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A Small Rebellion: How to Catalyze Innovation Through Self Actualization*

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How do you teach creativity? In this paper, we explore ways to create an environment in which students do more than learn – they innovate. The Non-hierarchically Organized Design Engineering (NODE) model creates a new kind of faculty community – one that is collaborative and guided by humanistic values – and one that is able to create the conditions for students to self-actualize i.e., develop autonomy, self-awareness, and self-acceptance. And once they have acquired those attributes, they will have the freedom and the courage to innovate, be that in a prototyping exercise or in their personal lives. Students who are self-actualized will be more creative, more fulfilled in their work, and in the rest of their lives. They will have the ability to achieve peak experiences more frequently – and live with a sense of wonder.

Keywords: creativity; innovation; design; prototyping environment

1. Taking Control by Letting Go

For centuries, our educational system has stressed what academic researchers call literacy and numeracy, and what the rest of society calls The Three R's: reading, writing and 'rithmetic. Yet there is another, much less jaunty-sounding trio of Rs driving our pedagogy: rote, regimentation and rigor. This second triplet turns too many of our schools into assembly lines for minds, and stifles creativity. This may have been fine in the 19th and 20th centuries, as we moved through successive industrial revolutions, but problematic now that we need to foster innovation to deal with daunting challenges such as healthcare and climate change.

Too many of our social institutions are hostile to new ways of thinking and new ways of doing things. In "Discipline and Punish" [1], Michel Foucault wrote, "Is it surprising that prisons resemble factories, schools, barracks, hospitals, which all resemble prisons?" He posited that prisons resemble these other institutions not just because they have similar architecture, but because they all play a similar role in society: enforcing predictability, stability and conformity.

The US was a global innovation leader for nearly a century, but it is now being overtaken [2]. This does not bode well for our economy, our universities, or our students. We must find ways to reverse the trend. Over the last two decades, there has been a steady call for engineering schools to produce innovators [3], and most schools have added courses in hands-on prototyping, design, and entrepreneurship. That is a laudable first step, but schools aren't factories that can simply retool and switch from graduating engineers steeped in the values of efficiency and productivity to nurturing engineers who value creativity and self-efficacy. There seems to be the will, but not yet a way.

How do you foster creativity, innovation and startling new ideas? We believe innovation requires courage, which in turn requires a high degree of autonomy, which in turn requires self-awareness, which in turn requires self-actualization. We argue that by changing the milieu in which prototyping is done, we can go beyond just teaching an additional skill, and create an environment in which our students can self-actualize.

We will explore this new paradigm through case studies. The first one is a short memoir by Stanford alumnus Terry C. Smith about his harsh introduction to a new way of teaching, learning and creating.

1.1 Case Study #1: Letting Go [4]

> "Art professor Matthew Kahn and I didn't have any particular bond. Most of the time, in fact, I hated him. I remember huddling for hours on a cold stone bench in the Loggia dei Lanzi as a member of Italy Group V, working on a charcoal drawing of Michelangelo's 'David.' When I finally offered it to Matthew Kahn for comment, he said it was overworked, not free enough. Once clear of his office door, I swore quietly, determined to show him. I tried again and again, becoming nearly as much a fixture on the Loggia as the Cellini bronze of Perseus holding the severed head of Medusa. Each time, I presented the result. Each time, he dismissed it. 'Too finished,' he said.
>
> I hated him, but the more I hated him, the better I got.

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> After a dozen attempts to capture David's face, I became convinced I would never please Matthew Kahn. As my quarter in Florence drew to an end, other classes demanded my time. Finally, the night before the drawing deadline, I sketched one last David, relying on muscle memory from the previous drawing and on the marble countenance in my mind. I allowed just one chance at each line, and the quality of the image surprised me.
>
> Matthew Kahn studied it for a moment and said, 'This one is good. This one has life.'
>
> And then he tore it up. I was devastated, but the lesson stuck.
>
> 'Don't fall in love with what you create,' he told me.
>
> 'Don't hold onto it as if it were a stroke of luck. It was talent. And when you have talent, you can always create something even better.'
>
> More than 20 years later, I produced a film tracing the impact of teachers on successful people. The film won an award at the 1984 National Educational Film Festival in Oakland. After accepting the honor, I visited Matthew Kahn to thank him."

Professor Kahn refused to be constrained by social norms or his institutional environment and refused to let his students be hobbled by them. Most professors today don't believe they have that luxury, which inhibits them and their students.

Hierarchical organizations, by definition, maintain order and efficiency, and zealously defend the status quo. If we want efficiency, that type of organization should be favored. If we want creativity, another type of organization should be favored, one that gives more freedom, and more room for mistakes. More room for new ideas.

1.2 Four Axioms

Using Terry Smith's short memoir as our touchstone, we propose four axioms regarding the proper nurturing of innovators:

1. An over-emphasis on literacy and numeracy has conditioned most of us to seek conformity and judge our worth and talents by standardized measures of quality. This adherence to hierarchical and bureaucratic norms makes us less creative, and easier to control.
2. By creating special conditions for prototyping, we can increase the likelihood of students transcending the conditioning and control and becoming more creative.
3. Professors cannot help students self-actualize unless they, too, are self-actualized.
4. Students who transcend the conditioning will be better able to create novel technologies and innovative organizations.

In addition to the four axioms, here is a conceptual model of the joint program in design (JPD) at Stanford, where Professor Kahn was faculty. It was a partnership between the mechanical engineering department and the art department.

1.3 Essential Features

The joint program has six essential features: They are:

1. Hands-on.
2. Team-based.
3. Non-hierarchical.
4. Community-oriented.
5. Attentive to the interior life – sensations, feelings, imagination and action tendencies.
6. Inspired by humanistic values.

The meaning of these terms will become clearer in the next section, but we have laid out enough material to sum up our grand thesis: If we as educators can create such an environment and our students build prototypes in it, we will increase the likelihood that they will self-actualize and be highly innovative.

