Evolving Systems

Chapter 1 focused on design process and how it can be used to enhance creativity and manage it to enable engineers to better achieve project performance and schedule goals. This chapter has thus far focused on thought processes that can help an engineer generating and creating ideas. This final section will focus on system issues, including how engineers can more effectively work together in a team, without having to give up their individualities. Engineers must focus on their design task, but like a good optical system, they must have good depth in their field: they must be able to also focus on the broad needs of the system to ensure that their piece of the action is compatible with all the other pieces. Thus regardless of what part of a machine an individual is responsible for, or a single engineer happens to be developing at the time, the engineer must keep an eye on all the parts of the system:

- Structure and Geometry: What is the overall physical framework and what space does it require and what loads must it withstand?
- Kinematics/dynamics: What are the required/possible motions, speeds, and loads?
- Bearings: How will moving components be supported?
- Actuators: How will components be actuated and what are the power requirements?
- Sensors & Controls: What sensors are required, and what control system, including software, is required to process the data and operate the system?
- Manufacturing: How will all the components be manufactured, assembled, and tested?
- Maintenance & Support: How will the system be maintained and what types of customer support will be required?
- End-of-life: What happens to all the pieces when the system comes to its end-of-life? Can it be taken apart as easily as it was put together?

The glue that ties the team together should be awareness of the attributes and risks associated with each part of the system. The goal needs to be to minimize overall cost and risk and maximize overall performance. For complex systems, careful systematic dissection and analysis of the problem is the best way to succeed. Risk WILL be encountered, but risk represents opportunity and thus it is neither to be feared nor ignored, but rather it is to be managed by continual evaluation. Perhaps the best way to be an effective team member is to first do it alone so you can better appreciate how much stuff there is to do, and how easy it is to miss some minutia that later turns out to be a critical factor. Then when you are a member of a team, you will be able to contribute better, as well as coach others to be better contributors. You MUST become good designer in your own right, if you are to ever function effectively in a team.

Some people love teams and some people hate them, but the fact is humans are social life forms, and everything we have is because of teamwork catalyzed by individual spirit and drive. A good manager and a good team can create a positive experience for all if a passion catalyzed deterministic process is used to create and develop ideas. This process involves letting individuals first be individuals, and then gradually blending and evolving ideas:

- Individual thought:
  - Often the most creative.
  - Do before people are influenced by others.
- Peer Review:
  - First individual, and then group analysis and discussions, offer the best of both worlds.
  - Preloads all people to know what other team members are thinking.
- Group brainstorming:
  - Greatest breadth of resources applied collectively.
  - MUST do Individual and Rohrbach stages first!.

Consider contests where individuals must create, develop, build, test, and operate their robots. This, however, does not mean that you cannot share ideas and discoveries with your classmates. In the real world, companies often are friendly competitors where they develop and share pre-competitive technology because they know when they give a gram, they often get a kilo back from the group. Final success is a strong function of how well ideas are implemented, how robust the final product is and how well it is supported.

What technologies are common to most ideas that have evolved? Can these generically required ideas be developed and shared by the students in your lab section? How about mounting motors, or bearings or gears or wheels? How about wiring and use of the control system? What is the best way to design and cut gears and layout, cut and bend sheet metal?

Evolving Systems: *Individual Thought*

Pendulums tend to swing with very predictable dynamics. The problem occurs when pendulums are added to pendulums and compound motions start to occur. So it is with complex ideas, and indeed the problem becomes even more chaotic, if that even seems possible, when teams of people become responsible for bringing a complex product to market. So how are complex projects ever completed, and what role does the individual play? The answer is that good products come from good *project management* by a s*trong visionary leader* who is aided by *competent creative individuals*.

Indeed, very few products can be developed by individuals; on the other hand, very few teams can function without strong leadership. It takes a team to do everything from identifying the need, to creating and developing the idea, to producing, distributing, and supporting it. However, the weakest link in the chain is still the individual be it an engineer, machinist, or manager. When faced with a difficult problem, an individual must not think "someone else will take care of that". The individual must either plan on addressing the problem (opportunity!) or determine who exactly will handle it. In this manner, critical things will not be overlooked. Remember, all it took was a simple O-ring embrittled by the cold to cause the Space Shuttle *Challenger* to blow up in 1986! An individual engineer thought of the problem and passed the thought on to an individual manager who did not think that the risk was significant. A failure of individuals' thought processes led to the demise of the team. including the astronauts.

