FUN*da*MENTALS of Design

Topic 1

Design is a ***Passionate*** Process

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Design is a ❤*Passionate*❤ Process

Long before any design project starts, the design engineer has to believe that there is a problem that is worthy of their attention. The design engineer must *feel* a need to solve the problem. The design engineer must have a *yearning* to solve the problem. The design engineer must be ***passionate*** about solving the problem!

However, one must be very careful about managing one's passion, lest one's excitedness overshadows true opportunity. In the world of business, it does not matter if the design engineer passionately creates a product that does not meet customer needs. Passion means little if the design is tainted by ignorance and inattention to detail.

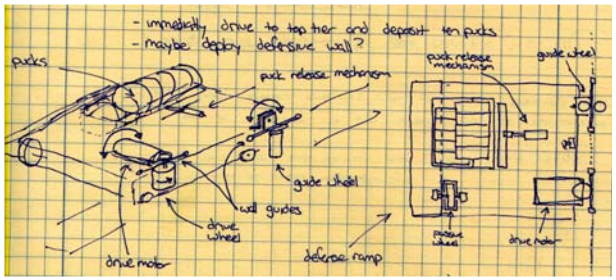
This book is thus very much about exploring ways to turn *un*structured problems into *FUN*structured opportunities! ***Passion*** is a necessary, but not sufficient, component of a good design engineer's effort to solve a problem. Accordingly, this chapter introduces design as a ***passionate process*** to be carried out in a careful, systematic, deterministic manner catalyzed with random hyper adrenalin driven bursts of super creativity!

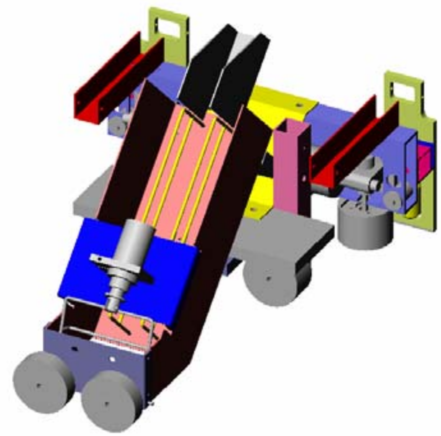
The notion that design can be studied or implemented as a process may seem oxymoronic to many creative people. Indeed, any good "design process" should allow even the most complex design to be broken up into manageable stages that encourage and catalyze free-spirited creative thinking *and* deterministic analysis. During each stage, the design engineer can focus on a portion of the problem with an appropriate amount of left and right brain effort. For example, when envisioning a new vehicle, one need not be too concerned with bolt stresses; such details will come later in the detail phase.

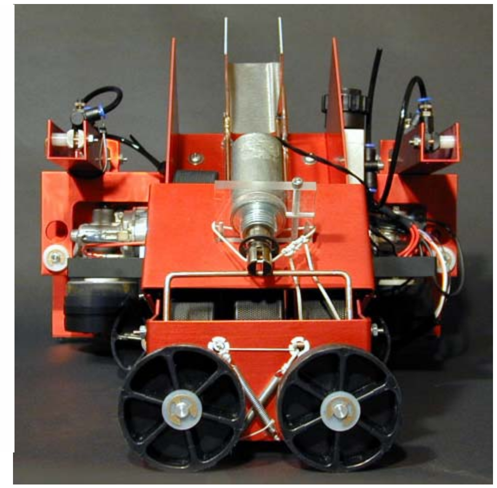
Most design processes typically involve repeating essentially the same steps as the design funnels down from broad concepts to details. Once the designer learns the fundamentals of a process, they can easily apply it over and over again as the design evolves from the concept to the detail phase. A good design process should be simple, flexible, and applicable to just about any problem one can think of.

So read and study with ❤***Passion***❤ while thinking about how to design a better robot for your favorite robot competition, or how to design a fun weekend!

Topic 1
Design is a ♥*Passionate*♥ Process

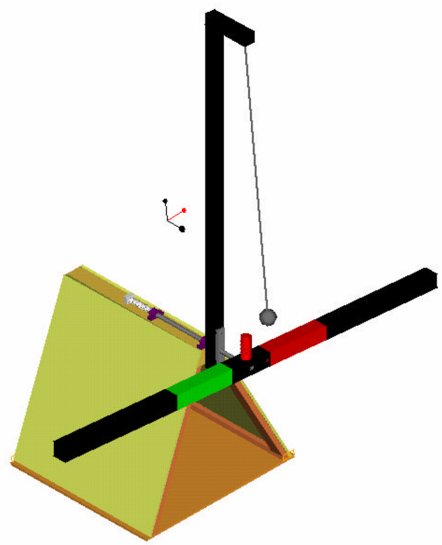






Topics:

- ***Passion***
- Deterministic design
- Systematic Organization of Ideas
- Design Processes
- Milestones



Design Contests

Since the 1960's, sophomores in MIT's Department of Mechanical Engineering have been taking the hands-on Introduction to Design course "2.70" (which evolved into course 2.007 in 1995). The course teaches the fundamentals of mechanical design process and machine elements via hands-on engineering challenges. Lectures assume students have done the reading (this book!) so they can focus on potential solutions to the homework design problems. The homeworks help guide the students the design and build a remote controlled machine for use in an end-of-term celebration (contest!).

A new contest is created each year by students who have just completed the class, and they use the design process learned in class. About 10% of the previous year's students become current year's Undergraduate Assistants (UAs), who help run the class, and this helps generate a feeling of student ownership. Student participation is a key element in the design of good contests, for what teachers may think is most excellent, students may find boring. It is critical to incite students' passion and sense of ownership, while providing a rich environment for teaching fundamental principles. It is also important for students and teachers alike to have fun!

To help illustrate the principles and ideas presented in this text, the 2002 MIT 2.007 design contest *The MIT and the Pendulum* will be used as a case study. In this type of design contest, the playing field has a variety of obstacles and scoring methods, and students drive their radio controlled machines in one-on-one contests to see who can score the most points.

Put yourself into the mind of a student creating a machine for *The MIT and the Pendulum*, which is of course a geek twist on Poe's *The Pit and the Pendulum*. The table is symmetrical with a scoring bin on each end and a rigid pendulum on each side in the middle of the table. Each pendulum is made from a square hollow plastic tube half-filled with blue street hockey balls. Its center of gravity is below its pivot point both with or without the balls. On the table, there are also street hockey pucks and balls.

The pendulums start hanging straight down in the middle of the designated starting area for each contest machine (robot). As shown, your score is a function of the total mass of balls and pucks collected in the bins and the total angular distance traveled on the pendulum. Each term of the scoring equation has a small constant to increase the richness of potential winning strategies!

The question is how to use the pendulum to your advantage, without your machine getting bashed by the swinging pendulum? There are a lot of balls in the pendulum and if it is swumg just right, the balls will empty and bounce into the end scoring bin.

What

Would

You

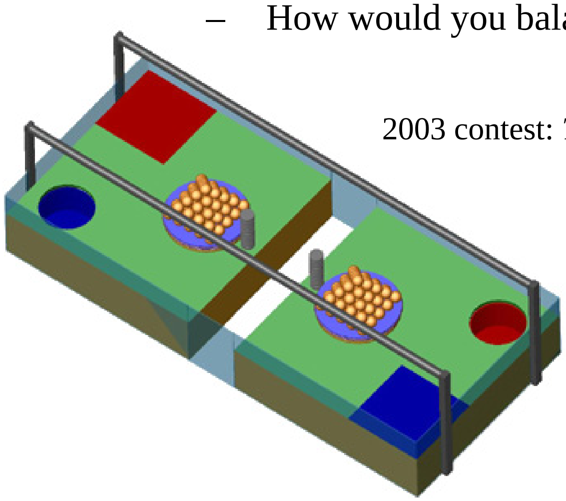
Do!?

Design Contests

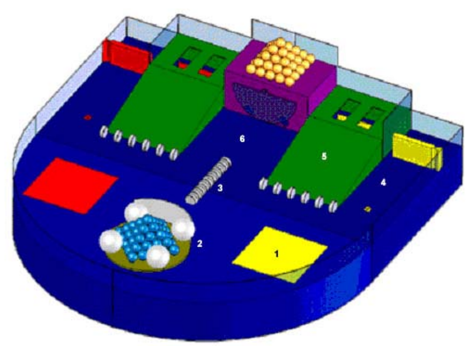
- Theme: Multiple ways to score (mass and motion)
- "Rules":
  - Only use materials in the kit and plus fasteners and adhesives
  - Machine must fit into starting zone (0.5m x 0.5m x 0.5m cube)
    - You can start with your machine engaged (wheels preloaded) to table features
  - "Score" is evaluated at the end of 45 second contest:

$$Score = \left(\theta_{\text{cumulative rotation}} + 1\right)\left(m_{\text{total puck \& ball mass in grams}} + 100\right)$$

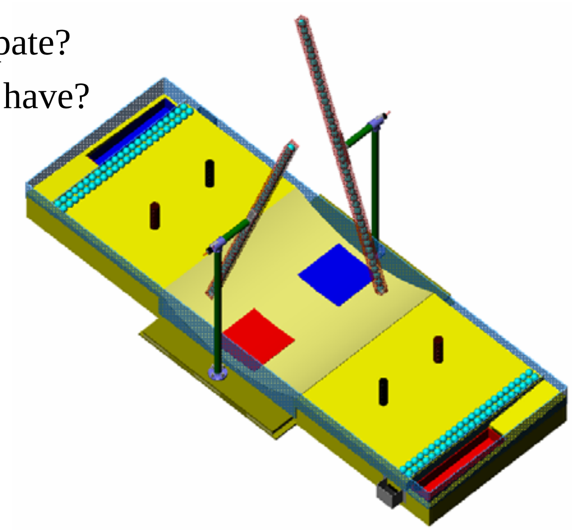
  - You may not interfere with your opponent's ability to score until you first score by getting a puck or ball into your scoring bin
  - You may not damage the table or willfully damage your opponent
    - No nets or entanglement devices
- What would ***you*** do?
  - How would you go about designing and building a machine to participate?
  - How would you balance your effort with all the other obligations you have?



2003 contest: *The 2 Tables*



2004 contest: *The Big Dig*



2002 contest: *The MIT & the Pendulum*

❤*Passion* ❤ *LOVE to Create*

History is replete with examples of people who achieved extraordinary goals by means of their brilliance or sheer will, but rarely without passion. History is also replete with people who never accomplished much of anything because they could never bring themselves to pry themselves away from mind numbing inactivity. Designers usually are passionate about the concept generation aspects of design; however, details can often appear boring, but the details are every bit as important to a design as the overall concept if the goal is to bring to market a truly inspiring product.[1] The difference in a product that is just created verses one that is created with ❤***Passion*** ❤ is like the difference between a handshake and a honeymoon!

The first step in developing a *personal passion plan* is to realize that that there are different orders of ❤***Passion*** ❤ as a catalyst for accomplishing a goal, ranging from the simple realization that a task needs to be accomplished in order to pay the rent and buy food, to the realization that the idea on which you are working could change the world. The second step is to gauge the task at hand and select an appropriate level of passion, for if one expects to save the world by mowing the lawn, one may be in for a letdown. The third step is to think of how you and others will benefit from what you are doing, and how big a "thank you!" you will get either now or in the future for accomplishing the task. The fourth and perhaps most critical step is to think of your most desirous intellectual and physical activities, and realize that the task at hand can be a means for you to better enjoy the things you love most!

Just about any activity can be conducted in a manner that helps one to grow in the context of their goals in life both professional and personal. With this in mind, consider the some of the author's fun functions:

- Most desirous intellectual activities: Designing and building new things, playing games, and solving puzzles
- Most desirous physical activities: Exercise, Snowboarding, SCUBA diving, triathlon...

Physiologically, passion goes hand in had with the release of endorphins in the brain. Hence to feel good when doing details that may otherwise not be big endorphin releasers, map the activities onto other activities that can help to stimulate endorphin release. Mental tasks can be mapped onto games and puzzles. While doing mental tasks, one can also incorporate light exercise which is a proven endorphin generator. Some activities, such as washing dishes or doing the laundry, require such a low level of brain activity that one can do them while also designing new gadgets to help to accomplish the boring task. Table 1 provides some examples.

Table 1: Injecting passion into common activities

Activity	*Intellectual Mapping*	*Physical Mapping*
Background research: Creating a list of functional requirements, investigating what has been done, conducting surveys...	You are creating a treasure map that will lead you to the buried treasure (contained in the wallets of countless consumers!)	Go for a walk and meet customers. Walk and observe others using competing products.
Making drawings before making stuff in the shop	This is a video game! As you detail the parts imagine them being machined and assembled. Keep your eyes open for short-cuts to minimize the number of parts and make them effortlessly snap together in an obvious way.	Create a dance that makes you the part as it goes through the manufacturing process, and do the dance. Walk through the factory imagining each step of the manufacturing process.
Writing reports	Create poems to describe ideas. Using the Nth, Mth… letter of each page, create secret messages…	Do chair-based exercises and stretches (very important for health).
Washing dishes	How can I design a self washing dish? How would I automate this? What if I could read water molecules' memories?	An opportunity to do calf and balance exercises!

"Curiosity, like coffee, is an acquired need. Just a titillation, at the beginning, it becomes with training a raging passion" Nicholas S. Thompson

Imagine your robot zooming ahead to victory, AND the satisfaction you will get knowing that you engineered every aspect of your machine. You used physics to catalyze the creation of creative ***concepts***, and your machine performed as predicted. It was built on time and on-budget! You now have the capabilities and the confidence to conquer any task. You see yourself leading the Mars Lander design team… Now, start thinking of ***strategies*** to win!

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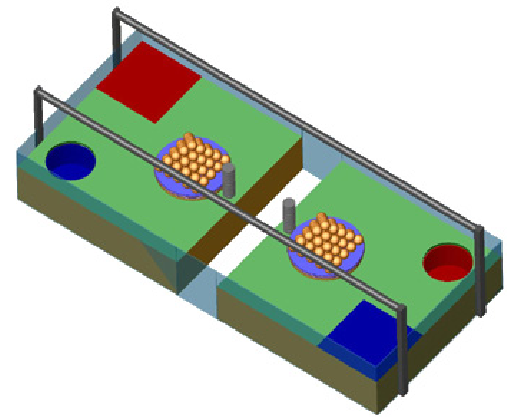
1. Great insightful books about passionate designers include: Robert A. Lutz, Guts, John Wiley & Sons, New York; Ben Rich, Skunkworks

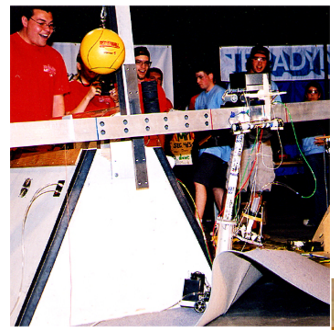
♥*Passion*♥ *LOVE to Create*

"Enthusiasm is one of the most powerful engines of success. When you do a thing, do it with all your might. Put your whole soul into it. Stamp it with your own personality. Be active, be energetic, be enthusiastic and faithful and you will accomplish your object. Nothing great was ever achieved without enthusiasm"

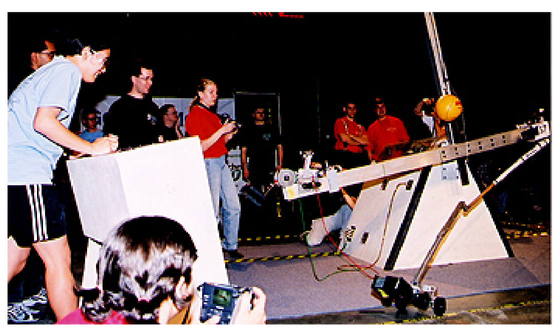
Ralph Waldo Emerson



- Use ♥*Passion*♥ as a catalyst to make ideas become reality:
  - Never stop asking:
    - "Is this really the best I can do"
    - "Can the design be made simpler"
  - Create, never stagnate
    - Do you see machines in ink blots?



Ink-Blot milling machine by Peter How



Passion Focus!

The “F word” inspires fear in many people, because it means that they will have to control their wild ways and learn to *FOCUS*. The ability to *focus* on a problem helps one create a good working solution in an appropriate amount of time using an appropriate amount of resources. The words *elegant* and *efficient* come to mind when one thinks of an engineer who has focused on and finished a problem. Just as the optical term implies, focusing on a problem means to define a field of view, clearly see what needs to be done, and then do it in depth! Engineers are typically given poorly defined problems else they would not be problems. Some guidelines to help focus include:

- *Maximize aquatic avian linearity:*
  - Get your ducks in a row
    - Dissect the problem into its components and requirements
- *Maximize avian termination with a minimum number of projectiles:*
  - Kill two birds with one stone
    - Systematically generate solution strategies and machine concepts
      - Look for similarities between elements of the problem
- *Lacerate bovine growth by-product:*
  - *Cut through the bulls#!t:*
    - Identify the primary tasks that must be completed to succeed
    - Establish a set of goals and work efficiently to meet them
    - Avoid fluff and beware of productivity perils and endless discussions without resolutions
- *Minimize deceased equine flagellation:*
  - Do not beat a dead horse
    - Learn to recognize when an idea is destined to be intractable given your allowable resources, and then drop it
    - Keep your ego in check, and learn to put your failures on the front page next to your successes
- *Impactus maximus ad gluteus maximus:*
  - Give the project a BIG kick in the butt and do not delay starting!
    - Maintain momentum and strive to finish ahead of schedule!
    - Help others to get focus

The design of anything, from machines to software to prose, follows the same types of guidelines[1]. So be on the lookout for how you can apply these guidelines to other things you do. Your mind is a giant bio neural net, just waiting for new connections to be made! Just think of Mick Jagger, Keith Richards and Henry Maudslay! Their maxims will be with us forever!

Creative people often have a difficult time focusing, because as soon as they convince themselves that an idea they are working on is doable, they are often easily distracted by some other wonderful opportunity that arises. Given that many of us are required to work on several projects simultaneously, or to take several courses, focusing can be just as difficult. It requires will-power, pure and simple. It is just one of those things you have to learn to do; therefore, learn to say the "F word" to yourself. FOCUS! When you focus, then the other fun "F words" will also be yours: "Finish" and "Fun" and that great 4 letter "F word" expression, "Free time"!

Take a careful look at the contest table and play with it, either physically or in your mind. Think about the ways to score, their apparent difficulty, and the potential for a simple means to dominate each scoring method. Consider your commitments to other activities, and determine how much time you will actually have to spend on your robot. Next, carefully apportion that time to different phases of the design process (strategizing, conceptualizing, detailing, building, testing). Within each phase, think about creating a clear set of goals towards which you will efficiently work; AND maintain constant vigilance against things that would have you detract from your goals. Always have a simple alternate path to take should you end up in the woods!

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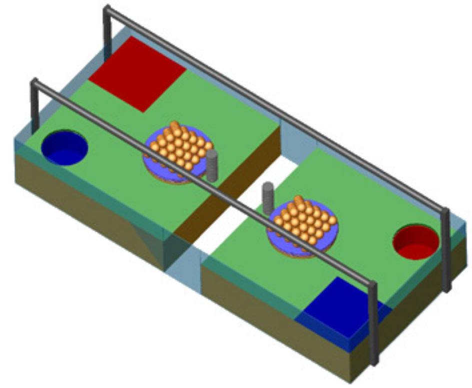
1. From “Politics and the English Language” George Orwell, 1946, http://eserver.org/langs/politics-english-language.txt:
   a Never use a metaphor, simile or other figure of speech which you are used to seeing in print.
   b Never use a long word where a short one will do. (iii) If it is possible to cut a word out, always cut it out.
   c Never use the passive where you can use the active.
   d Never use a foreign phrase, a scientific word or a jargon word if you can think of an everyday English equivalent.
   e Break any of these rules sooner than say anything outright barbarous.

Henry Maudslay

from J. Roe English and American Tool Builders, © 1916 Yale University Press

♥Passion♥ FOCUS!

