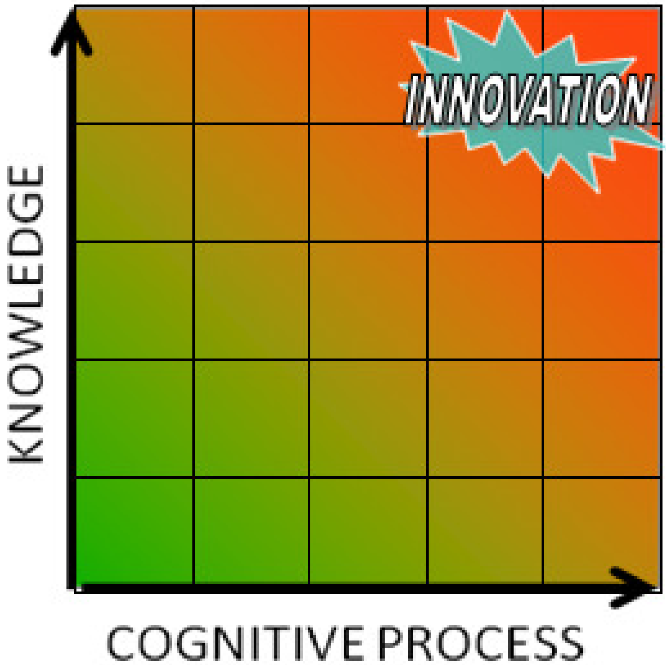

Figure 24 - An attempt to illustrate the idea that Innovation lies at the high end of both axes of Kratwohl's Education Taxonomy

Figure 24 is an attempt to illustrate the two orthogonal axes of the Kratwohl taxonomy, and my belief that innovation is to be found in the intersection of high values in *both* dimensions. As should be obvious from the structure of Kratwohl's taxonomy, these extreme values on the two axes are values only likely to be found in the highly educated, or expert practitioner.

This is tantalizing simple, which raises the fear that it may be simplistic, but it provides a justification for my premise that expertise is indeed necessary for innovation. Of course, this begs the question of the definition of expertise, and the determination of how much expertise is needed, since there are clearly different levels of expertise. In this case I will opine, but not prove, that the Kratwohl method is useful because it is not so much about expertise *per se*, but rather about the cognitive processes that the expert uses.

5.3: Creativity as a social product

Thus far we are building the case that innovation or creativity may not demand extreme intelligence, but it does demand expertise, and recognized expertise at that. Further, via the examples of "brash engineers" we see that this innovation takes place within a social structure. Further, it is well known that most engineering takes place as the result of teamwork. Indeed, we first encountered this principle during the discussion of the Rhodes 4-P model, (Rhodes, 1961) wherein one of the Ps was "persons." The question at this stage then is what type of social structure is most likely to yield successful innovation.

Dr. Brian Uzzi has conducted interesting studies of the nature of successful and unsuccessful creative teams. In Uzzi (2005) he presents a discussion of the right "chemistry" required in the creative team. Uzzi's research uses Broadway musicals as his laboratory for creative success. Musicals are attractive to the scientist because they all consist of a five-person team: Composer, lyricist, librettist, choreographer, and director. There is also available a straightforward metric of creative success, via box-office revenues.

Uzzi developed a tool for measuring what he calls the “world size” of the creative team. World size is measure of how many degrees of separation exist between the participants in the team and their respective universe. This is a common expression in popular culture, where we speak of “six degrees of separation,” with the meaning that no two people on earth are separated by more than six steps of acquaintanceship: “I know a fellow who knows a fellow who knows… the King of Spain.” Indeed the six degrees of separation are Uzzi’s work.

A writer for The New Yorker (Lehrer, 2012) does an excellent job of making Uzzi’s research readable. I quote from Lehrer:

"Uzzi found that the people who worked on Broadway were part of a social network with lots of interconnections: it didn’t take many links to get from the librettist of “Guys and Dolls” to the choreographer of “Cats.” Uzzi devised a way to quantify the density of these connections, a figure he called Q. If musicals were being developed by teams of artists that had worked together several times Figure 25*before—a common practice, because Broadway producers see “incumbent teams” as less risky—those musicals would have an extremely high Q. A musical created by a team of strangers would have a low Q.”*

Uzzi himself illustrates this with the figure reproduced as Figure 25.

One might expect that a low-Q musical would perform poorly, because strangers weren’t insiders in the industry, in a manner similar to my discussion of outside inventions mailed to the Department of the Navy. Further, we might then go to the other extreme and expect well-connected insider teams to be the most successful, and this is where Uzzi’s finding may surprise: Uzzi found (see Figure 26) that there is an optimum degree of connectedness, and that all-insider teams were not the highest performing. Let me allow Lehrer to tell the story again:

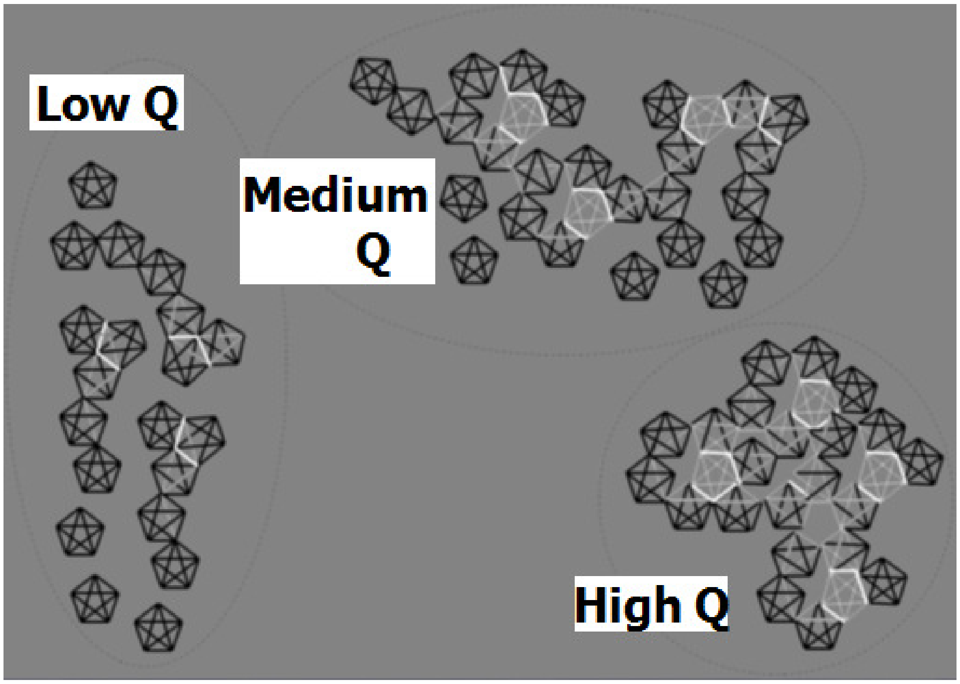

Figure 25 - Illustration from Uzzi (2005) depicting the parameter "Q" which measures the degree of interconnectedness of creative teams

"[W]hen the Q was too high (above 3.2), the work also suffered. The artists all thought in similar ways, which crushed innovation. According to Uzzi, this is what happened on Broadway during the nineteen-twenties, which he made the focus of a separate study. The decade is remembered for its glittering array of talent—Cole Porter, Richard Rodgers, Lorenz Hart, Oscar Hammerstein II, and so on—but Uzzi's data reveals that ninety per cent of musicals produced during the decade were flops, far above the historical norm. 'Broadway had some of the biggest names ever,' Uzzi explains. 'But the shows were too full of repeat relationships, and that stifled creativity.'

"The best Broadway shows were produced by networks with an intermediate level of social intimacy. The ideal level of Q—which Uzzi and his colleague Jarrett Spiro called the "bliss point"—emerged as being between 2.4 and 2.6. A show produced by a team whose Q was within this range was three times more likely to be a commercial success than a musical produced by a team with a score below 1.4 or above 3.2. It was also three times more likely to be lauded by the critics. 'The best Broadway teams, by far, were those with a mix of relationships,' Uzzi says. 'These teams had some old friends, but they also had newbies. This mixture meant that the artists could interact efficiently—they had a familiar structure to fall back on—but they also managed to incorporate some new ideas. They were comfortable with each other, but they weren't too comfortable.'

"Uzzi's favorite example of "intermediate Q" is "West Side Story," one of the most successful Broadway musicals ever. In 1957, the play was seen as a radical departure from Broadway conventions, both for its focus on social problems and for its extended dance scenes. The concept was dreamed up by Jerome Robbins, Leonard Bernstein, and Arthur Laurents. They were all Broadway legends, which might make "West Side Story" look like a show with high Q. But the project also benefitted from a crucial injection of unknown talent, as the established artists realized that they needed a fresh lyrical voice. After an extensive search, they chose a twenty-five-year-old lyricist who had never worked on a Broadway musical before. His name was Stephen Sondheim. "

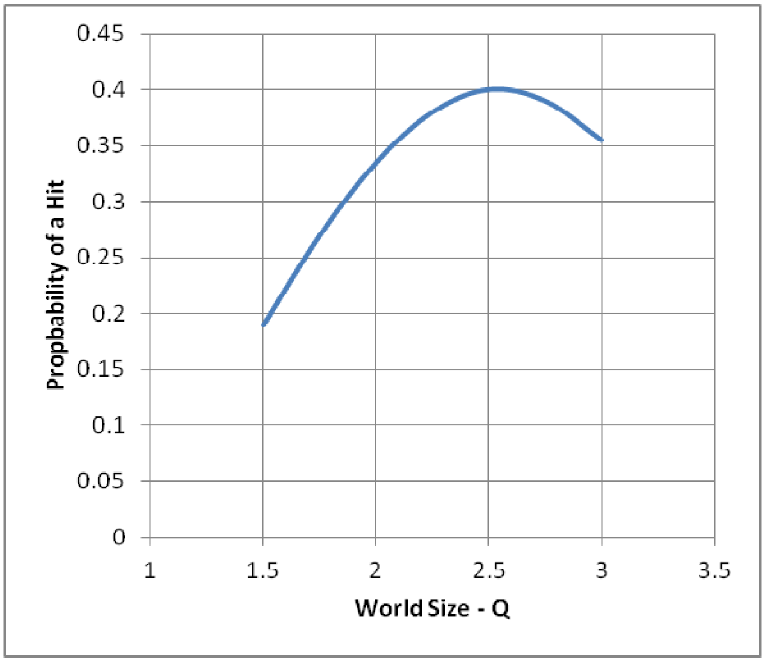

Figure 26 - Broadway musical success versus World Size (Uzzi, 2005), re-drawn by author)

Uzzi's finding is tantalizing, and would again make a fine study in engineering. The naval engineering enterprise is at least as much of a definable community as is the Broadway musical community. If we wish to assemble project teams from that community and expect of them significant creative success, then – inferring from Uzzi – we should be aware of the existing network of relationships within that community, and we should be selecting teams that are neither too interconnected, nor too disparate. Unfortunately, the tool for the quantification of that connectedness remains undeveloped.

5.4: Measuring innovation aptitude

Up to this point I have described the place of innovation within the field of creativity, or within the field of engineering design. I have stated that innovation, in order to be successful, requires expertise. It remains however evident in my experience that innovation also requires a certain type of thinking, or a certain mindset, or a certain psychology. We saw this same point touched in the remarks by Stahl earlier, wherein we learned that innovation is not merely an offspring of intelligence.

What then is the psychological 'furniture' that predisposes one engineer to be innovative? This turns out to be the subject of a substantial body of research in itself within the field of psychology. I wish in this present dissertation to only harvest the high points of that research, and use its findings to allow us to "filter" individuals to see if they are innovators or not. I intentionally state that simplistically, for clarity. In reality, as we will see the scale is not a black and white "innovator or not" but is replete with grey areas.

In my research I have found one explicit attempt to measure innovation aptitude: The Kirton Adaptor - Innovator Inventory (KAI) is a psychological test which returns a numerical indicator of where a person falls on a spectrum from Adaptor to Innovator (Kirton, 1994). It is conceptually similar (but narrower in focus) to the popular Myers Briggs Type Indicator (Myers, 1995) that is already extensively used in DOD.

The Kirton Adaption–Innovation Inventory (KAI) tool measures individual styles of problem definition and solving. An adaptor uses existing knowledge and procedures to solve problems by time-honoured techniques, while an innovator tends to look beyond what is given to solve problems in new ways. We will below discuss more about the implications of these style differences, but at this point let me point out that what we are talking about here is indeed a *style,* a preference, a preferred way of tackling problems. It is most emphatically *not* a measure of an individual's skill at implementing the style. The KAI may indicate that a person is by nature an innovator, and that person may still be a failure in engineering product development, because of (among other possibilities) a lack of expertise.

An Adaptive Style, in this case, refers to an adaptive, building, or analogical problem-solving style versus an innovative or pioneering style. Both skills are needed for organizational problem solving, but the differences often are not recognized or measured. The American Chemical Society (ACS, 2012) provides the list, "Characteristics of adaptors and innovators" replicated as Table 6. It is also enlightening to look at a somewhat high-contrast version of how the "other side" often sees extreme adaptors and innovators – Table 7.

The KAI is a 32-item questionnaire used to measure an individual's problem-solving style on a scale from 32 to 160. A person with an adaptive style will usually score in the 60–90 range, whereas a person with an innovative style will score between 110 and 140[23]. This inventory has been found to be extremely accurate and has been globally validated across many cultures over decades (Kirton, 1984).

More important than the absolute score, however, is the relationship between their score and the score of the people they are working with. One may be either the more innovative or the more adaptive member of a team, depending upon the other team member's preferences.

It has also been found that a large disparity between team mates, say 20 or more points, is such a big difference in cognition that the two individuals will work poorly together – they are effectively speaking different languages in their approaches to problem solving. Consider the following remarks from Dr. Curt Friedel (Friedel, 2012):

"One of the hallmarks of AI theory is that more than a 20-point gap between two individuals, or an individual and the problem at hand, will result in stress. Then there must be motivation to cope beyond this gap to work together and solve the problem. If motivation is lacking, then there is failure in solving the problem. So AI is a bit of a moving target and the focus is not so much an understanding of self, but an understanding of how to better work together."

Note that what Dr. Friedel is suggesting is that, in the face of a large AI disparity within the team, the team must exercise a metacognitive process. This may, in fact, be one of the reasons that innovation requires metacognition, as described above.

It is fairly well known in industry that the Myers-Briggs Type Indicator can be used as a tool for designing engineering teams and facilitating cooperation between individuals. Hughes (Hughes, 1994) conducted a limited scope correlation of MBTI scores with KAI scores, using a class of military officer students at the National Defense University. This study concluded that persons scoring EN_P on the MBTI were more innovative than others. However it is worth noting that the correlation with _N__ was

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[23] I (McKesson) scored 132 which is in keeping with the evidence of my career. According to Friedel (2012) *"The mean score is 95, and 95% of the population is between 61 and 129. So a rough estimation is that a 132 would be among the top 2% of the most innovative. I think the reason Kirton does not view scores this way is if you were working with an individual who had a 145, you would be more adaptive to this individual. Further, Dr. Kirton values the necessity of diversity of thought within teams and does not make claims that a certain score would be most suitable in a particular profession (even though some professions do have higher and lower averages). For example, a group of accountants may be more adaptive and a group of people in finance may be more innovative, but that doesn't mean a highly adaptive individual would be uncomfortable in finance. On the contrary, Dr. Kirton would argue the case for more adaptors in finance, if this was the case."*

Table 6 - The American Chemical Society list "Characteristics of adaptors and innovators" (ACS, 2012)

Adaptor	Innovator
• Efficient, thorough, adaptable, methodical, organized, precise, reliable, dependable	• Ingenious, original, independent, unconventional
• Accepts problem definition	• Challenges problem definition
• Does things better	• Does things differently
• Concerned with resolving problems rather than finding them	• Discovers problems and avenues for their solutions
• Seeks solutions to problems in tried and understood ways	• Manipulates problems by questioning existing assumptions
• Reduces problems by improvement and greater efficiency, while aiming at continuity and stability	• Is a catalyst to unsettled groups, irreverent of their consensual views
• Seems impervious to boredom; able to maintain high accuracy in long spells of detailed work	• Capable of routine work (system maintenance) for only short bursts; quick to delegate routine tasks
• Is an authority within established structures	• Tends to take control in unstructured situations

Table 7 - How the "other side" often sees extreme adaptors and innovators (ACS, 2012)

Adaptor is seen as:	Innovator is seen as:
Dogmatic, compliant, stuck in a rut, timid, conforming, and inflexible	Unsound, impractical, abrasive, undisciplined, insensitive, and one who loves to create confusion

substantially higher than the correlation with E___ or ___P. Thus I would restate Hughes conclusion as that Jungian Intuitives are more likely to be innovators than are the Jungian Sensors.[24]

However, at this point in the dissertation we are discussing the use of KAI as a tool for inventorying an individual's innovation aptitude. What we see is that the KAI does accomplish this, but that the definition of whether she is an innovator or not, depends upon the context and the team that she is working with.

This situational condition opens the door to a discussion of innovation management and the use of KAI and other instruments in designing ideal engineering teams. This feels to me like a fruitful subject for engineering management, but it lies outside the scope of the present study. The interested reader is referred to coursework in the management of innovation and technology, such as is offered in UNO course MANG 6710.

5.5: Think Like Leonardo da Vinci

Michael J. Gelb (Gelb, 1998) published a book entitled "How to think like Leonardo da Vinci." I would have overlooked this book for its populist title, were it not for that fact that it was on sale in the United States' National Gallery of Art. This sales venue seemed to lend a credibility to the work, and I am pleased to have made the purchase.

Gelb identifies Leonardo da Vinci as the greatest innovator of all time. He then describes seven cognitive characteristics that he calls da Vincian Principles:

- *Curiosità* – Curiosity, a constant thirst for new knowledge
- *Dimostrazione* – Testing knowledge (and hypotheses) and learning from the results
- *Sensazione* – Training of the five senses, including the ability to imagine
- *Sfumato* – A high tolerance for ambiguity
- *Arte/Scienza* – A balance between art and science, or whole-brain thinking
- *Corporalita* – Physical elegance
- *Connessione* – Systems thinking

Gelb describes each of the seven characteristics and how they contributed to da Vinci's creativity, and he then develops exercises that the reader can undertake to grow those characteristics in themselves.

In the context of this dissertation there are two relevances of Gelb's work: First, since Gelb provides us with a program for learning those attributes, this book forms a segue into the discussion of means of teaching innovation. It is my thesis that innovation can be defined, can be facilitated by tools, and can be taught. This will be expanded on below.