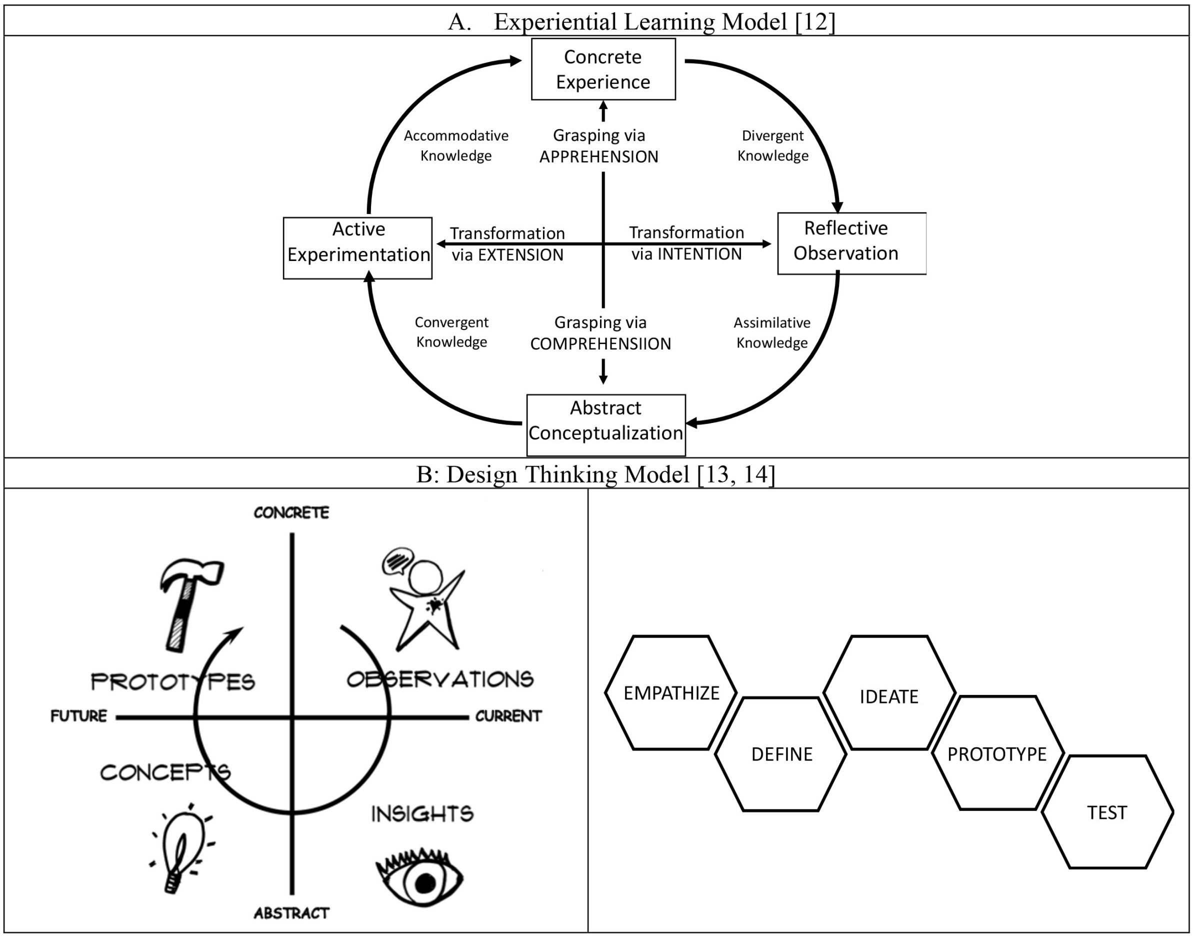
2. Defining Our Terms

2.1 What is Innovation?

There is no innovation without invention, which we define as the creation of a new device. Innovation is the introduction of this device into the public sphere – that could be in the marketplace, a private enterprise, the military, or simply the patent office. For example, the development of the computer mouse began at the Stanford Research Institute (SRI) in 1960. The first prototype was built in 1964; a patent was filed in 1967 and issued in 1970. SRI then licensed the technology to Apple, Xerox and other companies. The mouse became commercially viable in 1984 [5)]. This means it took roughly 20 years from invention of the first prototype to innovation in the marketplace. Thus, innovation requires some degree of belief, patience and perseverance.

2.2 Why Is Innovation Important to Design Educators and Researchers?

Innovation has always been intriguing to engineering design educators, but the drive to formally study the design process surged in the US in the 1980s, when the productivity and innovativeness of Japanese companies – particularly in automobiles, electronic devices, and microprocessors – far exceeded the performance of US companies. This provoked a national crisis that resulted in the creation of the National Science Foundation's design theory and methodology program [6], and the development of a new set of accreditation criteria for engineering education, the ABET 2000 [7–9]. The mandate of the NSF design theory and methodology program



A. Experiential Learning Model [12]

B: Design Thinking Model [13, 14]

Fig. 1. A depiction of the similarity between Kolb's Experiential Learning Model and the Design Thinking Model – two popular models used by engineering design educators to nurture innovation.

was to, "improve the creativity of engineering design and the effectiveness of product design and development, leading to improved national productivity and international competitiveness." [6]

This response was like the reaction to an event sometimes referred to as The SPUTNIK Shock, roughly 30 years earlier, when Americans awoke to the news that an unmanned Soviet satellite was flying overhead. The National Defense Education Act (NDEA) was enacted in 1958 [10], the Advance Research Program Agency (ARPA) was created by the Department of Defense – it later became DARPA – and has been one of the primary drivers of innovation in the U.S. since then. DARPA's mission is to ensure that the United States, ". . . would be the initiator and not the victim of strategic technological surprises." [11]

Those two crises led to a strong linkage between education, technology development capability and innovation. Following the SPUTNIK shock, there was an emphasis in the 1960s on science education. In the 2000s, following the ascendance of Japanese companies, there was an emphasis on capstone design courses.

2.3 *How Does Innovation Happen?*

The honest answer is that no one seems to know, precisely, but a close examination of what's being used in universities to foster it offers some clues. In Fig. 1, we show two popular models – David Kolb's Experiential Learning Model and the Design Thinking Model.

Scientific practice emphasizes observation and active experimentation; design thinking focuses on empathy (observation) and rapid prototyping (experimentation). Both models depend on hands-on learning. Note that neither process guarantees invention or innovation, which leads to the next vexing question...

2.4 *Why is it so Difficult to Innovate?*

The simple answer is that most of us do not want to innovate, and do not know how. In an essay on the paradox of innovation, lecturer, art reviewer and AI researcher Pierro Scaruffi wrote about the hostility to it:

> "I see two instincts at work in nature. On the one hand there is 'imitation': each living being tends to imitate

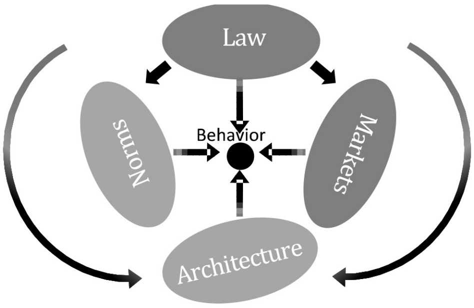


Fig. 2. The Forces Constraining an Individual's behavior in Society [16].

> what other living beings are doing. This is a widespread instinct . . . It is pervasive in human society. . . People who imitate are considered 'nice.' They behave in a way that conforms to what society expects from its members.
>
> Innovation, on the other hand, is not something that we find in nature. Innovation is a risk. Animals 'innovate' when there is a genetic mistake. In most cases, those animals die. In rare cases, they survive. They might generate a new species. They cause instability in the existing ecosystem. Innovation is rare and, when it survives, often catastrophic.
>
> . . . Innovation in human society is rarely welcomed. It is most often met with skepticism, hostility and plain accusations of heresy or madness. It is correctly perceived as a threat to the established order [because] innovation is the social equivalent of a genetic mistake. It takes time for society to accept it. . . ." [15]

Given the threat innovation poses to society, it is no wonder we have erected so many institutions (rules, norms, and enforcement mechanisms) to discourage it. Harvard law professor Larry Lessig points to four major societal constraints that guide – or coerce – an individual or group to act in a preferred (socially acceptable) way: Law, Social Norms, Markets, and Architecture [16].

1. Law directs behavior and threatens sanctions if not obeyed.
2. Social norms regulate familial and communal activities, constraining an individual's behavior, and maintaining traditions.
3. Markets regulate behavior through the mechanisms of price and scarcity.
4. Architecture, including infrastructure and physical relief, both restricts and enables behavior.

The interplay of these constraints is shown in Fig. 2.

These barriers, in addition to a fear of social repercussions, are all that an innovator has to overcome. Easy, right?

2.5 What Conditions are Required for Innovation?

Faced with these formidable barriers, innovation requires a small rebellion, a willingness to defy the norms and as we said earlier, to do these requires courage, and a high degree of autonomy. However, these are not enough. It also requires a youthful mind (of any age), a high level of open communication, and a nurturing culture.

2.6 What Personal Traits are Required for Innovation?

The two key traits necessary for innovators are courage and self-actualization. In the Stanford design program model we presented earlier, courage can be mapped to the attribute "attentiveness to interior life" and self-actualization can be mapped to the attribute "inspired by humanistic values." We shall describe each in turn and explain why they matter.