Keep Your Eye on the Prize



"You can't always get what you want
But if you try sometimes well you might find
You get what you need"

Mick Jagger & Keith Richards 1969
http://lyrics.all-lyrics.net/r/rollingstones/letitbleed.txt

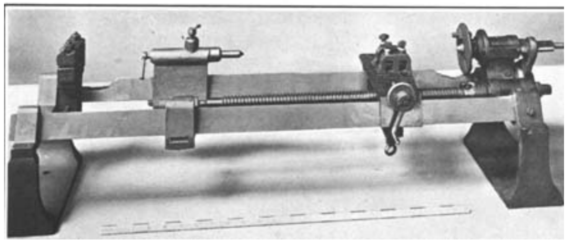
Get a clear notion of what you desire to accomplish, then you will probably get it

Keep a sharp look-out upon your materials: Get rid of every pound of material you can do without. Put yourself to the question, 'What business has it there?'

Avoid complexities and make everything as simple as possible

Remember the get-ability of parts

Henry Maudslay's Maxims (1700's, a father of modern machine tools)



Maudslay's screw cutting lathe

from J. Roe English and American Tool Builders, © 1916 Yale University Press

Deterministic Design

Everything happens for a reason, and we merely need to apply the proper resources and focus in order to discover and understand the issues that would otherwise lead to uncertainty. Minimizing uncertainty, and hence risk, makes a design more deterministic. *Deterministic design*[1] can be facilitated through the use of a structured design process. While it might be possible to debate whether design itself is a deterministic or stochastic (shoot-from-the-hip) process, it is best to focus creative and analytical forces on real design problems in order to stay on the schedule.

Engineering design problems are essentially cost and performance trade-offs, and a key element of performance is time to market. It does not matter how good your solution is if you miss the market window. Consequently, engineers with a vibrant passion for success live on the (appropriate) edge. Because the edges move as cost/performance requirements change, engineers and managers must remain nimble, open-minded, and on continual lookout for *disruptive technologies*[2] that can deliver far more performance for far less cost (e.g., integrated circuits verses vacuum tubes).

The *stagnant edge* is the realm of the complacent engineer who is asking a competitor to come and take away market share and the business. All too often an engineer gets good at doing something and then fails to realize that new methods have been developed that can provide better performance for less cost. This is akin to riding on the flat bottom of your snowboard while gazing at the sky. You are asking for a face plant or a tree hug!

The leading edge is the place to be as it means that it is very difficult for a competitor to do better than you unless they spend a lot of resources, and you are likely doing better than all your competitors. The leading edge can only be maintained by constant vigilance and being ready to switch to a different technology curve. This is akin to switching between the toe and heel edge of your snowboard as you weave your way through the woods.

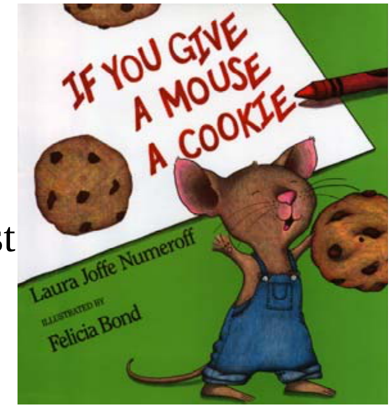
The *bleeding edge*[3] is the place for paranoid engineers who refuse to change their ways and instead think that with just a little more effort, things will work out; however, soon they run out of resources and fail. Creative solutions may appear to be more clever than solutions arrived at by analytical means; however, if analysis was not applied, it is likely that the solution rests on the bleeding edge. This is akin to the snowboarder who refuses to turn because the hill is too steep, and instead runs off into the woods. Time after time, it is shown that individuals or teams who can simultaneously harness the power of creative and analytical and computational methods outperform those who use less than all three. Only then can you consistently identify the slope with the finest possible powder and then make first tracks!

Consider the evolution of the machines on which your parts will likely be produced. Linear actuators are key elements that determine the speed, accuracy and force with which the axes move. Sliding contact leadscrews worked great for over a hundred years until they gave way to ballscrews which are starting to give way to linear electric motors. Each succeeding technology costs more than the other but provides better performance. However, for the new growth area of small machine tools to make mesoscopic (cm^3 sized) parts, large forces and strokes are not needed. DC voice coil actuators have all the advantages of linear electric motors yet do not require expensive commutation circuits; thus they can have lower cost and higher performance. Understanding the physics of the problem and the scaling laws is critical!

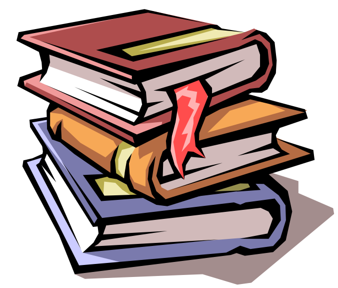
Create a table of the basic physical properties and capabilities of the kit parts, and a spreadsheet to study time, motion, power required to score by each different means. Forecast what might be easy and what would be difficult ways to score, and think of ***strategies*** and ***concepts*** for ideas that are not easy, yet not too difficult. Then think of ***strategies*** and ***concepts*** for the more challenging scoring methods!

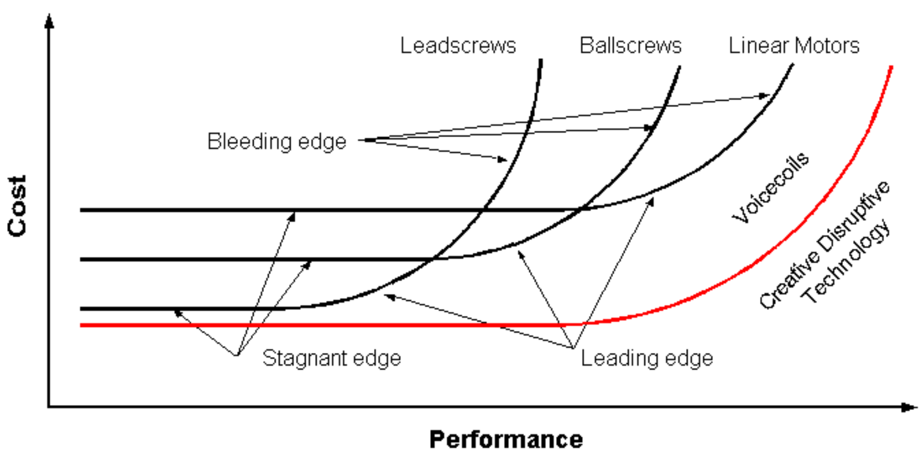
1. R. Donaldson, "The Deterministic Approach to Machining Accuracy", SME Fabrication Technology Symposium, Golden, CO, Nov. 1972 (UCRL preprint 74243).
2. Clayton M. Christensen, The Innovator's Dilemma, 1997 Harvard Business School press, Boston, MA. USA
3. The term *bleeding edge* was coined by Richard W. Slocum III, a gifted project manager and a key catalyst in the life of his little brother who is eternally grateful for the butt kickings he received that enabled all you are reading to come to be. Thanks Rick for keeping me focussed!

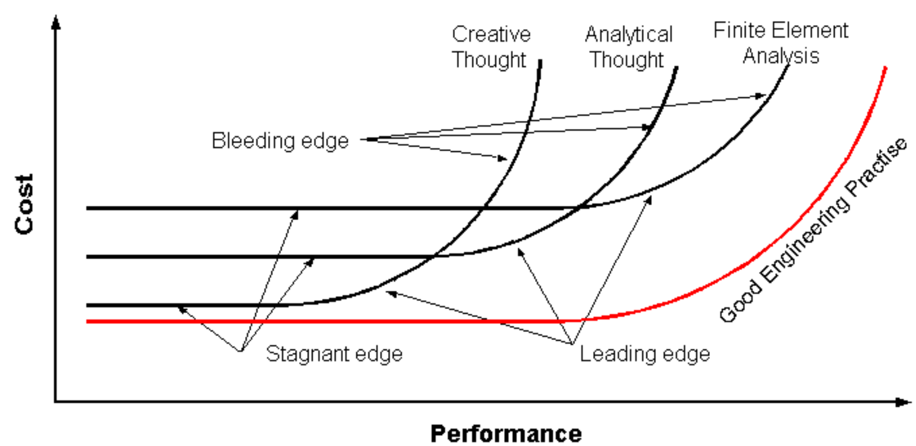
Deterministic Design



- Everything has a cost, and everything performs (to at least some degree)
  - If you spend all your time on a single tree, you will have no time for the forest
  - If you do not pay attention to the trees, soon you will have no forest!
  - You have to pay attention to the overall system and to the details
- Successful projects keep a close watch on budgets (time, money, performance)
  - Do not spend a lot of effort (money) to get a small increase in performance
    - "Bleeding edge" designs can drain you!
  - Do not be shy about taking all the performance you can get for the same cost!
- Stay nimble (modular!) and be ready to switch technology streams
  - It is at the intersection of the streams that things often get exciting!
  - *"If you board the wrong train, there's no use running along the corridor in the opposite direction"* Dietrich Bonhoeffer







Deterministic Design: *Play*

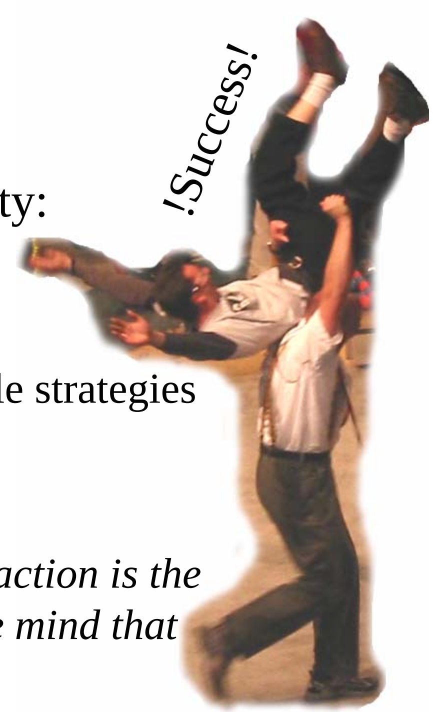
An engineer or a team with focus can follow a natural progression of events and they will likely be successful. A large part of the process will require the engineers to fully immerse themselves in the development of the solution. In the case of a mechanical problem to be solved, this often means a lot of physical play. In the case of a software problem to be solved, virtual play rules! In all cases, just as we learned as children by playing, playing continues to be a very important part of the adult learning process.

- Playing with problems and available resources enabled humans' brains to evolve. Play involves all the senses, and as they send signals to our brains, our bio neural nets are activated, and the ideas begin to flow:
  - Look at the problem and resources available to you:
    - Create mental 3D images and movies of the problem and manipulate them in your mind so your bio neural net can work on solutions while you do the laundry.
  - Touch the parts of problem and resources available to you:
    - The weight and size and feel of the physical elements enters your neural net through your fingers and you become one with the hardware so you can better imagine the actual physical response of the system.
  - Listen to the sounds that are associated with the problem and the resources:
    - Patterns in sound often give rise to identifying the true performance of a system.
  - Smell the problem and resources to build a better actual bio neural virtual net model of the challenge.
  - Taste victory (or the resources if this is a food-based challenge) by imagining your solution is the one that wins!
- Sketching the problem and possible solution strategies and concepts is how we communicate with others, including ourselves:
  - Sketch the problem so you can look at it from different perspectives.
  - Sketch possible solution strategies and concepts so you can tape them to the wall and scan them all simultaneously and search for strengths and weaknesses.
- Modeling the problem and possible solution strategies and concepts allows you to better play and develop and evolve solutions:
  - Simple physical models allow you to better play with the system and they often help to identify the system's most sensitive parameters.
  - Analytical models can allow you to identify the most sensitive parameters of the problem and help guide your solution path:
    - Analytical models can identify equine orientation BEFORE you hitch your wagon to them (and then try to beat them to move).
    - Analytical models can enable you to optimize your solution to minimize cost and effort.
    - Analytical models allow others to understand your intent.
- Detailing the solution before you build can help identify minute yet critical features that may otherwise cause failure:
  - Bolt holes should be drawn so you can envision how the system will be assembled.
  - Every little chamfer need not be put in if you are creating a bench level prototype.
- Building and testing your solution is the physical realization of all that you have worked so hard to achieve:
  - Like ourselves, most things have to evolve, so finish early and be your own toughest customer!
  - If you were continually assessing risk and planning countermeasures, if tests reveal a problem, you will be more likely to recover.

Following pages will systematically describe a design process that can be a useful catalyst to help you develop your ideas.

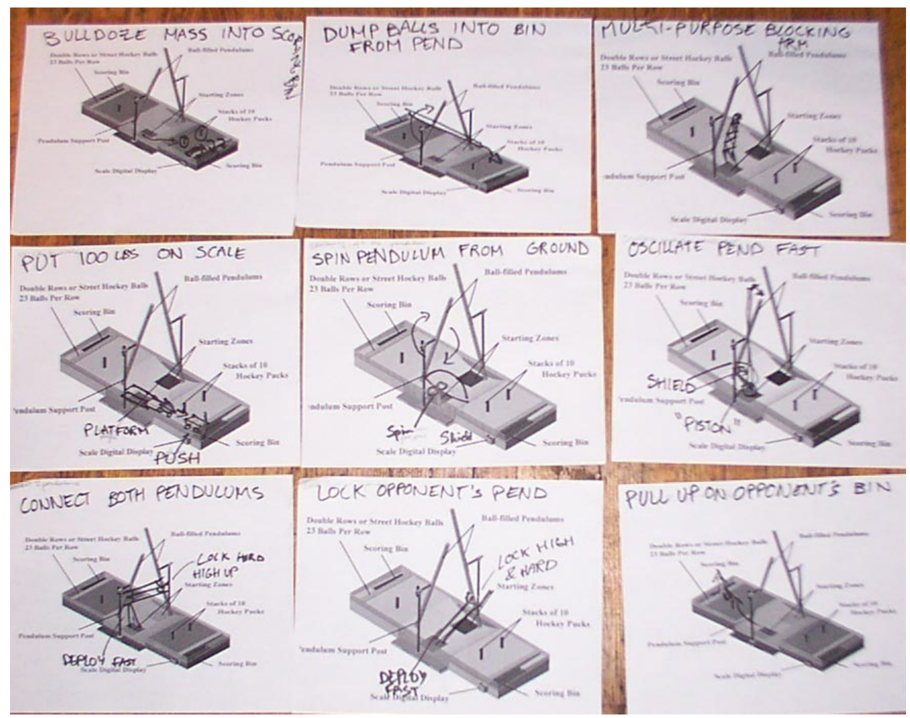
Play with the contest table and the kit parts. Sketch the different operating conditions of the table and animate them in your mind to see what might be most easily exploited. Make a solid model of the table and collect solid models of the kit parts. Use the solid model of the table to acquire mass and inertia properties and combine these with the power of the motors to get an idea of what might be achievable in the allotted contest time. Create some simple physical models that allow you to better play with the table and to help you better identify scoring opportunities and develop elegant strategies. Think ahead about how much detail will be required to realize your strategies, and determine if you have the resources to actually build and then test your solution. Update your web page (as you should do every time you have a significant advance. No more reminders will be given, you all are big geeks now).

Deterministic Design: *Play!*



- Engineering is often a tactile, visual, verbal, cerebral, and physical activity:
  - Play with the table and the kit parts
  - Sketch ideas
  - Create physical & analytical models to identify opportunities and test possible strategies
  - Detail the machine using all the engineering skills and tools at your disposal
  - Build & test your machine!
  - *"Personal self-satisfaction is the death of the scientist. Collective self-satisfaction is the death of the research. It is restlessness, anxiety, dissatisfaction, agony of the mind that nourish science"* Jacques-Lucien Monod

Martin Jonikas' high scoring machine and idea evolution. Can you figure out how it works (Reverse Engineering) and create an even better machine?



Deterministic Design: *Analytical Instinct*

How do some great design engineers just seem to "know" what to do? How can some people just pour out the analysis while others must struggle with every single formula? Are some people just born with what it takes? Are some people funda-bio-mentally incapable of being creative or power geeky? There is no doubt that some people have a knack or are just plain gifted with respect to creative or analytical thought. They have an instinct that is hard to match; however, there are ways in which you can develop your ability to be more creative or analytical.

The first thing that you must do is learn to trust your instincts, and then to purposely thwart them. When you are presented with a problem, do just what your instincts tell you to do and approach the problem from either a visual, creative, wild, far-out, zany, draw-and-play perspective; OR carefully analyze the situation and create an analytical model from which you can predict the best answer.

<u>AND THEN DO THE OPPOSITE</u>

If you first approached the problem from a creative aspect, force yourself to carefully systematically analyze your creative thoughts. Write down in words the physics that describes the problem and your solution. Write down or develop the equations that can model the problem and your solution. Study the analysis and look for the "fat rabbit variables". If you were starving and had to hunt to survive, you would not waste your time hunting the thin fast rabbits, you would go after the slow plump ones! Life is a Jacobean, so start differentiating amongst the variables to determine the sensitive regions on which you should focus your effort!

If you first approached the problem from an analytical perspective, which is actually no less creative in many respects than a wild visual foray, then it is time to raise your shirt and contemplate your belly button! Pull out the lint and instead of determining how much more you need to knit a sweater, contemplate the cosmos and what combination of fundamental particles has formed somewhere in the universe to solve your exact problem! An infinite expanse of an infinite number of particles means that somewhere the solution to your problem already exists, and all you have to do is tune your mind to the cosmic ether in order to find it!

Recognize what your strong points are, and keep exercising them so they remain strong; however, you must also specifically recognize your weak points and work to make them strong! then, randomly think in a manner opposite to that which is your norm. You should force yourself to consider the opposite of what you are thinking (as long as they are nice thoughts!). The stress of forcing yourself to think and then think different is a good thing![1]

For example, in the *Pass the Puck* 2.007 contest at MIT there was a barrier between two sides of the table, and the goal was to move balls and hockey pucks from your side of the table to the opponents side of the table. The barrier was difficult to climb, and some students had the bright idea of creating a platform from which their vehicle could zoom over to the other side, thus knocking a few of the balls on the ridge onto the other side, and then pin the opponent to prevent them from scoring. Tim Zue saw that many people were building platforms, and everyone had the same motors and the same weight limit. He used analysis: maximum tractive (pushing) effort is the product of the normal force and the coefficient of friction. He had to figure out a way to maximize the coefficient of friction between his vehicle and the platform. While others made metal platforms, Tim secretly planned to glue sandpaper to the surface of his platform... The rest is history and he won!

Perhaps most importantly, after you complete an experiment or analysis, check the results with analysis or an experiment, and find out what worked and what didn't, so you can develop and calibrate your instincts and be ready for the next problem!

What do your creative instincts tell you about the contest table and the best way to score? What does your analysis say is the "fattest scoring rabbit" that will yield the highest score? Look at your kit parts and what creative thoughts come to mind with respect to how you might use them? What analytical tools do you have to determine the physical limits of the kit parts? Make sure to look at your course website to see what is already available!

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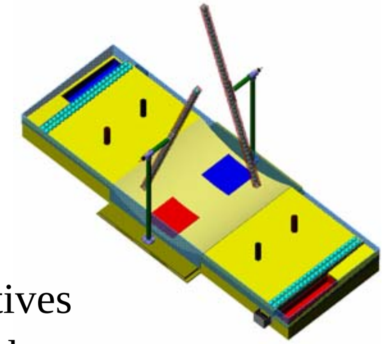
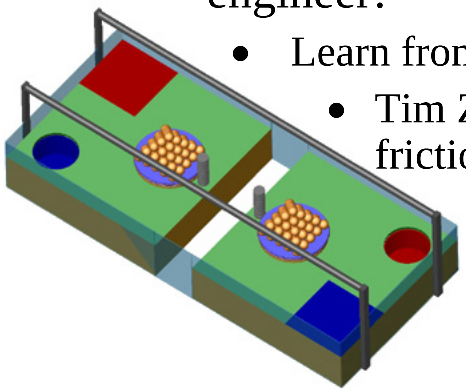
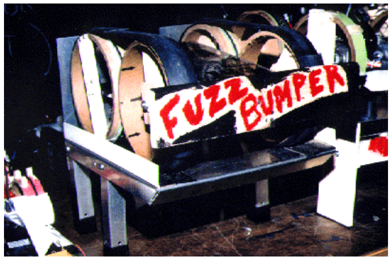
1. Some scientists believe that evolution happens most rapidly when a system is stressed. Others believe that genetic mutations happen at random. But perhaps both are correct!