Second, I confirm from my own experience that these characteristics are indeed contributory to an attitude of innovation. I will develop this in the paragraphs immediately following.

I would like to be able to cite a large statistical universe of data on the basis of which I can confirm or refute the hypothesis that these da Vincian characteristics are common in successful innovators. Unfortunately I have no such data and I must leave this study for my Appendix A.

I do, on the other hand, confirm that these seven characteristics are very much a part of my own character, and to the extent that I may be considered typical of an innovator, then my experience supports the hypothesis.

Indeed, these seven characteristics are so close to my character that the following seven subsections have been very challenging to write. The seven alleged attributes of Leonardo da Vinci are

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[24] My own MBTI score is INTJ, so my own correlation with KAI scores rests on the N.

very definitely attributes of my own character, to the point where writing about them nearly brings me to tears. Needless to say, this degree of passion is unusual in an engineering dissertation!

In the brief treatments that follow I will attempt to show how these characteristics have shaped my own professional practice, with the intent that from that the reader may infer a more general applicability.

5.5.1: *Curiosità* – Curiosity, a constant thirst for new knowledge

Gelb describes da Vinci's astonishing breadth of interest, from sculpture to painting to mechanical engineering to anatomy. He goes on to assert that this catholic curiosity was contributory to da Vinci's success as an innovator.

Breadth of curiosity contributes to two aspects of engineering innovation: First, within the technical discipline (in our case, ship design) the curiosity serves to expand and develop the engineer's expertise. In engineering, curiosity manifests by asking questions and then applying our engineering skills to develop answers. This process will necessarily grow our individual expertise as we continue to apply our tools to solve new problems. Indeed, in the context of formal education this is exactly why we have homework problems: Because skills grow when you use them.

Secondly, curiosity will grow our ability to apply outside-domain solutions to inside-domain problems. By this I mean that the exercise of a vibrant curiosity will help us to be able to apply TRIZ's solutions, or to see the application of a beaver's tail to ship steering.

This is, of course, because the engineering curiosity, with it's formula of "gee I wonder if I can model and solve *that*", will train us to better be able to model situations. And that training in turn requires us to be able to realize that such-and-such may indeed be a model of the task at hand. And from this ability to recognize models, comes the ability to recognize disparate analogs of all sorts, whether they be biomimetic in origin or if they come from a list of TRIZ solutions.

5.5.2: *Dimostrazione* – Testing knowledge (and hypotheses) and learning from the results

The role of *dimostrazione* is closely allied with *curiositá*. Above I likened engineering *curiositá* to the making of analytical models for phenomena of interest. If that stands, then *dimostrazione* is the solving of those models. We test our models and learn from the results. The application is direct.

5.5.3: *Sensazione* – Training of the five senses, including the ability to imagine

Under the heading "*Sensazione*", Gelb (1998) encourages practitioners to exercise their senses, to become active listeners, active seers, active tasters, etc. (These terms are mine, not Gelb's.) I know that in my own life this rings true: I enjoy collecting data. When I tour a ship I really look at her, at her systems, and her details.

I have found it interesting to take ship tours with a group of undergraduates. The first few times I did this I would find myself chatting with them saying "Did you notice …" and the student would not have noticed that feature. After a few repetitions of this experience I realized that the students don't see the things that I see – because they don't know how. I now enjoy taking ship tours with students but I tend to narrate these walk throughs: "Hmm, why is that bulkhead insulated? The one on this side isn't." "What is that monorail in the overhead for?" "Why do they label all the pipes? What is the color code?"

Students have often thanked me for these monologues, because they say they have learned a lot, because it allows them to see through my eyes. From this "seeing," it is a short step from looking at details to thinking "I wonder why her designer made that choice?"

This exercise, looking in detail and then thinking about the design process that gave rise to that detail, is yet another tool for developing expertise.

5.5.4: *Sfumato* – A high tolerance for ambiguity

In the pursuit of innovation we often try to take an idea from another discipline, or an idea that is inchoate in some fashion (such as TRIZ's transformations) and apply it to our problem at hand. When we do this, we usually run into stumbling blocks right off the bat.

I have found it useful to suspend concern with those stumbling blocks, and press forward gently with the innovation for a while. Sometimes I find that the innovation idea fails anyway, so I needn't have dealt with that stumbling block. In other cases I have found instances where some other feature of applying the idea ends up resolving the stumbling block as an unexpected by-product, so again I needn't have dealt with the issue directly. And of course, sometimes I have merely put the investigation off, and I have to tackle it eventually.

But there have been enough of the first two types of situation that I have learned to suspend judgment a fair while in the development of an innovation. I believe that this is an engineering manifestation of Gelb's "tolerance for ambiguity." It is very easy for engineers to feel the need to tackle each objection as it comes up, as opposed to taking the approach of simply noting those objects for attention later.

5.5.5: *Arte/Scienza* – A balance between art and science, or whole-brain thinking

Gelb's book is not a treatise on innovation, so it is not surprising that one of his seven characteristics does not fit easily into my innovation framework. As regards this need to embrace both technological and aesthetic realms, let me simply point to the need for expertise, pointed out earlier, and the need for aesthetic quality, which follows below.

5.5.6: *Corporalita* – Physical elegance

Under this issue of physical elegance I choose to include the whole topic of aesthetic quality. Clearly one aspect of physical elegance, in ship design, would be the design of beautiful ships. But I believe that beauty of design is also expressed in "elegance" of design. This term – which is one of those "I know it when I see it" terms – conjures to mind a design in which there are no extraneous moving parts, a design with optimal efficiency, and so forth.

Further, I believe that design elegance is itself a subset of a greater characteristic called "Quality." In this term I mean quality as developed by Robert Pirsig first in "Zen and the Art of Motorcycle Maintenance" and then later in "Lila" (Pirsig, 1974 & 1991.)

Pirsig's metaphysics of quality (MOQ) has given rise to a substantial body of literature and it is worthy of study by any person wishing to pursue a career as an innovator. It is, however, a sufficiently large and mature body of research to be worthy of dissertations in its own right (see Appendix A for a list of topics that have come to mind during the writing of the present work.)

5.5.7: *Connessione* – Systems thinking

Systems thinking should be a *sine qua non* for naval architects. Gelb emphasizes it for his lay audience, but we take it as foundational in ship design, and we have even built upon that foundation in our interface-based innovation tools such as multitasking, Muda, and others.

5.5.8: McKesson's da Vincian Exercises

As I read Gelb's book, I found myself noting areas where I had done things that fit into Gelb's prescription. I believe that these habits of mine – many of which are no more than play – have been contributors to my skill as an innovator.

I offer them here merely as a form a self-exposure, in the hope that the exercises I describe may spark ideas in my readers.

- Try wearing a skirt (if you are male). Can you construct a logical reason why skirts are better suited to the male anatomy than are trousers? Can you construct a logical reason why men should not wear skirts? Why are there no “Dress Sandals” for men? Why don’t male office workers paint their fingernails?
- Take words apart. It is fascinating to see the relationship between ideas that end up embedded as merely a relationship between words. For example, the word “sinister” is derived from the Latin for the left side. To be left-handed is, in some sense, sinister. What a fascinating and insight-provoking fact.
- Learn a foreign language. I often find that thinking in French will take my thoughts in a different direction than would occur if I thought in English..
- Think in metaphors, constantly creating analogies. “it’s like…” I get a lot of positive comments from my students because I am able to describe complex physics in terms of analogies. An example is my explanation of propeller cavitation as being analogous to “tearing” a spoonful of Jell-O from the bowl. The analogies are definitely not exact, but they may be useful top-level models which can (a) help understand and (b) provoke further learning.
- Change jobs. I have changed jobs many times, including throwing over a successful career as a defense contractor in order to become an academic. I have never regretted these moves.
- Learn to read upside down. The orientation of the letters is, after all, totally arbitrary. This would not be true if we’re reading comic books or pictographs, but with a written alphabet there’s no empirical reason that the “A” must point upwards, except convention.

5.6: Characteristics of team leaders

NASA engineers Michael Ryschkewitsch, Dawn Schaible,and Wiley Larson, in their 2009 paper "The Art and Science of Systems Engineering" (Ryschkewitsch *et al*, 2009) directly tackled the question “What are the characteristics of successful engineering team leaders?” This paper is an entire textbook in Systems Engineering in 22 pages, covering the systems engineering process, the procedural keys to success, and – relevant to our topic at hand – the required characteristics of a good systems engineering leader. Their list of characteristics – reproduced below – resonates strongly as the characteristics of a good inventor / innovator as well.

Intellectual curiosity. This reflects the inventor's passion for asking "Why?" "Why" is a very important question in the context of invention and innovation - indeed I nearly titled this dissertation as "Engineering by asking ‘Why?’" "Why" is the question that provokes the engineer to even dream in the first place that there might be an answer other than the one that will be found by simple derivative evolution. "Why" is the question that provokes revolution.

Ability to see the big picture. This foreshadows the need to remember the real goal of the device being invented, and not to fall into the trap of sub-optimization. We have seen this concept recur in many guises in the innovation algorithms discussed, as well as explicitly as an ‘algorithm’ of its own under the heading of teleological decomposition.

Ability to make system-wide connections. This is a characteristic that will give rise to innovation by multi-tasking, and it is also highlighted by Stahl earlier in setting up the innovation task and the team to tackle that task.

Exceptional two-way communicator. In combination with the system-wide connection skill, these two skills may relate to the ability to look far afield for solutions, such as using a patent database as a window into diverse industries, rather than sticking with the comfort of the 'home turf.

Strong team member and leader. Unfortunately this skill is not common among inventors, it is only common among *successful* ones.

Comfortable with change. We saw this skill enjoined by Gelb in the da Vinci discussion.

Comfortable with uncertainty. Again, one of Michael Gelb's da Vincian attributes.

Proper paranoia. To my mind the most important aspect of this 'proper paranoia' is the important question "What could go wrong with this?" This question is fundamental in all of engineering, but it becomes even more important when one is digressing from the tried-and-proven into a higher-risk solution. Just what *are* those risks? I have earlier suggested that innovation must include some success, and that the success is the fruit of expertise. Here I am saying that the success-producing *application* of expertise comes about because the innovator has asked the right paranoid questions, and has in consequence stopped all the technical gaps in his innovation.

Diverse technical skills. Here again we see a skill related to breadth of knowledge, and the ability to incorporate solutions from other applications, finding the similarities to those applications and mapping them into the task at hand. We also must see that this skill is cousin to the paranoia mentioned above. How can we know what might go wrong? If our knowledge is narrow then our ability to be properly paranoid will also be narrow.

It is well known in the aviation industry that the known-unknowns are tractable, while it's the unknown-unknowns that bite you. Indeed, in that industry these are called "Unk-Unks." In order to find – prior to testing – Unk-Unks and make them into known-unknowns, requires a tremendous breadth of expertise and imagination.

Self confidence and decisiveness. I believe this is a cousin to the issue of "comfortable with change" and "comfortable with uncertainty." What I mean is that the leader of a successful innovation team will find that she has to make decisions on the basis of insufficient data, and yet it is essential that she make those decisions in order for the project to move forward.

There are of course tools for managing the risk of this type of decision-making, and those tools should be used. But the essential point here is that for innovation to succeed the decisions must be made, or else progress will grind to a halt. By very definition the innovator is working in a realm where there is not sufficient data *a priori* to instill total confidence in all choices. "There comes a point where you pay your two dollars and take your choice."

Appreciate the value of process. Last in Ryschkewitsch *et al*'s (2009) list is this item, and again it rings true in my own experience. The authors are saying – and let us recall that they are writing about systems engineers, which is a broader set than the set of engineering innovators – the system engineering success is rendered more likely when a formal process is followed. In fact, when stated in that manner this becomes almost synonymous with the whole motivation for the present dissertation: The innovation process described herein will lead to improved innovation success.

5.7: Conclusion: The characteristics of innovators

The above paragraphs have described the characteristics of innovators. Some of these characteristics are innate, such as the Myers-Briggs cognition preference, whereas others are teachable, such as two-way communication skills. I believe that this section of the dissertation can be developed into a human capital development program. Engineers may be tested for their KAI and MBTI scores and other metrics (e.g. tolerance for ambiguity.) These scores can be used to develop a curriculum for personal development, or it may even be possible to develop a self-awareness tool to help an employee realize that he is not an innovator, and save himself the frustration of being a square peg in a round hole for many years of his career.

In the same vein, the opportunity to use such metrics to best allocate corporate training resources is also obvious.

The possibility of using the “Characteristics of Innovators” dataset to develop training and growth programs is vast in scope, and I have identified a handful of excellent follow-on thesis topics in Appendix A and Appendix D.

By way of summary, I conclude that:

- Innovators are experts. They need to be expert not only in their field, but in the field of metacognition and in the field of analyzing and critiquing.
- The innovator is not necessarily the smartest member of the team. Innovation aptitude is a different skill from intelligence.
- The innovator is probably a Myers-Briggs "N" type.
- The innovator understands the old system, and he can show that he respects its origins.
- The innovator works in a team that is neither too isolated nor too cohesive.
- Properly blended, these skills result in an engineer who can say "I understand why the old way works, but here is a new way that will work better."

6: What are the social and institutional barriers and facilitators of innovation in ship design?

There are many barriers to creativity. A significant number of papers have been published on the characteristics of a workplace that is "innovation friendly." These papers often also contain essays upon the character of the innovators, since an innovation-friendly environment is a pleasant one to innovators, but it is likely to be "The Workplace From Hell" for adaptors.

This dissertation will not go far down this path. I wish here to include a minor unit on the characteristics of an innovation-friendly environment (what Rhodes called 'Press' in the 4P model) but I will leave the bulk of this topic to those other courses that already exist on this subject. In fact, much of what I will say here is only a summary of material I was taught in UNO MANG 4407 "Management of Technology and Innovation." It nevertheless needs to be repeated here, despite not being my own original work, because it is fundamental (in the sense of being a foundation) to innovation success.

6.1: Six themes of success for an innovation enterprise

These six themes represent the best practices in technology and innovation. Of course, there are other attributes that are needed for overall corporate success. This list is concerned only with success in the management of technology and innovation.

6.1.1: Business Focus

A successful implementation of innovation requires a business focus. This is the same as my earlier statement that innovation must be requirements-driven, but here we are enjoining not merely a set of technical requirements for the engineering product, but also a consistency of course for the business. A business that is inconsistent in its support for innovation or its expression of the goals for the innovation will strongly impede the success of the innovation team.

6.1.2: Adaptability

Innovation-friendly firms are adaptable. Here again we see the business reflecting an attribute that we have also enjoined upon the staff – the tolerance of change and ambiguity that was identified by Ryschkewitsch *et al* (2009) as a characteristic of a good systems engineer.

6.1.3: Organizational Cohesion

Organizational cohesion turns out to be important for corporate success at innovation. The causation here is less obvious, but I believe this is because this cohesion is the organizational ligament that holds the team together in the seas of uncertainty and change. It will also lead to mutual respect and trust within and without the team, such that "the system" is able to tolerate the strange rabbit trails that innovation sometimes follows.

6.1.4: Entrepreneurial Culture

A corporation needs to view innovation as a product discriminator. If the company values taking the lead in product development (rather than, say, waiting for innovative mission descriptions from ship owners) then they are far more likely to be able to create and maintain innovation teams within their quiver.

6.1.5: Sense of Integrity

All people, innovative ship designers at least as much as anybody else, want to feel that their work is for some higher good.

6.1.6: Hands-On Top Management

Innovation-friendliness starts at the top of the corporate hierarchy, and requires constant nurture by that top level.

Practically, this requires the top management to have the technical credentials to be involved in the innovation process.[25] In a ship design firm we can easily see examples of this: The liner UNITED STATES was the innovative product of a firm chaired by William Francis Gibbs, a world-class naval architect himself. My own employer John J. McMullen Associates produced the very advanced and innovative Sa'ar V corvette for the Republic of Israel, at a time when the firm was managed by naval architects all the way to the top. The firm's successor, after several buy-outs, allowed the innovation excellence to atrophy, while staffing the top management with businessmen and retired military leaders.

6.2: Project selection process

In addition to the above-mentioned, an innovation-friendly corporate structure will have recognizable characteristics to their project selection process. In general the process will consist of recognizing and encouraging the development of ideas, rather than the establishment of ever-higher hurdles.

This is a bit difficult for me to describe successfully, but my best attempt is to conjure to mind the difference between "Prove to me that your idea will work" and "Let's work together to see if that will work."

6.3: Organizational culture

The innovation-friendly firm will have the following features as part of the organizational culture. It is interesting to note the correlation between these features and Ryschkewitsch's list of attributes of the successful systems engineer.

- Individual Initiative: The firm will grant individuals an appropriate degree of freedom. The determination of how much is 'appropriate' is the subject of many lectures.
- Risk Tolerance: The firm recognizes the risky nature of innovation and embraces the inevitable failures as learning experiences and contributions to the experience base, not as mistakes to be punished.
- Direction: Consistent with the issue of "Individual Initiative", the firm will provide direction in how to manage and implement the innovation project, but will eschew the micromanagement of the technical development.
- Integration: We have seen that innovation often requires reaching across rice bowls. An innovation-friendly firm will facilitate this via an integrated corporate structure. See also below for an interesting essay in the use of physical architecture to help facilitate integration.
- Management Support: Again, the innovation friendly firm provides management based up "how can I help you succeed?" instead of "How can I prevent you from failing?"
- Control is one of the management tools that must be used subtly, and subject to many detailed lectures and texts.
- Identity: Innovation requires risk-taking, and it involves many failures for every success. This can be a morale-depressing environment, and one tool for withstanding the energy-depleting effect is to build a corporate culture of strong identity.

[25] The opposite of this is the "pointy haired boss" in the Dilbert comic strip, who is clearly clueless as to the technical work of his engineers.

- Reward System: A corporation's real beliefs are expressed by their reward system, and may often conflict with what their words say.
- Conflict Tolerance: Again, the corporate expression of one of Ryschkewitsch's list of attributes.
- Informal Communication: I am not clear whether this is chicken or egg, but the teaching is that innovation is fostered by a culture of informal communication. What I don't know is whether this is because the innovator herself will be impatient with formal communication, as may easily be inferred from the KAI attribute discussions earlier.