2.6.1 Courage

In Pierro Scaruffi's excerpt above, he made the role of courage in innovation obvious: "Innovation is a risk. Animals 'innovate' when there is a genetic mistake. In most cases those animals die." That is the most extreme scenario, but courage in this context can be manifested in many ways. Rolf Faste, a former Stanford Design professor, diagrammed a more prosaic but no less compelling risk-taking behavior:

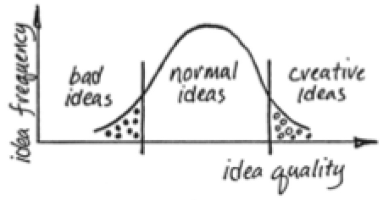
> "The fundamental difference between invention and innovation is made clear in the sequences shown in [Fig. 3]. Invention involves the conception and vertical growth of a new idea in the fringe of the idea distribution. Innovation is associated with the horizontal movement that occurs as these new ideas are incorporated into products, organizations, or systems on a broad scale. Both involve taking risks, and both are properly associated with creativity. At the same time, they require different skills and abilities. Invention has more to do with personal courage, while innovation has more to do with organizational courage" [17].

In a sense, then, personal courage has to do with personal time, materials and artifacts an individual can access and manipulate independent of others, and based on personal judgment. Organizational courage also has to do with personal time; however it involves people in the broader culture who may have values different from those of the individual and/or are opposed to what the individual would like to do for different reasons.

Thus, innovation can be particularly problematic in a culture that values individuality.

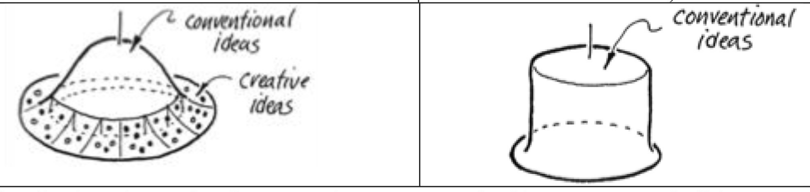
The relationship between personal courage and organizational courage is an important one, because the two are coupled. A courageous person in a fearful organization runs the risk of being silenced. A fearful person in a courageous organization runs the risk of weakening it.

A: The Creativity Bell Curve (CBC)

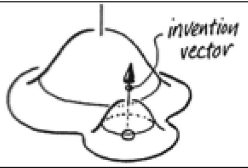


B1: A Visualization of the CBC in which Creativity is Encouraged (i.e., there are no "bad" ideas).

B2: A Visualization of the CBC in which Creativity is Discouraged (i.e., only "normal" ideas are allowed)



C. A Visualization of Invention (i.e., a creative, non-normative idea emerges vertically)



D: A Visualization of Innovation (i.e., the culture is "shifting" horizontally to accommodate the invention)

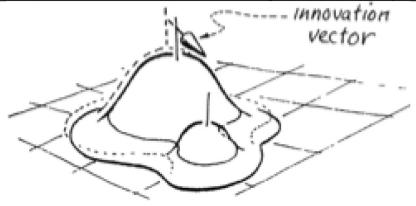


Fig. 3. A visual representation of standard conceptualizations of creativity, or the Creativity Bell Curve (CBC); a reconceptualization of the CBC as a 3D bell curve in which creativity is encouraged (B1) and discouraged (B2); a visualization of invention (C); and a visualization of innovation (D).

2.6.2 Self-Actualization

Self-actualization is a concept made popular by Abraham Maslow [18]. According to him, self-actualization is the need and ability a person has to become the best version of oneself. This could mean becoming more and more what one is, or becoming everything one is capable of becoming. Maslow identified a hierarchy of needs that drives human behavior, starting with physiological needs, then safety needs, love and belonging needs, esteem needs, and, finally, self-actualization needs, which he defined as the need to pursue and fulfill one's unique potential.

Maslow included several caveats for his hierarchy of needs, but while his model has been widely adopted, the caveats have mostly been ignored. We mention a few of them here because they are relevant to our thesis:

1. While higher needs generally won't be pursued until lower needs are met, a need does not have to be completely satisfied for someone to move onto the next need in the hierarchy.
2. Some individuals might pursue higher needs before lower ones. For example, people driven by the desire to express themselves creatively may pursue self-actualization even if their lower needs are unmet. Individuals dedicated to pursuing higher ideals may achieve self-actualization despite adversity that prevents them from meeting all of their lower needs.
3. We all have different values, desires and capacities, so self-actualization will take different forms for different people. One person may self-actualize by becoming a parent, another an artist, and still another will invent new technologies.
4. Because it can be so difficult to fulfill the four lower needs, very few people become self-actualized, or only do so in a limited capacity.
5. Self-actualizers share certain characteristics, such as high creativity, autonomy, concern for humanity, an acceptance of themselves and others and the ability to achieve peak experiences – moments of joy and transcendence – more frequently than other people.

3. Exploring the Axioms

Our four axioms come from the memoir of Terry Smith. In order to build on them and connect our learnings back to the memoir, we find helpful to use John Sowa's Janus-like model of a two-stage mapping from theories to models to the world [19], Fig. 4.

This approach follows an engineering paradigm in which our intention determines the model we build, and the performance of the technologies we develop.

A case in point: classical models and theories in thermodynamics did not emphasize variables such as exergy and availability because the earth's atmosphere was modelled as a thermal reservoir. Thermal Reservoirs are bodies that can exchange an infinite amount of heat with the system. The temperature of a thermal reservoir never changes. However, global warming and rising temperatures proved this is not the case, and new variables have been conceived and incorporated into the classical models and new theories have been developed, so that we can design better thermodynamic power systems.

This is the approach we are applying to humans and their organizations. In Fig. 5 we have extended the Janus-Model to include an individual instructor, a dyad consisting of an instructor and a student, and an organization, in this case the department.

We will now explore each of the axioms in the context of this model.

3.1 Axiom #1: An over-emphasis on literacy and numeracy has conditioned most of us to seek conformity and judge our worth and talents by standardized measures of quality. This adherence to hierarchical and bureaucratic norms makes us less creative, and easier to control.

Our opening case study of Terry Smith struggling over his charcoal drawing of Michelangelo's "David" represents an interaction in which the student is enabled to see the world for himself by an instructor who is not preoccupied with hierarchical systems or enmeshed in a bureaucracy. Thus, in the absence of the control-oriented hierarchical system, the instructor becomes the model between the world and the theory. The new Janus-like model is shown in Fig. 6.

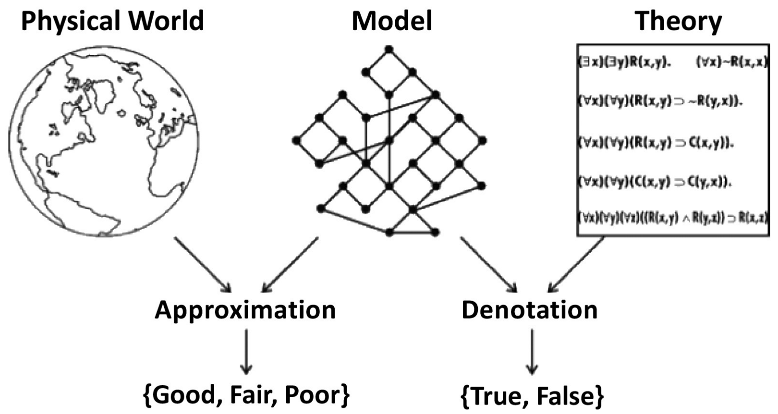


Fig. 4. The Janus-Like Model of a two-stage mapping from theories to models to the world. On the left is the physical world, which contains more detail and complexity than any humanly conceivable model or theory can represent. In the middle is a model that represents a domain of entities D and a set of relations R over D. On the right are theories, which are predictive statements about how changes in R vary with changes in D and vice versa.