Deterministic Design: *Analytical Instinct*



- ***TRUST*** your analytical & deterministic training
  - Seek to create and then defeat ideas by exploring ALL possible alternatives
    - In a Mr. Spock™ - Commander Data™-like manner, logically seek to establish the need, understand the problem, create many concepts, subjectively evaluate ideas, analyze the bajeebees out of the idea.
      - This is the careful execution of the *Design Process*
      - This is what the best designers do to turn dreams into realities
- ***& LISTEN*** to your instincts
  - Be wild, random, and impulsive, and take great ideas that your bio-neural-net produces and keep evolving and hammering it until it yields an invention!
    - Sketch the first thoughts that come to mind when you encounter a problem!
      - This is the Captain Kirk™, shoot from the hip, John Wayne approach.
        - This is the element of passion that is the essence of great design!
        - This is what drove Mozart, Edison, Einstein, Elvis….the great creators!
- Combine *analysis & instinct* to become a successful *passionate* design engineer!
  - Learn from experience how much of each to use!
    - Tim Zue's tracked vehicle won, because he used sandpaper to increase the friction on his starting platform!





Deterministic Design: *Reverse Engineering*

Everyone always seems to remember after the fact that history repeats itself, and those who do not study history will forever walk around with backside binocular syndrome! Therefore, a critical step in developing new technologies is the study of competing designs in order to understand their *design intent*, and to hopefully identify and exploit a weakness or an opportunity that your competition missed! This process is called *reverse engineering* and it is considered a critical part of the product development process.[1 2] It can also be thought of as a "prior art" search, which is the term used by the patent office.

Reverse engineering involves physically taking apart a competitor's product in a very systematic manner. Each component and its function are analyzed to understand each parts' function and why it was designed the way it was. In fact, in order to effectively reverse engineer something, you merely have to follow good engineering practice, as discussed earlier, in reverse. Whenever you get stuck, go back a few steps and then try to move back forward. In the case of a design contest, reverse engineering of the contest table itself can help to develop a better physical and analytical intuitive feel for the contest, as well as potentially uncover "keys" to winning.

The ultimate goal of the reverse engineering process is to find a *eureka!* element that was overlooked by the original designer (or placed there by the contest designer for the astute competitor to find). *Eureka!* elements have the potential to be disruptive technologies, which are the holy grails of the design world. Given the tremendous potential of reverse engineering, consider the contest *The MIT and the Pendulum* and pretend you are reverse engineering the contest table and the winning machine:

- Play with the contest table and kit parts to activate your bio neural net so the ideas begin to flow:
  - Look at the contest table and your kit parts and create mental 3D images and movies of all the elements and practice manipulating them in your mind so your bio neural net can work on solutions while you do the laundry. In your mind, disassemble and reassemble the table.
  - Touch the parts of table and kit and experience their mass and inertia. Connect a motor to a power supply and feel its torque. Can it rotate one of the pendulums? How could power from the motor be applied to the pendulum? Measure the period of the pendulums. Feel the weight of the scoring parts and roll them around on the table and up over the wall and into the scoring bin. Measure the coefficient of friction between each potential wheel material and different surfaces on the table. Feel the stiffness and apparent strength of each of the structural elements in the table and the contest kit.
  - Listen to the sounds of the pendulums as they swing, the scoring elements as they are pushed around the table, and to the kit motors.
  - Smell the contest table and the kit elements. Scent is one of the most powerful senses for recall!
  - Taste victory (or the resources if this is a food-based challenge) by imagining your solution is the one that wins!
- Sketch the table and draw motion path arrows to illustrate the motions you observed that were possible. Sketch in kit actuators to imagine them causing the motion paths to happen…
- Model the motions of the table elements in terms of time and motion potential and the forces and torques required. A spreadsheet or MatLab model will allow you to compare different scenarios that the kit motors could make happen; consequently you may discover the true design intent of the contest creators.
- Create a simple physical model, perhaps a sketch model from cardboard, of a reasonable idea you have thus since identified, and play with it on the table, using your hands in place of the kit motors to move the elements. You can rapidly make many different sketch models, and then if one seems to be promising, you could even create a working physical model in order to run a bench level experiment on the table using the kit motors for power.
- Detailed concepts should NOT be a part of this initial process, but rather they should enable you to discover the design intent of the contest creators, and help you to formulate different strategies for exploiting it.

Building and testing whatever best concept finally evolves from the completion of your design process will be totally dependant on how well you executed the above.

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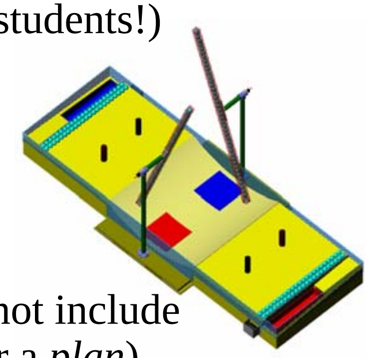
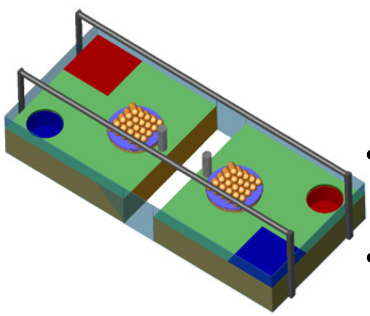
1. K. Otto, K. Wood, Product Design, Prentice Hall, Upper Saddle River, NJ, USA 2001
2. Karl T. Ulrich, Steveen D. Eppinger Product Design And Development, 2000 The McGraw-Hill Companies, Inc. Boston, MA, USA

Deterministic Design: *Reverse Engineering*

- How would you create a contest where the overall goals are:
  - – The inertia of the machines is on the order of the inertia of the system
  - – The system is SIMPLE to build and solid model (for the staff and the students!)
  - – The contest can have MANY different possible winning strategies
    - Engineering analysis can tip the scales in a student's favor!



- The answer is to:



  - Envision potential *strategies*
    - – A *strategy* is an approach to solving a problem, but it does not include mechanism detail (a *strategy* can be thought of as a *tactic* or a *plan*)
  - Consider the feasibility of *strategies* in terms of physics, resources required, and resources available (available materials, equipment, time…)
  - Select one or two *strategies* for further development which define the detailed mechanism….
    - – *Concepts, Modules, Components*
  - Follow a process whose pattern of development repeats at each level of detail
- What better way to design a robot for a contest than to understand and use the process used to design the contest?!
  - – Try to ***reverse engineer*** the contest, including building and taking apart a model (CAD solid model or a physical model) of the table and recreating the analysis that likely went into its design

Deterministic Design: *Disruptive Technologies*

When a company finds a fundamental new way of solving a problem, competitors often slap their foreheads and say "duh!" because physics is indeed elegant and essentially simple. No cheese is given to the team that whines that the winner cheated by taking advantage of a new (or old!) design or by using new materials or technologies. Despite the existence of disruptive technologies, they rarely happen so fast that they totally dominate the marketplace. Countermeasures thus can include maintaining market share by increased quality and customer service and by lowering prices and tightening margins. Time-to-market with a robust working product is often the most critical issue, but this does not mean that you can avoid change!

In a robot design contest, some say that there should be no potential winner-take-all solution because then one person might discover it and then dominate and make other students feel bad. On the other hand, perhaps it is best to have a design contest where there *is* potentially a winner take all strategy, but it requires a machine to be extremely clever and well engineered. Furthermore, finishing early and then practicing with your machine has been proven time and again to be the most "disruptive technology" as far as your competition is concerned. When you finish early, you not only have a chance to find and fix problems, you have a chance to observe others and devise blocking modules that you can add to overcome others' disruptive technologies! Consider past 2.007 students and their machines:

The 1995 contest "Pebble Beach" placed ping pong balls on platters in the midst of a field of plastic pellets. Machine after machine wallowed in the pellets. Rachel Cunningham used to help her dad handcraft precision rifles for Olympic shooters, and she created a very elegant, simple, and precise projectile shooter that consistently scored a dozen balls. She made it to the semifinals and then her rubber band broke and her machine misfired. Her massively disruptive technology merely needed a maintenance schedule (she should have replaced the rubber band each round). Hyoseok Yang went on to win with a well-made robust design with which he had practiced driving many times.

Sami Busch and several others in the 1996 contest "Niagara Balls" discovered the disruptive technology of extending a scoop to catch and direct the balls as they flowed over the waterfall. In the final round, his opponent from Harvard deployed what he thought would be the winning disruptive technology: a scoop that would bring the balls to his scoring bin, AND an arm to extend over the opponent's scoring bin. Sami was watching carefully during the night's competition and he took advantage of the fact that when the contest started, it took about 2 seconds for the balls to come cascading over the edge: Harvard immediately deployed, and Sami deployed ½ second later. Sami's machine pushed the Harvard scoop and blocking arm out of the way and Sami captured every single ball to win (much to the relief of the MIT crowd)!

Tim Zue and a handful of others in the 1997 contest "Pass the Puck" discovered the disruptive technology of a raised platform that would enable their bulldozeresque machines to launch themselves across the barrier and pin their opponent thus scoring a few points and preventing their opponent from scoring. But what happened when two such raised bulldozers faced each other? Tim, however, had finished early and recognized the problem and identified the fundamental physics: traction. His disruptive technology was sandpaper applied to the top of his platform so his bulldozer won every time against those trying to drive off of simple aluminum surface platforms!

Colin Bulthap in the 1998 contest "Ballcano" thought to score modestly and then use a fast mobile *Botherbot* to *bother* and confound competitors. His machine scored using a simple wall crawler to drag a fabric tube from his scoring bin to scoop balls as they flowed out of the Ballcano. This enclosed design also prevented other Botherbots from confoundifying him!

David Arguellis and a handful of other students consistently were able to place 10 pucks in the top scoring hole in the 1999 contest "MechEverest". Dave had finished early and realized he had the time and the ability to make a Cage module to collect the hockey pucks at the base of MechEverest as his machine started up the slope, and then the pucks fell through the lower scoring hole as they were dragged across it. This put his score over the top.

Kevin Lang in 2000's "Sojourner This" took Botherbots to new heights with a Botherbot that moved to the opponent's scoring bin and dropped itself in so its welding rod top totally closed off the scoring zone. Kevin’s bulldozerbot then proceeded to push balls into his own scoring zone!

For every scoring ***strategy*** you have, envision the simplest ***concept*** possible to score and to block it, just in case your opponent thought of the same ***strategy***!

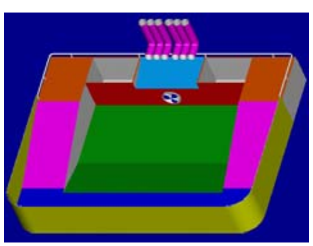
Deterministic Design: *Disruptive Technologies*

- Analysis is the lens which brings a problem into focus and lets you clearly see the best return on your investment
  - Value analysis of scoring methods
  - Physics of scoring methods
  - Risk analysis
  - Schedule analysis

Hyoseok Yang

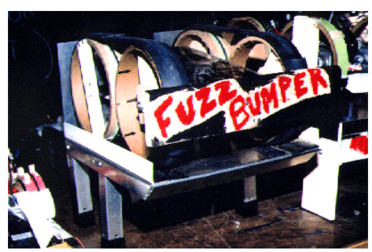
1995's ***Pebble Beach!***

Sami Busch

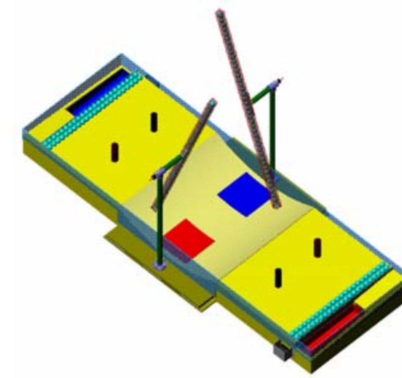


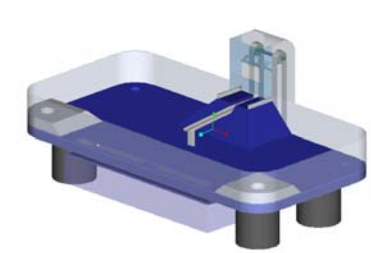
1996's ***Niagara Balls!***

Tim Zue



1997's ***Pass The Puck!***





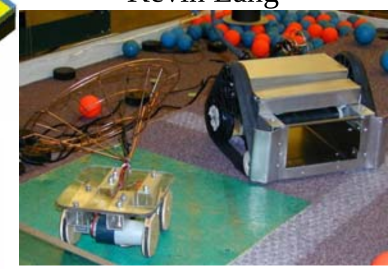
Colin Bulthap

1998's ***Ballcano!***

Will Delhagen & Alex Jacobs

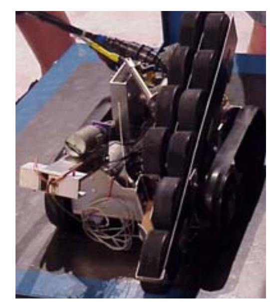
2001's ***Tiltilator!***

Kevin Lang



2000's ***Sojourner This!***

David Arguellis



1999's ***MechEverest!***

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Deterministic Design: *Best Engineering Practice*

Engineering is distinguished from tinkering by the former's use of fundamental principles to stimulate and assist the creative process and guide implementation; in addition, engineering implies the use of analytical and computational tools to optimize a project. These tools are not only concerned with classical analytical engineering endeavors required to move the project from the concept to production stages, they are also concerned with keeping the project on schedule and on budget. An engineer must have a positive attitude towards the design process and project management. Best engineering practice must be the standard to which all team members adhere if a project is to be successfully completed on time and on budget:

- Awesome Engineers:
  - Place ethics and morals above ALL else
  - Are team players
    - Freely exchange ideas and offer constructive criticism
    - Think of the needs of others and the project, and not just their own requirements
  - Do not suffer fools or tolerate obstructionists
  - Follow a deterministic design process
    - Document their analysis and development methods so others can follow/learn
    - Never guess, or hope something will work before they release it for production.
    - Earn respect by thinking "smart" not just putting in long hours
  - Follow a schedule
    - Deliver on schedule without stressing-out themselves and everyone else
  - Document their work
    - Keep engineering notebooks and/or other records so others can check their work, or build upon it
- Yucko Gunky Icky Engineers
  - Try to take shortcuts and get away with things…
  - Hog resources
  - Think they can just cut-&-fit on the fly and change directions at random
  - Put things off and fail to meet milestones
  - Work late hours the night before the ship-date and produce hacked together contraptions

In between these two extremes are engineers who may have good intentions, but they are not applying fully engineering principles to their own actions. Some engineers just get too excited about a project, so they jump on their workstation horses and attempt to gallop off into the pretty CAD background; however, ignoring best engineering practice is tantamount to forgetting to untether the horse! In a similar manner, some engineers misguidedly substitute trial and error for careful analytical or computer modeling and optimization.

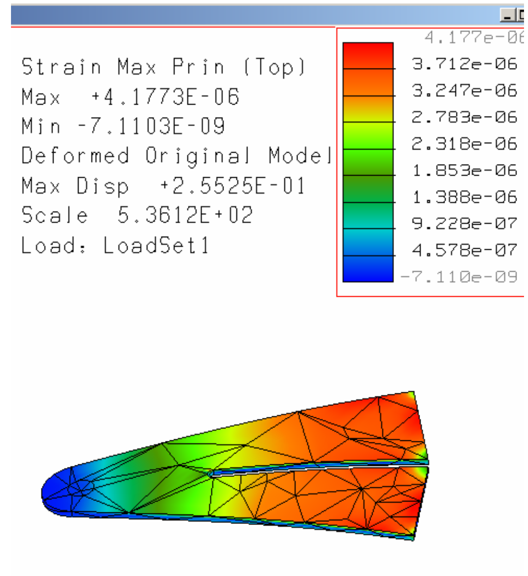
Unfortunately, too often engineers think that a poorly defined problem gives them license to proceed in a poorly defined manner, and they excitedly set off in too many directions at once. Such haphazard approaches to problems indicate a lack of deep understanding, and this can lead to an internal lack of confidence which makes the engineer think they had better think of even more "out of the box crazy" ideas. A vicious cycle forms and the project falls way behind schedule. Other sad problems include endless meetings where format dominates over function and trying to do too much which results in a Rube Goldberg type solution. All of these issues can lead to a great idea at the last moment, but it just will take a little more time, even though the project is way behind schedule, and the idea has yet to work even a little bit.

To help combat these common problems, the ISO 9000 and ISO 9001 family of standards were created by the International Standards Organization. These standards are concerned with making sure companies have best engineering practice procedures in place. Soon it will be difficult for a company to sell its products if it is not ISO certified; therefore it is advisable that every engineer, whether practicing or in training, develop best engineering practice habits.

Create a simple web page to document your understanding of the problem, your solution approach as you initially see it (it will change!), your schedule, and your progress. Document your thought process so others may follow and learn and make useful suggestions. Review the work of others so that you may help them and in the process, help yourself. Enter your observations about the contest and any initial ideas that come to mind.

Deterministic Design: *Best Engineering Practice*

- Before we can talk about a process for design, we must consider the things the best designers do as they solve problems
  - *Best Engineering Practice* entails careful forethought and following standards
    - ***62.5 grams of prevention is worth a kilogram of cure!***
    - ***"Random Results are the Result of Random Procedures"*** ***Geoffe Portes***
  - Prevent problems before they occur, for example:
    - Does not meet customer needs
      - Prevention:
        - » Identify the *Functional Requirements* (FR)
        - » Develop a *Design Parameter* that accomplishes each FR
    - Failure
      - Prevention: Design to withstand external and internal loads
    - Poor performance
      - Prevention: Design to be robust to tolerances and errors
    - Cost too much
      - Prevention: Create clever, frugal, manufacturable designs



- *Deterministic Design* is a key element of *Best Engineering Practice*
  - It is a means to systematically solve even the most complex problems in a rational, logical manner, while still allowing you to have wild crazy creative *zoombah* illuminated thoughts!

Deterministic Design: *Schedules*

Although there are many different elaborate models of how designs develop, most would agree that overall there are essentially three basic phases to the development of products: ***Strategy*** *&* ***Concept***, *Detailed Engineering & Development*, and *Integration & Test*. Each of these phases, when executed properly, take about a third of the total development time. Too much or too little time spent on one of the phases means that you will likely be rushed in one of the other phases, and quality and performance will suffer.

There are many different detailed methodologies ranging from *House of Quality*[1] *to Rapid Product Development*[2] *to Axiomatic Design*[3]*;* however, all of them require a sequencing of events and thus all require the engineer to maintain a schedule. Needless to say, there are an equally large number of scheduling methods, but at this phase, the method is not as important as the net effect. What matters is that the total time allotted for completion of the project be partitioned to each of the basic phases, and then each phase be further partitioned to ensure that an appropriate amount of time is allotted to each task. A simple table often thus suffices to outline what needs to be done, which by the way, is the same process used to manage the creation of a major written work, or the composition of a symphony, or the cooking of a large meal, or creation of a major software program! *The patterns of best design practice repeat!*

Given a project that is already broken up into thirds, the best way to decide how time should be spent in each of the phases is to assess the cost/performance issues associated with the project. Starting with a fundamental assessment of the physics of the problem and of possible solutions, one is likely to identify potential leading edge ***strategies***, and possibly even a disruptive technology. These potential strategies should be investigated first, and then a detailed development schedule can then be created.

Each of the thirds can be thirdified into thirdlets! Given a 12 week development process for a robot to be entered into a design contest, the first trimester is allotted to developing ***strategies*** and ***concepts***. The first week should be devoted to developing a deep understanding of the problem and using this understanding to create ***strategies*** ranging from shoot-from-the-hip instinct ideas, to ideas driven and guided by analysis. The second week should be spent doing experiments and more detailed calculations to weed out lame or super risky ideas, and evolving a leading edge ***strategy***. The third week is then spent generating, creating, and evolving ***concepts*** to arrive at a best ***concept*** for development. The fourth week is float time, It might be needed because more than expected experiments and analysis was required during the third week; or a leading edge concept might indeed have been identified, and then the next trimester can be entered early and you can get ahead of schedule!