6.4: Physical architecture

Most of the foregoing in this chapter has been staple material in management courses. There is in addition some intriguing research suggesting the relationship between the physical design of the workplace as a means of fostering increased innovation and creativity. The New Yorker article "Groupthink" has the following interesting story about the physical workplace: (Lehrer, 2012)

"A few years ago, Isaac Kohane, a researcher at Harvard Medical School, published a study that looked at scientific research conducted by groups in an attempt to determine the effect that physical proximity had on the quality of the research. He analyzed more than thirty-five thousand peer-reviewed papers, mapping the precise location of co-authors. Then he assessed the quality of the research by counting the number of subsequent citations. The task, Kohane says, took a 'small army of undergraduates' eighteen months to complete. Once the data was amassed, the correlation became clear: when coauthors were closer together, their papers tended to be of significantly higher quality. The best research was consistently produced when scientists were working within ten meters of each other; the least cited papers tended to emerge from collaborators who were a kilometer or more apart. 'If you want people to work together effectively, these findings reinforce the need to create architectures that support frequent, physical, spontaneous interactions,' Kohane says. 'Even in the era of big science, when researchers spend so much time on the Internet, it's still so important to create intimate spaces.'

"A new generation of laboratory architecture has tried to make chance encounters more likely to take place, and the trend has spread in the business world, too. One fanatical believer in the power of space to enhance the work of groups was Steve Jobs. Walter Isaacson's recent biography of Jobs records that when Jobs was planning Pixar's headquarters, in 1999, he had the building arranged around a central atrium, so that Pixar's diverse staff of artists, writers, and computer scientists would run into each other more often. 'We used to joke that the building was Steve's movie,' Ed Catmull, the president of both Disney Animation and Pixar Animation, says. 'He really oversaw everything.'

"Jobs soon realized that it wasn't enough simply to create an airy atrium; he needed to force people to go there. He began with the mailboxes, which he shifted to the lobby. Then he moved the meeting rooms to the center of the building, followed by the cafeteria, the coffee bar, and the gift shop. Finally, he decided that the atrium should contain the only set of bathrooms in the entire building. (He was later forced to compromise and install a second pair of bathrooms.) 'At first, I thought this was the most ridiculous idea,' Darla Anderson, a producer on several Pixar films, told me. 'I didn't want to have to walk all the way to the atrium every time I needed to do something. That's just a waste of time. But Steve said, 'Everybody has to run into each other.' He really believed that the best meetings happened by accident, in the hallway or parking lot. And you know what? He was right. I get more done having a cup of coffee and striking up a conversation or walking to the bathroom and running into unexpected people than I do sitting at my desk.' Brad Bird, the director of 'The Incredibles' and 'Ratatouille,' says that Jobs 'made it impossible for you not to run into the rest of the company.'

"In the spring of 1942, it became clear that the Radiation Laboratory at M.I.T.—the main radar research institute for the Allied war effort—needed more space. The Rad Lab had been developing a radar device for fighter aircraft that would allow pilots to identify distant German bombers, and was hiring hundreds of scientists every few months. The proposed new structure, known as Building 20, was

going to be the biggest lab yet, comprising two hundred and fifty thousand square feet, on three floors. It was designed in an afternoon by a local architecture firm, and construction was quick and cheap. The design featured a wooden frame on top of a concrete-slab foundation, with an exterior covered in gray asbestos shingles. (Steel was in short supply.) The structure violated the Cambridge fire code, but it was granted an exemption because of its temporary status. M.I.T. promised to demolish Building 20 shortly after the war.

"Initially, Building 20 was regarded as a failure. Ventilation was poor and hallways were dim. The walls were thin, the roof leaked, and the building was broiling in the summer and freezing in the winter. Nevertheless, Building 20 quickly became a center of groundbreaking research, the Los Alamos of the East Coast, celebrated for its important work on military radar. Within a few years, the lab developed radar systems used for naval navigation, weather prediction, and the detection of bombers and U-boats. According to a 1945 statement issued by the Defense Department, the Rad Lab 'pushed research in this field ahead by at least 25 normal peacetime years.' If the atom bomb ended the war, radar is what won it.

"Immediately after the surrender of Japan, M.I.T., as it had promised, began making plans for the demolition of Building 20. The Rad Lab offices were dismantled and the radio towers on the roof were taken down. But the influx of students after the G.I. Bill suddenly left M.I.T. desperately short of space. Building 20 was turned into offices for scientists who had nowhere else to go.

"The first division to move into Building 20 was the Research Laboratory of Electronics, which grew directly out of the Rad Lab. Because the electrical engineers needed only a fraction of the structure, M.I.T. began shifting a wide variety of academic departments and student clubs to the so-called 'plywood palace.' By the nineteen-fifties, Building 20 was home to the Laboratory for Nuclear Science, the Linguistics Department, and the machine shop. There was a particle accelerator, the R.O.T.C., a piano repair facility, and a cell-culture lab.

"Building 20 became a strange, chaotic domain, full of groups who had been thrown together by chance and who knew little about one another's work. And yet, by the time it was finally demolished, in 1998, Building 20 had become a legend of innovation, widely regarded as one of the most creative spaces in the world. In the postwar decades, scientists working there pioneered a stunning list of breakthroughs, from advances in high-speed photography to the development of the physics behind microwaves. Building 20 served as an incubator for the Bose Corporation. It gave rise to the first video game and to Chomskyan linguistics. Stewart Brand, in his study 'How Buildings Learn,' cites Building 20 as an example of a 'Low Road' structure, a type of space that is unusually creative because it is so unwanted and underdesigned. (Another example is the Silicon Valley garage.) As a result, scientists in Building 20 felt free to remake their rooms, customizing the structure to fit their needs. Walls were torn down without permission; equipment was stored in the courtyards and bolted to the roof. When Jerrold Zacharias was developing the first atomic clock, working in Building 20, he removed two floors in his lab to make room for a three-story metal cylinder.

"The building's horizontal layout also spurred interaction. Brand quotes Henry Zimmerman, an electrical engineer who worked there for years: 'In a vertical layout with small floors, there is less research variety on each floor. Chance meetings in an elevator tend to terminate in the lobby, whereas chance meetings in a corridor tended to lead to technical discussions.' The urban theorist Jane Jacobs described such incidental conversations as 'knowledge spillovers.' Her favorite example was the rise of the automobile industry in Detroit. In the eighteen-twenties, the city was full of small shipyards built for the flour trade. Over time, the shipyards became centers of expertise in the internal-combustion engine. Nearly a century later, those engines proved ideal for powering cars, which is why many pioneers of the automotive industry got their start building ships. Jacobs's point was that the unpredictable nature of innovation meant that it couldn't be prescribed in advance.

"Building 20 was full of knowledge spillovers. Take the career of Amar Bose. In the spring of 1956, Bose, a music enthusiast, procrastinating in writing his dissertation, decided to buy a hi-fi. He

chose the system with the best technical specs, but found that the speakers sounded terrible. Bose realized that the science of hi-fi needed help and began frequenting the Acoustics Lab, which was just down the hall. Before long, Bose was spending more time playing with tweeters than he was on his dissertation. Nobody minded the interloper in the lab, and, three years later, Bose produced a wedge-shaped contraption outfitted with twenty-two speakers, a synthesis of his time among the engineers and his musical sensibility. The Bose Corporation was founded soon afterward."

7: Measuring innovation

The thrust of this thesis is to understand and thus control innovation, ideally reaching as far as "innovation on demand." But an axiom in control theory is "you can't control something you don't measure." Thus we must take a moment to look at the tools and definitions that can be used to measure innovation.

The first step is to consider what one means by saying "measure innovation." Do we wish to know how innovative the idea is, or do we wish to know how successful the idea is?

The question of how innovative the idea is, is an intriguing question, but I opine that it is a fruitless one: Why would we care if the idea is a big change or a small change, provided that it "carries its weight" by being a good change? Switching from measuring the magnitude of the innovation and instead measuring the merit of the innovation (which is what I mean by "carrying its weight") has the effect of shifting our inquiry to the second question: How successful is the innovation?

In fact, one correspondent of mine (Bruinessen, 2013) embeds the idea of success within the very definition of innovation, defining innovation as a "successfully introduced change." He writes *"[an innovation] can be anything: from a process to a ship, to a thruster or crane for example; in that respect, not every change is an innovation, you need to evaluate the success of an object (if you take a look at large innovations as 'the jet-plane' or the 'internet') you need to evaluate them before you can call them an 'innovation'… The infinite discussion whether we 'do innovation' insinuates that we already know we will have success."*

This concept that innovation must be successful is not foreign to my own definition, in that I have mandated a requirement for "quality" within the engineering innovation. But it definitely serves to underscore the need for an ability to measure the success or quality of the innovation.

In the foregoing paragraphs I suggested that the metric should be a "weight" in which benefit is measured the various "costs" of the innovation, which might include impacts upon industrial processes, impacts upon resource needs including human capital, and so forth. Fortunately all of these costs are amenable to quantification by well-known management tools, and no new research is needed here. What is needed is a new definition for the numerator of the merit fraction, a metric of the benefit of the innovation.

How to measure the benefit of innovation is another hot topic in the literature. COMPENDEX lists 33,000 papers on "measuring innovation," with production amounting to about ten per day (see Figure 27.) It appears that the majority of the citations on this subject address the topic from a commercial point of view, and use various commercial measures of success, such as "increased sales."

These measures are not suitable to measuring the success of an innovation in ship design, especially in warship design. In warship design the nearest equivalent to "increased sales" is "increased 'wins' in warfighting." By the time warfighting data is available it would be far too late to use the result in any meaningful go/no-go decision regarding the innovation.

Of course, warfighting data may be simulated via wargaming, just as commercial success data may be simulated using required freight rates and other economic tools. In these cases it is possible to measure the benefit of an innovative ship, on a whole-ship level, in comparison to other benchmark ships. The means to this end would be to use any of the several whole-ship assessment tools that exist in industry, populating that tool with data that reflects completing the innovative ship design to the needed level of detail.

The problems with this approach are two-fold:

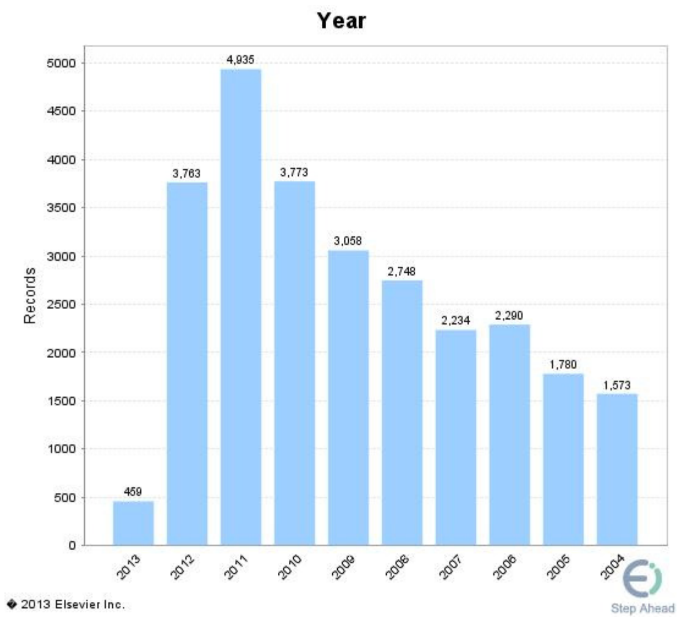


Figure 27 - Compendex records of publications on "Meausirng Innovation" for the past ten years

First, the effort of completing the ship design to the necessary level of detail may be unreasonable in light of the magnitude of the innovation. For example, an innovation at a very low level within the ship, such as development of a new circuit breaker concept, should be assessable without having to develop an entire ship around this circuit breaker.

Further, the circuit-breaker example highlights the second problem: The impact of an innovative circuit breaker upon whole-ship economic or military merit is probably nil. A better circuit breaker is likely to be one that does a better job of protecting systems, for example by tripping faster. This will not manifest itself as a benefit in the vast majority of simulation scenarios, because most scenarios assume "nothing goes wrong." Does this mean that the circuit breaker is an unsuccessful innovation? It seems instead to suggest that the assessment of merit has been carried out at too high a level.[26]

In attempting to resolve this conflict I find only one other author (Hauschildt, 1991) who has tackled the issue of measuring innovation merit at the design stage. Despite having his critical work published in 1991, I am also disappointed to find few cases of subsequent authors drawing upon his work. Apparently the push to measure success in the sales bottom line continues to drive.

The author in question is Prof. Dr. J. Hauschildt, (1991). Hauschildt builds the case for measuring different aspects of innovation, using different measurement techniques, at different stages in the innovation timeline. The overview of this recommendation is presented in Table 8.

Within this table one may clearly judge that the majority of the ship design effort falls in the first two rows: Product Idea and R&D. And Hauschildt's recommended method for measuring innovation quality at these stages consists largely of expert opinion.

[26] This question of what level is too high, gives rise to interesting ideas. One could argue that the only proper level for assessment is the global level: Does this make the planet a better place to live? I wonder, however, if any innovation could be shown to be unequivocally meritorious at this lofty level, or if all the benefits of the myriad good innovations of the past would be diluted into invisibility by distance.

Table 8 - Hauschildt's association of measurement techniques with process stages

Serial No.	Process Stage	Issues of the measurement of success	Results of evaluation: Dimensions, criteria, scales, ranks, etc.
1	Product idea	Reports, more or less elaborate models	Number of ideas/alternatives. Evaluation of ideas/ alternatives by experts, referring to the scientific/technological innovativeness
2	Research & development	Construction, test plants, prototypes	Technical progress. Improvements of productivity. Increase of output, decrease of input. Evaluations of performance by experts.
3	Invention	Patents, publications	Number of patents, publications, citations, rewards, prizes. Evaluation by scientists.
4	Investment, production, marketing	Marketable products, marketmg practicable techniques	Detailed descriptions to give evidence of improvements in comparison to existing solutions. Evaluation of product innovations by marketing managers, of process Innovations by engineers. Imitations.
5	Introduction of the new product on the market or of the new technique into the production	Turnover, cost savings, profit contributions	Monetary units, ratios, relations, indices. Comparison over time and with competitors
6	Regular sales, regular usage	Changes in sales, in market shares, in cost savings, in profit contributions during the course of the life cycle	Evaluation by industry-experts. Rise of stock priees.

Hauschildt arrives at this matrix from an interesting beginning, and there is a second of his figures that is important for our discussion of measuring innovation in ship design; his illustration of the many different domains of effect that an innovation may have, depicted in Figure 29.

This is paralleled in Caspar van Rijnbach's thesis that there are "Six W's and an H" to guide the determination of how to measure innovation (Rijnbach, 2013):

"WHO" do you measure for? In this thesis we wish to measure innovation for a decision-maker at the design stage, when test data is not available. Note that we also wish to measure innovation quality as a means for providing feedback to the innovator, for skill development.

"WHY" do you measure? This is related to the above, but note that the two stakeholders mentioned above have different needs. The decisionmaker needs to decide whether or not to pursue the innovation. The innovator needs to know whether he has employed a successful innovation method, or if he needs to "do better next time."

"WHAT" do you want to measure? Do you measure output, input or process efficiency and/or effectiveness? It is here that I find Hauschildt (1991) so helpful, and I opine that the reasonable way to measure during the design stage is via expert opinion. We may dream of a day when expert opinion can be modeled by artificial neural networks and the like, but at the present state of the conversation the subjective human evaluation appears to be the only viable tool.

"WHERE" do you measure? By "where" van Rijnbach is really asking "at what process stage?" This has been answered in our case at the outset, in that I have restricted this entire discussion to the "measuring innovation during design."

"WHEN" do you measure? Do you measure at the beginning, middle, end of the project, or years after the end of a project? This is an interesting question and one that I may not have a good answer to. I find it easy to believe that measuring often could have either a stimulating or a stifling effect upon the innovation, depending upon the personality of the innovator. Further, it seems reasonable to me that it would be useful to go back many years later and see if "that" innovation is still a good or bad one. This would re-train our evaluation model, as well as capturing whether some environmental variable has changed.

"HOW" do you measure? Here I draw from Hauschildt and suggest that expert review is the appropriate tool, and in my own career it has always been a BOGSAT that passed the go/no-go judgment on my innovations.

This in itself however is not necessarily bad, because we do have tools for making the subjective "expert judgment" a little more objective. Myself, I am partial to the use of the Analytical Hierarchy Process, wherein we must first ask the panel of judges to define their criteria and relative weights, and then to assess the innovation upon those criteria. And indeed, this can be done using two separate panels of judges, one to establish criteria, a second to 'grade' against those criteria.

Thus I conclude that the only appropriate early-stage metric, useful in a ship design process, is to employ expert opinion. I would then make this subjective process more objective by employing the AHP and similar tools.

The final component of the measurement question is "how to measure the education." I suspect that this question could actually be the subject of useful study by practitioners of education theory, but I am not expert in that school. My engineer's answer to this question is to simply measure the extent to which the education has made the student a better innovator, as demonstrated by her production of better innovations.

A step toward implementing an innovation curriculum – as I have proposed – will be to develop rubrics for the assessment and evaluation of that curriculum's effectiveness. At present I do not have these rubrics developed, but the crux of the matter is to distinguish between Assessment (typically formative) and Evaluation (typically summative.) I look forward to undertaking the creation of instruments for these two stages.

Note that even if instantiated in the form of rubrics, the core assessment/evaluation tool will still be opinion. As an engineer this disturbs me, in that I want metrics that can be collected completely objectively, but as an engineering educator I know this to be impossible: Much educational assessment now hinges upon the instructor's subjective opinion. As engineers we eschew this and attempt to adhere to numerical formulae, but let us admit it: When we assign a "7 out of 10" to a student's homework there is a fair amount of subjectivity in the decision of whether that was a "7" and not a "5" or "8."