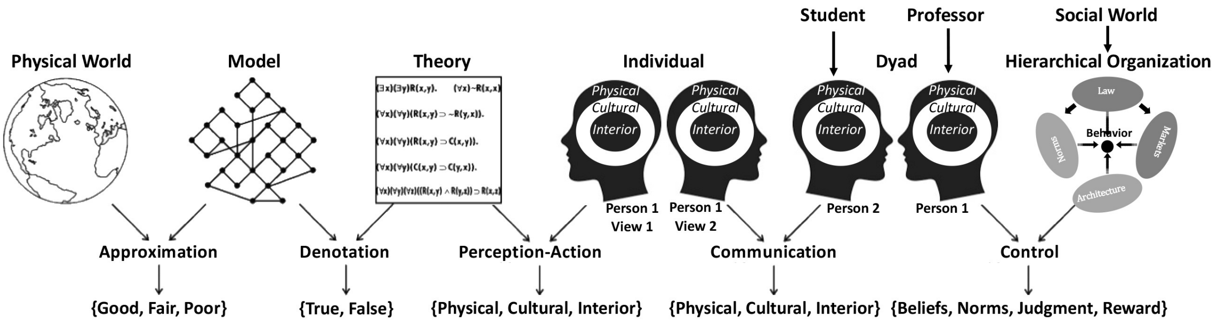


Fig. 5. The Janus-Like model extended to include the individual instructor, the dyad comprising the instructor and the student, and the organization, nominally their department.

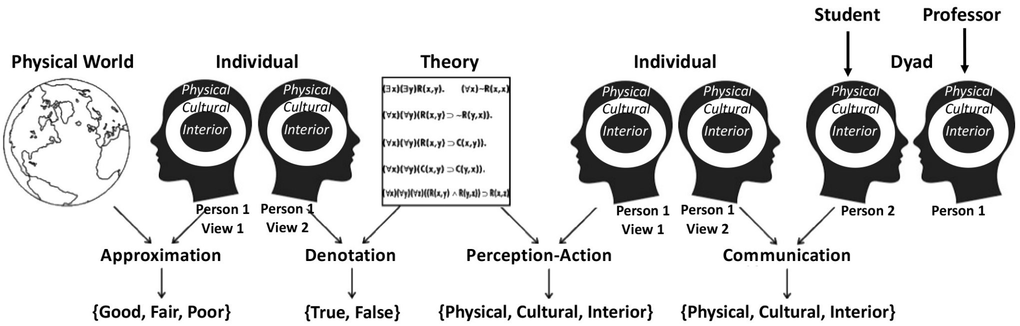


Fig. 6. Model Showing an instructor not preoccupied with a hierarchical system or enmeshed in a bureaucracy, and helping a student sense, perceive, and respond to the world through the visual arts.

The alternative model, in which an instructor is preoccupied by a hierarchical system and enmeshed in a bureaucracy, is the default model we showed earlier in Fig. 5.

Thus, if all an educator sees is a hierarchically organized world, this is what is conveyed to students, implicitly and explicitly. This brings us to our second axiom:

3.2 Axiom #2: By creating special conditions for prototyping, we can increase the likelihood of students transcending the conditioning and control and becoming more creative

Hierarchies encourage standardization and reduce variation, and as engineering educators, we have for too long focused on efficiency and productivity. We have done a very poor job of developing faculty with the confidence and culture needed to develop the creative capacity of our students. The conditions under which prototyping is done matter because learning is holistic and in addition to learning the skill, students are also paying attention to the faculty. They internalize the behavior of their teachers.

The narrative we will use to explore this assertion comes from Bernard Roth's book, "The Achievement Habit" [20]. Roth was a member of the Design Division at Stanford, whose flagship program, JPD, was a collaboration between the mechanical engineering department and the art department. JPD was founded in 1958 by Bob McKim (Mechanical Engineering) and Matthew Kahn (Art). Here Roth describes how his experiences with the arbitrariness of organizational leadership and the exercise of power led him to discover a new and powerful paradigm:

> "Growing up in America, I was brainwashed to believe that every organization needs a formal structure with a leader on top. . . My experience at Stanford – regarding leadership, working with groups of colleagues and with groups of students – has been remarkable, and somewhat atypical. Originally, I was a member of the mechanical engineering department, which had about twenty-five faculty members grouped into three divisions. I was a member of the Design Division. The chairman chose a director for each of the three divisions; this was an efficient arrangement because he only had to deal with three professors, instead of all twenty-five. . . It was the mid-1970s, and people were reconsidering many things within the social order. It was a time of student unrest, social protest, and the questioning of traditional societal structures and values."
>
> "The Design Division had eight faculty members, and we unanimously decided to restructure our group to operate as a flat organization without a director. . . Our new structure hinged around an hour-long weekly meeting, open to all Design Division faculty and staff. The meeting had no chair-person; we simply went around the table, taking turns bringing up any issues that required the division's decision, reporting on past happenings, and announcing future events. We operated by consensus and negotiation, almost never voting on anything. There was almost no acrimony, and people treated each other with respect, collegiality, and a spirit of shared purpose and commitment. . . We were all in charge, and we all wanted to make it work. . . We now had the most powerful form of organization in the department because we were a large group of people with one voice. . ."
>
> "It was a powerful new model. . . We chose to divide up the jobs and rotate among them in order to be efficient and to make it easy for others to deal with us. One of us was responsible for the finances, another handled course scheduling, another represented us at the chairman's weekly meeting with the other divisions' directors; yet another person dealt with staff issues, and the dreariest position of all went to the person who dealt with office and classroom space. (To compensate, we decided to let him have the exalted title of Space Czar.)"
>
> "All these positions were regularly rotated, and new positions were created on an as-needed basis. We all had an equal voice. Those who cared most about an issue took on the leadership to get it handled. If nobody cared, we did not do much about that issue until someone wanted it resolved."
>
> "The new system went a long way toward creating a unique and strong culture. Interestingly, whenever we acquired new faculty... they quickly adapted to become fully contributing members to this unique group. . ."
>
> "There is a long-standing argument for the idea that

> one person needs to be in charge. It goes way back to Adam Smith's writings in 'The Wealth of Nations.' Even Friedrich Engels agreed with Smith that 'a ship needs one captain.' I certainly am not an expert on ships, and I hate to disagree with the luminaries of both capitalism and communism, however this is at variance with my experience. The flat, participatory model we developed worked very well. . ."

What Roth and his colleagues created for themselves was a new world, a new way of being an educator, and a new way of structuring power. Young faculty now had the opportunity to be themselves rather than seek to conform to the demands of a hierarchical organization. And if students interacted with self-actualized faculty, the chances of them self-actualizing were greatly improved. Since those early days, members of the design division have gone on to introduce several other innovations into education more broadly and engineering education in particular. The most prominent of these being the Stanford d.school, which introduced the design-thinking mindset to the world. Based on Roth's experiences, we have adjusted our model to show the non-hierarchical social world of the design division (see Fig. 7).

Faculty's view of the world is influenced by their situation and their psychological milieu. This, in turn, influences the psychological milieu they create for the students to do prototyping, thus affecting student learning and development.

3.3 Axiom #3: Professors cannot help students to self-actualize unless they, too, are self-actualized

Engineering students and faculty have traditionally been involved in modeling and optimizing mathematical equations related to fairly well understood phenomena and technologies. In many schools, faculty have not had to deal with the internal emotional experience of the creative process and non-hierarchically organized teams. However, with increasing emphasis on creativity and innovation, there is a need to confront the internal world and to self-actualize.