The second trimester is for detailed engineering and development. The first two weeks are for dividing the ***concept*** up into ***modules*** and for developing and testing the most risky ***module***. Accordingly, at the end of the sixth week of the project, the most risky module should actually be all designed and ideally a *Bench Level Prototype* completed and tested. The next two weeks are for completing the detailed engineering of the remaining **modules**. If there is any uncertainty, a ***module*** can be engineered and a *Bench Level Prototype* can also be designed and tested.

The first two weeks of the third trimester are for completion and testing of remaining ***modules***. The eleventh week is for integration and testing of the ***modules***, and the twelfth week is for continual use to find any flaws that may remain. If all goes according to schedule, and it will if one is careful to follow a deterministic design process, the entire process of conceiving of an idea, growing it, and then giving birth to it will be a joyous happy experience!

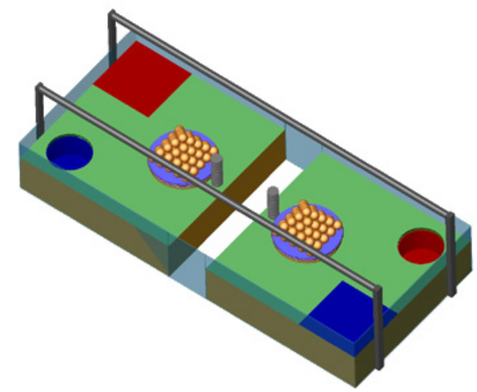
Remember, *"It takes 9 months to gestate a human baby, no matter how many women are assigned the task!"*[4]

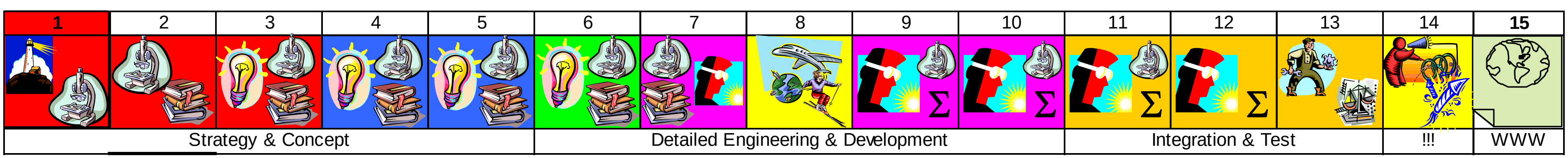
Carefully read through ALL of the milestones required for the development of your project and develop a strong internal urge and commitment to work deterministically and to adhere to the schedule. Start off on the right foot by completing Milestone ONE as soon as possible! Engineers who consistently miss milestones will soon find themselves looking for burger flipping opportunities.

1. K. Otto, K. Wood, Product Design, Prentice Hall, Upper Saddle River, NJ, USA 2001
2. Karl T. Ulrich, Steveen D. Eppinger Product Design And Development, 2000 The McGraw-Hill Companies, Inc. Boston, MA, USA
3. Nam. P. Suh, Axiomatic Design, Advances and Applications, 2001 Oxford University Press, New York
4. Frederick P. Brooks Jr. The Mythical Man-Month, 1995 Addison-Wesley Longman, Inc. Reading, MA. USA

Deterministic Design: *Schedules*

- Time is relative, but you will soon run out of it if you keep missing deadlines!
  - No matter how good your ideas are, their value decays exponentially with every day they are late
    - Once a customer starts buying a product, if the manufacturer maintains diligence, you will find it extremely difficult to regain market share
- The process of getting a product to market involves phases
  - Identify & study problem, develop solution strategies and evolve “best one”
  - Create concepts and evolve “best one”
  - Create modules
  - Detail design, build, & test the modules starting with the most risky
  - Assemble, integrate, test, and modify as needed
  - Document and ship
- You must create a schedule and stick to it!
  - This is true in ALL pursuits
  - Yes, sometimes the schedule will slip…this is why you have countermeasures for risky items that fail, and you build in capacitances (float time) to allow for troubles…





Deterministic Design: *Risk Management*

Imagine the first time you thought to ask someone out on a date (if you never have, maybe this will help)! Popular media parodies the pleasures and perils; however, we exist and that means we have parents; therefore the process must work and be worth it! That first luscious lackadaisical lifeform that caught your eye, the uncertainty, what if you were rejected? The shame, the embarrassment, oh how could you do it?! Finally, one day, you just did it, and you know what? The lifeform laughed and ran away! At that point you thought to become a hermit, but then a voice inside you said “Hey, that wasn’t so hard, and even though I got laughed at, it means I can do it again because I have parents so its bound to work sooner or later!” The next time, you focus on a lifeform in shop class with a very high IQ, and before you finish asking the question, they ask you what time they should meet you for a game of chess!

Thus it often is with engineering design. Too often we get enamored with a sexy design that tempts us to run after it, while it remains aloof and unobtainable, when a little bit of forethought would have made us realize the futility of our fantasies. Once again, applying good engineering practice prevails: Dream your wildest fantasies, but then carefully evaluate them, including performing analysis. Which classes and clubs are they in? What chat rooms do they visit? Who are their friends? What is their favorite machine tool? What CAD program do they like best? What languages can they code? Run some experiments such as ask a friend to see help casually determine if there might be any interest. Then make casual conversation about what a great time you had in the shop this weekend. All projects have risks, which represent the potential to succeed, so learn to identify and assess risks, and manage them by best engineering practice, having a contingency plan, and learning when to use it.

Risk is inherent in every project and good engineers must never make decisions based on hope or hype. If you find yourself praying for success, you likely did not design deterministically! Religion can be a wonderful part of your life, but it should not be part of the engineering design process. Facts, calculations and data are essential to making good decisions:

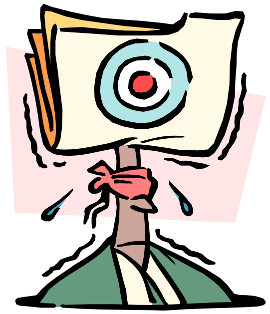
- First and foremost, do a safety assessment to ensure that the ***concept*** is inherently safe, or make sure that you have plans for safety devices.
- Search and see if someone else has already solved the problem, and if they have, reverse engineer their solution to see if you can create a better idea:
  - Use the Internet or the scientific method to get the facts:
    - Formulate a hypothesis, analyze or experiment, torture the data, and draw conclusions.
- Preliminarily analyze the idea for power, geometry, and complexity:
  - Create a power and force analysis to see if you have enough to do what's required in the time allotted.
  - Evaluate motion and space (packaging) requirements.
  - Estimate the number and types of modules and parts that will be required, and seek to minimize their numbers!

Deterministic design requires continuous risk assessment and identification of contingencies should the risk prove too great or the schedule not allow further investigation:

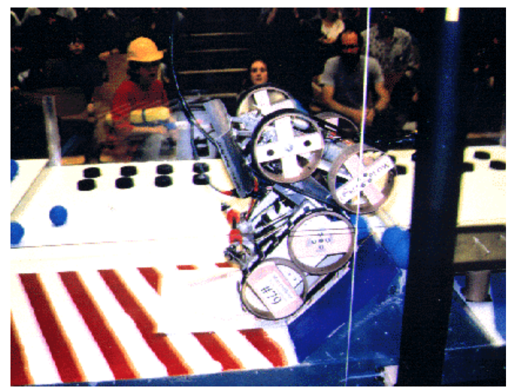
- Lower Risk Design:
  - If you can confidently create an analytical model for a design, then it is likely that the path you are following is "safe" and is low risk.
  - The design has been done many times before, and you merely have to scale or copy the solution and focus on implementation.
- Higher Risk Design
  - If it is hard to analytically model a design, BUT the design has fewer parts and has the promise of elegance, it is a risky design that is worth investigating
    - Such designs might be developed using advanced computer models and/or bench level experiments or prototypes
    - Continually evaluate the risk to see if it is subsiding as engineering progresses. Keep an eye on the schedule and be prepared to revert to your contingency plan.
  - Always have a lower-risk alternate design as a contingency plan!

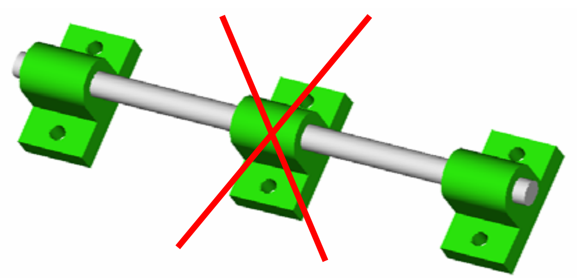
Review your different ***strategies*** and reassess risks and possible countermeasures to minimize risk. Where risk has the potential for big payoff, make sure you have a solid easy-to-implement contingency plan. This often can be accomplished with redundant or alternative modules that can be incorporated into the risky strategy.

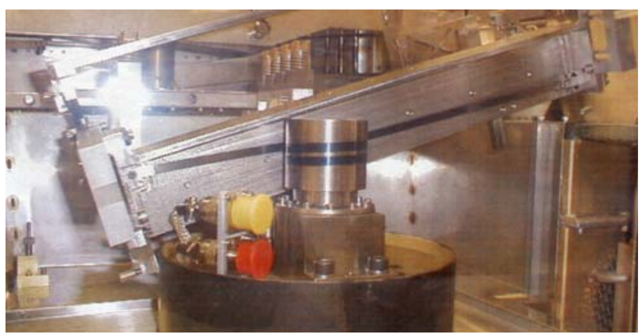
Deterministic Design: *Risk Management*



- The key to deterministic design is risk management
- For every idea, risk must be assessed
  - Ask yourself which ideas and analysis (physics) are you most unsure of?
    - Which element, if defined or designed wrong, will neutralize the machine?
  - For every risk identified
    - Estimate the probability of occurrence (High, Medium, Low)
    - Identify a possible countermeasure
  - Prioritize your risk and continue to do analytical, computational, or physical *Bench Level Experiments* (BLEs) to test ideas before you move forward!
  - *Good Engineering Practice* continually applies!
    - Prayer is for your personal life!
    - Determinism is for design!







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Deterministic Design: Coarse-to-Fine *Funnels*

From first thoughts to final details, many ideas emerge, but only one can be chosen. It is as if all ideas enter a nozzle, and in some true thermodynamic sense of the word, they merge and emerge as one. It is as if design can be thought of as a series of nozzles or funnels through which ideas flow.

There are patterns in the way each of us designs, and different patterns are more reliable and successful than others. Your goal should be to identify and develop the patterns that will enable you to best solve complex unstructured problems. You may think trial and error is the best method, but before you settle in on that type of pattern, try deterministic thinking and you will be amazed at how much faster and better you will be able to design. To illustrate this, graph a horizontal line, a sloping line, a parabola, and a cubic function. Determine the area under each of these curves. The first three are trivial. The latter two can be accomplished by manually breaking the shapes up into little trapezoids and up the area under each. However, calculus makes the task so much easier. No matter how complex the curve, you do not care, as the method of the calculus applies to all. For complex functions, you can integrate by parts. Aren't you glad you learned calculus? The same lesson will apply to learning design process.

Given that an entire machine, down to the finest detail, will one day emerge from your box of resources, you need to imagine what you could do. Imagine you are standing 3 meters away from the quarter finalists' machines. Can you see the type of fasteners that hold the perntoid to the gangleflexor? Not unless you are an eagle, so why are you worrying about that now? In the beginning, you are far away from the end, so you should only be looking at the overall configurations of the machines and observe how they would seem to move and score. It appears that some score with the pendulum and some score with the balls and that some have two parts that score with the pendulum and zoom off to play with the opponent. You are observing different ***strategies*** for winning the contest. Accordingly, you want to apply good engineering practice to develop many different ***strategies*** without worrying about the actual mechanism at this point. The focus should be on overall size and motion and power requirements. You select the ***strategy*** that has the best apparent potential to realize a maximum score. You decide that the volume is best evaluated using a combination of simple formulas and volume integrals.

Taking several imaginary steps towards the machines, you still cannot see the types of fasteners used, but you can definitely see that among your favorite ***strategies*** that one machine uses a robot arm and the other uses a bucket to move the scoring elements over the wall into the scoring bin. Several of the machines appear to have the ability to score in essentially the same manner. They represent different ***concepts*** for machines that all score essentially the same way; so you want to apply good engineering practice to develop many different ***concepts*** without worrying about the detailed size of the elements. The focus should be on ensuring that the power exists to accomplish the desired motions. You select the concept that has the best apparent potential to realize your ***strategy***. You envision that it is comprised of spherical, tubular and curvy looking thingies.

A few steps closer, and you still cannot see the types of fasteners used, but you can definitely see that your favorite ***concept*** has several clearly recognizable modules. You see a robot arm mounted to a base that moves using crawler tracks, and that it also has second robot it carries on its back. Accordingly, you want to apply good engineering practice to develop many different ***modules*** without worrying about the detailed size of the fasteners at this point. The focus should be on ensuring that the power and torque and strength and space exists to assemble everything while still accomplishing the desired motions. The robot arm appears to be the most risky module in your concept. Imagine you can see all the detail! Get out your mental calipers and magnifying glass and carefully study that robot arm and all its detailed components. Run the robot in your mind and see how you want it to move and then you will be more likely to be able to see the details!

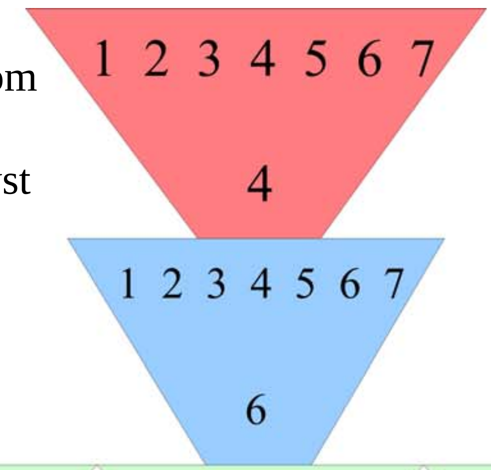
Note that in the above discussion, each of the paragraphs sounds like the other. In fact, the author might have cut and pasted them and then just changed a few of the words. Wait a second, the level of machine detail discussed increases with each paragraph, yet the method of discussion is the same! Wow, that's cool! That saves a lot of time! Lets go snowboarding!

Visit the website's gallery of pictures from past contests and study them from different distance perspectives. Think of ***strategies***, imagine…

Deterministic Design: *Coarse-to-Fine Funnels:*

Strategies ***Concepts*** ***Modules*** ***Components***

- Deterministic Design leaves LOTS of room for the wild free creative spirit, and LOTS of room for experimentation and play
- Deterministic Design is a catalyst to funnel creativity into a *successful* design

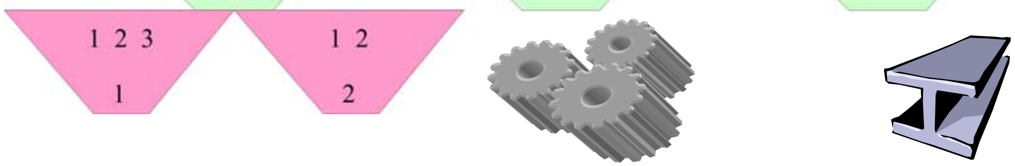


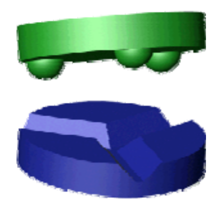
Strategy: Plan or tactics to score but there may be many different types of machines that could be used

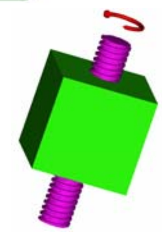
Concept: An idea for a specific machine that can execute a strategy

Module: A sub assembly of a machine that by itself executes a certain function

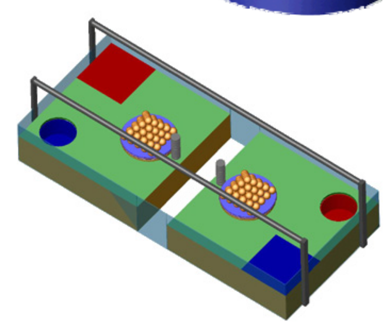
Component: An individual part

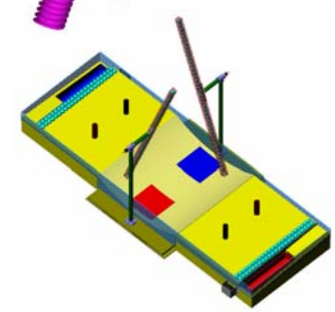






- It is OK to iterate…
  - A *goal* is to never have to backtrack
    - A good engineer, however, knows when its time to let go…





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Deterministic Design: FRDPARRC

No matter how creative or analytical you are, you will do better if you organize your thoughts in a manner that not only helps you, but also helps others to understand what you did. No matter how you design, in the end there are a minimum set of things that need to get done, so you might as well keep track of them from the start. A good way to do this is to use a table that you fill in as a reminder to make sure and do all the things that need to get done! There are six categories of thought that should be accomplished for every design project and they form the column labels for a FRDPARRC table (pronounced *fred park*):

- Functional Requirements (FRs) or events
- Design Parameters (DPs) or ideas
- Analysis
- References
- Risks
- Countermeasures

The first column is the most important, for it lists the independent *Functional Requirements* (FRs) which are the things that the design must do. or the events that the design must accomplish. It is important that the FRs be as independent from each other as possible. This will aid the design in later being made more modular and more robust! The FRs are not mere specifications, hence they are typically expressed as words, although a specification (number value) can be listed as a guideline for an FR. When the order in which the FRs are to be accomplished is important, *Function Structures*[1] can be drawn which are useful diagrams that put a time ordering to the FRs to indicate which FRs are done serially and which can be accomplished in parallel. Some systems use a separate flowchart to indicate ordering of functions.

The second column contains at least one *Design Parameter* (DP) for each FR. The DPs are ideas for how to achieve the FRs, and they can be expressed as words or sketches. They also should ideally be as independent as possible, or else a change in one DP may cause undesirable ripple effects in a design. Ultimately, there will be one DP per FR, but in the beginning, it is important to list all of your thoughts and options.

The third column is the *Analysis* column, which starts off describing in words the governing physical or analytical phenomenon for each DP. If you can't say in words what you are trying to analyze and how you propose to analyze it, then you probably will not succeed with equations. Words are also the key to enabling others to quickly learn what you are doing. After the words, come the equations or other means to perform sensitivity studies in order to obtain quantitative answers. If needed, perform appropriate experiments.

The fourth column is for listing the *References* you use for the analysis or the ideas for the DPs. This makes it easy for others (and yourself!) to figure out what you have done! Include information from websites, books, journal articles, and pictures and of past devices.

The fifth column is the *Risks* column and it is where you must objectively ascertain what might go wrong with the pursuit of each DP. If you are not taking risks, you are likely not developing something that can give you a competitive edge. Not every element of a design must be risky, but the overall idea of the design should differentiate your design from others and have the promise to give you a competitive edge. Note that this does not mean a design must be complex, on the contrary, the best design might be small, fast, and easily controllable, and the race is won with practiced driving skills!

The sixth column contains the *Countermeasures* to be undertaken if the risk proves too great and the intended DP has to be abandoned. It is vital that no risky design parameter be put on a project's critical path unless there is a viable countermeasure. Countermeasures usually entail trading off risk for performance or cost, but if it is the difference between succeeding or failing, go with the countermeasure. Remember that not meeting the schedule often constitutes failure!

Create a table of FRs, DPs, Analysis, References, Risks, and Countermeasures and enter in the ***strategies*** that you have thought of since starting to play with the contest table. This FRDPARRC table can be expanded and revised easily if you create it as a table in a word processor or develop it as part of your web page. Are all of the ***strategies*** safe?

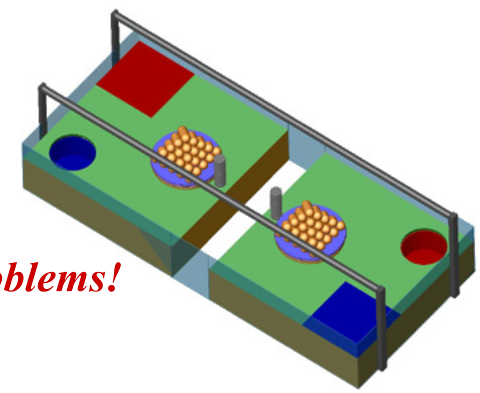
1. K. Otto, K. Wood, Product Design, Prentice Hall, Upper Saddle River, NJ, USA 2001. Also see http://ditc.missouri.edu/ for a in-depth discussion of many other design methods.