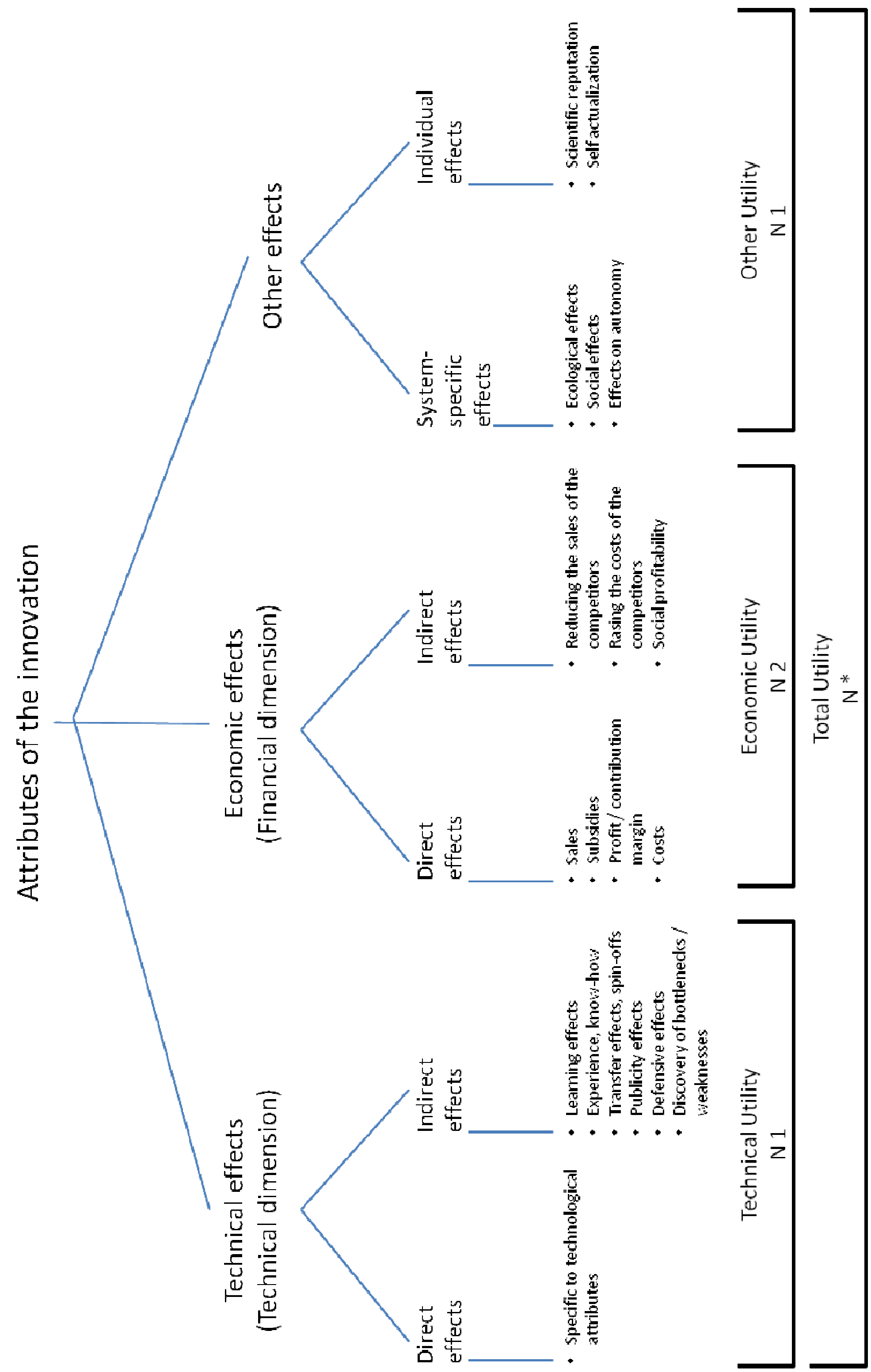


Figure 28 - Hauschildt's breakdown of innovation effects

7: Conclusions and recommendations

This dissertation has accomplished the task set for it: Three years ago I set out to fulfill the mission "Can you teach other naval architects how to be innovators?" This lead to many subordinate questions: What is innovation? How do innovators think? Can it be taught? Today I am able to publish a substantial answer to the question, and a foundational work upon which further edifices of creativity may be built. Further, I have outlined a curriculum that could be used in the first attempt to explicitly teach innovation in ship design.

In this work innovation is shown to be a subset of creativity. Creativity is manifest in engineering in the specialty known as design. Innovation is further a subset of design, which is focused upon breaking the derivative approach to design, and instead producing designs which have no forebears.

Innovation is found to have many algorithms, some of which purport to show how it *has* been done, others which purport to show how it *may* be done. However I have observed that all of these algorithms share a common architecture, and that this common architecture does give rise to a useful tools set for engineering innovation. Further, I have shown that these algorithms are applicable to the design of ships, either by citing actual projects, or via my repeated employment of a rudder design example.

I have opined that not all engineers have equal aptitude for innovation, and I have shown support for this opinion, and have identified the KAI as a tool for testing for innovation aptitude. But the KAI is much more than an innovation test, it is also a psychological profile, and the KAI results have substantial implications for the success of the individual in any specific team. And of course, innovation is equally the product of the team as of the individual, so these KAI implications become important in managing for innovation success. I have used my own KAI results to support this claim.

I have shied away from the other aspects of institutional facilitators and barriers of innovation success, because these are well covered elsewhere. This is not to say that these are unimportant – indeed, the mere fact that they are well covered elsewhere suggests that they are of primary importance.

I look forward to deploying the insights and lessons of this work, via the formal teaching of innovation in ship design.

8: Bibliography

ACS, (2012)	American Chemical Society; 2012; Characteristics of adaptors and innovators; http://pubs.acs.org/subscribe/archive/ci/31/i11/html/11hipple_box3.ci.html; retrieved 18 October 2012
Afuah, (1998)	Afuah, A. ; 1998; Innovation Management: Strategies, implementation, and profits; Oxford University Press; New York, NY
Akao, (1994)	Akao, Yoji; 1994; "Development History of Quality Function Deployment"; In: The Customer Driven Approach to Quality Planning and Deployment; ISBN 92-833-1121-3; p. 339; Asian Productivity Organization; Minato, Tokyo 107 Japan
Berelson, (1964)	Berelson, Bernard and Steiner, Gary A.; 1964; Human behavior: An inventory of scientific findings; Harcourt, Brace & World; New York, NY
Bers, (2005)	Bers, J. and Dismukes, J.; 2005; Accelerated Radical Innovation: A New Way of doing Business; PICMET 2005; Portland, OR
Bers, (2007)	Bers, J. A. and Dismukes, J. P.; 2007; Principles and practice of Accelerated Rapid Innovation; PICMET 2007 Proceedings
Biologicalexceptions, (2012)	Biological Exceptions; 2012; As Many Exceptions as there are Rules; http://biologicalexceptions.blogspot.com/2012_08_01_archive.html; retrieved 17 August 2012
Bloom, (1956)	Bloom, Benjamin S., et al.; 1956; *Taxonomy of Educational Objectives: The Classification of Educational Goals, Handbook I: Cognitive Domain;* David Mackay; New York, NY
Bolton, (2012)	Bolton, John; 2012; verbal remarks at CPAC 2012 (Conservative Political Action Conference) recorded on video; http://www.youtube.com/watch?v=PNSx_fUAtKw; retrieved 14 August 2012
Browning, (2010)	Browning, Tyson R.; 2010; Modeling Design Processes; Briefing to US Navy Design Process Workshop
Bruinessen, (2013)	Ties van Bruinessen, private communication February 2013
CEF, (2012)	Creative Education Foundation; 2012; What is CPS? ; http://www.creativeeducationfoundation.org/our-process/what-is-cps; retrieved 6 September 2012
Christnesen, (2003)	Christensen, Clayton; 2003; The Innovator's Dilemma; Harper Paperbacks; New York, NY
Crockenberg, (1972)	Crockenberg, Susan B.; 1972; Creativity tests: A boon or boondoggle for education?; Review of Educational Research; Vol 42; No. 1 (Winter); pp 27-44

Cronbach, (1958)	Cronbach, L. J.; 1958; Intelligence? Creativity? A parsimonious reinterpretation of the Wallach-Kogan data; American Educational Research Journal; 1968
Daupert, (1996)	Daupert, Dennis; 1996; "The Osborne-Parnes Creative Problem Solving Process Manual"; http://www.kaplans.com/Daupert/Daupert%20Opening.htm; retrieved 16 August 2013
Dehaan, (1957)	DeHaan, R. F. and Havighurst, R. J.; 1957; Educating gifted children.; University of Chicago Press; Chicago, IL
Dewar, (1986)	Dewar, R., & Dutton, J. E. ; 1986; The adoption of radical and incremental innovations: An empirical analysis; Management Science; Vol 32 ; No. 11
DID, (2012)	Defense Industry Daily; 2012; The USMC's Expeditionary Fighting Vehicles; http://www.defenseindustrydaily.com/the-usmcs-expeditionary-fighting-vehicle-sdd-phase-updated-02302/; retrieved 21 September 2012
Domb, (1998)	Domb, Ellen - TRIZ Journal; 2012; The 39 Features of Altshuller's Contradiction Matrix; http://www.triz-journal.com/archives/1998/11/d/index.htm; retrieved 16 August 2012
Doyle, (1892)	Doyle, Arthur Conan (Sir); 1892; *A Scandal in Bohemia*
Ebel, (1974)	Ebel, Robert L.; 1974; And Still the Dryads Linger; American Psychologist; Vol 29; Issue 7 (July); pp 485-492
Eder, (2009)	Eder, W. Ernst; 2009; Analysis, Synthesis and Problem Solving in Design Engineering; International conference on Engineering Design, ICED '09; pp 2-13 - 2-23
Fascati, (2004)	Frascati Manual. ; 2004; A summary of the Frascati manual - Main definitions and conventions for the measurement of research and experimental development (R&D); http://www.oecd.org/document/6/0,2340,en_2649_34451_33828550_1_1_1_1,00.html; Retrieved August, 2004; OCDE/GD(94)84; Cited in Popadiuk, (2004)
Fischer, (2001)	Fischer, M. M. ; 2001; Innovation, knowledge creation and systems of innovation; Annals of Regional Science; Vol 35; pp 199-216
Friedel, (2012)	Friedel, C; 2012; Personal communication (e-mail received 25 August 2012)
Garcia, (2002)	Garcia, R., & Calantone, R. ; 2002; A critical look at technological innovation typology and innovativeness terminology: A literature review; Journal of Product Innovation Management; Vol 19; No. 2
Gardner, (1978)	Gardner, Martin; 1978; *Aha! Insight;* W.H. Freeman; New York, NY
Gelb, (1998)	Gelb, 1998; Gelb, M. J.; 1998; How to Think like Leonardo da Vinci; Bantam Dell; New York, NY
Getzel, (1969)	Getzel, J.; 1969; Creativity; in: Encyclopedia of Education Research; 4th Edition; MacMIllan; New York, NY

Guilford, (1973) Guilford, J. P.; 1973; Creativity tests for children; Sheridan Psychological Services; Orange, CA

Hauschildt, (1991) Prof. Dr. J. Hauschildt, "Towards Measuring The Success Of Innovations," University of Kiel, 1991

Henderson, (1990) Henderson, Rebecca M. and Clark, Kim B.; 1990; Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms; Administrative Science Quarterly; Vol 35; No. 1; pp 9-30

Hubka, (1967) Hubka, V.; 1967; Der grundlegende Algorithmus für die Lösung von Konstruktionsaufgaben' (Fundamental Algorithm for the Solution of Design Problems); Internationales Wissenschaftliches Kolloquim der Technischen Hochschule Ilmenau (12th International Scientific Colloquium of the Technical University Ilmenau); Section L -- Konstruktion (Design); pp 17--25; Ilmenau, DDR

Hughes, (1994) Hughes, Melanie; 1994; *Myers-Briggs Type Indicators and Kirton Adaption-Innovation Inventory Correlations;* Executive Research Project F-28; National Defense University

Infovisual, (2012) The Visual Dictionary; 2012; Morphology of a flying insect; http://www.infovisual.info/02/038_en.html; retrieved 17 August 2012

Khatena, (1973) Khatena, J. & Torrance, E. P.; 1973; Thinking creatively with sounds and words; Norms technical manual; Personnel Press; Lexington, MA

Kirton, (1984) Kirton, M. J.; 1984; Adaptors and innovators—Why new initiatives get blocked; Long Range Planning; Vol 17 ; No. 2, April 1984; pp 137-143

Kirton, (1994) Kirton, M. J.; 1994; Adaptors and Innovators, Styles of creativity and problem solving; Routledge

Kratwohl, (2002) Kratwohl, David R.; 2002; A Revision of Bloom's Taxonomy: An Overview; Theory Into Practice; Vol 41; Number 4 - Autumn 2002

Lang, (1968) Lang, Thomas; 1968; *A Generalized Engineering Design Procedure*, Ph.D Dissertation; Pennsylvania State University Department of Aerospace Engineering

Lehrer, (2012) Lehrer, Jonah; 2012; Groupthink; The New Yorker; January; 2012

Linsey, (2007) Linsey, Julie S.; 2007; *Design-by-Analogy and Representation in Innovative Engineering Concept Generation" Ph.D Dissertation;* University of Texas, Austin; USA

Linsey, (2008) Linsey, Julie S., Wood, K. L., Markman, A. B.; 2008; *Increasing Innovation: Presentation and Evaluation of the Wordtree Design-By-Analogy Method;* Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information Engineering Conference; Brooklyn, NY; Aug 3-6 2008

Lopez, (2006) Lopez-Mesa, B. and Thompson, G.; 2006; On the significance of Cognitive Style and the selection of appropriate design methods; Journal of Engineering Design; Vol 17

McDermott, (2002)	McDermott, C. M., & O'Connor, G. C. ; 2002; Managing radical innovation: An overview of emergent strategy issues; Journal of Product Innovation Management, 19(6); Vol 19; No. 6
McKesson, (2011a)	McKesson, Chris B.; 2011; The Utility of Very Simple Models for Very Complex Systems; SCS M&S Magazine; 2011; No. 1
McKesson, (2011b)	McKesson, Chris B.; 2011; "The use of Transport Factor as a Very Simply Model of whole-ship synthesis," Proceedings of the International Conference on Fast Sea Transportation FAST 2011
Mednick, (1962)	Mednick, Sarnoff A.; 1962; The associative basis of the creative process; Psychological Review; Vol 69 (1962); pp 220-232
Myers, (1995)	Myers-Briggs, I.; 1995; Gifts Differing: Understanding Personality Types; Davies-Black Publishing; Reprint edition (May 1, 1995); ISBN 0-89106-074-X
Nazzaro, (1978)	Nazzaro, Jean N. (ed.); 1978; Identification of the gifted and talented; Council for Exceptional Children; Reston, VA
Nolan, (2012)	Nolan, Vincent and Williams, Connie; 2012; A Visual Overview of the Synectics Invention Model; http://synecticsworld.com/pdf/A_Visual_Overview_of_the_Synectics_Invention_Model.pdf; Retrieved 11 Sep 2012
NPS-CS, (2012)	Naval Postgraduate School Computer Science Department; 2012; The World Ahead: Our Approach to Educating Our Masters Students; http://www.nps.edu/academics/schools/gsois/departments/cs/; retrieved 14 August 2012
Orloff, (2006)	Orloff, Michael; 2006; *Inventive Thinking Through TRIZ;* Springer; Berlin, GE
Pederson, (2004)	Pedersen, C. R., & Dalum, B. ; 2004; Incremental versus radical change—the case of the digital north Denmark program; http://www.schumpeter2004.uni-bocconi.it/papers.php?tric=Pedersen&cric=author&Invia=SEARCH&Invia=SEARCH; Retrieved August, 2004; Cited in Popadiuk, (2004)
Pirsig, (1974)	Pirsig, R. M.; 1974; Zen and the Art of Motorcycle Maintenance; William Morrow & Company; New York, NY
Pirsig, (1991)	Pirsig, R. M.; 1991; Lila; Bantam Books; New York, NY
Popadiuk, (2006)	Popadiuk, Silvia and Choo, Chen Wei; 2006; Innovation and knowledge creation: How are these concepts related?; International Journal of Information Management; Vol 26 (2006); pp 302-312
Reali. (2012)	Reali, Paul - OmniSkills Llc; 2012; Creative Problem Solving; http://creativeproblemsolving.com/; retrieved 16 August 2012
Rhodes, (1961)	Rhodes, M.; 1961; An Analysis of Creativity; The Phi Delta Kappan; Vol 42; pp 305-310
Rijnbach, (2013)	"Using the 6 W's to Measure R&D and Innovation" http://www.innovationmanagement.se/2012/08/02/using-the-6-ws-to-measure-rd-and-innovation/ , retrieved March 2013

Rogers, (1983) Rogers, E. M. ; 1983; Diffusion of innovations; New York: The Free Press

Rowe, (1974) Rowe, L. A., & Boise, W. B. ; 1974; Organizational innovation: Current research and evolving concepts; Public Administration Review; Vol 34; No. 3; pp 284-293

Ryschkewitsch, (2009) Ryschkewitsch, Michael, Dawn Schaible, and Wiley Larson; 2009; The art and science of systems engineering.; Systems Research Forum; Vol 3; No. 2; World Scientific Publishing Company

Santanen, (2002) Santanen, Eric L., Briggs, Robert O., de Vree, Gert-Jan; 2002; Toward an Understanding of Creative Solution Generation; Proceedings of the 35th Hawaii International Conference on System Sciences; 0-7695-1435-9/02 (c) 2002 IEEE

Saunders, (1957) Saunders, CAPT Harold E.; 1957; Hydrodynamics in Ship Design; SNAME; New York, NY

SD&C, (2003) Lamb, Thomas (Ed.); 2003; Ship Design and Construction; The Society of Naval Architects and Marine Engineers; Jersey City, NJ

Sower (2006) Sower, Victor - Creative Problem Solving; 2006; MGT 575 - Creative Problem Solving; http://www.shsu.edu/~mgt_ves/mgt575/CreativeProblemSolving.ppt; retrieved 16 August 2013

Stahl, (1977) Stahl, Robert J.; 1977; A Creatively Creative Taxonomy on Creativity: A proposed model; The North Carolina Association for the Gifted and Talented; Vol 3; Usse 3 (Summer); pp 8-16

Stahl, (1980) Stahl, Robert J.; 1980; A Creatively Creative Taxonomy on Creativity: A New Model of Creativity and Other Nov el Forms of Behavior; Ann. Meeting of the American Educational Research Association; Boston, MA

SWBS, (1985) Naval Sea Systems Command ; 1985; Expanded Ship Work Breakdown System for all Ships and Ship/Combat Systems; S9040-AA-IDX-010/SWBS 5D

Taravella, (2013) “Science Non-Fiction”, UNO Magazine, http://magazine.uno.edu/science-non-fiction/ retrieved March 2013

Torrance, (1963) Torrance, E. Paul ; 1963; Education and the creative potential; University of Minnesota Press; Minneapolis, MN

Torrance, (1966) Torrance, E. Paul ; 1966; Torrance tests of creative thinking: Norms-technical manual; Personnel Press; Princeton, NJ

Torrance, (1975) Torrance, E. Paul ; 1975; Creativity research in education: Still Alive; In: Perspectives in Creativity; pp 278-296; Aldine; Chicago, IL

Utterback, (1994) Utterback, J. M. ; 1994; Mastering the dynamics of innovation: How companies can seize opportunities in the face of technological change; Harvard Business School Press; Boston, MA

Uzzi, (2005) Uzzi, Brian and Spiro, Janet; 2005; Collaboration and Creativity: The

Small World Problem; American Journal of Sociology; Vol 111 ; No. 2 September 2005

Vance, (1976) Vance, H.; 1976; Creativity and the Gifted; NCAGT Quarterly Journal,; Vol 2; No. 3 (Summer); pp 38-44

Von Hippel, (1990) von Hippel, Eric "Task Partitioning: An Innovation Process Variable." Research Policy 19, no. 5 (October 1990): 407–418.