3.4 Axiom #4: Students who transcend the traditional conditioning and control will be able to create novel technologies and innovative organizations.

Given the environment we have described and the exposure to professors who are role model, we believe we would increase the likelihood of students to self-actualize. Following from Maslow's observation [18], we further believe that becoming self-actualized will allow our students to be more creative, and more fulfilled in their work.

4. You Can Get There from Here

Our goal in this section is to give faculty some idea of what to expect from students when schools change the conditions under which they do prototyping. For the last 30 years, we have been studying students at Stanford with the goal of developing metrics to characterize their design behaviors. We briefly highlight four studies culled from Ph.D. dissertations that offer some of these metrics.

4.1 Study #1: Creating the Conditions for Radical Breaks

Engineering design prototypes come in a cascade of formats, from pencil sketches to CAD print-outs, from prototypes made of wood, and those made of steel. The cascade can be put in a 2x2 matrix according to the level of abstraction (how much detail is included) and the resolution (the level of refinement), Fig. 8 [21].

Building on this work, Jonathan Edelman [22] developed a framework (Table 1) to describe three classes of designer behaviors that predict if the prototyping process would lead to incremental improvements or radical breaks.

Let's take a closer look at each class of behaviors. We have added three descriptive terms – locus of attention, dialog, and plot or flow – to make his classes more readily understandable.

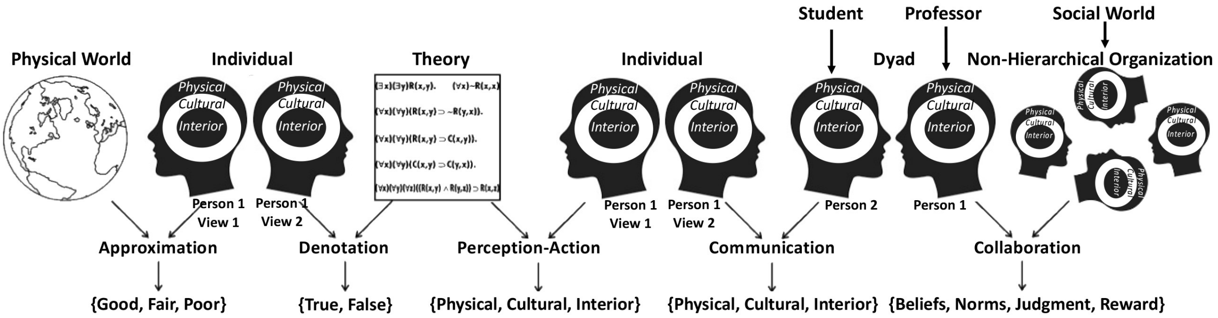


Fig. 7. Model showing an instructor not preoccupied with a hierarchical system or enmeshed in a bureaucracy. Instead, the instructor is part of a non-hierarchical organization as described by Roth.

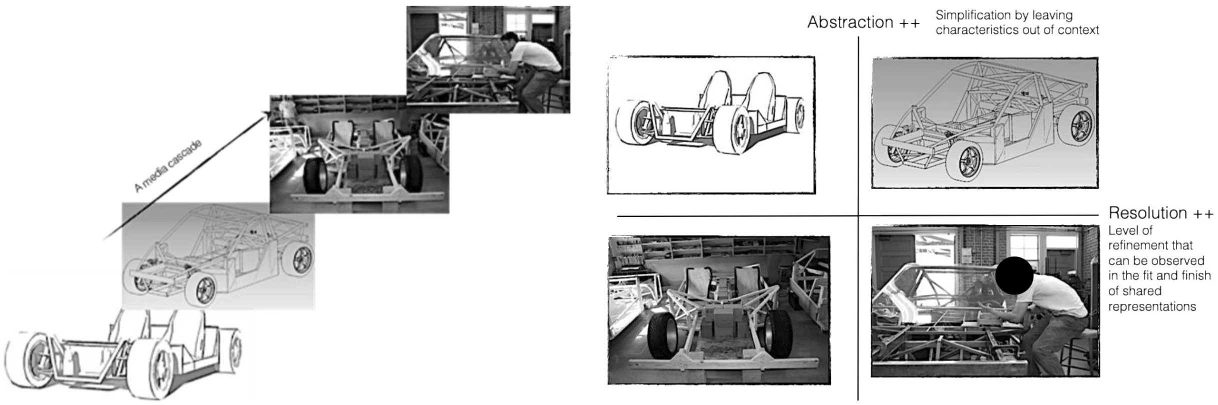


Fig. 8. The Media Cascade through which engineering design work progresses.

Table 1. Edelman's Innovation Behaviors Framework

	Incremental Improvements	**Radical Breaks**
Design Behavior	***Mode***	
Dimensions of Engagement	Object: ++ Surface + Depth n/a Core World: Usability ++ Scenario + System n/a	Object: + Surface ++ Depth + Core World: Usability + Scenario ++ System +
Media Response and Interaction	**Anchoring**	**Scaffolding**
Path Determination	**Navigation**	**Wayfinding**

(#1) Dimension of Engagement (locus of attention)

Edelman observed that designers constructed real and imaginary worlds and real and imaginary objects. In those worlds, they may focus on the whole system, a use scenario, or the usability of a particular aspect of the world. Regarding the objects, they may focus on its core functionality, surface level features, or deeper level features. Designers who did not focus on an objects core functionality, nor took a whole systems view of the real or imaginary worlds they constructed were highly unlikely to make radical breaks. This is shown in the table as n/a.

(#2) Media Response and Interaction behaviors (dialog)

Here Edelman made the distinction between anchoring behaviors, where designers appeared to be fixated on an object or system, and scaffolding behavior, where designers use the object or system as means for some other end.

(#3) Path Determination (plot or flow)

Path determination refers to how designers determined what they would do and when. Edelman made a distinction between navigating and wayfinding. According to him, Navigation involves a predetermined plan of what and how to redesign. Many of the tools and practices in traditional engineering tacitly or explicitly rely on navigation to structure the activity of design. Groups that excel at incremental redesign engage in navigation behaviors. Wayfinding, on the other hand, requires *in situ* determination of path based on perceptual cues from the real or imagined environment, often accompanied by prose. Radical Breakers enlist wayfinding to discover, explore and unpack novel product concepts and use scenarios.

From this sample of Edelman's work, we can see that radical breakers will be harmed by a hierarchical structure.

4.2 Study #2: Noun Phrases as Surrogates for Measuring Early Phases of the Mechanical Design Process [23, 24]

A co-author of this paper, Ade Mabogunje, began his work developing knowledge-based hierarchical models of student work in a seven-month-long design class. Every week, he collected all their notes, writings, drawings, and correspondences, and from that developed a hierarchical model of their evolving designs. It was common then to point to chess as an model of reasoning and human problem solving, but he noticed how little the work of the students resembled a chess match, with its clearly defined "theater" (the board), "actors" (the 32 pieces, all of them named) and the "script" (the many rules defining moves and strategies and endgames). Instead, what he saw was a "chess game" in which the players created new pieces, new rules and ignored the checkerboard grid to play on whatever field their imaginations landed upon.