Deterministic Design: *FRDPARRC*

Functional Requirements (Events) ***Words***	***Design Parameters (Idea)*** ***Words & Drawings***	***Analysis*** ***Experiments, Words, FEA, Equations, Spreadsheets…***	***References*** ***Historical documents, www…***	***Risk*** ***Words, Drawings, Analysis…***	***Counter-measures*** ***Words, Drawings, Analysis…***
A list of independent functions that the design is to accomplish. Series (1,2,3…) and Parallel (4a, 4b..) FRs (Events) can be listed to create the *Function Structure*	Ideally independent means to accomplish each FR. AN FR CAN HAVE SEVERAL POTENTIAL DPs. The "best one" ultimately must be selected	Economic (financial or maximizing score etc), time & motion, power, stress… EACH DP's FEASABILITY MUST BE PROVEN. **Analysis can be used to create DPs!**	Anything that can help develop the idea including personal contacts, articles, patents, web sites….	High, Medium, Low (explain why) risk of development assessment for each DP	Ideas or plan to mitigate each risk, including use of off-the-shelf known solutions

Reciprocity: 1/R=CM?!

- To actually use the FRDPARRC Table:
  - Create one actual table that becomes your development roadmap
  - Dedicate one sheet to each FR/DP pair



The FRDPARRC table is an exceptional catalyst to help you identify opportunities for applying reciprocity to uncover new ideas and solve problems!

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FRDPARRC and Funneling Example: *Dinner*[1]

The ideas of FRDPARRC charts and funneling may be a little intimidating at first, so let's examine a simple example like choosing what to have for dinner. It's 5pm and you're hungry. You have a lot of work to do before class tomorrow so you don't have time to go to the bank or spend a lot of time preparing or eating dinner. You're only means of transportation is your bicycle. It's been a hard week and you want something that tastes really good. So what do you do? Approach the problem systematically with a FRDPARRC chart. You have four main *Functional Requirements*: Time, Money, Distance and Desirability. Remember, *Design Parameters* are ways to achieve the functional requirements. You also need analysis, references, risks and countermeasures.

So how much time can you spend on dinner? It's 5pm now. You need to be in bed by 10pm to get to class on time in the morning. You have approximately 4 hours of work left to do this evening. That leaves 1 hour for dinner. This is your *Analysis*. Your *References* are your watch, which tells you what time it is right now, and past experience, which tells you what time to go to bed, how long your work will take, and sources of food. Your major *Risk* is that you won't finish your work. A secondary risk is that you won't get enough sleep. A good *Countermeasure* to ensure both completed work and enough sleep is to ask a friend for help. This usually cuts the amount of time your work will take in half, leaving extra time for dinner.

To stay within budget without visiting a bank you check your wallet (this is your reference). You should always have an emergency $20 bill in your wallet so that leaves $20 for dinner. This is your *Analysis*. Your major *Risk* is that you won't be able to buy that exciting new CD this weekend if you spend that $20 bill on dinner, so you should consider eating a less expensive meal or eating at home as a *Countermeasure*. The design parameters, analysis, references, risks and counter measures for the other two functional requirements (distance and desirability) are shown in the FRDPARRC chart.

This first FRDPARRC chart helps to fully define the problem. Now that you know what your goals, requirements and constraints are you can start to formulate ***strategies*** to solve the problem. So what are the ***strategies*** for dinner? You can raid the refrigerator for something tasty and eat at home. You can call for delivery. You can place an order and get take out. Or you can simply go out and eat at a restaurant. A FRDPARRC chart can be used to systematically compare the ***strategies***. Eating in requires an hour to prepare dinner (and clean up) and 15 minutes to eat it. The food in your pantry is already paid for so it does not affect the cash in your wallet. Delivery in your area takes about a half an hour to get the food and about 15 minutes to eat it. Dinner will cost around $10 plus tip. Assume that the total cost will be $12. Take out requires you to ride your bike to the restaurant and then bring the food back home. This will also take about a half an hour to get the food and about 15 minutes to eat it but it requires more effort on your part and only saves you the $2 tip. Eating out always takes at least an hour plus travel time and the bill is usually more than $20. It looks like your best options are eating in or delivery. The effort and the cost are worth the convenience and tastiness of delivery and you decide to get delivery for dinner.

Now that you have decided on a ***strategy***, you must come up with ***concepts*** for implementing that ***strategy***. The best delivery options in your area are pizza, Chinese food, hamburgers or subs. Again, you can use a FRDPARRC chart to compare the different ***concepts*** or you can use a less formal method. You remember that you had Chinese food last night. The hamburger place sometimes forgets to bring the French fries and the sub place delivery time can be really slow around dinner time. You decide to have pizza for dinner.

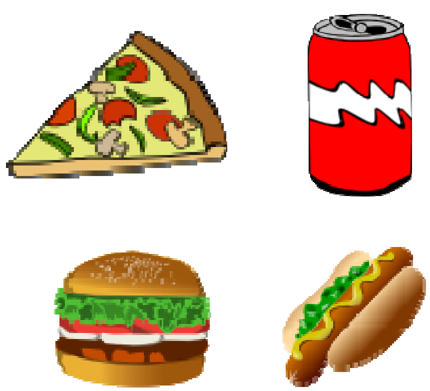
But what pizza place will you choose? Once you choose a pizza place, what kind of pizza will you have? Once you choose what kind of pizza to have, what size will you order? Every decision that you make leads to another level of detail where you can apply the same process from the previous level to make a new decision. Eventually, you will find that your decision process has funneled you towards your final meal. Tonight you will have a medium pepperoni pizza with extra cheese from The Geek House of Pizza.

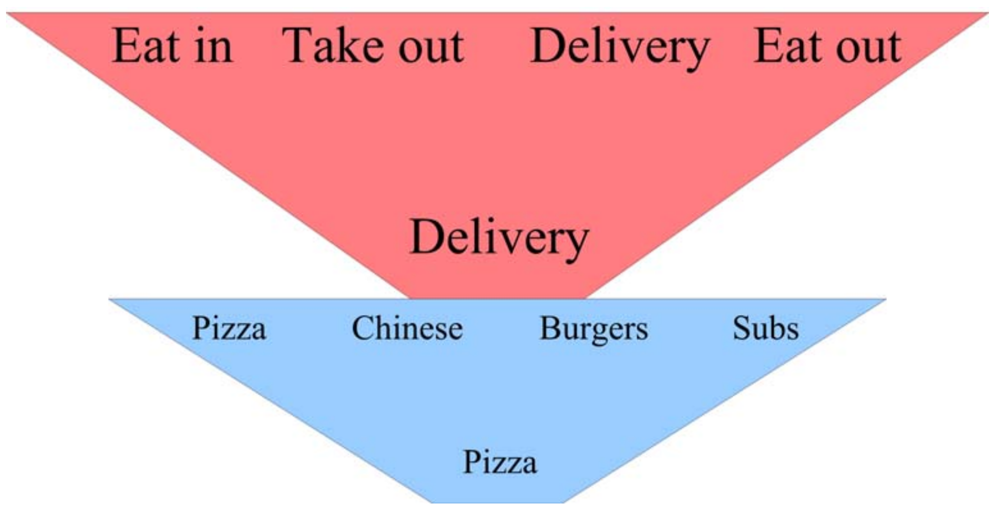
Whether it is deciding what to have for dinner or designing a robot, the use of funneling and FRDPARRC charts can be a huge help in making the best decision. Does one always write down detail like this even for such seemingly simple tasks as dinner? No. As your design skills grow, the process becomes hard-wired into your bio-neural net. Until then, it's a good idea to write down the detail!

1. This example was created by Mary Kathryn Thompson (Kate).

FRDPARRC and Funneling Example: Dinner

Functional Requirements	*Design Parameters*	*Analysis*	*References*	*Risk*	*Counter - measures*
Within budget	*< $20*	*Weekly salary - total already spent*	*Wallet*	*Can't buy new CDs*	*Eat cheaper or at home*
Easy to get to	*Within 3 miles*	*Bikable distance in 10 minutes*	*Past experience*	*No bike parking*	*Walk, order in or eat at home*
Fast	*Within 1 hour*	*Time now - work left to do*	*Watch*	*Won't finish homework*	*Ask friend for help*
Tasty	*Eat at home* *Take Out* *Delivery* *Eat Out*	*Brain storm for ideas*	*Online menus, refrigerator contents*	*Nothing tasty at home*	*Eat out!*





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Design is a Series of Steps Blended Together

Do you put your shoes on before your underwear? Now is the time to assemble all the ideas that have been discussed previously into a systematic process. Ten steps are listed and there may be more or less depending on the design process used at wherever you work. The important thing is that there is a process to follow which leaves plenty of opportunity for creativity!

Some would argue that any attempt to use a design process stifles creativity. Others would argue that if the world were left to creative designers to do as they please, nothing would ever get done! As with many debates, the truth is probably actually somewhere in the middle, and the answer, involves ❤**Passion**❤. From early characterization of the idea of determinism in design for precision machines[1] to the development of an axiomatic design method[2], to a detailed treatise on practical analysis and implementation steps to create precision machines,[3] attempts have been made to get designers to slow down and think about what they are doing. The fundamental issue, however, is that this goal is diametrically opposed to what the popular view of what motivates brilliant designers. The popular notion is that brilliant designers like to be free and unfettered with their minds soaring above all constraints. In reality, the most brilliant designers are those that have a bio-neural-net programmed for deterministic axiomatic thought while simultaneously achieving rapid-fire multi-techno happiness enhancement. Examples of such passionate mega-designers include: Westinghouse (air brakes for railroads, electric power), Edison (light bulb, electric consumer products), Tesla (AC power generation), and Johnson (SR71 Blackbird, Lockheed's Skunkworks). Who is your favorite designer?

The best designers dream wild thoughts, and these wild thoughts (**coarse** outlines), are then optimized by physics (fine details) to create major new products. Taking a cue from the world of television, consider the optimal pair formed by Captain Kirk and Mr. Spock of Star Trek™ (or Captain Picard and Data). Spock was the interface between the wild, creative, shoot-from-the-hip Kirk, whose instincts were unmatched. Spock took the instincts and optimized them and made them into reality. The best designers can switch back and forth between these two modes of thought. The best designers combine different steps of design into a fluid graceful dance.

A design process is not a software program or analysis tool. A designer's creativity should be catalyzed and assisted, not forced into a box of conformity. Awesome designers will rebel at such constraints and flee. Companies that impose such policies will be left with designers who will not be able to compete with creative designers now working at the competition. As a practicing designer with five dozen patents and many high tech products on the market, the author can attest to the need to be free and unconstrained, yet tempered by physics, philosophical processes, and business realities.

In order to walk along the path of product development, one must take steps. Different designers will take different numbers and types of steps (step, skip, run…), but they must move forward. Even if a good designer denies following a process, a pattern is likely to be seen, because humans are creatures of habit. The development of a product involves essentially three basic phases: *Strategy & Concept*, *Detailed Engineering & Development*, and *Integration & Test*. Each of these phases can be broken up into steps, and within each step, the designer is free to be as creative as they can be. It is important for the designer to take a breather now and then and organize their ideas and write them down so others can understand what they have done. But it is important that the design must be done to deliver a product on time.

To deliver a product on time, you must have a good design process. If a designer is spending so much time on generating a creative concept for a design that the milestone to start detailed engineering is missed, what makes them think they will be able to spend less time working out the details? They will have even less time to test and debug the design! To not follow a design process that has milestones is to assume that if one works faster near the end, time slows down, thus giving more time to design! The shocking truth is that this is not the case. The good news, however, is that design process can actually enhance creativity because it lets designers be free to think while reminding them of the tasks to come, hence stimulating concurrent engineering, design for manufacturability, design for recycling…

Assess how much time you have to spend on this course, and allot evening and weekend time to it that you keep sacrosanct! Do the same for your other commitments. Make a commitment to think and do with efficiency!

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1. R. Donaldson, "The Deterministic Approach to Machining Accuracy", SME Fabrication Technology Symposium, Golden, CO, Nov. 1972 (UCRL preprint 74243).
2. N. P. Suh, The Principles of Design, Oxford University Press, Inc., 1990
3. A. H. Slocum, Precision Machine Design, Society of Manufacturing Engineers, 1995

Design is a Series of Steps Blended Together

- Follow a design process to develop an idea in stages from **coarse** to fine:

Explore *Experiment* *Create* *Detail* *Build & test*

  - ***First Step:*** Take stock of the resources that are available
  - ***Second Step: S***tudy the problem and make sure you have a clear understanding of what needs to be done, what are the constraints (rules, limits), and what are the physics of the problem!
    - Steps 1 & 2 are often interchangeable
  - ***Third Step:*** Start by creating possible ***strategies*** *(ways to approach the problem)* using words, analysis, and simple diagrams
    - Imagine motions, data flows, and energy flows from start to finish or from finish back to start!
    - Continually ask “Who?”, “What?”, “Why?”, “Where”, “How?”
    - Simple exploratory analysis and experiments can be most enlightening!
    - Whatever you think of, others will too, so think about how to defeat that about which you think!
  - ***Fourth Step:*** Create ***concepts*** *(specific ideas for machines)* to implement the best ***strategies,*** using words, analysis, and sketches
    - Use same methods as for ***strategies***, but now sketch specific ideas for machines
    - Often simple experiments or analysis are done to investigate effectiveness or feasibility
    - Select and detail the best ***concept***…
  - ***Fifth Step:*** Develop ***modules*** *(sub assemblies of parts)* using words, analysis, sketches, and solid models
  - ***Sixth step:*** Develop ***components*** *(individual elements)* using words, detailed analysis, sketches, and solid models
  - ***Seventh Step:*** Detailed engineering & manufacturing review
  - ***Eighth Step:*** Detailed drawings
  - ***Ninth Step:*** Build, test, modify…
  - ***Tenth Step:*** Fully document process and create service manuals…

First Step: *Resource Assessment*

Once presented with a challenge, the most important first step is to make an assessment of the resources available to you. This will help to catalyze your thoughts as well as to help keep them realistic. Accordingly, the most important first resource to consider is ***time***! The first aspect of time is when is the project due, for this will allow you to immediately divide the project into thirds. *One-third for creating, one-third for engineering, and one-third for building and testing*. Anyone who romanticizes about working until the middle of the night on the last day to do "their really creative thinking" is fooling themselves. The best and the brightest know how to manage their time! Hence it is very important to keep an eye on the calendar and know when your risky endeavor should be set aside for a more reasonable countermeasure so that you can stay on schedule!

This rule of thumb for dividing a project up into thirds also works well for taking tests and doing other assignments as well! It is such a simple rule to follow, and those who do, rule! Anyone who thinks they can radically change their design the night before it is due is doomed to fail. They will not be welcome in any well-run successful engineering organization.

Within the thirds that are set aside for each of the major design functions: creating, engineering, and building & testing, you also have to honestly determine how many person-hours a week can be spent on the project. A typical engineering course requires 12-15 hours per week. This is actually an amazing catalyst for keeping your clever ideas simple! You must also see when the shop is open or how busy the mechanists are, and make sure to design for manufacture! Will you have enough computer time available? Design engineers are often way too ambitious, and over committing yourself and being late just feeds the managers!

Next, carefully consider what materials and components are available? Lay out all the materials that you have (physically or in catalogs) in front of you and play with them. Let them talk to you. What are their limits? How have others used them? For example, in ultra precision instruments, even changes in air pressure can cause size variations that are of concern. In a robot contest, the materials in a kit may seem limiting, but they can be very rich in the ways that they can be combined. With only four base pairs, DNA leads to a huge number of lifeforms!

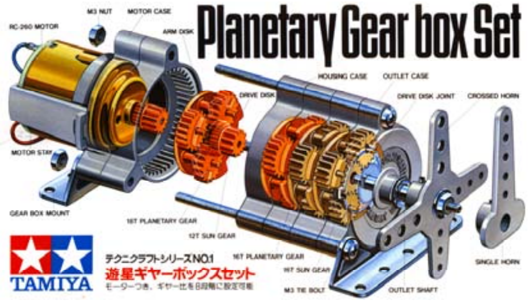
Your awareness of materials and components is only the first step. You must be aware of the manufacturing processes that can be applied to each of the materials. How can they be machined? Can they be formed? How can they be fastened or bonded to other materials? Can they be welded? And of course there is the issue of time. How long does it take to perform each of the manufacturing processes?! Where can you assemble and test modules? Will you have enough time on the playing field in a contest to test and debug your machine? Often an awareness of how materials can be processed or attached can provide a powerful catalyst to the creative process.

The availability of engineering resources must also be carefully considered. From software to people, knowledge resources will be required, and those with superior command of the resources often create superior designs. Software can be as simple as pre-existing spreadsheets or MatLab files, or it can require mastering a new program Do you have the solid modelling skills required, or can you learn as you design? Do you have access to a finite element analysis package and do you know how to use it? How can you simulate your linkage? The more you can do on the computer to prove out a design before you build it, the better off you will be.

Remember, two weeks tinkering in the shop can often save an hour simulating on the computer! Conversely, *everything always works on paper and analysis paralysis can be equally unproductive*. Always seek to maximize effectiveness and minimize time to get things done, while developing a deep understanding for how your design fundamentally performs!

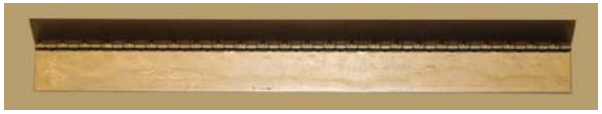
Finally, never be shy. Seek out your colleagues and advisors and ask them to review your work, but come prepared with your FRDPARRC tables and sketches to show them. Make meetings short and hyper productive and you will always be welcome.

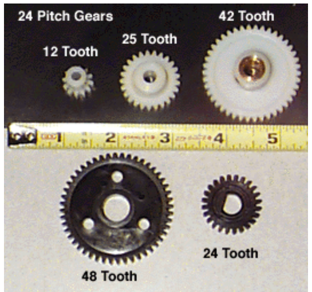
Carefully examine all the parts in your kit. Play with them, study them, think about their performance limits. Check the course website: http://pergatory.mit.edu/2.007, and many other websites that describe how things work, as well as equipment manufacturers' web sites to see how they do things. You can tell a lot from a picture!

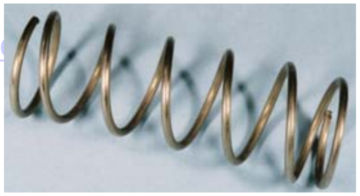


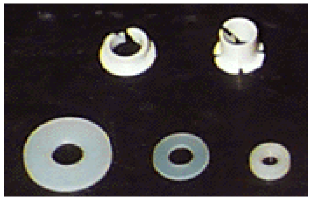
First Step: *Resource Assessment*

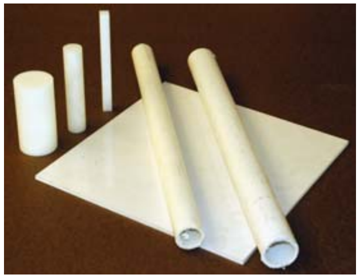
- Before even thinking about potential solutions to a problem, one has to first take stock of the available resources:
  - What time is available?
    - When is the project due?
    - How many person-hours a week can be spent on the project?
    - What are the hours of operation for support facilities (library, shop, computers…)
    - Designer engineers are often ***way too*** ambitious!
  - What materials and components are available?
    - Lay out all the materials you have (physically or catalogs) in front of you and play with them, let them talk to you, what are their limits, how have others used them…
    - Look through hardware magazines
    - Check the Web: http://pergatory.mit.edu/2.007 , http://www.efun
    - Look at other machines and search patents
    - Knowing your hardware is a POWERFUL design catalyst
  - What manufacturing processes are available?
    - You may not have access to a wire EDM, nor the time to send out the parts!
    - You may not have the time to have a casting made!
  - What people are available?
    - Engineering?
    - Manufacturing?
    - Management?
    - Marketing….?