Wallas, (1926) Wallas, G.; 1926; The art of thought.; Harcourt, Brace ; New York, NY

Whetten, (2011) Whetten, David, & Cameron, Kim; 2011; Developing Management Skills, 8th Ed.; Prentice Hall; Boston, MA

WTA, (2002) John J. McMullen Associates, Inc; 2003; Development of a Hybrid Fuel Cell Ferry; Report delivered to San Francisco Bay Area Water Transit Authority; 21-Aug-03; From author's personal archives

Zwicky (1967) Zwicky, F. & Wilson A. ; 1967; *New Methods of Thought and Procedure: Contributions to the Symposium on Methodologies;* Springer; Berlin, GE

Zwicky, (1969) Zwicky, F. ; 1969; *Discovery, Invention, Research - Through the Morphological Approach;* The Macmillan Company.; Toronto, ON

Appendix A: Future research

The foregoing thesis presents a foundation for understanding the problem of innovation in ship design, and the range of tools available for tackling that problem. In the course of developing this foundation I have identified many opportunities for further research. I envision a series of works, starting with the present foundation work, and then followed by (for example) a work specific to TRIZ, or a work specific to the teleology of ship systems, or other specialized study. My hope would be that the present project would establish a framework for publication in the field of Innovation in Naval Engineering, which framework could then be built upon by several subsequent works.

Thorough application of TRIZ to a ship design

The present dissertation is an omnibus treatment of the many available models and algorithms, each of which has some merit even if only in a limited domain. The omnibus work serves as a foundation for the study of innovation in Naval Engineering.

Upon this broad foundation it is possible to erect several edifices, and one of them could be devoted to TRIZ. I envision, thus, a second work (either my own or another candidate's) which is specific to the application of TRIZ to naval architecture. This work would focus mainly on applying the TRIZ algorithm and thus 'translating' TRIZ into maritime paradigms. This would be an interesting work and useful to the industry, but as explained above I leave it to a 'phase II' of this line of study, in the belief that the foundation is the necessary starting point.

Find a real ship problem and apply TRIZ rigorously. This would first require the practitioner to be certified in TRIZ, to make sure that the test results are not tainted by the novitiate of the practitioner. Ideally, this would be repeated with several different naval architectural problems, so that we could construct a “map” of where TRIZ was most useful – mapping laterally according to which discipline it was best at, and mapping vertically to see whether it was best at whole-ship problems, or component-level problems.

Historical analyses

Using historical information of US Navy design projects, attempt to reconstruct a mapping between innovation success/failure against a variety of the factors identified in the dissertation, as listed in the sub-sections below.

This research would probably have to be conducted simply by interview with remaining members of the various project teams, and may be rendered useless by various personal factors. I suggest that some sort of industrial psychologist or interview expert may need to be included in the research team.

Tools used

What innovation tools did the historical team use? It is extremely unlikely that any tools were used by name, so the interviewer will need to extract what the creative process was, and then attempt to map that process into the generic tools types (taxonomy) presented above.

The goal would be to learn that tool X seems to be most useful for problems of type Y.

Note that here again both lateral (range of technical discipline) and vertical (scope from component to whole-ship) dimensions should be addressed.

World Sizes

What is the ‘world size’ of naval engineering? Does the world size correlate with innovation success, as has been shown for other creative endeavors? I would love to see the work of Uzzi (2005) repeated in the naval design realm. I find it easy to imagine that the Q for the naval design community is too high for good innovation.

Repeat this using different vessel projects which may be classed as innovations. Examples of innovation success include the USN T-AGOS 19 SWATH, or the recreational J-24. The SWATH-like "SLICE" craft may also be studied, and it is possible to debate whether this should be viewed as a success or a failure.

KAI Scores

Inventory the KAI scores of naval ship design personnel. Separately characterize those personnel on a scale of innovation, by self-identification and peer interview. Do the KAI scores correlate with the scale of innovation? Does the correlation change with ascension of the corporate ladder?

MBTI Types

Same as above but using Meyers-Briggs Types. Again, does MBTI correlate with the scale of innovation? Does the correlation change with ascension of the corporate ladder?

daVincian character in successful innovators

The third of three similar studies, except here we look to the da Vincian characteristics of the people involved.

VV&A of Innovation Success Predictors

Based on the foregoing studies it should be possible to create an "innovation success predictor" that would make some use of the foregoing metrics. This predictor should then be subjected to validation, verification, and accreditation, and it could then be used as aproject management tool

Teleological decomposition of an entire ship

It would be interesting to teleologically decompose an entire ship. What I propose is to develop a comprehensive functional, or 'teleological', breakdown of a ship, by decomposing an existing US Navy asset. I expect that this process will uncover numerous cases where functions are competing, and where solutions are not synergistic.

Once a comprehensive list of all the ship's functions has been generated, then we can attempt to combine those functions into logically similar groups, and reconstruct the ship from them. It is possible that this will identify some very novel architectures.

A second follow-on work that I can currently envision would be to attempt a comprehensive detailed teleological decomposition of a ship. By taking a work breakdown system such as the US Navy Standard Work Breakdown System (SWBS, 1985), one could develop a list of all of the functions that are present on a ship, and the functions that they support, and the functions that support them. For example, the man is on board to steer the ship, the HVAC system is on board to support the man, the chilled water plant is there to support the HVAC. A comprehensive map of all these functions – all these *teleos* – might provide very interesting opportunities to eliminate Muda or pursue multitasking.

Project structure guidelines for innovation in ship design

The foregoing thesis contains enough detail that it can be used to construct a project for maximum innovation potential. This will involve two components: The selection of the project personnel, and the design of the project approach. An example of this is given in the following, but the real intent here is to suggest developing project structure guidelines, of which the following may be predecessor.

Personnel selection

Personnel selection should take place in consideration of the project technical needs, as is well known. Further, in the foregoing we see that the project team should be sufficiently self-contained that all project interfaces will lie within the control of the team. For example, if the project team will need to modify the ship structure as part of the innovation, then the structural engineer should be part of the team.

On the other hand, the corollary to this is that the team should include *only* those disciplines inherent in the task. And thus if a structural interface is not foreseen for the innovation, then the ship structural engineer should not be included in the innovation task team.

Further, the team members should be surveyed for their MBTI types, so that team cohesion and functionality is maximized. This is basic business school practice and is not a subject addressed in this dissertation.

But in a similar manner, and as addressed herein, the team should also be assembled with due regard for the KAI scores of the participants. Recall that a high KAI-gap can lead to team friction, and also recall that KAI scores are not absolute, but relative. Thus it is possible that, given the other resource constraints, we end up with a project team lead by somebody who is fairly much an adaptor. But if teamed with people with even stronger adaptor tendencies, then even this team leader will tend to be innovative in comparison.

Project Structure

Similar to studying the people engaged in the work, we may suggest studying the structure of the work itself. Without developing the thesis at length, I submit that it would be clearly advantageous to structure the team's investigations to explicitly parallel the innovation morphology. Thus, rather than conventional feasibility, concept, and detail phases, (or perhaps in addition to them) we would enjoin phases of problem definition, problem generalization, search for solutions, etc.

Product

The product of the proposed study would be a set of Project Structure Guidelines that can be used as a cookbook for creating innovation project teams. These guidelines could be captured in the form of a management practice, or as a lecture series in a management course.

Software: Horizontal integration

Tools exist for several of the invention methodologies discussed herein, but these tools tend to be vertically integrated. Thus for example there is a TRIZ software. What I do not find, however, is a horizontal software such as, for example, a comprehensive tool for the "finding analogies" step that would use all of the methods mentioned: Image analogies, word analogies, patent databases, and word antonyms. Developing such a software would result in a "stereoscopic" tool that would present the inventor with many directions from which to tackle his problem, and would result in a much more robust candidate solution space.

Software: Analogy ranking

Building on the previous software solution, we may then imagine an algebra that would combine the software-found analogs. In this scheme we may imagine that an analog is found in, say, biology and the lexicon and the patent database. The fact that this same analogy is found in three very different types of search might suggest that it is a particularly fruitful one for investigation. Therefore it might be interesting to find a means for counting these "hits" and scoring each analogy with some sort of measure of merit, thus ranking them so that the software automatically presents a 'most-likely to be fruitful' subset. This scheme is similar in effect to the way that Google ranks websearch findings to present a 'most likely to be what you wanted' front page.

Paper: When to avoid fixation.

Many of the fundamental authors have touched upon the need to maintain an open mind as long as possible, to avoid fixating on a design solution. This is, for example, axiomatic in brainstorming wherein the participants are required to suspend judgment until a specific point in the process.

The research question for this paper would be: Is the point up to which we must suspend judgment a common point for all of the methods? I.e., do we suspend judgment up through step {x} of the morphology, regardless of which techniques we are using at each step? Or are there some techniques that are more 'judgment tolerant'?

This could have important application to which techniques one should employ, if one knows, for example, that she is working with a group that is prone to hasty judgment, or prone to avoid judgment.

Engineering by interaction rather than component

As mentioned in the section on the work of Dr. Tyson Browning, (Browing, 2010) I see a relationship between his focus upon interactions in design (which is also found in other models, including TRIZ) and the Cognitive Network Model and its attention to associative distance and interactions between concepts. It would be interesting to apply Browning's philosophy by actively studying, not concepts, but the associations between concepts, explicitly. As a mental placeholder for this future research, imagine studying adjectives instead of nouns. If instead of studying "apples" what if we studied "red"? If instead of studying bearings we studied “things that move?” What would be the engineering benefit of designing a research project based on interactions rather than components?

Which tool for which engineer?

Given that engineers have different cognition characteristics, as measured say by the Meyers-Briggs Type Indicator or the Kirton Adaption/Innovation Inventory, do we find a preference for one innovation toolset over another, that correlates with these personality characteristics?

I believe that the cognitive style of the person will affect his choice of preferred tool at each step of the process. I can imagine visual thinkers enjoying the visual analogies method, while lexical thinkers enjoy WordTree. This is a fruitful avenue of future research

What kind of engineer takes to each of the various tools or algorithms? Is one tool best suited to the least innovative, and another to the least adaptive? This is interesting to me personally. I find TRIZ a bit tedious, but then I am already a pretty good innovator. In consequence I am reluctant to take the time to slowly learn TRIZ, since I think it would only make me slightly better, not hugely better. In the sections above we discussed the personality characteristics of innovators. At this stage I merely state that it would be interesting to know what type of engineer “takes to” TRIZ the most easily – are these the linear algorithmic thinkers, or are they the wild hare creative ones? This might be a fruitful area for future research.

Right-sizing the information flow in naval design.

Based on von Hippel (1990) we may consider that specialists working on one part of a design problem don't actually need the full capability of the interfacing tasks, but might be able to get away with using relatively simple surrogate models for those tasks. Thus for example does the hull form designer really need to know the characteristics of the propeller, or is it sufficient to know merely the diameter? As one can see by this example, the interface between design tasks would be streamlined in accordance with this philosophy.

Starting with the USN Design Process Model it should be possible to determine information needed by each of the blocks of the process. This information need can then be compared to the information actually produced by the interfacing block. It is my expectation that we may find several cases where information is produced that is actually not used by the interfacing tasks – a sort of “data Muda.”

Sometimes the production of that information is an unavoidable by-product of the task itself, but I wonder to what extent there is data-Muda that can be eliminated, yielding a concomitant streamlining of the design process.

The use of KAI in the design of engineering teams

The Kirton Adaption-Innovation Inventory (KAI) returns a numerical indicator of where a person falls on a spectrum from Adaptor to Innovator (Kirton, 1994). It is conceptually similar (but narrower in focus) to the popular Myers Briggs Type Indicator (Myers, 1995) that is already extensively used in DOD.

As discussed in the body of this dissertation, it should be possible to use KAI scores as one of the parameters in selecting members of an engineering team, and assigning the tasks to those individuals.

It would be fruitful to take this simple fact and develop a management-grade short course on how to implement this practice within the naval engineering enterprise.

MOQ in ship design

Robert Pirsig's Metaphysics of Quality (Pirsig, 1991) has given rise to a substantial body of literature which is focused upon defining Quality, and defining procedures that lead to the production of Quality.

It would be interesting to attempt a journeyman-grade application of those teachings into the field of ship design. The goal would be to define something like "How do you know when you have done a good job, as a ship designer?"

Formalization of this process would be a great boon for practical ship design.

Metacognitive maturity

As I have repeatedly stated "not everybody can do it." It seems to me – and this would be a fruitful avenue for future research – that one has to have progressed pretty far on the knowledge axis in the metacognitive realm, and pretty far along the cognition axis into the creative realm, for invention to be easy. This would be a fruitful topic for statistical study.

Appendix B: Menu of possible innovations in ship design

As a result of developing this dissertation the author has identified a number of opportunities for innovation in ship design. Some of these opportunities are huge, with potentially dramatic impacts. Some of them are smaller component-level ideas. And some of them are probably bad ideas.

In this section I will present these ideas. Some of them have been introduced previously. For completeness sake I repeat them here. I will present these ideas as future research topics – projects that somebody else could complete. I have not myself tackled them yet.

In my presentation I will attempt to show how each of the proposed innovation flows from the principles above. My purpose in this dissertation is not to create a menu of innovations, but rather to put forward a lesson in cooking which can yield many and diverse menus. The examples in this section are merely "serving suggestions."

Unmanned merchant ship

The principle of Muda elimination gives rise to the idea of a remotely-operated merchant ship. We are invited to imagine a line-haul container ship which is manned via a satellite link from the flag state.

For purposes of visualization, we assume the vessel is piloted to the sea buoy via a pilot close by on the pilot boat. Once the pilot disengages control, the control transfers to the remote site.

In the event of a commlink failure at sea, the vessel is programmed to go into a station-keeping mode, perhaps steaming slowly in a circle, while chirping a distress code.

The Muda being eliminated is "world tours for sailors." The advantages of eliminating the onboard humans include the following:

- Space
- Weight
    - Systems eliminated:
        - Berthing
        - Sanitary
        - Food service and stowage
        - Non-cargo HVAC
        - Lighting
        - Lifesaving
    - Systems redesigned:
        - Different motion limits, since no humans
        - Different structural loads, due to different motions
        - Different survival / risk strategy, since no loss-of-life danger

Kite soat

A high speed marine vehicle combining an aerodynamically supported cabin and a marine propulsion unit.

The origin goes to a personal vision: Once upon a time I wanted to move to San Diego. But while I could find work there, I cannot afford to live there. So I thought of living in Mexico and commuting across the border. But rather than spending hours each day in queue at the border, could I make the crossing by boat, and enjoy the much shorter queues at the San Diego Harbor Police dock? The answer is yes, but the problem this introduces is that in winter months the seas can be quite rough – reaching 8 to 12 feet. So I invented a vehicle that would allow very high speeds in high sea states, as follows:

The concept is of a boat towing a kite. The kite would include the passenger cabin, and might (depending on feasibility) be fully enclosed and protected. The tow vehicle may be thought of as an overgrown JetSki. The two units are coupled together by an umbilical that serves as both tow line and control circuit conductor.

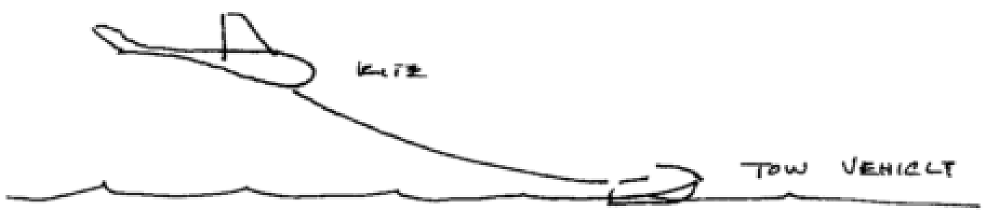


Figure 29 - Kite Boat concept sketch – author's sketch 13 June 2003

The tow vehicle will be subject to the seas, and may be envisioned as leaping from wave to wave in severe weather. Since there are no people on the tow vehicle, this becomes only a driver of ship structure and some machinery considerations.

The kite is towed by the umbilical, and is insulated from the motions of the tow vehicle by the length, elasticity, and catenary of that umbilical.

Upon reaching port the umbilical is reeled in, and the kite is landed in a purpose-built cradle on the back of the tow vehicle. The system then navigates as a surface craft in a rigidly coupled mode.

Figure 30 - Kite Boat in coupled "harbor" mode - author's sketch 13 June 2003

Advantages:

- Benign motion of passenger cabin compared to wave jumping
- Efficiency of marine propulsion
- Passive flight control – no pilot needed
- All machinery in tow vehicle – kite can be -10 dbSM
- 30+ knots in rough water in comfortable enclosed cabin

Composite non-heated ship

Composite materials (specifically foam-cored FRP sandwich) are attractive to shipbuilding because of weight savings and flatness (for stealth.) Designs have been developed that exploit these features, resulting in the elimination of some ship size (due to the weight saving) and some ship cost (due to the ease of making flat surfaces, compared with expensive hot work required for metal structure.) An example of such a ship is the Royal Norwegian Navy *SKJOLD* class patrol vessel - Figure 31.

I have been told, however, (in a personal communication from the SKJOLD's Captain) that her composite structure has an unintended feature of being extremely good thermal insulation. So much so that apparently even in a Norwegian winter the ship runs her air conditioning, rather than her heating plant, due to the heat generated by the crew and equipment on board.

I am not able to verify this statement, so I am willing to believe that it may contain hyperbole. But what if we were to take the idea to the foreground? Is it possible that by utilizing the insulating properties of the composite – and in fact designing for these properties, and not merely the structural properties – we could eliminate an entire shipboard heating system? This elimination of Muda might turn out to be of even greater weight and cost savings than the other benefits already ascribed to composite construction.

Under what circumstances would this work? Does it demand a ship of a certain configuration (e.g. a small ratio of surface area to internal volume)? This would be an interesting study.

Figure 31 - RNON *SKJOLD*. (Public domain image)

Tyvek ship

Today we design ship structure such that the two functions "hold the ship together" (strength) and "keep the water out" (water tightness) are performed simultaneously. This is a good application of the principle of multitasking, and it may be the best way to build a steel ship.

It has not always been the way ships are built, however. Eskimo kayaks, to use one example, separate the two functions, by using a non-tight structural framework, and then providing water tightness via a skin of non-structural (in the sense of global bending) seal skin. The result is a vessel that is somewhat flexible, but is very light weight – much lighter than attempts to duplicate the design in aluminum or fiberglass or other 'integrated' material.