Hence the first stage in the development of a team must be the development of the individuals. Each individual must first learn their strong and weak points and their limits; thus when they are on a team, they will know when to volunteer, and when to ask for help. Bravado can not only hurt yourself, it can hurt others. Do you want to be responsible for other people losing their jobs because you were not doing yours? The first step in teamwork is for each individual to recognize early on in their educational pursuit of a degree that they will one day be a member of a team. They must realize that other people will not be there to carry them, so study hard and efficiently. It means the smarter you learn[1], the more fun the entire team will have! Education is not a game, it is your future, so you must learn to learn in whatever form information is available, and to never stop learning!

Now that the house is heated, the first step a team takes after being assembled, is to take a first-pass at defining the problem (opportunity!); however, the team must not start suggesting ***strategies*** or ***concepts***. This would likely pollute individual's thoughts. Accordingly, the next step is for the individual team members to disperse and go think about the problem by themselves. In this mode, the individual's job is not only to think of ***strategies*** and maybe some ***concepts*** to solve the problem; the individual must also ask the question "did the team really define the problem, or maybe the real opportunity is...?"

In order to best do this task, the individual should play with the problem, and bend it, twist it, pull it... The individual needs to extricate themself from the fray and let their mind be free and unencumbered of confining boundary conditions. Taking walks is one of the best ways to get the creative juices moving. Baths and swimming endless laps are also great ways to get the ideas flowing. Putting all ideas down on paper helps to solve the mystery. Singing songs about the solution can also create a melody of ideas. Thinking while preparing elaborate meals can also get your idea generator cooking!

The most important thing of all, however, is to alter your states while thinking. From physical relaxation, to physical exertion, think about the opportunities the problem presents, including the potential to redefine the problem, and how you might develop a ***strategy*** to solve it. From massive endorphin release to total panic about not having enough time to complete the project, think about possible ***strategies*** and ***concepts***. And to catalyze it all, scan through technical journals, trade magazines, and web sites in many different fields!

After all this is done, gather your thoughts and arrange them in FRDPARRC tables. Let the tables speak to you, and select very risky, moderately risky, and no problemo ***strategies*** and possible ***concepts*** to bring to the team for consideration.

Do all the above to define the contest goals, create the appropriate FRDPARRC tables and develop ***strategies*** and ***concepts***!

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1. The author learned his sophomore year to apply essentially the design process that is presented in this text to his schoolwork, and was then able to zoom through school while maintaining a healthy diet of extracurricular activities of various fun forms; although he admits he did not start snowboarding till the early 1990's.

Peer Review Evaluation Process (PREP)

When a group of creative people gather to discuss new ideas, often with donuts and coffee as a catalyst, an hour of discussion frequently does not result in consensus. However, if thinkers first summarize in writing (and drawing) their best individual thoughts and then circulate them for their peers (team members) to review, confrontation can be avoided and egos can be mellowed. Rohrbach defined a particular version of this process where six people each bring three ideas to the table, and then each person evaluates each other person's ideas without discussion[1]. The evaluation is done without any discussion by writing thoughts and questions down on the papers that describe the ideas. Because people have to write their ideas down, ideas are often better formulated. This also gives reviewers the ability to easily sketch ideas that can enhance or solve a problem they may find with the idea. In addition, it is very useful to require that any negative comment be accompanied by a constructive comment that suggests how to rectify the observed problem.

Once all the reviewing is done, individuals review the comments that others made on their ideas, and any misunderstandings are cleared up. If time permits, the documents should once again be circulated so all the team members can see all the comments on all the ideas. This further helps to develop a better understanding of all ideas, and it helps team members to learn by observing what they might have missed. The team then breaks so that individuals can think about the comments they received, and about the other ideas they reviewed. They each know what the other members are thinking and their minds become one with each other. They are now PREPed for brainstorming. Invariably the loud aggressive person who is used to having their ideas accepted without question will ponder a really neato idea that the new shy quiet person had, so when the team reconvenes for brainstorming, the truly best idea is most likely to bubble up to the top.

This coming together of minds to learn about other team members' ideas without discussion has a very important psychological effect. It allows people to constructively criticize and be criticized without confrontation. It allows shy people to have their ideas be brought forth where otherwise they might never be presented for fear of rejection. Furthermore, it establishes a written record that documents the thought process. This enables others in the future to go back and see if the team considered some particular facet of the problem. This can also be important for protecting ideas in the case of patent litigation.