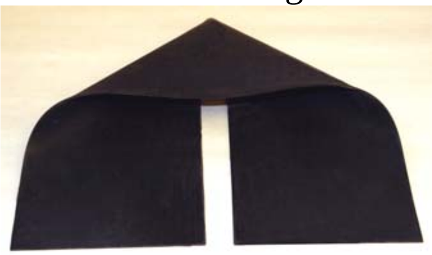


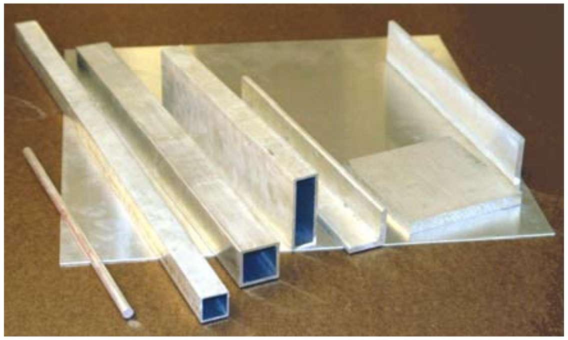












Second Step: *Understanding the Problem (Opportunity!)*

The **Passion** activity of *play* is an ideal way to discover the dynamics and the limits of the system. After you get an initial feel for the system, a first order model of the physics can provide insight into strategies that play might not reveal, or it can help sort strategies into realistic and fantasy pursuits.

A Lagrangian approach to dynamic systems[1] is useful because it assumes a system can be modeled in terms of kinematic, potential, and energy dissipative elements. Of course one can also use fundamental principles to derive the equations of motion of the system. There are five basic components in any mechanical system: Force or Torque sources (motors, amplifiers), Masses (inductances), springs (capacitances), dampers (resistors), and transmissions (transformers). These elements are connected by geometry (including switches), and all may have linear or non-linear behavior. All systems have dynamics to some degree, and with a model of the system, one can find the most sensitive parameter, how it can be measured, and how it can be controlled. This is the essence of robotics and manufacturing equipment design as well as the essence of product design. In the latter, however, the greatest non-linearities are often the customers and their attitudes!

The first step to understand the problem is to fully understand the geometry or connectivity between all the elements. This will enable you to create a lumped parameter model of the system. Every real system is actually a continuum, but as much as we would like to write a differential equation for everything, we do not have the time and will have to settle for lumped elements. In a machine, the connectivity is usually defined by the joints and bearings, as well as distinctive geometric features, such as a wall. But how is the geometry controlled?

The second step is to take stock of all the energy storage elements in the system. Starting with the movable masses (inertias) in the system, assess their energy motion and energy storage capabilities. Are they free to move in any direction or are they guided by a bearing system? Using basic $F = ma$ type analysis, a simple trapezoidal motion profile, and knowledge of the power in your actuators, estimate how far you can move the mass in the time allotted. Consider a simple pendulum which is an inertia held by a pivot (or a string). Its period is simply $(g/L)^{1/2}$, but if the goal is to get the pendulum moving should you just tap it at its natural period, or should you force it which means you will have to consider motor power and pendulum inertia? Is it worth it to force the pendulum, or maybe just excite it at its natural period? What energy would it take to raise a mechanism along the pendulum to engage the support shaft and start the pendulum spinning like a windmill? How much potential energy mgh is stored by the masses in the system, and how much can be harnessed or must be controlled when a mass is released?

Speaking of potential energy E, linear springs store energy as a function of the spring constant k and the amount the spring is displaced x, *where* $E = \frac{1}{2} kx^2$, and springs are not always coils. For example, when a machine tool cuts a part, the cutting forces bend the part and after the tool passes by, the part springs back. If you have a machine whose bearings (wheels) are preloaded to a surface, the surface will also deform and the preload might not be what you think it is.

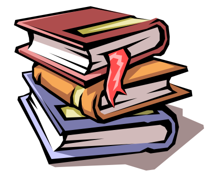
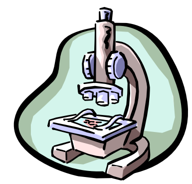
The third step is to take stock of all the energy dissipative elements in the system. Any non-elastic elements will dissipate energy. Just like running in sand, friction is your enemy if you are trying to overcome it. On the other hand, if you are trying to increase tractive effort, it is your friend.

Take stock of all the contest table's energy storage and dissipative elements. What is the period of the pendulum? What effect do the balls inside it have on the dynamics? Is it worth figuring out a way to dump the balls inside the pendulums? Examine the thin-walled square tube that is the pendulum. If you are to design a robot to climb to the top of the pendulum, the wheels will have to be preloaded against the tube. If the static coefficient of friction between the wheels and the tube surface is 0.1, then count on the dynamic coefficient of friction being about 0.05 and thus the preload force between the wheels and the tube needs to be twenty times the weight of the robot. Will this damage the tube and disqualify you? You must do analysis of the effect of clamping on the tube before you clamp!

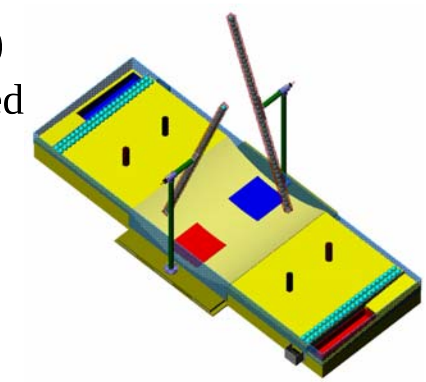
1. This is a method typically covered in a university engineering course on dynamics of systems.

Second Step: Understanding the *Problem (Opportunity!)*



- Any problem can be dissected and understood by establishing a starting point, and then analyzing the system and its elements
  - It is like creating a design in reverse
- Study a problem and then define it in terms of its energy storage and dissipative elements, and its geometry and materials:
  - ***Simple physical models***
    - Physically play with the kit and contest table: Let the hardware talk to you….
    - A *sketch model* made from simple materials enables you to play with the problem
  - ***Simple drawings***
    - A simple hand-drawn isometric figure helps you to pattern the problem into your bio neural net
    - A simple solid model can also be very useful, particularly when later seeking to test your solid model solution on the problem
  - ***Physics: First-Order-Analysis***
    - Words to describe the physics
    - Simple analysis with guestimates of realistic numbers (spreadsheets)
  - ***Words*** (in a table or bulleted list) to describe what problem must be solved
    - What must be accomplished? (e.g., tip a balance…*functions, events*)
    - What are the constraints? (e.g., rules, cost, size, time)



Third Step: Developing Strategies

Having become familiar with the deterministic design process and having familiarized yourself with the problem (opportunity!) and resources available to you, it is time to start getting creative and generating ***strategies*** (ways to approach the problem) . However, the last thing you should do is starting drawing or sketching detailed ideas for mechanisms, because this may lead you to create a design that is far from the best way to accomplish the task. Just as creative designers say they do not want to be hemmed in early by a design process, a creative designer should not want to be hemmed in early by a specific concept, such as using a screw to lift a load, when a piston may be the best way. Therefore the creative designer should first seek to develop as many strategies as possible for solving the problem. Take care NOT to propose a ***strategy*** in too much detail, lest you fall in love and commit yourself without first considering herds of alternatives. A ***strategy*** is an idea initially described in the simplest of forms that can specify types of motions, but not how they are achieved. A FRDPARRC Table will describe what the ***strategy*** will accomplish, and how it will do it. It may also be useful to provide a simple sketch of the ***strategy*** in the form of a stick figure, or even just arrows to show what might move where, just like a football coach draws play diagrams!

The *Functional Requirements* for developing ***strategies*** are the different physical effects that bound the problem. The ***strategies*** are then the *Design Parameter* entries in the table. For example, in the robot design competition *The MIT and the Pendulum*, the FRs for developing the ***strategy*** might be: a) score with the balls on the cylinder, b) score with the balls and pucks, c) score with the pendulum, d) block the opponent. Each of these FRs may have many different DPs (***strategies***) or there may be only one reasonable strategy:

- ***Strategy 1:*** Block pendulums and focus on getting balls and pucks into the goal
- ***Strategy 2:*** Create no block zone around pendulum and focus on spinning the pendulum.

By not saying something like "drive over to the balls and grab them high and then drive over to the scoring bin" you avoid eliminating other possible solutions. For example, what about a ***strategy*** to block and scoop which might be realized with a ***concept*** for a machine that throws a gate across the table and then a robot arm picks up the balls and deposits them in the goal. What about a machine that first scoops all the balls up before they can be knocked down by the opponent, and then leisurely drives over and deposit all the balls.

Early on when many ***strategies*** are being developed and initially compared, there may not be time to do *analysis* on each one, so the designer may have to trust her analytical instinct in order to evolve the potential ***strategies*** and come up with just a couple that warrant a more detailed analysis. When the time comes to choose between a few choice ***strategies***, simple physics should be used as a first-order reality check. Next a spreadsheet (or MatLab script) based on time and motion study, forms a time budget to allow you to compare which design can better achieve the desired effect (e.g., score points in a robot contest). The time and motion study can be based on conservation of energy limited by the power of the available actuators. An actual calculation of the speed of a vehicle will depend on selecting the proper gear ratio, for example, and this is too detailed for this stage of the design process.

References for different ***strategies*** may include machines from the past that have performed similar functions, or other competitor's machines that are accomplishing a similar goal. References may also be made to programs, books, or articles that describe how to analyze the strategy.

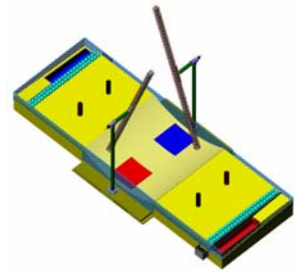
Risks for different ***strategies*** will likely depend on the number of motions that need to be performed, the energy to be consumed, or the potential complexity or sophistication of mechanism that may need to be created. A good indicator of risk is also the amount of precision that is required by the ***strategy***. The greater the required precision, the greater the risk.

Countermeasures for the different risks can be as simple as "use a different strategy". Or they can require that the ***strategy*** have redundant modules or alternate paths or backup systems.

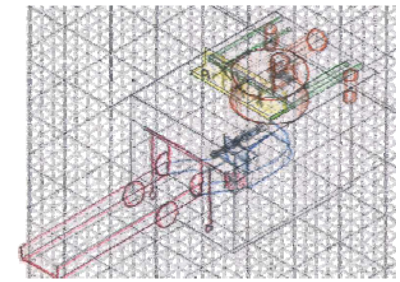
Review the ***strategies*** you have developed thus far and make sure that you have thought of every possible variant and appropriately considered all possible safety issues, references, risks, and countermeasures. Have a friend look it over as a peer reviewer. Start comparing the risks and determine if you need to do some analysis or run experiments in order to evolve the best ***strategy***.

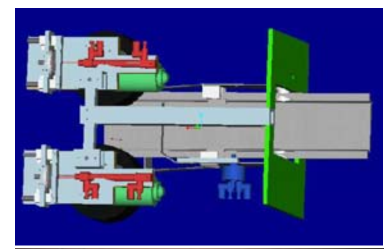
Third Step: *Developing* ***Strategies***

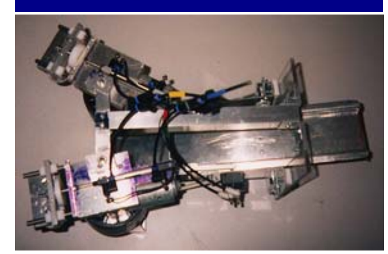
- A ***strategy*** is a general approach to a problem, and there may be many different actually ways of implementing it (i.e., many different concepts).
- ***Strategies*** are developed by:
  - Playing
    - Play with the contest table and the kit parts
    - Create simple experiments
  - Drawing
    - Sketch all the motions that might occur (use arrows to indicate motions)
    - *ROUGH* Sketch potential concepts (just stick figures)
    - Overlay sketches and search for patterns and AHAs!
  - Reading
    - Study past 2.007 contests
    - Study construction equipment, websites of mechanisms and other robot contests
  - Writing
    - Write a story about how the contest was won…..imagine the future!
    - The FRDPARRC Table is a fantastic catalyst
  - Arithmetic (analysis)
    - Analyze the effectiveness of different scoring methods with a sensitivity study
    - Create time/motion studies of the table and study geometric packaging options
    - Sketch free-body-diagrams to understand how the forces flow within the system
    - **Create a preliminary power budget (see page 7-26 and *Power_budget_estimate.xls*)**
  - Load your mind with information
    - let your bio-neural-net create images of what gets the most done with the least effort



Alex Sprunt's 2.007 machine development







Third Step Example: *Precision Linear Motion System*

Linear motion axes supported by frictionless “infinite life” air bearings are commonly used in many precision manufacturing systems, particularly in semiconductor manufacturing. bearings must be preloaded to give them good stiffness and omnidirectional load capacity. This typically requires the carriage supporting the air bearings to wrap around the linear motion axis (bearing rail) so the bearings act on all sides of the rail. The rail must be machined with all surfaces straight and parallel, to within microns, or else the air bearing pads might touch down and fail.

Some designers try to overcome the need for precision tolerances by utilizing springs to preload one set of bearing pads against a fixed set; but, this adds complexity and still requires a cumbersome design in which the carriage wraps around the axis structure. Others use vacuum pads to preload air bearings, thereby eliminating the need to wrap around the structure. Vacuum, however, can only generate an order of magnitude less force than the air bearings themselves. Therefore, vacuum preloaded air bearings systems are not good at resisting overturning moments. In addition, if vacuum is lost on a vertical motion stage, the system can fall apart and crash catastrophically. Magnets have also been used to preload air bearings, but this adds cost and complexity.

Given this background, a “fresh look” was to be taken at high speed, high precision linear motion axis design with a FRDPARRC table. Note that minimizing cost is not entered as a FR because it is almost always implied. As the table is filled out, sketches are made. Shown is a page from the designer’s notebook (a Tablet PC). It may seem like a mess, but at this stage, this is what can be expected. Other members of the design team should be familiar enough with the project that this type of presentation is clear. At this stage to provide a more formal presentation would slow the designer down. Only if a formal design review is to be done with outsiders does the work need to be beautified.

As Table 2 and 3 show, the author was just filling out the columns without an exact idea of what to do when Occam’s razor catalyzed him in the countermeasures column. The revelation came from realizing that air bearings (pressurized air is fed into the bearings which meter air flow to the surface using resistances, see Page 10-17) and linear electric motors (a rotary motor with an infinite radius of curvature!) were really the best technologies. It was but a few minutes of sketching the simplest configuration, adding the preload force vectors through the air bearings and aligning the motor forcer along the resultant so its attractiveness to the permanent magnets preloaded the air bearings. The net result was US Patent #6150740, and a new technology for industry.

Even when you think that you know what you need to do, it is important to list all the possible physical effects (e.g., mechanical, vacuum, magnetic...) This helps to *generate* ideas!..

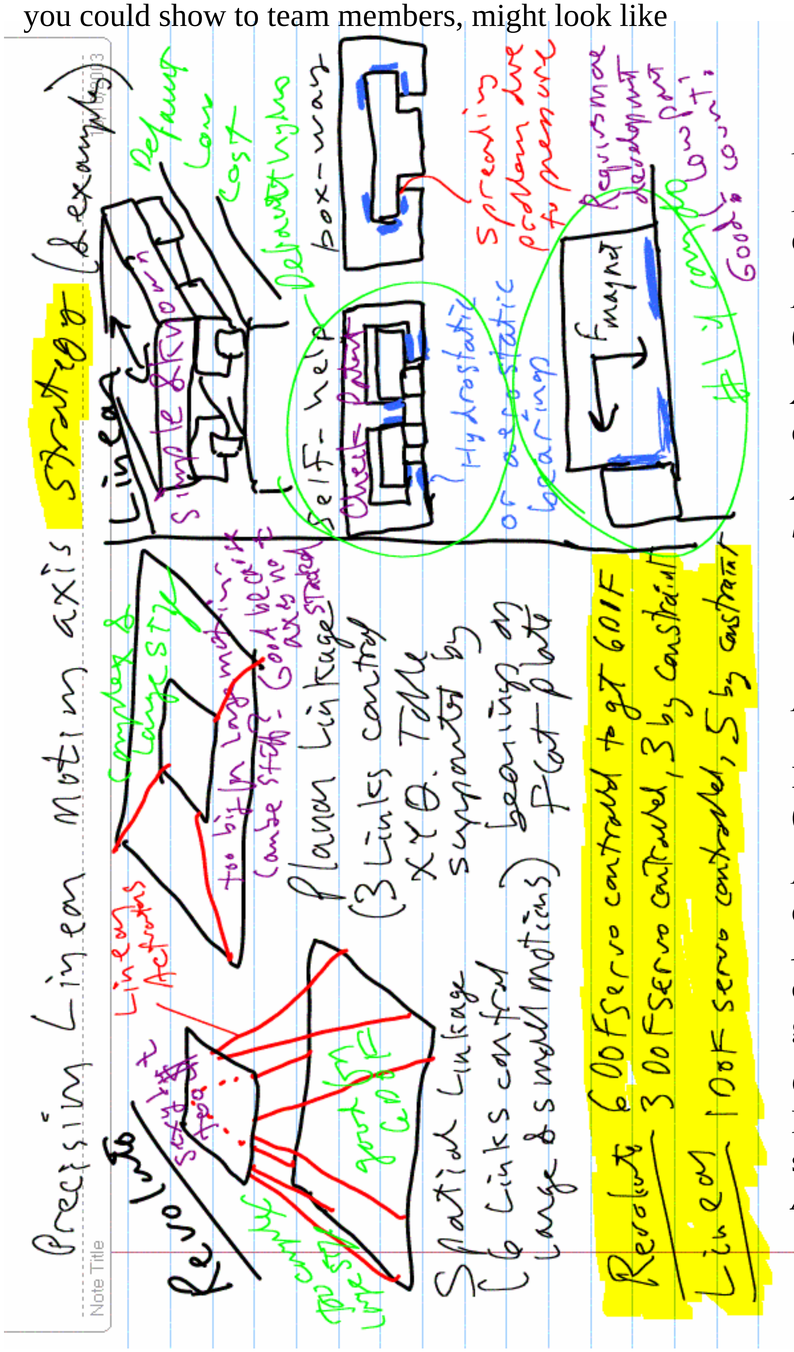
Table 2: FRs, DPs, & As for frictionless high speed linear motion

Functional Requirements	**Design Parameters** (possibilities)	**Analysis** (dominant physics)
Precise linear motion	1) Linear ball bearings 2) Air bearings 3) Magnetic bearings	1) Force & moment analysis 2) $F_{bearing} = P_{pneumatic}$*Area/2 2) $F_{bearing} = P_{magnetic}$*Area/2
Omnidirectional load capability with long life	1) Modular profile rail bearings 2a) Wrap-around preload 2b) Vacuum preload 2c) Magnetic preload	1) Life = $K(F_{applied}/F_{max})^{1/3}$ 2) Force & moment analysis 3) Dynamic system analysis
rapid acceleration	1) High-helix ballscrews 2) Linear electric motors	1) Shaft whip 2) $F_{axial} = P_{magnetic}$*Area $F_{attractive} = 5$*$P_{magnetic}$*Area

Table 3: Rs, Rs, & Cs for frictionless high speed linear motion

References (includes prior art)	**Risks**	**Countermeasures**
1) Catalogs 2) www.newwaybearings.com 3) Slocum, <u>Precision Machine Design</u>	1) Wear and limited life 2) Difficulty preloading, touch-down 3) Cost & development time	1) Oversize and lubricators 2) Porous graphite, new preload method? 3) Air bearings
1) Catalogs 2) Internet, Slocum, <u>Precision Machine Design</u> 3) ibid	1) none 2) manufacturing errors, generating sufficient force, pitch ripple 3) Cost, cost, cost	1) none needed 2) careful engineering, multiple forcers, mapping 3) Air bearings
1) Catalogs 2) Catalogs, Internet	1) Wear, shaft whip 2) Cost, heat	1) Oversize 2) Less parts offsets cost. Use motor attractive force?

REAL designer notebook entry (Tablet PC-based notebook) for strategy development. This is what your notebook, that you could show to team members, might look like



Third Step Example: *Precision Linear Motion System*

FRDPARRC Sheet Topic: Precision low cost linear motion stage

Functional Requirements (Event) Precision linear motion, loads applied from any direction, minimal cost

Potential Design Parameters (description of idea) Revolute joints (planar and spatial (hexapod), Linear joints (linear ball bearings, hydrostatic bearings, aerostatic bearings

Analysis (physics in words) Revolute systems: complex motion analysis (machine control). All bearings require preload to withstand loads from any direction.