What if we adopted this paradigm today? What if we built a ship as a space frame with a plastic, say "Tyvek" skin?

Or we may continue this logic further: Why do we require ships to be rigid? Can we imagine a container ship where the containers are placed in a sort of giant watertight sock, and then towed across the ocean? Again, this sock would be perhaps a Tyvek bag, looking not unlike a giant sausage casing or balloon full of cargo units.

Boundary layer steering

Is it possible to steer a ship only by manipulating the ship's boundary layer? We are all familiar with the fact that the spin on a curve ball modifies the pressure distribution on the ball and produces the curve. Can this same principle be used to steer a ship?

Several manifestations come to mind. Perhaps the simplest to conceive (although not to implement) is a sliding belt flush with the side of the ship. Imagine a giant belt-sander recessed into the hull of the ship. By speeding the belt opposite to the ship's path, a region of higher pressure would be created. Having the belt on the opposite side of the ship move in the opposite direction ("downstream", so to speak) will cause a reduced pressure on that side. Properly located longitudinally, this port/starboard pressure differential could be used as a steering force.

This is an example of ideation by analogy, where we observe the fact that a curve ball has no rudder, but is steered nevertheless. Pursuing the analogy and applying it to ship steering, we have conceived a steering system that actually reduces the ship resistance (at least on one side) and also has no appendages to foul nets, swimmers, etc.

Appendix C: Menu of innovation algorithms

There are many published (and no doubt many unpublished) tools for innovation. Here I present summaries of about a dozen significant tools. This is by no means a comprehensive list of all of the innovation algorithms published. It does, however, appear to capture the spectrum of such algorithms' techniques.

This appendix provides working descriptions of those tools gleaned from publicly available sources. Some of the tools summarized in the appendix have formal certification or credentialing programs associated with them, and it should be admitted that the author does not possess these third-party certification. Thus the summaries in Appendix C should be taken as indicative, rather than definitive.

Some of the innovation tools are extremely formalized, proprietary (copyrighted), and / or supported by formal research and teaching institutions. The poster child for this set may be TRIZ. Others of the tools are unstructured, and have taken on the position of generic tools within the popular culture. The poster child for this set may be Brainstorming. A wide range lies within the extremes.

Quintilian's seven questions

Perhaps the earliest 'algorithm' for innovation was Quintilian's seven questions, published in the first century A.D. These were actually put forward as an algorithm for understanding, but understanding is clearly the first step in invention. Einstein is quoted as saying "if you give me 20 days to solve a problem, I will spend the first 19 of them in problem definition."

Quintilian's seven questions are:

- Who
- What
- Where
- With what
- Why
- How
- When

Mathematical problem solving

Martin Gardner (1978) identified the following tools and techniques, writing about mathematical problems:

- Can the problem be reduced to a simpler case?
- Can the problem be transformed to an isomorphic one that is easier to solve?
- Can you invent a simple algorithm for solving the problem?
- Can you apply a theorem from another branch of mathematics?
- Can you check the result with good examples and counterexamples?
- Are there aspects of the problem that are actually irrelevant for the solution, and whose presence in the story serves to misdirect you?

Gardner's list of techniques resonates very strongly with me personally, perhaps because I first read Gardner's book when I was a boy of 13 years. And I note a great similarity between his list and my own tool box of techniques. For example Gardner's last point about "*irrelevant details*" leads naturally to McKesson's embracing of Very Simple Models (McKesson, 2011a and 2011b). And indeed, "simple models" is Gardner's first rule. Further, Gardner's isomorphism rule leads naturally to the tool of teleological decomposition, discussed below.

Teleological decomposition

Teleological decomposition is my own term for the principle of stepping back to remember the real purpose of the thing being designed. Consider the design of a ship rudder. In derivative design I start by looking at prior art and finding out what ship rudders look like. But if I start with teleology I would start by studying the purpose…: What is the purpose of a rudder? It is to give a ship direction. Well, what are some of the other ways that things are given direction?

I look at airplanes and I see that they use things that look like rudders.

I look at some recreational boats driven by outboard motors. They don't have rudders, they have combined rudder/propellers. But I looked also at porpoise in Monterey Bay, and they don't have a vertical fin. (Sharks do, fish do, porpoise don't). They have horizontal rudders, and I wonder why?

But there are still other methods: I once went on a VIP sea trial of a new ship, and watched as the captain put her through her paces. Finally we docked at the pier and I complimented him on his shiphandling skills. His reply surprised me: "She'll do even better next week when we install the rudders." He had accomplished the entire outing steering only by differential thrust.

But my teleological study doesn't end there. Tired of the waterfront I go to the park and watch a boy throw a curve ball. He simply generated pressure forces right on the body, with no appendage at all! Gee that might make a very interesting rudder, with no power requirement(?), with no "aft steering compartment", no special sea and anchor detail. In fact, if I'm trying to eliminate rudder-related systems, how about this one: What if I just point the ship in the right direction to begin with?

My point isn't to lecture about how to steer ships, and I have allowed myself to be purposely playful. It is to lecture about how to decompose the problem by "peeling it back" from what we think the problem is, to what it really is. This is the technique that I call 'Teleological Decomposition.'

ARI - Accelerated Radical Innovation

One 'brand name' technique is "Accelerated Radical Innovation" (Bers, 2007) which provides methods aimed at shortening the innovation time, and thus avoiding loss of innovative momentum and initiative. This technique has garnered sufficient momentum to lead to the establishment in 2004 of the International Accelerated Radical Innovation Institute.

ARI is not, however, a tool for engineering innovation per se, but is rather a procedure for accelerating the innovation process by a system for guidance and implementation.

ARI has ten steps, as follows:

1. Identify a 10X Opportunity or Threat
2. Conceive Breakthrough Innovation Area
3. Identify Grand Challenges
4. Information Retrieval, Pattern Recognition, and Knowledge Management
5. Address Hurdles
6. Envision Radical Innovation
7. Cluster-Based Economic Development
8. Guided Probe and Learn
9. Radical Innovation Prototype Design
10. Standard Design

As may be seen, these are interesting planning and management steps and ARI could be a useful business strategy tool, but it is not a tool for the engineering design innovation itself.

Osborn-Parnes Creative Problem Solving Process

The Osborn-Parnes Creative Problem Solving Process (CPS), was developed by Alex Osborn (the inventor of brainstorming) and Dr. Sidney J. Parnes in the 1950s (Daupert, 1996). CPS includes a problem solving morphology that is very similar to the present author's proposed morphology. Further, Osborne-Parnes' structure groups the problem solving steps into three "stages." This structure is presented in Table 9.

Table 9 - Overview of the Osborne-Parnes Creative Problem Solving process

Process Stage	Step
1. Explore the Challenge	a) Objective Finding (identify the goal, wish or challenge)
	b) Fact Finding (gather the relevant data)
	c) Problem Finding (clarify the problems that need to be solved in order to achieve the goal)
2. Generate Ideas	d) Idea Finding (generate ideas to solve the identified problem)
3. Prepare for Action	e) Solution Finding (move from idea to implementable solution)
	f) Acceptance Finding (plan for action)

CPS is intended to be flexible, and suitable for a wide variety of situations. The steps can be (and often are) used in a linear fashion, from start to finish, but it is not necessary to use all the steps. For example, if one already has a clearly defined problem, the process would begin at Idea Finding.

The crux of the Osborn-Parnes process is the use of both divergent and convergent thinking at each step. Thus we first diverge on the definition of the objective, before re-converging on the selected objective. Then one diverges during the fact-finding, drawing facts from far and wide and not necessarily the domain of interest, and the converging on those facts and selecting those which are relevant. Each step begins with divergent thinking, a broad search for many alternatives. This is followed by convergent thinking, the process of evaluating and selecting.

Table 10 through Table 12 from CEF (2012) summarizes the entire CPS:

Table 10 - The Osborne-Parnes Creative Problem Solving process, Overview (CEF, 2012)

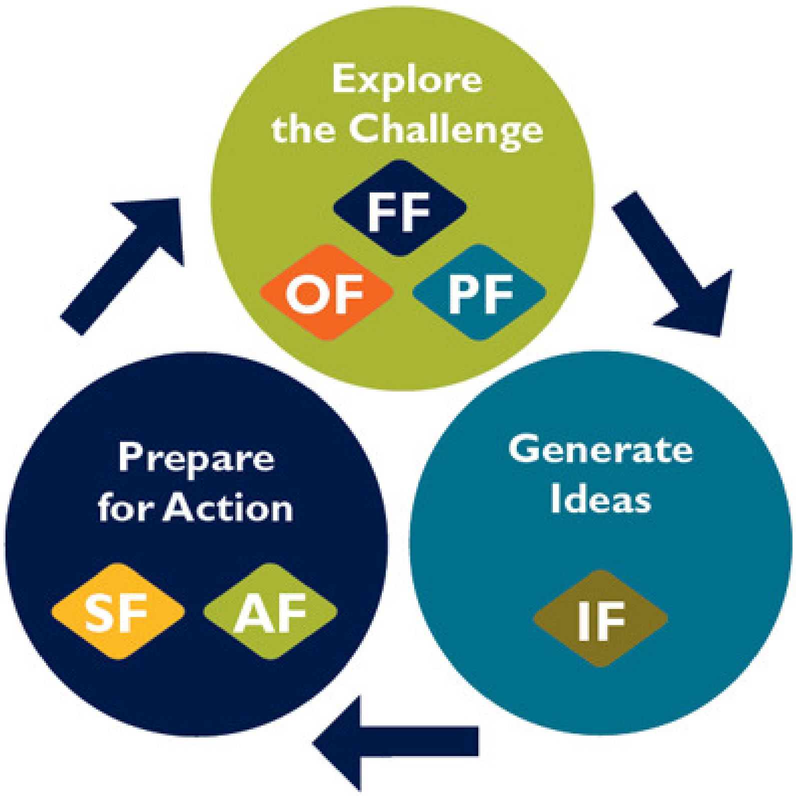
WHAT IS CREATIVE PROBLEM SOLVING?
Creative Problem Solving is a proven method for approaching a problem or a challenge in an imaginative and innovative way. It's a tool that helps people re-define the problems they face, come up with breakthrough ideas and then take action on these new ideas. Alex Osborn and Sidney Parnes conducted extensive research on the steps that are involved when people solve problems, the result of which is the following 6 steps that are broken down into 3 stages:

At the same time that CPS is a structured process, it's also a very flexible one. When you begin to use and internalize the CPS process, you find that it's cyclical. You begin to see how to move from step to step, and how to jump back and forth between steps. When CPS becomes part of your own way of thinking and working, you can use one step at a time, as you need it, when you need it. Once you understand the fundamentals of CPS, you can adapt this process to every situation you encounter, thereby realizing its power.

Table 11 - The Osborne-Parnes Creative Problem Solving process, Stage 1 (CEF, 2012)

EXPLORE THE CHALLENGE	
OF	**Objective Finding – *Identify Goal, Wish or Challenge*** This could be a wish or a goal. It might be the initial dissatisfaction or a desire that opens the door to using the CPS process.
FF	**Fact Finding – *Gather Data*** Assess and review all the data that pertains to the situation at hand. Who's involved, what's involved, when, where, and why it's important. Make a list of the facts and information, as well as the more visceral hunches, feelings, perceptions, assumptions and gossip around the situation. In this step, all the data is taken into consideration to review the objective and begin to innovate.
PF	**Problem Finding – *Clarify the Problem*** In this step, explore the facts and data to find all the problems and challenges inherent in the situation, and all the opportunities they represent. This is about making sure you're focusing on the right problem. It is possible to come up with the right answer to the wrong problem. Re-define what you want or what's stopping you.

Table 12 - The Osborne-Parnes Creative Problem Solving process, Stages 2 & 3 (CEF, 2012)

GENERATE IDEAS	
IF	**Idea Finding –** ***Generate Ideas*** Generating ideas is much more than brainstorming. During this step, be vigilant about deferring judgment and coming up with wild, outrageous, out-of-the-box ideas. This is where you explore ideas that are possible solutions and have the most fun. It's also where you need to stretch to make connections, take risks, and try new combinations to find potentially innovative solutions.
PREPARE FOR ACTION	
SF	**Solution Finding –** ***Select and Strengthen Solutions*** First, try to strengthen and improve the best ideas generated. Next, generate the criteria that needs to be considered to evaluate the ideas for success. Apply that criteria to the top ideas and decide which are most likely to solve the redefined problem. The best idea needs to meet criteria that makes it actionable before it becomes the solution. A creative idea is not really useful if it won't be implemented.
AF	**Acceptance Finding –** ***Plan for Action*** In this step, look at who's responsible, what has to be done by when, and what resources are available in order to realize this idea as a full-fledged, activated solution.

TRIZ

TRIZ (Orloff, 2006) is a very interesting technique. It is the life work (40 years in development) of Genrik Altshuller. TRIZ is a Russian acronym for "Theory of Inventive Problem Solving" (теория решения изобретательских задач.) TRIZ includes the ARIZ, or Algorithm for Inventive Problem Solving.

Altshuller developed TRIZ by studying inventions, both successful and unsuccessful ones. His goal was to find out what made the difference.

In brief, the crux of TRIZ is that every invention is faced with some paradox: Make it stronger but lighter, make it transparent but bullet-proof, make it small but comprehensive. TRIZ states that the first key step is to identify the particular conflict(s) that dominate the problem at hand. Once a conflict is identified TRIZ then guides the inventor to express this conflict in terms that are not specific to any industry. Finally, by a lengthy analysis of successful inventions, Altshuller has assembled a stunning menu of candidate ways to resolve each type of generic conflict. The inventor then "paws through" this menu of candidates until he makes his breakthrough.

TRIZ relies on the hypothesis that "*the key to the solution to problems lies in the discovery and elimination of contradictions in the system,*" and "*tactics and methods for solutions to problems can be created by analyzing important inventions.*" (Orloff, 2006)

Altshuller found that both the conflicts inherent in the problems and the "tactics and methods for solutions" could be simplified to a few dozen items of each sort. The inventor's task then is to correctly classify the contradiction in his particular problem, and then to find suitable solutions from the menu created by "analyzing important inventions."

Identifying a problem: contradictions

Altshuller believed that inventive problems stem from contradictions (one of the basic TRIZ concepts) between two or more elements, such as, "If we want more acceleration, we need a larger engine; but that will increase the weight of the car," that is, more of something desirable also brings more of something less desirable, or less of something else also desirable.

These are called *technical contradictions* by Altshuller. He also defined so-called physical or inherent contradictions: More of one thing and less of the same thing may both be desired in the same system. For instance, a higher temperature may be needed to melt a compound more rapidly, but a lower temperature may be needed to achieve a homogeneous mixture.

An *inventive situation* which challenges us to be inventive, might involve several such contradictions. Conventional solutions typically "trade" one contradictory parameter for another; no special inventiveness is needed for that. On the other hand, what Altshuller calls an "inventive" solution would be develop an engine that produces more acceleration without increasing the weight of the engine.

Inventive principles and the matrix of contradictions

Altshuller screened patents in order to find out what kind of contradictions were resolved or dissolved by the invention and the way this had been achieved. From this he developed a set of 40 inventive principles and later a matrix of contradictions.

The 40 inventive principles are 40 techniques that can be exploited to overcome a contradiction. In the "matrix of contradictions" Altshuller went further and indicated guidance on which of the 40 principles are most appropriate to each of the 39 x 39 possible contradictions.

Table 13 below presents the list of 39 features. The list of 40 principles is presented in Table 14.

The 39 x 39 matrix of contradictions is unreadable at any practical scale in this dissertation but legible copies may be found online. Rows of the matrix indicate the 39 system features that one typically wants to improve, while columns refer to undesired results on the features. Thus row 9, column 1 implies that the speed improves, but the weight gets worse. The contradiction matrix cell (9,1) contains the entries 2, 13, 28, 38, meaning that the principles of taking something out (2), doing something the other way around (13), substituting an alternative mechanism (28), or introducing a strong oxidant (instead of air) (38) might each be means to resolving this conflict.

Each matrix cell points to principles that have been most frequently used in patents in order to resolve the contradiction.

Let us attempt a maritime application of TRIZ, taking this cell (9,1) of the contradiction matrix. In this case the project may be a patrol boat that needs increased speed, but we find that increasing the speed by simply installing larger engines results in too much weight growth, perhaps exceeding a davit-capacity limit or other constraint.

The TRIZ contradiction matrix, as noted above, points to four inventive principles:

- taking something out (inventive principle 2),
- doing something the other way around (inventive principle 13),
- substituting an alternative mechanics (inventive principle 28),
- introducing a strong oxidant (instead of air) (inventive principle 38)

Let us explore each of these in naval architectural terms:

- Taking something out: This is the naval architect's standard tool of weight reduction – what is there in the boat that we can remove?
- Doing something the other way around: This action is defined as "*Invert the action(s) used to solve the problem. Make movable parts (or the external environment) fixed, and fixed parts movable. Turn the process 'upside down'.* "
  In our patrol boat example this principle might lead us to question why we need the speed, and whether there were some means to move the target closer to the boat, rather than moving the boat toward the target.
- Substituting an alternative mechanics: This action is defined as "*Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means. Use electric, magnetic and electromagnetic fields to interact with the object. Change from static to movable fields, from unstructured fields to those having structure. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.*"
  In our example we might consider this as pointing to the invention of a new propulsion device. We could argue that waterjets use a different mechanics than do propellers. Or perhaps magnetohydrodynamics might be the right propulsor mechanics for this boat.
  Or perhaps the new mechanics needed is not in the propulsor, but in the prime mover: Switching from a piston engine to a turbine engine might be argued to be a new mechanics of combustion power. Or a switch to nuclear power, similarly.
- Introducing a strong oxidant: This is an interesting principle and is not one that I have ever seen considered in a naval architecture case. While we do have turbocharged engines, I have never seen an application of, for example, a nitrous oxide 'boost' system. (I'm sure it has done by boat hot-rodders somewhere.) But for certain specialized problems, such as helping a planing boat boost over hump speed, this idea may have merit.

I hasten to remind the reader that I am not a TRIZ certified practitioner, and thus my application example is probably not as good an example of maritime TRIZ as is possible. But even this fledgling example has shown that TRIZ has merit in conjuring new concepts to mind, and provoking a focused divergent-thinking process.