Peer review of ideas before brainstorming thus creates and documents a collective mind, so everybody knows what everyone else has been thinking, thus giving egos a chance to mellow. In general, PREP works very well, but it depends on how well people seek to make it work. Teams have to try using PREP, subject to their own unique culture. The 4 steps are:

- Individual thought and document concepts
- Silent peer review
- Group brainstorming
- “Best” concept selection

In a teaching environment, PREP helps students learn to give and to constructively process constructive criticism, and to learn that others' different views often leads to exciting new ideas. PREP is a powerful tool for teaching the value of teamwork. It also helps students to acquire new skills, because when they see the work of others augmented by technology, it makes them want to learn how to use that technology (e.g., solid modeling). Furthermore, it helps students reach an equilibrium level as to what is the appropriate level of effort. The best students will always overproduce because it is in their nature. More mellow students will directly see the advanced effort of their classmates, and will be motivated. Finally, students will receive feedback on their designs without having to wait for a week for the instructor to grade them.

Work in a design review group with *N* members whose responsibility is to use PREP to evaluate each others ideas via commenting on weekly milestone reports. Get to know your group members and coordinate schedules to ensure that the milestone reports can be exchanged efficiently either by a weekly face-to-face meeting, or by exchanging documents via the internet. Keep track of the value of the comments made by your partners to see how they do, and make sure to provide them with feedback on the vale of their comments. This is an important management skill. The amount of effort you put into this process will be reciprocated N+ times because you not only get feedback, you also learn by looking at the work of others.

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1. G. Pahl and W. Beitz, Konstruktionslehre, Springer-Verlag, Berlin, 1977. Translated and published as Engineering Design, Design Council, London, 1984, pp. 87-88.

PREP: *Example*[1]

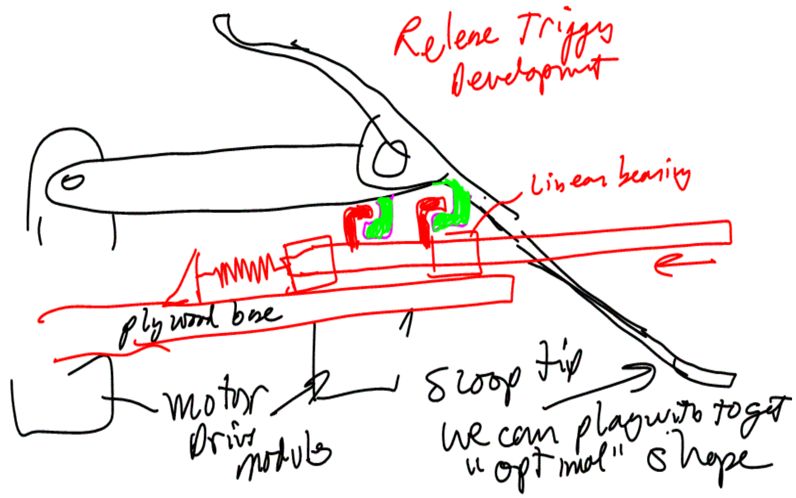
The images show sketches made by a designer creating a GeekPlow car for the *2.007 MIT & the Pendulum contest*. Sketch (1) is a simple side-view *stick figure* that embodies the primary elements of the designers FRDPARRC table. Can you imagine what might be the FRs and DPs? What *analysis*, *risks*, and *countermeasures* come to mind? What would the comments from your peers help you to think about? If you were reviewing this idea, would you have any additional comments to add?

Sketch (2) shows some more detail for the car, which evolved in parallel with playing with the spreadsheet on Page 7-16. Two motors would have enough power, but wheel slippage could occur, so it was decided to use 4 wheel-drive. Past experience (*references* in your FRDPARRC table) showed that connected sets of wheels on each side of the vehicle with belts or gears has never been effective, and thus to ensure high efficiency and minimal complexity of the car, four motors would be used. However, they can be wired in two sets of two, so we would still have two control channels left. With four motors driving, there should be no shortage of power, and enough vehicle speed could be obtained to enable the car to ram the balls and send them flying over the lip of the table into the scoring bin. In addition, the ramp could perhaps ram the puck stacks and make them fall onto the upper part of the ramp, and then they could fall into the scoring bin. What would the comments from your peers help you to think about? If you were reviewing this idea, would you have any additional comments to add?

Sketch (3) is a *layout* of the gearmotor/wheel most-critical-module. Note that as sketched in (2) two sets, mirror images, would have to be made. Is this bad? Should 4 identical units be made instead? What is the level of *granularity* of the elements in these modules? By fine granularity we would mean that most of the elements are identical, only the baseplate onto which the units were assembled would be mirror images. Once again, what would the comments from your peers help you to think about? If you were reviewing this idea, would you have any additional comments to add?