Mabogunje expanded his study by extracting noun phrases, key components for building knowledge-based models, from all the formal documents

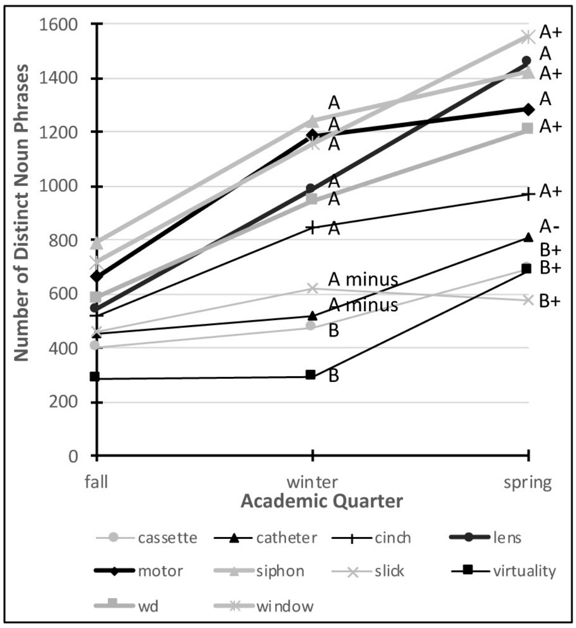


Fig. 9. The Evolution of Noun Phrases in 10, Seven-Month long Projects.

submitted by all the teams each quarter for three quarters and compared the results with the grades the teams received. His work showed a positive association between the grade and the number of distinct noun phrases used, Fig. 9, and that the creation of new noun phrases could be used as a metric for the creation of new concepts.

The significance of this work can be seen in a critique of engineering writing by J.E. Conner in his book "A Grammar of Standard English" [25]:

> "In the newer technologies – notably in engineering – the {nomenclature} conventions are not systematic or clear; the {engineers} themselves are either unaware of the lack of clarity and system, or do not choose to make the effort to repair it. Therefore anyone who reads technical documents must make his way through agglomerations like these:
>
> - the highest previously available intrinsic coercive force;
> - single side band transmission;
> - high frequency stability;
> - high-energy particle accelerator;
> - internal transducer excitation supply;
> - the segmented multiple ablative chamber concept;
> - combustion chamber crossover manifold coolant passages.
>
> . . . This situation will stay with us until the {engineers} establish some firm conventions and hold to them as chemists and mathematicians hold to theirs."

If we combine Edelman's media cascade with the fact that engineers do not seem to be conforming to grammatical conventions, we see that a hierarchical system imposed on their process may impede their creative process. This will become even clearer in the next study.

4.3 Study #3: Asking Generative Design Questions: A Fundamental Cognitive Mechanism in Design Thinking [26, 27]

By analyzing video data collected during a two-week design project of graduate engineering design students told to design, prototype and race a paper bicycle, Ozgur Eris observed that some questions posed by the students seemed to have a strong effect on pivotal decisions, while others had no discernible impact. He found that question-asking taxonomies from fields as varied as philosophy, education, artificial intelligence and cognitive psychology captured most of the types of questions asked by engineering designers. He then wanted to find out if there was a specific kind of question that led to key decisions.

The empirical data from which questions were extracted was collected in a series of 90-minute, quasi-controlled experiments in which 14 teams of three graduate mechanical engineering students designed and prototyped a device that measures the length of body contours. When the published taxonomies were used to categorize the questions, 15.4% of the questions did not fit into any of them. Analyzing the nature of these questions and why they were not represented in the published taxonomies resulted in the identification of an overlooked domain. He called this domain Generative Design Questions, to distinguish them from the other questions, which he called Deep Reasoning Questions. According to Eris, the premise behind the published taxonomies is that a specific answer, or a specific set of answers, exists for a given question. Such questions, he claimed, were characteristic of convergent thinking, where the questioner is attempting to converge on "the facts." The answers to converging questions are expected to hold truth-value since the questioner expects the answering person to believe his/her answers to be true.

In contrast, the Generative Design Questions tended to operate under a very different premise: for any given question, there existed multiple alternative known answers, as well as multiple unknown possible answers, and being true or false was irrelevant. Such questions, he claimed, were characteristic of divergent thinking, where the questioner is attempting to break free from the facts to consider the possibilities that can be generated from them. Eris's comparison of the taxonomies is shown in Table 2.

This, as in the previous two cases, tells us that engineering designers are operating under very different premises from those of the rest of society.

4.4 Study #4: Group Hedonic Balance and Pair Programming Performance: Affective Interaction Dynamics as Indicators of Performance [28, 29]

The final study comes from the domain of soft-

Table 2. Eris's Comparison of Taxonomies and the Discovery of Generative Design Questions

ARISTOTLE	DILLON	LEHNERT	GRAESSER	ERIS
Existence (Affirmation)	Existence/affirmation	Verification	Verification	Verification
	Instance/identification			
Nature (Essence/Def.)	Substance/definition		Definition	Definition
			Example	Example
Fact (Attribute/ Description)	Character/description	Feature Specification	Feature Specification	Feature Specification
		Concept Completion	Concept Completion	Concept Completion
		Quantification	Quantification	Quantification
	Function/application	Goal Orientation	Goal Orientation ■	Rationale/Function ■
	Rationale/explication			
	Concomitance	Disjunctive	Disjunctive	Disjunctive
	Equivalence		Comparison	Comparison
	Difference			
Reason (Cause/ Explanation)	Relation		Interpretation	Interpretation ■
	Correlation			
	Conditionality & Causality	Causal Antecedent	Causal Antecedent ■	Causal Antecedent ■
		Causal Consequent	Causal Consequent■	Causal Consequent ■
		Expectational	Expectational ■	Expectational ■
		Procedural	Procedural ■	Procedural ■
		Enablement	Enablement ■	Enablement ■
				Proposal/Negotiation●
				Enablement ●
				Method Generation ●
				Scenario Creation ●
				Ideation ●
		Judgmental	Judgmental	Judgmental
	Rhetorical		Assertion	
		Request	Request/Directive	Request
	Deliberation			
	Unspecified			
	Unclear			

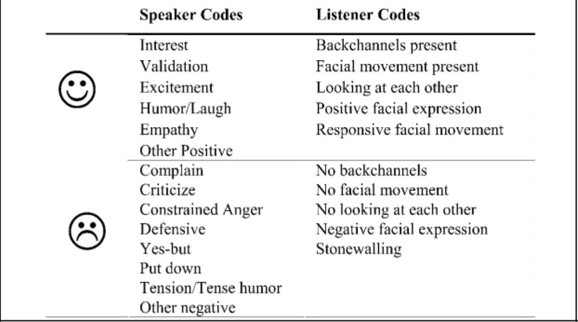
■ Deep Reasoning Question (DRQ). ● Generative Design Question (GDQ).

ware development. Pair programming is a method where two computer programmers work shoulder-to-shoulder at a single computer. Studies of university programming classes have shown that pair programming yields better design, more compact code, and fewer defects for roughly equivalent person-hours While past research focusing on pair programming interactions looked at the influence of personality types and collaborative behavior – such a keyboard switching, driving and navigating behavior, communication and system complexity – no research had focused on the quality of pair programming interactions by investigating affective interaction dynamics. Malte Jung had been a student in one of the design classes in the ME department, so he had experienced the emotional struggle design teams go through during strong disagreements. He sought to better understand the challenges teams faced and was inspired by researchers of married couples who had developed a model that related affective interaction dynamics with long-term subjective and objective outcomes. In particular, the study of Gottman and Levenson that showed it is possible to accurately predict (93%) the fate of a marriage based on the affective interaction quality determined from just a 15-minute video sample of a couple's interaction (30). In another study, divorce could be predicted based on the affective interaction quality during the first three minutes of a conflict episode with 80% accuracy (31). Using the same methods, it was possible to predict subjective marital outcomes such as satisfaction and objective outcomes such as divorce across a wide range of studies.