Table 13 - TRIZ's 39 "features" which apply to all invented systems (Domb, 1998)

No.	Title	Explanation
1	Weight of moving object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension.
2	Weight of stationary object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
3	Length of moving object	Any one linear dimension, not necessarily the longest, is considered a length.
4	Length of stationary object	Same.
5	Area of moving object	A geometrical characteristic described by the part of a plane enclosed by a line. The part of a surface occupied by the object. Or the square measure of the surface, either internal or external, of an object.
6	Area of stationary object	Same.
7	Volume of moving object	The cubic measure of space occupied by the object. Length x width x height for a rectangular object, height x area for a cylinder, etc.
8	Volume of stationary object	Same.
9	Speed	The velocity of an object; the rate of a process or action in time.
10	Force	Force measures the interaction between systems. In Newtonian physics, force = mass x acceleration. In TRIZ, force is any interaction that is intended to change an object's condition.
11	Stress or pressure	Force per unit area. Also, tension.
12	Shape	The external contours, appearance of a system.
13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.
14	Strength	The extent to which the object is able to resist changing in response to force. Resistance to breaking.
15	Duration of action by a moving object	The time that the object can perform the action. Service life. Mean time between failure is a measure of the duration of action. Also, durability.

16	Duration of action by a stationary object	Same.
17	Temperature	The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
18	Illumination intensity	Light flux per unit area, also any other illumination characteristics of the system such as brightness, light quality, etc..
19	Use of energy by moving object	The measure of the object's capacity for doing work. In classical mechanics, energy is the product of force times distance. This includes the use of energy provided by the super-system (such as electrical energy or heat.) Energy required to do a particular job.
20	Use of energy by stationary object	Same.
21	Power	The time rate at which work is performed. The rate of use of energy.
22	Loss of Energy	Use of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
23	Loss of substance	Partial or complete, permanent or temporary, loss of some of a system's materials, substances, parts, or subsystems.
24	Loss of Information	Partial or complete, permanent or temporary, loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, etc.
25	Loss of Time	Time is the duration of an activity. Improving the loss of time means reducing the time taken for the activity. "Cycle time reduction" is a common term.
26	Quantity of substance/the matter	The number or amount of a system's materials, substances, parts or subsystems which might be changed fully or partially, permanently or temporarily.
27	Reliability	A system's ability to perform its intended functions in predictable ways and conditions.
28	Measurement accuracy	The closeness of the measured value to the actual value of a property of a system. Reducing the error in a measurement increases the accuracy of the measurement.
29	Manufacturing precision	The extent to which the actual characteristics of the system or object match the specified or required characteristics.
30	External harm affects the object	Susceptibility of a system to externally generated (harmful) effects.

31	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These harmful effects are generated by the object or system, as part of its operation.
32	Ease of manufacture	The degree of facility, comfort or effortlessness in manufacturing or fabricating the object/system.
33	Ease of operation	Simplicity: The process is NOT easy if it requires a large number of people, large number of steps in the operation, needs special tools, etc. "Hard" processes have low yield and "easy" processes have high yield; they are easy to do right.
34	Ease of repair	Quality characteristics such as convenience, comfort, simplicity, and time to repair faults, failures, or defects in a system.
35	Adaptability or versatility	The extent to which a system/object positively responds to external changes. Also, a system that can be used in multiple ways for under a variety of circumstances.
36	Device complexity	The number and diversity of elements and element interrelationships within a system. The user may be an element of the system that increases the complexity. The difficulty of mastering the system is a measure of its complexity.
37	Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labor to set up and use, or that have complex relationships between components or components that interfere with each other all demonstrate "difficulty of detecting and measuring." Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring.
38	Extent of automation	The extent to which a system or object performs its functions without human interface. The lowest level of automation is the use of a manually operated tool. For the highest level, the machine senses the operation needed, programs itself, and monitors its own operations.
39	Productivity	The number of functions or operations performed by a system per unit time. The time for a unit function or operation. The output per unit time, or the cost per unit output.

Table 14 - TRIZ's 40 Inventive Principles which can be used to resolve contradictions

No.	Principle	Explanation
1	Segmentation	• Divide an object into independent parts. • Make an object easy to disassemble. • Increase the degree of fragmentation or segmentation.
2	Taking out	• Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object.

3	Local quality	• Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform. • Make each part of an object function in conditions most suitable for its operation. • Make each part of an object fulfill a different and useful function.
4	Asymmetry	• Change the shape of an object from symmetrical to asymmetrical. • If an object is asymmetrical, increase its degree of asymmetry.
5	Merging	• Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations. • Make operations contiguous or parallel; bring them together in time.
6	Universality	• Make a part or object perform multiple functions; eliminate the need for other parts.
7	Nested doll	• Place one object inside another; place each object, in turn, inside the other. • Make one part pass through a cavity in the other.
8	Anti-weight	• To compensate for the weight of an object, merge it with other objects that provide lift. • To compensate for the weight of an object, make it interact with the environment.
9	Preliminary anti-action	• If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects. • Create beforehand stresses in an object that will oppose known undesirable working stresses later on.
10	Preliminary action	• Perform, before it is needed, the required change of an object (either fully or partially). • Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.
11	Beforehand cushioning	• Prepare emergency means beforehand to compensate for the relatively low reliability of an object.
12	Equipotentiality	• In a potential field, limit position changes.
13	The other way round	• Invert the action(s) used to solve the problem. • Make movable parts (or the external environment) fixed, and fixed parts movable. • Turn the object (or process) 'upside down'.

14	Spheroidality - Curvature	• Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures. • Use rollers, balls, spirals, domes. • Go from linear to rotary motion, use centrifugal forces.
15	Dynamics	• Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition. • Divide an object into parts capable of movement relative to each other. • If an object (or process) is rigid or inflexible, make it movable or adaptive.
16	Partial or excessive actions	• If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.
17	Another dimension	• Move an object in two- or three-dimensional space. • Use a multi-story arrangement of objects instead of a single-story arrangement. • Tilt or re-orient the object, lay it on its side. • Use 'another side' of a given area.
18	Mechanical vibration	• Cause an object to oscillate or vibrate. • Increase its frequency (even up to the ultrasonic). • Use an object's resonant frequency. • Use piezoelectric vibrators instead of mechanical ones. • Use combined ultrasonic and electromagnetic field oscillations.
19	Periodic action	• Instead of continuous action, use periodic or pulsating actions. • If an action is already periodic, change the periodic magnitude or frequency. • Use pauses between impulses to perform a different action.
20	Continuity of useful action	• Carry on work continuously; make all parts of an object work at full load, all the time. • Eliminate all idle or intermittent actions or work.
21	Skipping	• Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

22	*Blessing in disguise* or *Turn Lemons into Lemonade*	• Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect. • Eliminate the primary harmful action by adding it to another harmful action to resolve the problem. • Amplify a harmful factor to such a degree that it is no longer harmful.
23	Feedback	• Introduce feedback (referring back, cross-checking) to improve a process or action. • If feedback is already used, change its magnitude or influence.
24	'Intermediary'	• Use an intermediary carrier article or intermediary process. • Merge one object temporarily with another (which can be easily removed).
25	Self-service	• Make an object serve itself by performing auxiliary helpful functions. • Use waste resources, energy, or substances.
26	Copying	• Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies. • Replace an object, or process with optical copies. • If visible optical copies are already used, move to infrared or ultraviolet copies.
27	Cheap short-living objects	• Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).
28	Mechanics substitution	• Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means. • Use electric, magnetic and electromagnetic fields to interact with the object. • Change from static to movable fields, from unstructured fields to those having structure. • Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.
29	Pneumatics and hydraulics	• Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).
30	Flexible shells and thin films	• Use flexible shells and thin films instead of three dimensional structures. • Isolate the object from the external environment using flexible shells and thin films.
31	Porous materials	• Make an object porous or add porous elements (inserts, coatings, etc.).

		• If an object is already porous, use the pores to introduce a useful substance or function.
32	Color changes	• Change the color of an object or its external environment. • Change the transparency of an object or its external environment.
33	Homogeneity	• Make objects interacting with a given object of the same material (or material with identical properties).
34	Discarding and recovering	• Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation. • Conversely, restore consumable parts of an object directly in operation.
35	Parameter changes	• Change an object's physical state (e.g. to a gas, liquid, or solid.) • Change the concentration or consistency. • Change the degree of flexibility. • Change the temperature.
36	Phase transitions	• Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).
37	Thermal expansion	• Use thermal expansion (or contraction) of materials. • If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.
38	Strong oxidants	• Replace common air with oxygen-enriched air. • Replace enriched air with pure oxygen. • Expose air or oxygen to ionizing radiation. • Use ionized oxygen. • Replace ozonized (or ionized) oxygen with ozone.
39	Inert atmosphere	• Replace a normal environment with an inert one. • Add neutral parts, or inert additives to an object.
40	Composite materials	• Change from uniform to composite (multiple) materials.

Brainstorming

Brainstorming is a well-known ideation method. Brainstorming was developed in the 1940s by Alex Osborn, who also created the Osporn Parnes process described above.

Osborn was a successful advertising agent, and in 1948 published a book in which he shared his creative secrets. The book – "Your Creative Power" – contained a mixture of pop science and business anecdote, and became a surprise best-seller.

Quoting from Lehrer (2012): *"'Your Creative Power' was filled with tricks and strategies, such as always carrying a notebook, to be ready when inspiration struck. But Osborn's most celebrated idea* *was the one discussed in Chapter 33, "How to Organize a Squad to Create Ideas." When a group works together, he wrote, the members should engage in a "brainstorm," which means "using the brain to storm a creative problem—and doing so in commando fashion, with each stormer attacking the same objective." For Osborn, brainstorming was central to his success. Osborn described, for instance, how the technique inspired a group of ten admen to come up with eighty-seven ideas for a new drugstore in ninety minutes, or nearly an idea per minute. The brainstorm had turned his employees into imagination machines. "*

"The book outlined the essential rules of a successful brainstorming session. The most important of these, Osborn said—the thing that distinguishes brainstorming from other types of group activity—was the absence of criticism and negative feedback. If people were worried that their ideas might be ridiculed by the group, the process would fail. "Creativity is so delicate a flower that praise tends to make it bloom while discouragement often nips it in the bud," he wrote. "Forget quality; aim now to get a quantity of answers. When you're through, your sheet of paper may be so full of ridiculous nonsense that you'll be disgusted. Never mind. You're loosening up your unfettered imagination—making your mind deliver." Brainstorming enshrined a no-judgments approach to holding a meeting."

Brainstorming is, in modern parlance, a technique for divergent/convergent thinking. Ideas provoke more ideas throughout the 'no criticism' period. Then the 'no criticism period is drawn to'a close, and a convergent process takes place where the ideas are evaluated and ranked.

The brainstorming technique does not offer any specific tools for stimulating the divergent thinking process, and indeed it might well be possible to use many of the other tools (such as 'analogy') within the context of a brainstorming session.

Muda

Muda is a Japanese word made popular by Dr. Amory Lovins of the Rocky Mountain Institute. Muda is often defined as "waste" but it is actually something much more subtle than that. Muda is "that for which there is no customer."

Pause for a moment and reflect on how that's different from waste. From an engineering point of view the big difference is that this definition introduces new ways of dealing with it. With "waste", we want simply to minimize the waste. But with Muda we get a second choice. We can get rid of it, or we can find a customer for it. We can redefine it so that it's not waste any more.

Waste-heat recovery systems are a well-proven example of eliminating Muda – the heat is no longer 'waste.'

Marcus Aurelius, in the "MEDITATIONS" 4.24, writes: "The majority of things being unnecessary, always ask yourself 'is this one of the necessary things?'"

The lightest piping system, or machinery component, or choice of deck machinery, is the one that is absent. And in many cases (but not all) these will also be the cheapest systems too – the cheapest anchor is none at all....unless the cost of beaching the ship is high.

So when trying to remove weight or cost (or carbon footprint or human resources, etc.) from a ship, a very powerful tool for that reduction is to entirely eliminate components of the ship.

Incremental improvements in such components go the other direction: Reducing the weight of a piping system can dramatically INCREASE the cost of the pipe. But eliminating the pipe completely certainly eliminates the cost of the pipe. The remaining question is whether it raises the cost of something else.

A more radical image of ship-Muda might be to consider the crew. Unlike in the days of sail the propulsion of a modern ship does not require human muscle. And if the ship is a cargo ship then her mission is to carry freight, not people. Transporting 20 seamen on a tour of the planet is Muda – That for which there is no customer.

So can we eliminate the Muda? Can we eliminate the crew? With satellite datalinks and redundant software could we not build a remotely operated ship? Having done so we would find a cascade of benefit: Eliminating the crew eliminates the galley, the stores, the sewage plant, the potable water plant, much of the HVAC system, and more. It might even change the hull design and structural loads, since the machine's tolerances may be very different from the man's.

Eliminating the Muda of 'world tours for sailors' might result in a radically innovative ship.

Dr. Amory Lovins is credited with introducing the concept of Muda in the USA. Dr. Lovins has exploited this concept (along with multitasking) to build a home in the Colorado Rockies that maintains a comfortable year-round climate despite having no identifiable heating or cooling plant.

Multitasking

In a 10,000 TEU container ship, there is more steel in the containers than there is in the ship.

To me this raises the question, as long as all those tons of containers are there anyway, can't I use them to hold the ship together?" What would it take to re-design the container ship paradigm such that it relied on the container itself for strength? I have a lot of ideas on this one, but let's just take it as an example. How about something less exotic:

How about using the pipes in the ship in a structural role? Why don't I rely on the firemain, bilge and ballast system, heating ventilating and air conditioning ducts, and other distributive systems to contribute to a ship's longitudinal bending strength?

In a ship design, taking advantage of those tons of pipes and ducts might take a few tons of steel out of the structure elsewhere, and those few tons of steel can be replaced by a few tons of bullets, bombs, or beans.

But this doesn't have to be just about structure, or just about weight. It is about reliability redundancy and cost too.

For instance, what if I used the conductive steel structure of the ship to carry data? Or power? Before you laugh remember that that's how your car is wired. The DC return leg in your car is the structural frame itself. This, in one fell swoop, cuts in half the number of wires that are run.

All of the above are examples of the principle of multitasking – making one component of the ship fulfill multiple roles, hopefully leading to the elimination of components.

Generalizing this to an innovation method calls for the engineer to take one or both of two paths: We can review each component of the system, look at it's characteristics, and then determine if this is another task in the system that these characteristics could be useful for.

The second approach starts at the other end, requiring us to look at each task in the system, determine what characteristics each task requires (e.g. conductivity, or strength) and then compare those and see what components of the system possess these needed characteristics.

As you can see, the most efficient way to execute this is to do both: Prepare a list of task and needed characteristics, and also a list of components and possessed characteristics, and then align these two lists.

Synectics

Synectics is a complete creative problem solving process, developed in the the 1950s by George M. Prince and William J.J. Gordon. Synectics is now controlled by the consulting firm that they started, Synecticsworld.

The process was derived by tape recording thousands of meetings and studying and analyzing those that were most successful at producing innovation. Prince and Gordon identified factors that contributed to success, including not merely success at the ideation stage of the process but success through all the way to implementation of the ideas. Synectics thus touches all steps of the innovation morphology.

Synectics is described (Nolan, 2012) in the graphic reproduced as Figure 32. It is interesting to immediately note a similarity to Rhodes' 4P model, in the inclusion of the climate (Rhodes' "press") and the persons.

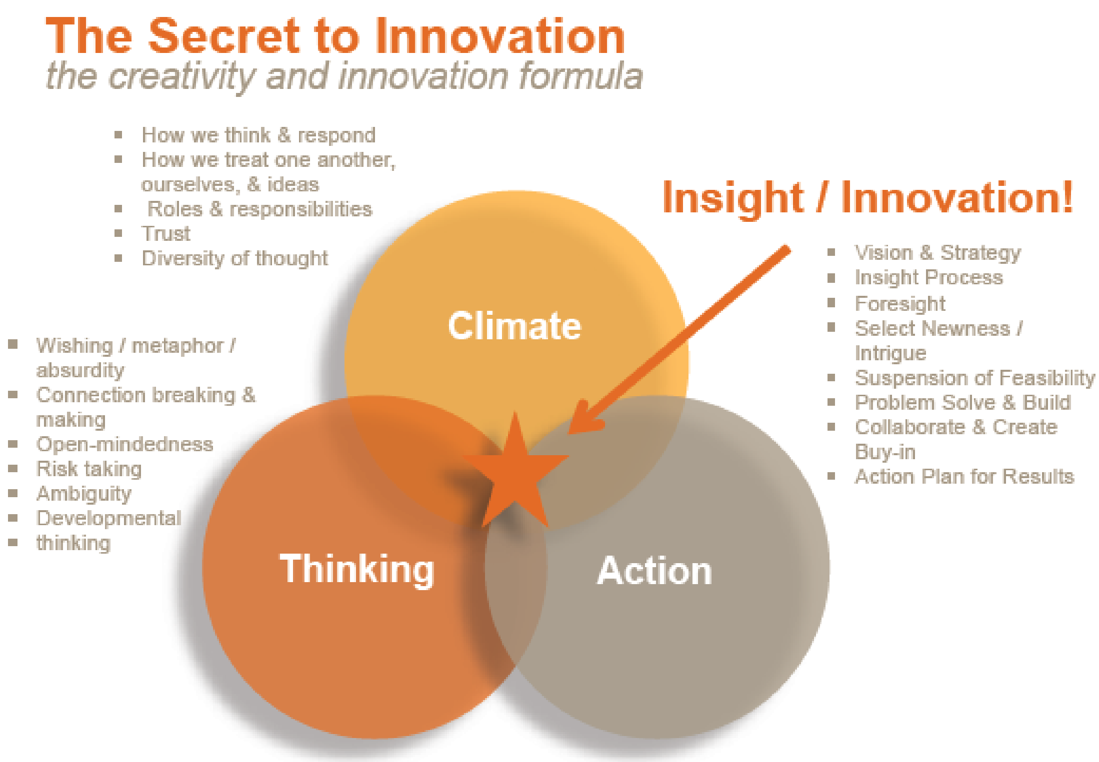


Figure 32 - A graphical overview of the Synectics process (from Nolan, 2012)

The ideation stage of Synectics emphasizes the use of divergent thinking. A synectics motto is "make the familiar strange and the strange familiar" or "trust things that are alien, and alienate things that are trusted." This encourages the problem generalization step in the morphology, including the alienation of the original problem through the creation of analogies. It is thus possible for new and surprising solutions to emerge.

Synectics tools go beyond ideation, and include tools for active listening during meetings, including a two-column notepad technique for capturing ideas that are provoked during the listening. Synectics is thus concerned not merely with the creation of the ideas, but also centrally with the human interactions that will be needed throughout the process, including in idea acceptance. Synectics includes specific practices and meeting structures which help people to ensure that their constructive intentions are experienced positively by one another.