What is the next most important module? Probably the plow because it could be just a simple static plow, a default countermeasure, or perhaps a more sophisticated unit as sketched. Making note of the FRDPARRC chart entries and then sketching a correlated element helps the idea to evolve: *Words trigger images, and the images highlight risks which catalyzes invention.* From this coarse layout sketch evolves more detail, where the next step would be to use solid modelling to further explore the geometry, or in some cases, analysis comes first. Before final commitment, a bench level experiment or bench-level prototype of this mechanism might be built and tested.

The result is a two-stage ramp/plow system shown in the sketch below. The rear link pivots and prevents the plow from raising the front of the vehicle as it collides with a rigid object. However, to prevent premature dumping, a trigger is used which must first impact the wall...



Sketch (4) brings it all together to show how countermeasures/design solutions evolved with risk identification: Just the way environmental pressures can cause a species to evolve, potential risks cause a design to evolve. This is the essence of the iterative process that we call *design*. What comments from your peers would help you to think about thisidea? If you were reviewing this idea, what would your additional comments be?

1. For a more in-depth discussion of this example, see page 8-10...and follow the threads!

Evolving Systems: *Group Brainstorming*

The term *brainstorming* can have many different meanings to many different people, from the thoughts of an individual, to an informal group discussion, to a formal process for idea generation by a group. In general, the latter is the preferred connotation. Although the rules for conducting the process can vary significantly, in general, the goal is to encourage the generation of as many ideas as possible without any criticism being brought against any idea. If resources allow, a recording person who is not a direct contributor to the process should capture all the thoughts and comments. Then after all the ideas have been generated and grouped according to type, a discussion period follows where the pros and cons of each idea are discussed, along with suggestions for enhancing the performance of each idea.

There is an old funny that says a camel is a race horse designed by committee. This suggests that whenever consensus is reached, the compromises lead to an idea that is worse than any of its parts; however, camels are far superior to thoroughbreds when it comes to surviving in the desert. Therefore the issue is really one of focus. The team must remain focused on developing ideas to meet the functional requirements of the problem, and it is the job of the team leader to keep the team focussed.

To ensure that all the functional requirements, including those of manufacturability, business viability, and service are addressed, a team of brainstormers should have a broad background and should include not only engineers, but representatives from marketing, management, manufacturing, and service. Although this may seem like it could lead to decreased focus, each of these people will be required to make the product successful, and the earlier they can be brought on board as enthusiastic team members, the better.

The key to maintaining harmony and focus is to insist that no negative comments are allowed. People are only allowed to offer constructive criticism. In other words, if you are so smart that you can just look at an idea and see that the fraggle pin will break, then you should also be smart enough to suggest a better design, or be smart enough to say "I am concerned about the loads on the fraggle pin, and I think we should calculate them, and if they are found to be too high, we could switch to a caniption pin". People should not be allowed to say "that design is useless because the fraggle pin will shear".

An interesting way to expand the outcome of a brainstorming session is to assign a different team leader to different brainstorming sessions, where each session focuses on the problem from a different perspective. Also, once several "best" ideas evolve, different teams of experts should brainstorm on the evolution of the ideas. For example, when the focus is on manufacturing, there should be mostly manufacturing engineers in the room, but there should still be representatives from each of the other areas. When the ideas have then made the rounds, there will be better buy-in from the rest of the company, and the idea will have benefited from the insight of all the company's top people.

One of the best ways to ensure success from a brainstorming session is to have members who think individually beforehand and carry out the Rohrbach process. This ensures that team members come prepared, and come aware of each other's ideas so that a minimum of time is spent explaining basic concepts. This allows the session to start with all the ideas that have been commented on to be taped to the wall, and discussions can start with:

- Are there any functional requirements that we initially missed?
- Are there any ideas that stand out as clear winners?
- Are there any combinations of ideas that stand out as clear winners?

Finally, brainstorming is not just for creating ideas that solve problems, it can be used to identify problems in the first place. Accordingly, it can be applied anywhere in the design process from **COARSE**-to-fine. Unforeseen problems often crop up, which is part of the risk inherent in any project. It is important that all team members realize that when they encounter a problem that they cannot solve with modest effort, that they invoke the power of the team to help solve the problem. This represents the use of the nested cost-performance curves discussed on page 1-6. If you find yourself spending more and more time trying to identify or solve a problem, and realizing less and less progress, invoke the power of the team!