Analysis *Ball bearings, loads from catalogs. For hydrostatic and aerostatic bearings:*

$$F_{\text{load capacity}} = \eta_{\text{efficiency}} P_{\text{supply pressure}} A_{\text{pad area}} \qquad K_{\text{stiffness}} = \frac{F_{\text{load capacity}}}{h_{\text{gap}}}$$

References: Numerous catalogs, book: Slocum <u>Precision Machine Design</u> (SME 1995), A.M. van der Wielen, P.H.J. Schellekens, F.T.M. Jaartsveld, Accurate Tool Height Control by Bearing gap Adjustment, Annals of the CIRP, 51(1/200), 351-354, (2002)

Risks: <u>*Revolute joints:*</u> size inefficiency, control complexity, stiffness normal to plane of motion. <u>*Linear joints:*</u> *Ball bearings:* limited life and damping for high cycle axes. *Hydrostatic bearings:* Higher pressures force-apart components in opposed-pad configurations. Pump power and fluid collection. *Aerostatic bearings:* Very small gaps make opposed pad designs too expensive.

Countermeasures: <u>*Revolute joints:*</u> none, <u>*Linear joints:*</u> *Ball bearings:* Externally lubricated or linked rolling elements (THK or Megatool). *Hydrostatic bearings:* Use self-help designs. Minimize bearing gap, pump coolant so do not have to collect. *Aerostatic bearings:* Preload with magnets (linear motor magnets?).

The words were written first, in particular, Risks and Countermeasures create images for strategies

Third Step Example: ***Strategies*** *for* ***The MIT and the Pendulum!*** *Design Contest*

When creating a FRDPARRC table for ***strategies*** for the 2002 contest *The MIT and the Pendulum*, the FRs are kept at a high level to leave room for creative thinking. "Score with balls" implies getting the balls to the goal. A simple review of the table indicates that there are three paths: along the ground, straight across, and in an arc. No mechanism needs to be designed in order to consider these three ***strategies***. In fact, considering the physics beforehand will help generate a wider variety of ***concepts*** than if one were to merely start with a bulldozer design. However, there is no reason to not also jot down ideas for ***concepts*** (mechanism) simultaneously with the development of ***strategies***, just fill out 2 FRDPARRC tables and use them to catalyze each other!

The ***strategy*** "score with the balls using a straight-line trajectory" implies that the balls will somehow be conveyed straight to the goal. In fact the use of the word "convey" implies that one of the ***concepts*** that could be considered is a conveyor belt that could be deployed by the machine. Another ***concept*** might use a machine that has a shelf with collecting features that collects the balls, races forward to deposit them into the goal. The *analysis* to predict ball motion is straightforward - no real difficulties expected here. A freshman physics text is the only *reference* that is likely to be required, although one may want to cruise various construction equipment websites, including those of conveyor manufacturers. A *risk* associated with this ***strategy*** is that the opponent could have a small fast machine that zooms out at the start of the contest and creates disorder on your side of the table. A possible countermeasure is to have a little ProtectorBot or an extending wall that blocks an opponent from your side of the table.

The ***strategy*** "score with the balls" implies that the balls will somehow be gathered and then raised to the goal. In fact, with this option, you can also gather pucks. The use of the word "gather" implies a ***concept*** where the balls or hockey pucks may be moved one-by-one to the goal, or they might all be collected into a bin and then dumped in the goal. The use of the word "bin" implies that maybe all the objects and their bin might be more easily dumped into the goal! An appropriate level of analysis would be to consider the size of the playing field, and how long it will take to gather a ball, deposit it in the goal, and then gather another ball.

To evaluate strategies, you can either compute motion profiles or at this stage, as a *reference*, observe the speed of past contest machines. Moving a model around on the table to simulate what you might do in the allotted contest time might be a more appropriate level of analysis. A *risk* associated with a serial collection of balls is you might run out of time or be blocked from scoring more than once. The *countermeasure* is to make sure your machine is fast and nimble, and create your own ProtectorBot. Past history shows that they are invaluable and that there are many effective designs! The primary *risk* associated with gathering all the elements you can and then dumping a load into the scoring bin is that the objects are large and your machine may become too unwieldy or the forces to raise all the objects may be too great, or you may run out of time or get blocked by your opponent. The *countermeasure* is to compromise and make your machine able to quickly move and gather a few objects, and to make a ProtectorBot.

A ***strategy*** that scores with the balls being shot into the goal implies momentum transfer. In fact, the use of the word "shot" suggests that one of the ***concepts*** that could be considered is to make the balls fall onto a ramp. At the bottom of the ramp, an impact plunger or paddle wheel shoots them into the goal. Another option is a rotating bat whose axis of rotation is inclined to the table so the balls are batted up pop-fly style to the goal. You may even want to consider rapidly counter rotating cylinders. The *analysis* to predict ball motion is more complex, but recall from freshman physics that the way to maximize projectile range is to launch it at a 45 degree angle. The launch speed can be determined by momentum transfer equations and by assuming the collision is elastic. Some experimentation will likely be required. Good references are a freshman physics text and observing past contest machines with ball shooters. The primary *risk* associated with these strategies is that the balls have to be hit just right and that the opponent may have a small fast knock-em-over bot. A *countermeasure* is to select a strategy where the balls are collected and then shot out of a barrel in a controlled fashion. One can also have a ProtectorBot.

While writing about the entries on the FRDPARRC table, a whole host of new ideas came to mind. Do the same for your FRDPARC table for developing ***strategies***. Pretend YOU are writing a book and you have to convey your thoughts. As you write, evolve the entries in the table accordingly. Does one best ***strategy*** stand out?

Third Step Example: *Strategies for The MIT and the Pendulum Design Contest*

Functional Requirements	Possible Design Parameters (**Concept's FRs**)	Analysis	References	Risk	Counter-measures
Score with balls	1)Scoop balls into the goal **2)Collect balls and pucks and later deposit in goal** 3)Bat them into the goal	1)Linear motion 2)Linear motion, Power to raise the balls to the goal 3)Trajectories, Conservation of momentum	1)Physics text 2)Past 2.007 contests 3)Ball shooters from past contests	1)Opponent scatters balls and pucks, you chase… 2) Machine becomes to big, opponent blocks 3) Balls are too large and heavy	1)Acquisition device must also be able to pick up from the ground 2)Gather a few, Set up blocking gate 3)Ball on ramp, pinball shooter
Score with pendulum	**1)Actuate from ground** 2)Actuate from pendulum	**?**	**?**	**?**	**?**
Block opponent from scoring	**1)Get in the way** 2)Anchor their pendulum	**?**	**?**	**?**	**?**

Fourth Step: *Developing* ***Concepts***

Once a ***strategy*** evolves, the really fun part occurs: developing ***concepts*** (specific ideas for machines). In order to ensure that the ***concepts*** fulfill the functions required by the ***strategy***, the *functional requirements* for the ***concept*** are the *design parameters* from the ***strategy's*** FRDPARRC Table. The FRDPARRC table for ***concepts*** can describe what the ***concept*** will accomplish, and how it will work. The *Functional Requirements* for developing ***concepts*** are the different physical effects that are to be achieved. The ***concepts*** are then the *Design Parameter* entries in the table. The ***concepts*** can be described in words, but after all the columns of the FRDPARRC table are complete and one or two top ***concepts*** evolve, sketches must be made of the top ***concepts*** in order for them to evolve further and for a final selection decision to be made.

Again, one must not be too detailed when developing ***concepts***. Just require the types of motions that need to be accomplished, but do not specify the detailed mechanism just yet unless it is a fundamental part of the ***concept***. For example, linear motion may be caused by a screw or a piston or a cable drive, and the best one does not need to be defined until the ***concept*** further evolves. It can sometimes even wait until the ***module*** design phase. With respect to visual representation of the ***concepts***, simple sketches are initially adequate. However, after the first few concepts are weeded out and a few prime ones evolve, more detailed sketches will be required. Solid models can be generated at any time during the ***concept*** phase.

When developing ***concepts*** it is important to recognize that there are three basic types of design: *scaled design*, *evolutionary design*, and *revolutionary design*. A *scaled* design recognizes that there is no shame in using an existing design that does the job well, and just needs to be scaled for the new application. A design contest example is scaling wheel size to get a different speed. An *evolutionary* design recognizes when an existing design is pretty good, but also sees the improvements can be made. A design contest example is to evolve a wheeled vehicle into a tracked vehicle to increase tractive force. A *revolutionary* design uses a totally new approach is used to achieve the same function, but with better performance. Design contest examples include use a robot arm instead of having a moving vehicle, or use a ball shooter instead of collecting and dumping balls. After the first use, a revolutionary idea becomes a scaled or evolutionary idea to the next person.

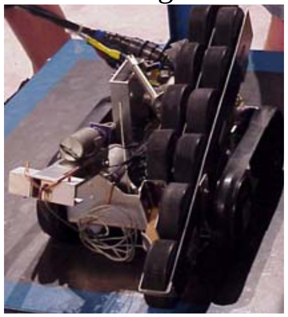
Early on, when many ***concepts*** are being developed and initially compared, there may not be time to do *analysis* on each one, so the designer may have to trust her analytical instinct in order to evolve potential ***concepts*** that warrant a more detailed analysis. Appropriate analysis at this stage can include simple cardboard or physical models that the designer uses to have mock competitions with each other, because the concept you reject may be the concept your opponent chooses. When the time comes to choose between a few ***concepts*** that evolved from the mock competitions, simple physics should be used as a first-order reality check. Now is the time for a realistic assessment of the physical performance of various concepts, including, for example, whether your actuators have the power required to meet the time and motion requirements of the concept. A simple first order analysis involves a *power budget*. A power budget calculates the power required for each action and then considers the power the actuators can provide. A first-order kinematic analysis may also be needed to determine if a linkage can be created to fit in the required space and have the required motion. Further, an *error budget* assessment should be made of the ***concepts'*** accuracy, which includes controllability.

Once again, *References* for different ***concepts*** may include machines from the past that have performed similar functions or other competitor's machines that are accomplishing a similar goal. References may also be made to programs, books, or articles that describe how to analyze the strategy. Similarly, *risks* for different ***concepts*** will likely depend on the number of motions that need to be performed, the energy to be consumed, the potential complexity or the sophistication of mechanism that may need to be created. A good indicator of risk is also the amount of precision that is required by the ***concept***. The greater the required precision, the greater the risk. *Countermeasures* for the different risks can be as schedule shattering as "use a different concept", or as simple as using a different type of actuator or linkage, which only involves changing or adding the design of a ***module***.

Start thinking about different ***concepts*** for each of your favorite ***strategies***. Create simple sketches of the ***concepts*** in different motion configurations and start to think about the different ***modules*** that make up your ***concepts***. Are they safe? Are there any common modules that all the ***concepts*** share, that you could make and test even before one ***concept*** is finalized, thereby reducing risk? Create power budgets for each ***concept*** to determine if your actuators have enough power. Later, when you design ***modules***, you can determine if you need a transmission to obtain the proper torque or force.

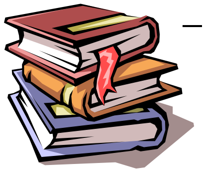
Fourth Step: *Developing* ***Concepts***

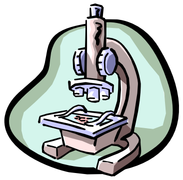
David Arguellis

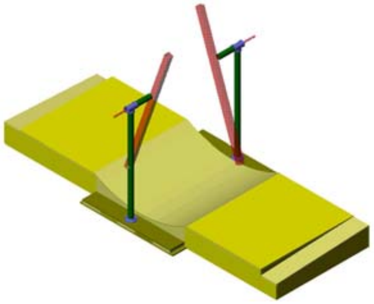


1999's ***MechEverest!***

- A ***concept*** is a specific vision of how one could actually accomplish the ***Strategy***:
  - Words to describe what the concept must do, and how it will work
    - Ideally in simple tabular form, like a FRDPARRC Table
  - Simple sketch
    - A simple hand-drawn isometric figure of the machine often suffices
    - A simple solid model can also be very useful
    - A sketch model made from simple materials can also be very useful
  - First-Order-Analysis
    - Spreadsheet-based time and motion study
      - More detail based on better estimates of machine size…
    - Preliminary power, accuracy, or stress calculations
      - More detail based on better estimates of machine weight…
    - **Refine the power budget to ensure your idea can be powered by the batteries (see page 7-26)**
  - The design engineer needs to take care to propose a concept in just enough detail to be assured that it could indeed be implemented







- Example: ***Concepts*** for ***Gather pucks and balls and deposit in goal*** *Strategy*
  - ***Concept A*** for ***Strategy*** 1: Drive around picking up pucks and balls and deposit them into the goal one-by-one, so as to avoid complexity or jamming
    - After scoring with objects, the vehicle could go and actuate the pendulum
  - ***Concept B*** for ***Strategy*** 1: Gather pucks and balls using a combine-like harvester that collects them and dumps them into a bin, and then drives over and raises the bin and dumps it into the scoring goal
    - After scoring with objects, the vehicle could go and actuate the pendulum

Fourth Step Example:
Precision Linear Motion System

The ***strategy*** developed in the Third Step Example was to use air bearings and linear motors. There have been many such designs in the past where the bearing system is decoupled from the actuation system and fantastic results have been achieved. Such systems routinely achieve sub-micron precision. However, is there a better concept? The designer was sketching arrangements of bearings and linear motors of different types and had the revelation that the attraction forces between a motor coil and a permanent magnet could be used to preload a set of bearings.

A principal advantage of this design is that it is deterministic, so equations for predicting performance could be easily written. This is a very important part of the conceptual design process. It is important to be able to use basic analysis to verify concepts for further development. In the case of the Axtrusion:

$$[A]=\begin{bmatrix} -1 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & z_2 & z_3 & 0 & z_5 & z_6 & -y_m \\ z_1 & 0 & 0 & z_4 & 0 & 0 & x_m \\ -y_1 & -x_2 & -x_3 & -y_4 & -x_5 & -x_6 & 0 \\ 0 & \dfrac{1}{k_2(x_2-x_3)} & \dfrac{-1}{k_3(x_2-x_3)} & 0 & \dfrac{-1}{k_5(x_5-x_6)} & \dfrac{1}{k_6(x_5-x_6)} & 0 \end{bmatrix}$$

$$[B]=\begin{bmatrix} F_{mm}\sin\theta+F_{Px} \\ -F_{mm}\cos\theta-m_c g-m_s g+F_{Py} \\ -m_c a-m_s a+F_{Pz} \\ -F_{mm}z_m\cos\theta-m_c g z_c-m_s g z_s+F_{Py}z_p-F_{Pz}y_p \\ -F_{mm}z_m\sin\theta-F_{Px}z_p+F_{Pz}x_p \\ -F_{mm}x_m\cos\theta+F_{mm}y_m\sin\theta+m_s g x_s+m_c g x_c+F_{Px}y_p-F_{Py}x_p \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} F_{B1} & F_{B2} & F_{B3} & F_{B4} & F_{B5} & F_{B6} & F_m \end{bmatrix}^T=-[A]^{-1}[B]$$

As can be seen, the analysis is straightforward and of the level that must typically be done. In fact, this analysis can be useful for other linear motion axes as well. The difference is that the problem was not set up before hand the way problems often are in school. The key to developing good concepts is to not only think creatively, but to be able to analyze what you create!

A spreadsheet *axtrusion.xls* was written to determine the feasibility of the concept, and it seemed feasible! The theory was verified with a sketch model made from steel with a carriage supported by ball-bearing wheels and preloaded with a permanent magnet. The next step was to build a single full scale precision motion axis. If this axis worked, two such axes could be placed at right angles to each other on top of a surface plate to create a machine to test grind parts.

The prototype axis was constructed from a granite square using modular off-the-shelf air bearings from new Way bearings and an Anorad linear electric motor. The system performed as predicted meeting stiffness and load capacity predictions. The overall accuracy was on the micron level; however, as hypothesized, pitch as a function of axial position occurred (pitch ripple) as the motor forcer passed over the magnets. The ripple was insignificant for most applications. hence the countermeasure of using multiple motor coils was not needed, but would be investigated at a later date.

A second axis was built and the two were put together at right angles to create a small grinding machine. parts were ground and were as good if not better as parts from a production grinding machine. Thus the concept was proved and a decision was made to develop a prototype production grinder.

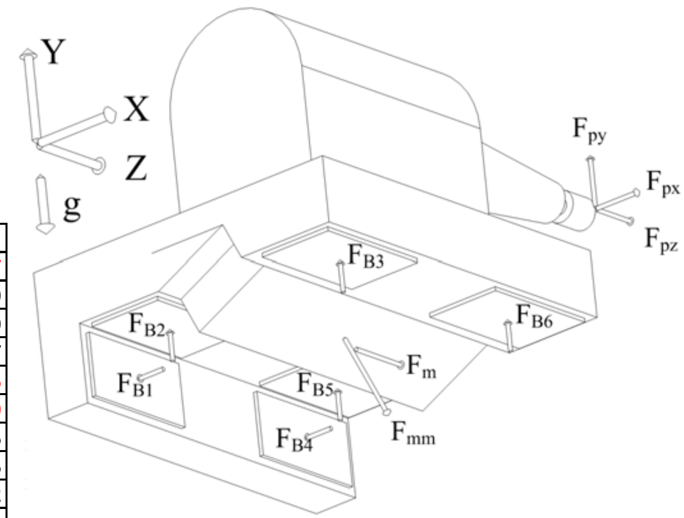
This case study illustrates an actual development process that engineers will be expected to be able to do when they work in an engineering company (or start one!). For design contests, the process is just as effective at minimizing uncertainty and accelerating the development process. Imagine the steps taken here in the context of the machine you are developing!

Fourth Step Example: *Precision Linear Motion System*

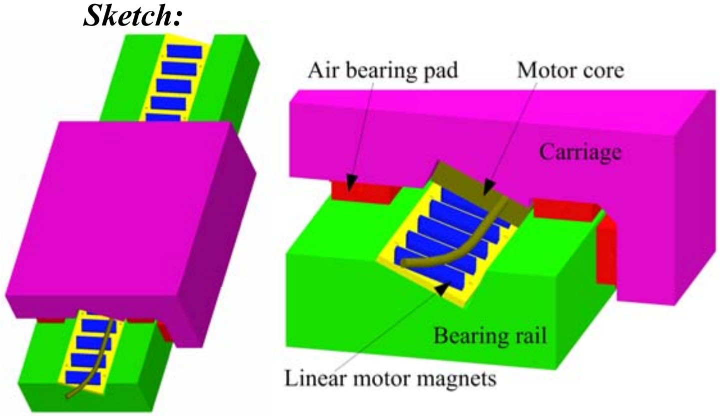
Concept FRDPARRC Sheet: Precision Low Cost Linear Motion Stage

Functional Requirement (Event) Preload air bearings for minimal cost

Design Parameter (Description of Idea) Preload air bearings using magnetic attractive force of motor: Bearings need only ride on 2 surfaces instead of having to wrap around a beam; thus many precision tolerances to establish bearing gap can be eliminated



Sketch:



Assume we want even preload pressure per pad	
Motor preload angle	26.57
Motor attraction force, Fm	4000
Motor width (mm), L	130
Motor thickness	47
Space for motor thickness	65
Supply pressure, Ps (Pa, atm)	600000
bearing efficiency, m	0.35
preload proportion of total load capacity, f	0.5
vertical/horizontal load capacity, vh	2
X direction pads' total area (mm^2), Ax	21994
Y direction pads total area, (mm^2) Ay	43989

Analysis (physics in words) The magnet attraction force is 5x greater than the motor force, so it can be positioned at an angle such that even preload is applied to all the bearings. As long as the magnet attraction net vertical and horizontal force are proportional to the bearing areas and is applied through the effective centers of the bearings, they will be evenly loaded without any applied moments.