As an invention tool, Synectics employs a technique called "springboarding" for getting creative beginning ideas. For the development of idea starting points, the method incorporates brainstorming and deepens and widens it with analogies; it also adds an important evaluation process for Idea Development, which takes new ideas that are attractive but not yet feasible and builds them into new courses of action which have the commitment of the people who will implement them.

Design by analogy

Design by analogy is properly a class of techniques, and not a single technique.

Design by analogy refers to the process of finding analogs to the present problem, whether within the present domain or outside it. When defined in this way it may be noted that conventional design – non-innovative design – is design by analogy, where the analog lies quite close to the project at hand.

The task in inventive design is to cast the net of analogy wider, and take in analogs that are not close to our particular problem, and potentially not even within our design domain. Linsey, (2008) describes this very nicely (internal references removed):

"*Professional designers often use analogies. Unlike biologists who mainly use analogies within their domain, engineers employ cross-domain analogies in their design process. This finding is based on protocol analysis of design team's conversations during conceptual design. Design teams also frequently use close-domain analogies in the form of references to past designs. Eckert, et al. found designers use references to previous designs for more than just conceptual design. Designers also use past designs in a number of other phases of the design process including process planning, cost estimation, and evaluation of concepts for a new product.*

"A few controlled experiments have explored the use of analogy within design. Casakin and Goldschmidt found that visual analogies can improve design problem solving for both novice and expert architects. Visual analogy had a greater impact for novices as compared to experts. Ball, Ormerod, and Morley investigated the spontaneous use of analogy with engineers. They found experts use significantly more analogies than novices do. The type of analogies used by experts was significantly different from the type used by novices. Novices tended to use more case-driven analogies (analogies where a specific concrete example was used to develop a new solution) rather than schema-driven analogies (more general design solution derived from a number of examples). This difference can be explained because novices have more difficulty retrieving relevant information when needed and have more difficulty mapping concepts from disparate domains due to a lack of experience."

As may be seen in this introduction, there are several different types of design-by-analogy, and I will below discuss a few of these.

Visual Analogies

The principle of using visual analogies is straightforward: we find parent designs that look visually similar to our product. This is obviously useful when the creative product is in the visual arts, but it can be used in engineering as well. Thus in the case of the design of a ship rudder we look at the rudders on other ships, and we look at anything that looks "rudder like", such as the rudder of an airplane, the tail of a fish, the tail feathers of an arrow, or the empennage of a windmill (see Figure 33.)

Some authors have written of the utility of using Google "Image Search" as a tool for finding visual analogies. The author tried this for the topic of rudder design, searching on the key words "steer rudder tail." The resulting images (Figure 34) are indeed thought provoking, including rudders – both marine and air – but also including the tails of swimming animals and even of flying lizards. These images might indeed spur thought of other ways that ships could be steered.

Figure 33 - An Aermotor windmill, iconic of the author's childhood

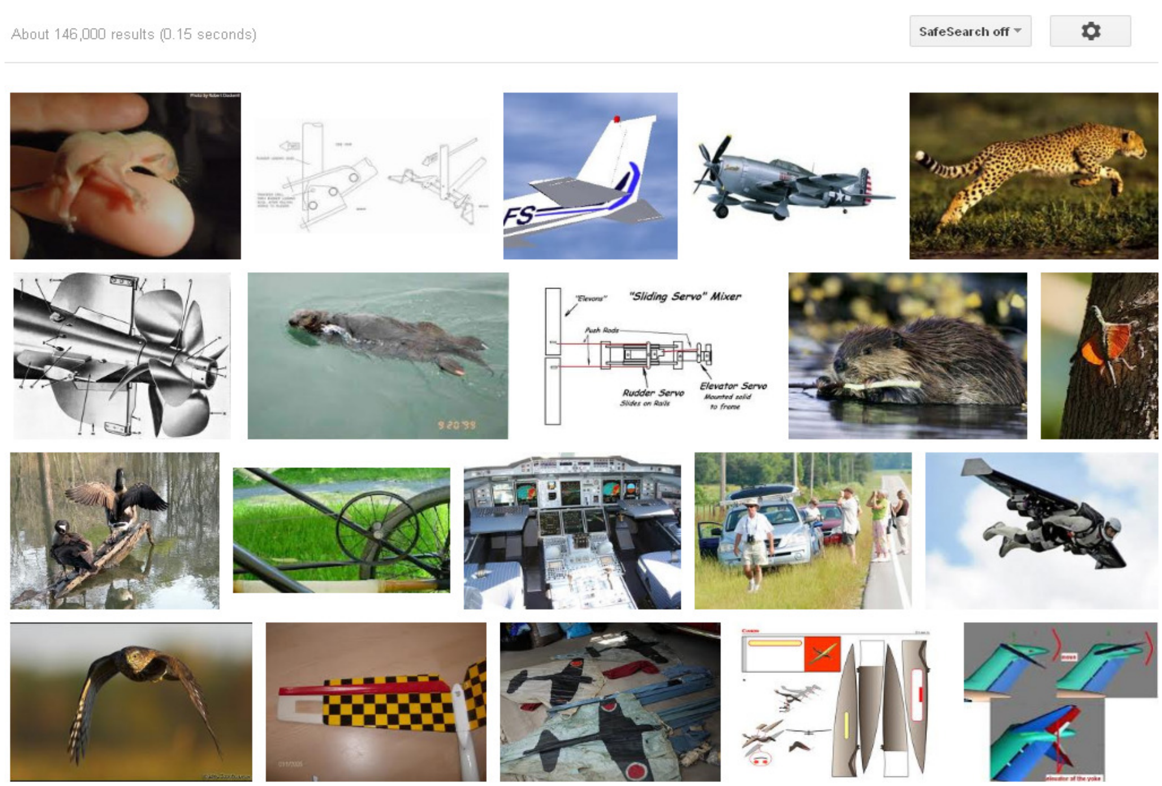


Figure 34 - Google Image Search results (unfiltered) for "Steer Rudder Tail."

A visual analog may be much less useful when the design product is less tangible, such as in the attempt to invent a new process or software algorithm, but even there I can imagine that for some aspects of the problem an image search might be a useful tool for provoking divergent thinking.

We should note, however, that at the present time the use of image search actually relies first upon a lexical presentation of the problem: We have to type in a *word* to the search box, not a picture. This leads directly to the use of words themselves as sources of analogy, as follows.

Lexical Analogies: WordTree

Linsey (2007 & 2008) develops a particular case of design by analogy using semantic analogs. Linsey's most entertaining example is the challenge of designing a self-cleaning cat litter box, where the analogies were panning for gold, and dump trucks. These analogies then serve as seed for the engineer to study, say, gold panning, and see if its principles can be applied to the cat box problem. Linsey goes on to develop a lexical technique for finding these analogies, by creating what she calls a 'word tree.'

Note that the WordTree method is a method specifically for finding analogies, and not for the full scope of inventive design. It thus addresses only one portion of the innovation morphology – the ideation step. However, this is a mature and well-documented method in its own right and deserves to be considered in this discussion.

Linsey describes WordTree as follows (Linsey, 2008), internal references and figures removed.)

"*The WordTree Design-by-Analogy Method systematically re-represents a design problem, assisting the designer in identifying analogies and analogous domains. … The method begins by identifying the "problem descriptors" which are the key functions and customer needs. These are then linguistically re-represented in a diagram known as a WordTree. Next potential analogies and analogous domains are identified. The potential analogies are researched and the analogous domains are used to find solutions in distant domains. New problem statements ranging from very domain specific in multiple domains to very general statements are written. Finally the analogies, patents, analogous domains and new problem statement are implemented in a group idea generation session. This session further refines the method's results into conceptual solutions to the design problem and provides additional inspiration for the designers.*"

"This WordTree method begins by defining the Key Problem Descriptors. The Key Problem Descriptors are single word action verbs derived from the functions and customer needs for the design problem. Prior research found that transitive verbs, which are action verbs, are more effective stimulus for idea generation. The Key Problem Descriptors are defined from the customer needs, mission statement, function structure and black box model. Key Problem Descriptors fall into a few categories. One set describes the overall function of the device with a single word. The next category is the critical or difficult functions to solve, and the final category is the important customer needs transformed into single action verbs. Normally the customer needs are a combination of an adjective and a noun. To be used in the WordTree Method, they must be converted to equivalent verbs. For example, the verb form of the customer need of "easy to repair" is "repair".

"The next step is to re-represent the key problem descriptors using WordTrees. This step facilitates the identification of analogies and analogous domains. The first, the design team uses rotational brainstorming to create sticky note WordTrees. …

"After potential analogies and analogous domain have been identified, the analogies are researched along with searching for solutions in analogous domains. Google Image© is an effective and efficient tool for finding information about a potential analogy. Patents in analogous domains should be searched for also. …

"Finally the teams use the results to generate more ideas. Two separate teams of designers are recommended to base their idea generation sessions on the results from the WordTree Method. … After

team idea generation, the results are summarized using any number of methods such as morph matrixes or mind maps. The team then continues with the design process and moves to idea selection. "

WordTree rings true in a personal anecdote: I have a daughter who has an uncanny aptitude to taking things apart and fixing them. This is not a result of any formal training, indeed her field of study is social history. In conversation with her she has told me that her aptitude is the result of a family habit during her childhood: We took words apart at the dining room table. When in her childhood her college-educated parents used a word that was not in her vocabulary, we would not then tell the kids the meaning of the word, but we would work with them to dissect the word, finding its roots, finding its similarities to other words that they did know. Kate tells me that she learned to fix machines via this same principle. Apparently the lexical training resulted in an ability to see patterns and relationships in machines as well as in words.

Taking this as a sort of primitive experiment in engineering skills suggests an interesting relation between lexical and mechanical thinking.

Note also that the word tree identifies the opportunity for analogy by a method very similar to the next item on my list.

Lexical Analogies: Synonyms, Antonyms and Homonyms

The simple act of defining a problem's synonyms, antonyms, and homonyms can be a very powerful tool for identifying analogies and alternative solutions. As mentioned, this is very close to the Word Tree method discussed above.

The synonyms component helps to identify alternative solutions that are used in other industries, such as pursuing the similarities between a ship rudder and a car's steering axle.

Antonyms can shed light on the problem in a reverse sort of way: The antonym of course identifies what the problem is not. But if we then attend to people attempting to design the anti-solution, we may find that their challenges are our opportunities. To continue the rudder analogy - the antonym of a rudder is directional stability. So perhaps a study of those things that are a problem for directional stability would identify a few candidates that might be made into ship-steerers? A vessel with a disabled rudder can be steered with a bucket towed astern, via a yoke leading to port and starboard bow cleats. (See Figure 35.)

Homonyms are those things that 'sound like.' The use of homonyms is twofold: It provokes wild-hare brainstorming ("Is there anything similar between Rudders and Udders? I doubt it!") and it may also help to identify other red herrings: Just because something sounds like a rudder doesn't necessarily mean it has relevance to our problem.

Personally I find the homonyms the least useful of these methods, but I take that as a result of my novitiate, and not as a limitation of the method.

Inspiration from Nature: Biomimetics

A very important class of Design by Analogy is biomimetics. In biomimetics one takes inspiration from nature. The application of this principle is fairly self-evident. Consider again our recurring example of the ship's rudder. In a biomimetic scheme we would look at the rudders found on fish, whales, birds, etc. We would apply engineering science to understand the 'niche' of each of those devices, such as the fact that flagella are effective at extremely small Reynolds numbers, whereas high-Reynolds number animals (whales) have rudders of more or less conventional form.

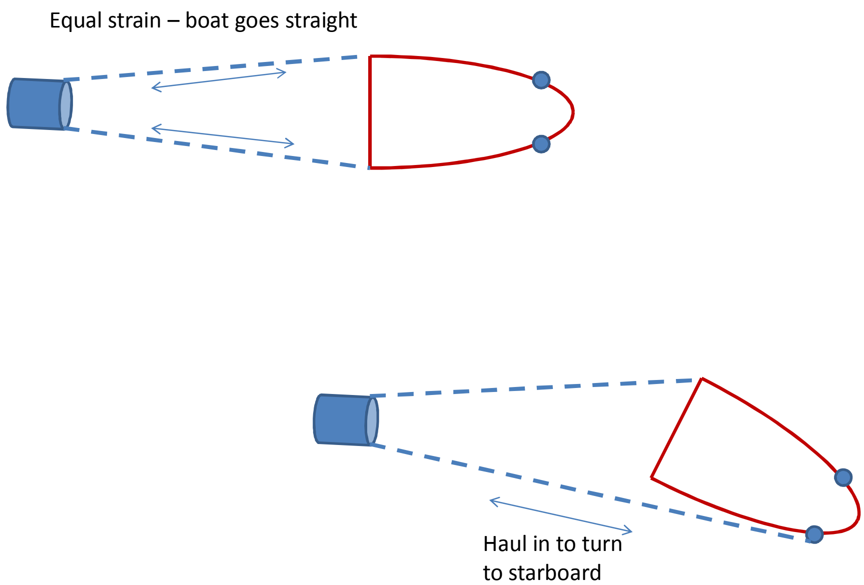


Figure 35 - Steering a boat with a bucket – A concept provoked by an antonym

Biomimetics may be used in many other applications as well. My example focuses upon mechanical analogs, whether they be rudders or bones-and-skin. But we may also find cognitive biomimetics, and indeed this present dissertation may be taken as such. To extrapolate from my near term goal, a dissertation such as this one might address the question "How does the flesh-and-blood innovator do it, and can I teach that method to a computer?" This would be an example of cognitive biomimetics.

Opportunities for biomimetics in naval architecture would seem to be many, but in fact the present author has only come up with a few examples. In that case this suggests that this might be a fruitful generator of new ideas, as it may be an untapped (or "under tapped") idea pool.

- Launching UAVs: How do birds take off? The prefer to drop from a perch (tree branch, telephone wire). So perhaps UAVs would be best launched by hoisting them to the masthead and allowing them to drop to take-off speed.
- Cods Head and Mackerel Tail: This phrase was a 17th century algorithm for ship hull design, intended to mate the favorable hydrodynamic features of these two animals. This, of course, was later superseded by the use of prismatic coefficient to control the hydrodynamics.
- Submarine L/D: It is not by chance that the prototype body-of-revolution submarine hull was named "albacore." This fish provided the pattern for the L/D=5 form that was validated by scientific testing.
- Dr. Taravella's Eel research: Emulating the propulsion system of anguilloform animals (Taravella, 2013).

Appendix D – A proposed curriculum in innovation

The following is an outline of a proposed formal course in Innovation in Ship Design. In outline form it looks short, but there are 20+ topics in the list, suggesting that this is at least a two-semester lecture series. (An average semester has 35 lecture hours, which is not sufficient to cover 20 topics.) I therefore have broken the content into three courses, as follows:

COURSE #1A: ENGINEERING CHARACTER

1. Know Thyself
    a. MBTI Survey and the Myers-Briggs types
    b. KAI Inventory and the Role of KAI scores
2. Personal Growth
    a. "Think Like Leonardo" course content (many examples on line)
    b. Pirsig Quality Exercise (harvest material from Zen And The Art…)

COURSE #1B: INSTITUTIONAL CHARACTER

3. Know Thy Community
    a. Survey of Expertise
    b. Survey of connectedness within community
    c. Survey of connectedness within classroom
    d. Survey of Innovation climate of your organization (MANG 6710)

COURSE #2: INNOVATORS TOOLBOX

4. Algorithms for Innovation
    a. The Innovation Morphology
    b. Tools for Problem Definition and Generalization
        i. Quintilian's Seven Questions
        ii. Mathematical Problem Solving
        iii. Teleological Decomposition
        iv. TRIZ
        v. Muda
        vi. Multitasking
        vii. Synectics
    c. Tools for the Search for solutions
        i. Mathematical Problem Solving
        ii. TRIZ
        iii. Muda
        iv. Multitasking
        v. Synectics
        vi. Design By Visual Analogies
        vii. Design By Lexical Analogies: WordTree
        viii. Design By Lexical Analogies: Synonyms, Antonyms and Homonyms
        ix. Design By Inspiration from Nature – Biomimetics
    d. Tools for Applying & Implementing Solutions
    e. Tools for Learning
5. Innovation project
    a. Assemble team from KAI & MBTI scores
    b. Execute project using the morphology

Alternatively, the same material may be presented in the form of a sequence of short courses or course modules, as follows:

Module 1: (approximately 2 hours)	The Innovation Morphology
Module 2: (approximately 4 hours)	Innovation Algorithms: Taxonomic Decomposition
Module 3: (approximately 4 hours)	Innovation Algorithms: Synectics
Module 4: (approximately 8 hours)	Innovation Algorithms: TRIZ
Module 5: (approximately 4 hours)	Innovation Algorithms: Design by Analogy
Module 6: (approximately 4 hours)	The Character of Innovators
Module 7: (approximately 8 hours)	Introduction to MBTI
Module 8: (approximately 8 hours)	Team Building using KAI
Module 9: (approximately 4 hours)	Assessing Corporate Support for Innovation
Module 10: (approximately 4 hours)	Growing Innovation Aptitude

TOTAL: approximately 50 hours

Note that the above durations are extremely compressed. Each course could be expanded by a factor of five without much effort, resulting in a 200+ hour lecture program.

Appendix E – A note on writing style

Professor Benford, in the SNAME publication “The Literate Naval Architect” writes:

The so-called impersonal style is gradually becoming obsolete. Avoiding reference to the first person supposedly convinces readers of your objectivity, but anyone who thinks about it realizes that the whole idea is merely a thin semantic disguise. Calling yourself "the writer" is not so much modesty as self-consciousness. And hiding behind "it is believed" instead of "I think" only obscures your ideas. Things get muddy indeed when you turn out written discussions with: "It is felt that the author's reference to the writer's views demonstrates the author's ignorance of the writer's opinion of the author's theories." You can imagine the author's reply.

In a similar vein, say "you," not “the reader"; and say "you can do it,” not "one can do it."

Technical people, having grown used to the impersonal style, are still apt to be a little shook up when they find an "I" in a technical report. Nevertheless, the advantages in clarity and brevity of "I think" in place of "the writer believes" or "it is thought" are too pronounced to deny forever. Let's keep chipping away at that conceited wretch, "the writer,” or even worse, "the author."

You will find that I have adhered to Prof. Benford’s teaching, and have written this thesis in the first person.

Vita

The author is a practicing naval architect with a 30 year career in ship design innovation. Born and raised in southern California, he practiced ship design as part of the US Naval Engineering Enterprise in Washington DC, and as a member of the fast ferry community in Seattle Washington and San Francisco California. McKesson is 55 years old and resides in New Orleans Louisiana and Bellingham Washington.