A key idea in all these studies was a balance theory of marriage, which says a couple's ratio of positive to negative affect (hedonic balance) is critical to the quality of their interactions and their long-term outcomes. Couples whose hedonic balance is more positive than negative are termed regulated couples. Couples whose hedonic balance is more negative than positive are deemed non-regulated, and the hedonic balance expressed as a gradient was shown to be predictive of marital dissatisfaction and divorce.

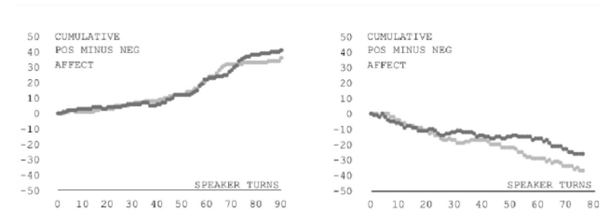
Jung hypothesized that pairs of programmers with a higher group hedonic balance will outperform those with a lower group hedonic balance.

He analyzed the video record of 16 teams, whose performances had been evaluated using two subjective and two objective measures. The two subjective measures were (1) satisfaction with the programming experience, and (2) satisfaction with the developed code. Both measures ranged from 1 (low) to 7 (high). The two objective measures were (3) duration to solve the calendaring task, and (4) code performance. Scores were determined by awarding one point for each test passed, resulting in a scale of 0 to 19 points. The average score for all pairs was 11.5, ranging from 0 points for the lowest



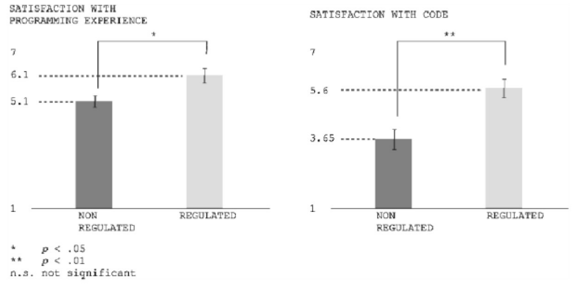
	Speaker Codes	Listener Codes
☺	Interest	Backchannels present
	Validation	Facial movement present
	Excitement	Looking at each other
	Humor/Laugh	Positive facial expression
	Empathy	Responsive facial movement
	Other Positive	
☹	Complain	No backchannels
	Criticize	No facial movement
	Constrained Anger	No looking at each other
	Defensive	Negative facial expression
	Yes-but	Stonewalling
	Put down	
	Tension/Tense humor	
	Other negative	

Modified RCISS Coding Scheme

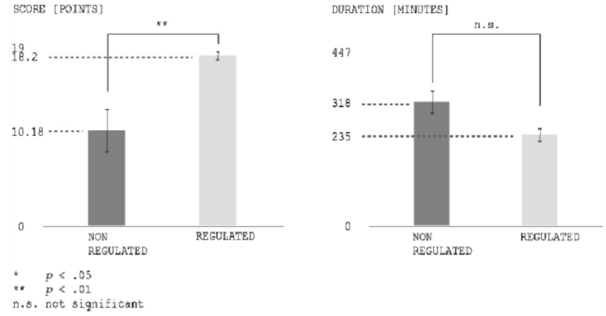


Point Graphs of Regulated and Non-Regulated programming pair.

Fig. 10. Emotion Codes and Point Graphs of Regulated and Non-Regulated Programming pair.



Subjective Performance



Objective Performance

Fig. 11. Bar Charts comparing objective and subjective performances of regulated and non-regulated pairs of programmers.

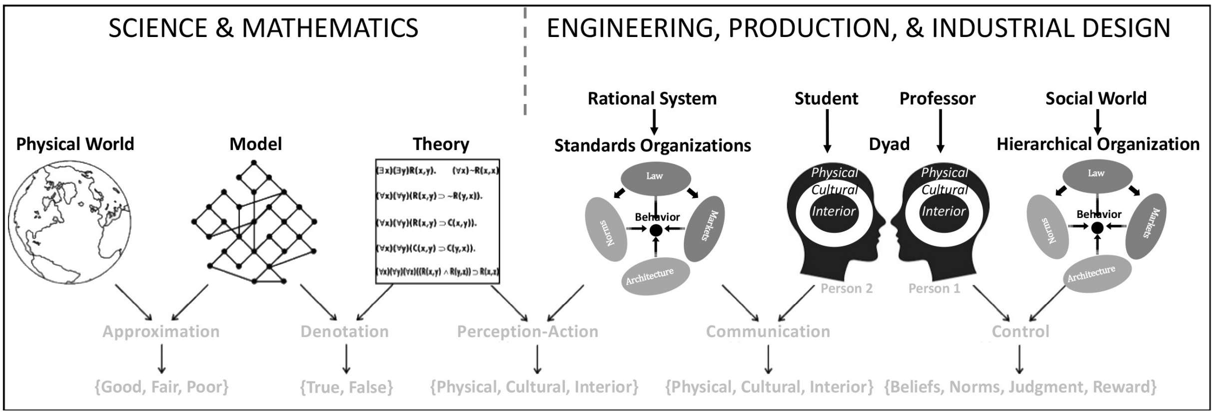


Fig. 12. Control-oriented Hierarchically Organized Design Engineering (CODE).

performing pairs to 19 points for the highest performing pairs. The results are shown in Figs. 10 and 11.

The results confirmed Jung's hypothesis. Good teams are like good marriages [29].

From these four studies, we can see that the inner life of designers is an important predictor of performance.

When thinking about bringing inventions to market – innovation – we can extrapolate from these results to predict that a start-up team whose affective interactions point to a divorce will have greater difficulty bringing a product to market.

We hope the four measures illustrated in this section – radical break behaviors, new noun phrases, generative design questions, and positive hedonic balance – show faculty what to expect from autonomous design teams whose primary purpose is to innovate. In addition, we hope we've shown how some of the attitudes and behaviors that foster creativity will be squelched in a hierarchically structured organization.

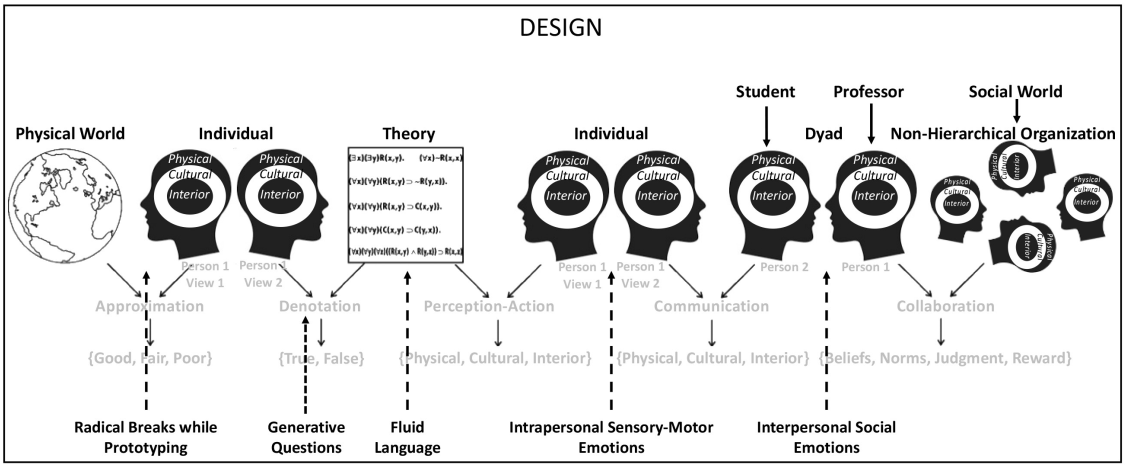


Fig. 13. Non-Hierarchically Organized Design Engineering (NODE).