Use the brainstorming process to identify common problems that you all face, and then think individually to create solutions to these problems. Next use the PREP and brainstorming processes to develop solutions you can all use in your individual designs. An example would be the best way to make crawler tracks or a four-wheel drive system for a vehicle or a leadscrew drive to actuate a bucket loader.

Evolving Systems: *Comparing Designs*

Selecting the "best" idea from several good contenders is often one of the most difficult aspects of design. Casting aside the really bad impossible ideas is often easy, so why should it really matter which potentially good idea is selected? The issue is that a "bad idea" may be considered bad because it is deemed too risky. In reality we often worry that later we will see with our 20/20 hindsight how good of an idea it really was, especially when someone else then develops it and impacts our glutes with it! Unfortunately, this can be a problem with consensus based team development of an idea. 9 of the 10 people on the team may mean well, but they may just not have the experience and knowledge of the shy quiet geek, and thus the team may select the wrong idea. Hence a process is needed for the ultra geek's mind to be heard by the herd.

One of the intrinsic problems with various evaluation methods is that different people place different emphasis on different functional requirements, even though their votes count equally and the functional requirements may not have the same effect on product performance. Instead of trying to compare all factors at once, it would make more sense first to determine the relative importance (priority) of each characteristic (e.g., accuracy versus friction, accuracy versus cost) at each level in the outline of design attributes (functional requirements) and then evaluate the relative characteristics of each component with respect to the most explicit characteristic (e.g., straightness, smoothness, static friction, and so on). This type of decision analysis is called the *Analytic Hierarchy Process* (AHP)[1]. The AHP method enables a team to structure a system and its environment into mutually interacting parts and then to evaluate their relative importance by measuring and ranking the impact of these parts on the entire system. This provides a **COARSE**-to-fine method for evaluating ideas.

Quality Function Deployment (QFD) also known as the *House of Quality*, is a matrix-type idea comparison method that is widely used in industry[2]. QFD is a methodology for defining the customer requirements (left hand column) and mapping how they are affected by the design parameters of the problem (top row). The relations or interactions between the design parameters are also mapped and form the "roof" of the house. Additional matrices allow benchmarking between products[3]. These methods are used in more advanced design courses[4].

Prof. Stuart Pugh[5] took the approach that these sorts of methods are powerful, but engineers may spend more time creating matrices and evaluating options than they do creating ideas. His approach was to call for a table, now referred to as a *Pugh Chart*, that lists the different ideas in the top row, and the comparison attributes or functional requirements in the left column. A baseline idea is selected, given it a score of "0" for each attribute. All other ideas are then compared giving them scores from "++" for far superior, to "+" for superior to "0" for equal to the baseline, to "-" for worse to "--" for much worse than the baseline. The "best" idea is the idea with the highest score; however that does not mean that this is the idea to use as is. Rather the goal is to then go back to the table and see which other ideas have higher individual ratings for some of the functional requirements, and then to see if their particular "++" attributes can somehow be used by the "best" idea; thus evolving the idea into a truly "best" idea. A *weighted design comparison chart* uses the same basic ideas as a Pugh Chart, but it includes a weighting column for weighting the importance of the design attributes. A compromise is to start with equal weights, and then if convergence is not reached, consider giving priority to some of the attributes. Again, the prime purpose of the chart is to identify the most promising ideas, and then replace whatever deficient modules they have with better modules from other ideas.

Create a weighted design comparison chart for your ***strategies*** and ***concepts*** and use it to help evolve "best" ones. Was it necessary to weight the functional requirements? How else would you have selected the "best ideas"? Try using this process by yourself and also with your design review group. Whenever there is a risk, make sure to have completed the appropriate analysis to help you turn the discussion from how do you "feel" about and idea, to how do you "think" about an idea! Feelings are for friends, but analysis, be it analytical or experimental, is for ideas!

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1. T. L. Saaty and J. M. Alexander, Thinking with Models, Pergamon Press, Elmsford, NY,1981.; and T. L. Saaty The Analytic Hierarchy Process, McGraw-Hill, New York, 1980.
2. D. Clausing, Quality Function Deployment, MIT Press, Cambridge, MA USA, 1994
3. K. Otto, K. Wood, Product Design, Prentice Hall, Upper Saddle River, NJ, USA 2001
4. M. Martin, S. Kementa, K. Ishii, "QFD and the Designer: Lessons from 200+ Houses Of Quality", *World Innovation and Strategy Conference*, August 1998, Sydney, Australia, pp 49-59
5. B. Ion, *Pugh's Total Design: Integrated Methods for Successful Product Design*, Prentice Hall, NY, NY, 2000