5. Preserving a Non-Hierarchically Organized Ecosystem

Before concluding, we want to elaborate on the potential tension between preserving an autonomous innovation ecosystem within a broader, more traditional institution. We will call this traditional one the Control-oriented Hierarchically Organized Design Engineering (CODE), Fig. 12; and the Emergent models, such as the JPD at Stanford, we call Non-Hierarchically Organized Design Engineering (NODE) Fig. 13.

It is important to acknowledge that there is a choice for most departments. We believe this is important because it might seem like a comparison between a Goliath and a David – the CODE model is used almost universally, and has been around for over a century, while the NODE model is employed and supported here by a student's memoir, Bernie Roth's positive cantankerousness, and several small-sample experiments. Even Roth, acknowledged that a non-hierarchical model, would not necessarily work in other contexts. He noted that the model suited his personality, and that his arguments for it were up against the opinions of Adam Smith and Max Engels, the fathers of capitalism and communism [20], as well as the rest of the Mechanical Engineering department at Stanford.

Despite these caveats, this alternative model, this "David," has worked for 50 years at Stanford and we believe there are some crucial lessons to be learned from it. We would like to focus on just a few, specifically those that throw light on how to preserve a non-hierarchically organized ecosystem within a larger hierarchically organized one.

5.1 Running Interference

The chair of the ME department had requested a list of publications from each faculty. As most people in academia know, publications are used to rank faculty productivity. Bernie Roth knew that certain key faculty within the design division had few to no publications because it was not their "thing." Roth liked to write and had many publications, so he suggested that the ME design group faculty submit their publications as a group. When they did this, their productivity was on par with other groups within the department and number of publications could not be used as a criterion to disadvantage the design group.

5.2 Keep the Faculty Group Small and Diverse

The design group consisted of faculty that emphasized different aspect of being an engineer – from Rolf Faste, who focused on the individual subjective experience of designing and ambidextrous thinking, to Larry Leifer who taught the team-based, graduate level, industry-sponsored projects, design course to David Kelley, who focused on the user, to David Beach who ran the Student Machine shop where students get to do hands-on prototyping, to Bernie Roth, a Kinematics expert, and several others whose primary tool was mathematics. Since members of the faculty were small, and met regularly, they were able to develop a fluency in translating between "languages" (emotions, hands-on, user needs, physical hardware, mathematics). Students working in this environment would often find the spark for their passion in one of the areas and develop this in a holistic manner, which often involved one or two other areas. Fig. 14 is a Venn diagram of the main areas mentioned above.

5.3 Being Vulnerable

One of the authors once asked Rolf Faste why he sometimes gave assignments for which he did not know the answer. His response was that it gave

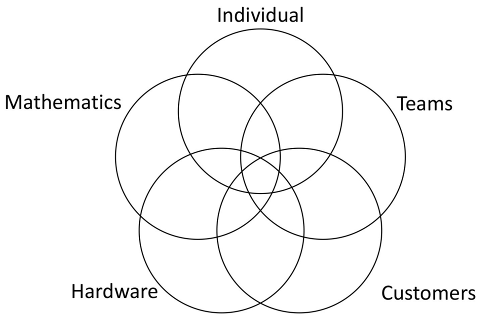


Fig. 14. The design group faculty often teach their courses in an integrated way combining three, four, or all of these areas, which pertains to different aspects of engineering practice.

students the opportunity to see him struggle in an authentic way and signaled to them that it is ok to struggle. Asked why many of his colleagues did not adopt this approach, he speculated that one reason might be a need to feel in control in the classroom.

5.4 The Science of Art

In the design group, equal emphasis was placed on art and science. Science as a way to know the world, and art as a way to know oneself. There was no hierarchy between science and art, between engineering and manufacturing, and between mathematical modeling and hardware prototyping. It was common for professors with passions in different areas to co-teach courses.

5.5 Reverse Hierarchy

The Stanford Design Faculty went to great lengths to meet the needs of the student. The following three excerpts from Peter Drucker's 1969 book, "The Age of Discontinuity," [32] captures the reason for this in three ways, and the redundancy is for emphasis.

> "Excerpt #1: The innovative organization needs a new attitude on the part of people on the top. In the managerial organization, the top people sit in judgment; in the innovative organization, it is their job to encourage ideas, no matter how unripe or crude. It is the job of the top people in the innovative organization to try to convert the largest possible number of ideas into serious proposals for effective, purposeful work. It is their job to say: '. . . what would this idea have to be for it to be taken seriously?' It is not their job, as in the managerial organization, to say: 'This is not a serious proposal.' "
>
> "Excerpt #2: The innovative attitude requires willingness on the part of people at the top to listen, to encourage, and to go to work themselves at converting crude guesses into understanding, the first glimpse into vision, and excitement into results. This is not, as so many people believe, 'creativity.' Nor is it 'disorganized.' It is a highly organized, disciplined, and systematic process. But it requires a different approach and different procedures from those of the well-managed organization."
>
> "Excerpt #3: 'Professional' management today sees itself often in the role of a judge who says 'yes' or 'no' to ideas as they come up. . . Only a top management that sees its central function as trying to convert into purposeful action the half-baked idea for something new will actually make its organization – whether company, university, laboratory, or hospital – capable of genuine innovation and self-renewal."

The rebellion of Roth and his colleagues was a social innovation and a pedagogical revelation. Nominally, as educators we are complicit in the production of students who would graduate to become cogs in the machinery of society. Now, with an alternative model, we can explore other ways of being. This is the power of the NODE model.

Going further though, Roth and his colleagues appear to have unknowingly done more than just discover a new way to organize. They made a revelation. They revealed that engineers can have the soul of artists, and the ethos and autonomy[1] of craftsmen [33].

6. Conclusion: The Innovation Rebellion Will Be Self-Actualized

> "The difficulty lies not so much in developing new ideas as in escaping from old ones." – *John Maynard Keynes*

We have argued in this paper that too many of our faculty and students are trapped in old hierarchies, and circumscribed by the dreaded Three Rs: rote, regimentation and rigor. Most design classes implicitly follow a hierarchical model, where the goal is imitation, not innovation. The NODE model, by contrast, creates a new kind of learning experience, and a new kind of community – one that is collaborative and guided by humanistic values. It is a place that fosters self-actualizing, i.e., developing autonomy, self-awareness, and self-acceptance. And with those attributes in place, students will have the courage to innovate, whether that be in a prototyping exercise or in their personal lives.

We posit that too much hierarchy inhibits self-actualization and reduces the rate of innovation. The flip-side of that: An engineering education ecosystem that promotes self-actualized and non-hierarchically-organized faculty increases the number of students who also self-actualize and can increase the rate of innovation in a society.

Students who are self-actualized will not do things merely to please their professors, or their managers. They will create rather than imitate. They will not conform to the old model. They will

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[1] Richard Carlson, an employment law professor wrote: "The ultimate success of modern firms was due in part to the erosion of autonomy of the various actors in the production process by the establishment of a strong managerial bureaucracy, the coordination of work activities, and the standardization of the procedure and specifications of work." [34]

be bold. They will be more creative, more fulfilled in their work, and more fulfilled in the rest of their lives. They will have a greater ability to achieve peak experiences – moments of joy and transcendence. We can think of no better goal for educators, and no better outcome for our students. Then again, as Matthew Kahn taught us, ". . . when you have talent, you can always create something even better." [4]

We don't claim to have talent. But we do claim to have the will and a way. Our intention with this paper is to contribute to the emergence of more thriving innovation ecosystems, both in academia and beyond.

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