Analysis

$$F_V = F_{magnets} \sin\theta$$

$$F_H = F_{magnets} \cos\theta$$

$$\frac{F_V}{F_H} = \frac{A_V}{A_H} = \tan\theta$$

$$\theta = \arctan\left(\frac{A_V}{A_H}\right)$$

References: Vee & Flat bearings used on many common machine tools where gravity provides preload. NEAT uses two magnet tracks, one horizontal and one vertical, to provide horizontal and vertical preload force. Patent search revealed no other relevant art.

Risks: The magnet pitch may cause the carriage to pitch as the motor's iron core windings pass over the magnets

Countermeasures: Add steel out of phase with motor core position, or if the error is repeatable, map it and compensate for it in other axes

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Fourth Step Example: *Concepts* for the Collect Balls & Pucks *Strategy*

The FRDPARRC table for developing ***concepts*** for the 2002 contest *The MIT and the Pendulum* has FRs kept at a high level; they are the *Design Parameters* of the ***strategy*** FRDPARRC Table. "Knock all balls down and pick up and deposit in goal" leaves plenty of room for creative thinking. The large size of the contest table suggests that a vehicle is probably the best way to collect balls and pucks. The large size also makes us wonder if there will be enough time to drive back and forth to the goal with balls and hockey pucks. This suggests a combine-harvester-type of machine that can scoop up the scoring elements and then deposit them all at once in the scoring bin. Again, no specific mechanism needs to be designed in order to consider these ***concepts***. In fact, considering the physics beforehand will help generate a wider variety of ***modules*** (see page 1-25) than if one were to merely start with a bulldozer design. However, one should still jot down ideas for ***modules*** (mechanism detail) simultaneously with the development of ***concepts***. Just fill out 2 FRDPARRC tables and use them to catalyze each other!

The ***concept*** "score where the balls and pucks are knocked down, picked up, and deposited in the goal one-at-a-time" implies that the balls and pucks will somehow be acquired and then raised to the goal. The use of the word "acquired" suggests a ***module*** where the balls and/or pucks are scooped up by a front end loader, or a more deterministic method that avoids chasing the across the table might be a robot gripper. The *analysis* to predict how well either of these two ***modules*** might work would likely be far too complex for this type of project. An appropriate level of *analysis* would be to research how others have accomplished this task. Then build a scoop and pretend you are a front end loader. Similarly, hold two paddles, pretend you are a robot, and try to grab the objects and move them over to the scoring bin. The next type of analysis is the time and motion study to determine how many trips your machine can make to the scoring bin in the allotted time. You can compute this, observe past contests and estimate how fast the vehicles can move, or build a test a simple car. Any of these three methods will help you to determine if it is feasible to achieve a respectable score in the allotted time. Helpful *references* may include observing past contests, and reviewing websites for front end loaders, robot grippers, and logging equipment. Is there a universal gripper that can just as easily pick up a ball or a puck? The primary *risk* associated with trying to pick up a ball or a cylinder with a scoop is that you could end up chasing it around; however, you might then also be able to pick up more than one element. The *countermeasure* is to see if you can combine the best of both worlds. How does a front end loader solve this problem? Can a scoop and a gripper be somehow combined? The secondary *risk* associated with a serial collection of balls is you might run out of time or be blocked from scoring more than once. A *countermeasure* is to make sure your machine is fast and nimble. You may also want to create your own ProtectorBot because history shows that they are very effective.

Consider a second ***concept*** "score where the balls and pucks are all knocked down, then picked up, and deposited into the goal as a group" implies that they will somehow be acquired and then raised to the goal. Two ***modules*** will likely be needed. The first ***module*** collects the balls or pucks using a combine-like harvester or a street sweeper. Rotating brushes or arms could collect and pull the scoring elements into a bin. A second ***module*** is needed to lift the scoring elements into the bin. This could be a linkage that raises and dumps the entire bin, or perhaps a conveyor belt? Once again, the *analysis* to predict how well either of these two gathering ***modules*** might work would be far too complex for this type of project. An appropriate level of *analysis* would be to research how others have accomplished this task, build a rotating brush, and test it. A time and motion study is important to help you determine how big to make your bin, so as to minimize the number of trips to take to the scoring bin. *References* that can help include observing past contests, as well as reviewing websites for street sweepers and farm equipment (combine harvesters). The primary *risk* associated with a sweeper is that it may become jammed. The *countermeasure* is to make sure it is reversible. A secondary *risk* is that you might be blocked from getting to the bin. The *countermeasure* once again is to create your own ProtectorBot.

Both of these ***concepts*** utilize a vehicle that conveniently can push the pendulum and start it swinging! Two scoring modes with one concept laves plenty of room for flexibility and design evolution!

While reading about the entries on the FRDPARRC table, perhaps a whole host of new ideas came to mind? Accordingly update your FRDPARC table for developing ***concepts*** and check the safety of each ***concept***. Pretend YOU are writing a book and you have to convey your thoughts. As you write, evolve the entries in the table accordingly. You now also have a major entry for your website.

Fourth Step Example:
Concepts for the Collect Balls & Pucks Strategy

Functional Requirements **(Distilled from Strategy's DPs)**	Possible Design Parameters **(Modules FR's)**	Analysis	References	Risk	Counter-measures
Gather pucks and balls and deposit in goal	1)Front end loader **2)Harvest and dump loads**	1)Time/Motion study, Friction/slip, Linkage design 2)Friction, slip, linkage design	8.01 text and Past 2.007 contests. Farm equipment websites	1)Not enough time to make multiple trips 2)Gather bin is too large	1)Gather 2 or 3 objects 2)Gather 2 or 3 objects
Actuate pendulum from ground	**1)Vehicle knocks pendulum as it drives by** 2)Fixed-to-ground spinning actuator	**?**	**?**	**?**	**?**
Get in the way	**1)Bother-bot** 2)Pendulum clamp **3)Cover goal**	**?**	**?**	**?**	**?**

Fifth Step: *Developing* ***Modules***

Once a ***concept*** evolves, the next really fun part occurs, that of developing ***modules*** (sub assemblies of parts). To ensure that the ***modules*** fulfill the functions required by the ***concept***, the *functional requirements* for the ***modules*** are the *design parameters* from the ***concepts'*** FRDPARRC Table. The FRDPARRC Table for ***modules*** can describe what the ***module*** will accomplish, and how it will do it. The *Functional Requirements* for developing ***modules*** are the different physical effects that are to be achieved. The ***modules*** are then the *Design Parameter* entries in the table. After all the columns of the FRDPARRC table are complete and one or two top ***concepts*** evolve, sketches must be made of the top ***modules*** in order for them to evolve further so a final ***concept*** can be selected.

Now its time to start thinking about details when developing ***modules***. For example, linear motion may be created by a screw or a piston or a cable drive. Until a decision can be made as to which is the best method, it is important to make room in the ***module*** for any of the options. First make simple sketches of the ***modules***, using different possible principle ***components***. This will help you determine what type of *analysis* to do in order to select and size ***components***. In the process of analyzing the different ***modules***, it will become apparent which ***module*** has the greatest amount of *uncertainty*, or *risk* in its development. This is the *most critical* ***module*** (MCM) and it is the one that is first engineered and tested. If it cannot be made to work, a different ***module*** may have to be created as a countermeasure. In the worst case, a different ***concept*** may have to be developed, but it will have to be a very simple one, because you will be far along in the schedule.

Both analytical and physical models can be used to help develop the *most critical* ***module***. However, just because it may not be immediately apparent how to analyze the performance of a ***module***, you should not hastily run off and build an experiment. One should always look in *reference* books, or search the Internet for an appropriate formula to use. There are also many software tools available for structural and kinematic analysis. For example, if you want to know the force that a screw can generate when driven by a screwdriver motor, you could spend several hours building a test fixture, or you could take 15 minutes to look up "screw, force from" in any number of machine design texts or handbooks. In order to grow as a design engineer, you have to keep applying the scientific method: develop a hypothesis and calculate what you expect, run an experiment, and compare the results with those you predicted. Only by continually closing this learning loop will you be able to fully develop your *analytical instincts*.

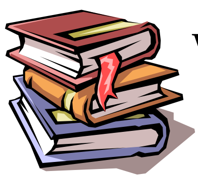
There are four types of detailed analysis that need to be considered in the design of a module and its components: *dynamic*, *kinematic*, *geometric*, and *structural*. *Dynamic analysis* typically consists of a power budget (see page 7-29) with force analysis to ensure the motors can generate the required forces. In more advanced machines, dynamic analysis would include a detailed dynamic system mode, including the control system, to predict performance and to identify resonant modes in the system. *Kinematic analysis* examines the motions the machine makes to ensure accuracy of the position, velocity, and acceleration of components in the system as they move. A *geometric analysis* checks that the module will fit in an assembly with all the other modules. ***A 3D CAD solid model of the module is an excellent way to check its geometry***. Geometric and kinematic analysis may also include an *error* or *tolerance* budget to verify that the machine will meet its accuracy target even though it is made up of many parts, each of which has its own set of errors. *Structural analysis* is of course how the machine behaves under internal or external loads. Remember, one of the biggest sources of failure in components is fatigue caused by misalignment or over constraint! External impacts also play a role, but these effects can be minimized with compliant bumpers.

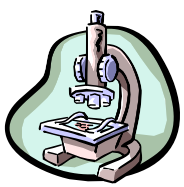
Analysis, however, is only as good as the model and the estimates of input parameters. The greatest *risk* in developing a ***module*** often comes from friction, backlash (looseness) and environmental effects (e.g., corrosion, and unforeseen loads) that are difficult to model. Trying to pack too large a device into too small a space often leads to an insufficient structure and early failure. Unforeseen loads can be external, such as an opponent's machine bashing into yours, or they can be internal, such as those caused by misalignment or over constraint.

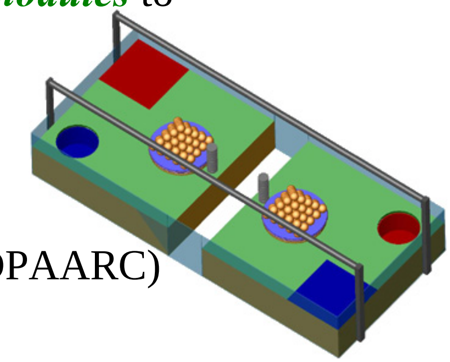
Start thinking about different ***modules*** for each of your favorite ***concepts***. Create simple sketches of the ***modules*** in different motion configurations and start to think about the different ***components*** that each will require. Create a spreadsheet or MatLab™ script for each major ***module*** and determine each one's potential feasibility. Determine which is your most critical ***module*** and create a plan to fully develop and test it.

Fifth Step: *Developing* ***Modules***

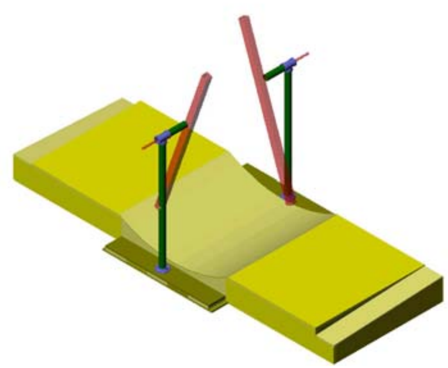
- A ***module*** is a subassembly that has a defined envelope and specific inputs and outputs that can be engineered, built, and tested and then assembled with other ***modules*** to implement the concept
  - Pick any ***module***, and you will also get sub- ***modules***
    - Example: Powertrain: Transmission, Motors, Crawler tracks
    - Hence the term "***module***" implies a *granularity* of detail







- Words to describe what the ***module*** must do, and how it will work (FRDPAARC)
  - Drawings
    - Initially a simple hand-drawn isometric will suffice
      - There may be many different ways of designing the module
        - » The process of ***strategy***, ***concept***, ***module***, ***components*** can be applied again!
    - A solid model (layout drawings) will eventually need to be created
  - First-Order- and Detailed-Analysis
    - Motion, power, accuracy, stress…
    - Greater detail as the module detail increases
  - Developing ***modules*** is the first part of what some called the "***embodiment***" phase of design
- Example: ***Modules*** for the ***Harvester*** Concept
  - ***Module 1*** for Concept B: Gatherer
  - ***Module 2*** for Concept B: Bin
  - ***Module 3*** for Concept B: Deposit mechanism
  - ***Module 4*** for Concept B: Vehicle



Fifth Step Example:
Modules *for the Harvester* ***Concept***

A *Functional Requirement* from the ***concepts'*** FRDPARRC table yields one *Design Parameter* (***concept***) which is then distilled into the many *Functional Requirements* for the ***modules'*** FRDPARRC table. Hence FRDPARRC tables would have to be developed for ***modules*** for the other ***concepts*** such as a *Botherbot* to bother your opponent. To keep an open mind, the term "harvest objects" leaves lots of room for creative thinking. We have already assumed that the objects will be scattered, and now we have to create a ***module*** that can collect and place them in a bin to later be transferred to the goal.

At this point, you should be sketching ideas that come to mind, as the creative juices begin to flow. Given that there are three types of motion, rotary and linear, and combinations of the two, start at the interface between the module and the components to be picked up. The interfaces are the most critical parts of a ***module*** because they determine the functionality of the ***module***. This leads to the creation of a rotating paddle wheel or brush, a reciprocating design, like a hoe, and a set of arms that reach out and scoops and pulls objects in, like a crab feeding. Analysis probably cannot help us at this stage to synthesize new ideas or determine which is the best, so it's time to check references. Search the Internet for street cleaner companies and past gathering-type contests. Look at past machines, but consider that evolution of past ideas may be most appropriate. What about a paddle that raises and lowers?

Reviewing the other ***module*** options for the other functional requirements, they seem like they will be less difficult, so the gathering ***module*** is the most critical ***module***. Since it is difficult to develop an analytical model of the gathering process, especially since we are not exactly sure which one we want to use, it is time for experimentation. The first level of experimentation should involve very simple elements that the designer moves with his hands to simulate the motions that he thinks he wants his mechanism to make. This is called a *sketch model*, as discussed on page 2-7, because it is just a sketch of an idea and we want to play with a physical embodiment of it to get a feel for how well the idea might work.

The sketch models can reveal which ideas have the best chance of meeting the functional requirements. Let us assume that this leaves the first two options. They are still too difficult to analyze because of the great variety of orientations of the scoring objects; thus the next level of experimentation is needed to assess the feasibility of the ideas. It is time to run a *Bench Level Experiment* (BLE), as discussed on page 2-8, which uses kit components, so if it works, there is a likelihood that a successful design has been found.

A BLE for the paddle wheel can be created by taking the power source (e.g., an electric screwdriver) and then fabricating a simple sheet metal paddle wheel, with say four paddles formed by crossing two half-slit sheets and then bolting or clamping them to a rod which is held in the screwdriver check. Arrange objects in different orientations and then pretend you are driving over to them. Experiment holding the paddle wheel at a fixed height, and also letting it move up and down as if it were on a pivot. Next you might want to try soft paddles made from rubber. The BLE is a great way to test extremes (rigid vs. compliant, linear vs. rotary, vertical vs. horizontal).

A BLE for the reciprocating gatherer should start with different blade shapes made from bent sheet metal. Your hand motions should give you an idea of the vertical and horizontal stroke that is required. Once determined, think of how to obtain this motion. Chapter 4 deals with linkages, but suffice to say at this point that a steam engine's drive linkage can provide some clues. A large rotating wheel with a link attached near the outside edge could create a sinusoidal motion at the blade. Is there a second link that must be attached in some manner somewhere to properly control the motion of the paddle?

The BLEs should yield definitive ideas about how to accomplish the tasks, and yield *manufacturability and safety clues*. In addition, the physics of operation should also be very clear, so an analytical model can be made of each contending idea. Combined with a *risk* assessment of complexity and the manufacturability review, you can select the best mechanism (see page 2-28). Then either keep the other idea as a countermeasure, or if your confidence is high, proceed with the development of the ***components*** for the *most critical module*. It will be assumed for the rest of this chapter that the reciprocating gatherer is to be developed because it seems to have the ability to better handle oddly shaped and oriented objects.

While reading about the entries on the FRDPARRC table, perhaps a whole host of new ideas came to mind? Thus update your FRDPARC table for developing **modules** and check the safety of each ***module***. Identify what you think is your most critical ***module*** and create a plan to develop it.

Fifth Step Example:
Modules for the Harvester Concept

Functional Requirements **(Distilled from Concept's DPs)**	Possible design Parameters **(Components' FRs)**	Analysis	References	Risk	Counter-measures
Harvest objects	1)Rotary paddles or brush **2)Reciprocating paddle** 3)Crab-claws	1)Angular acceleration 2)Linkages 3)Triggers	1)Street sweepers, Combine Harvesters 2)Hungry Hippos game 3)Crabs	1)Objects jam 2)Complexity 3)Complexity	2)Reversible, or raise and lower 2)Single central arm to make T 3) Rotary system
Bin	**1)Sheet metal dump truck bin** 2)Welded wire "cage"	**?**	**?**	**?**	**?**
Deposit mechanism	1)Conveyor **2)Raise & dump**	**?**	**?**	**?**	**?**
Vehicle	1)Crawler treads **2)4WD**	**?**	**?**	**?**	**?**

Sixth Step: *Developing* ***Components***

Modules may have subassemblies which are composed of individual ***components***. For the purposes of developing machines in a systematic way with FRDPARRC tables, ***subassemblies*** and ***components*** are considered at the same time. An example of a ***subassembly*** for the reciprocating gatherer would be the blade mounted to its shaft, or the linkage that creates the up-out-down-back motion. An example of ***components*** would be the bearings or the actuator (e.g., the motor). Hence for this discussion, the terms ***subassemblies*** and ***components*** are used interchangeably.

Ultimately, even the ***subassemblies*** are divided into individual part drawings where each part has a unique number. The list of all parts to create a ***subassembly***, ***module***, or machine is called the *Bill Of Materials*. The BOM is a vital tool in the production of a machine for it is used to make sure that every ***component***, down to the last washer, has been acquired.

subassemblies may still require a bit of design synthesis and sometimes sketch models, BLEs and BLPs may need to be tested. Hence in order to ensure that the ***components*** fulfill the functions required by the ***modules***, the *functional requirements* for the ***components*** are the *design parameters* from the ***modules'*** FRDPARRC Table. The FRDPARRC Table for ***components*** can describe what the ***components*** will accomplish, and how it will do it. The *Functional Requirements* for developing ***components*** are the different physical effects that are to be achieved. The ***components*** are then the *Design Parameter* entries in the table. The ***components*** can be described in words, but after all the columns of the FRDPARRC table are complete and one or two top ***concepts*** evolve, sketches must be made of the top ***modules*** in order to further evolve them in order to determine which component is to be selected.

Once again, both analytical and physical models can be constructed in order to develop and select the ***components***; however, analytical means are generally preferred at this stage, because they allow you to play "what if" scenarios with the ***components*** to see how their performance changes with varying parameters. The leadscrew example is a case in point. If you just make a leadscrew from a large diameter part in the kit, such as the PVC pipe, you will find that the force that can be generated is a small fraction of the force that can be generated from the threaded rod. The dominant parameters are the lead (pitch) and diameter of the screw thread. Understanding the physics of machine elements is critical if you are to become an effective design engineer. All the creativity in the world will do you little good if your thoughts do not lead to implementation because of ignorance of machine elements' operating principles and mechanics.

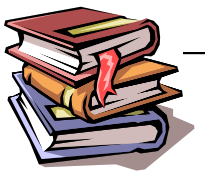
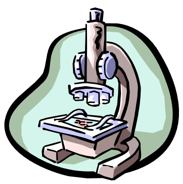
Dynamic, *kinematic*, *geometric*, and *structural* analysis become even more critical at this stage, because ultimately every dimension of a ***component's*** drawing could be tied back to a formula. Practically this is not the case, but in critical applications such as aerospace, most parts and their dimensions are indeed traceable to a set of calculations for ***component*** life. Spreadsheets or MatLab scripts that use formulas you derive or find in a reference book can be used to analyze the ***components***. Using a calculator is not a good idea, because it is impossible to determine if a keystroke error occurred. It also takes a long time to go back and re punch in the numbers should the design change a bit (and it will, many times)!

A significant part of ***component*** design is materials selection. All of our engineering achievements have been made possible by material discoveries. From flint to bronze to iron to silicon to whatever comes next, our society depends on materials. There are hundreds of thousands of different types of materials and coatings. Fortunately software is developing to make materials selection much easier.

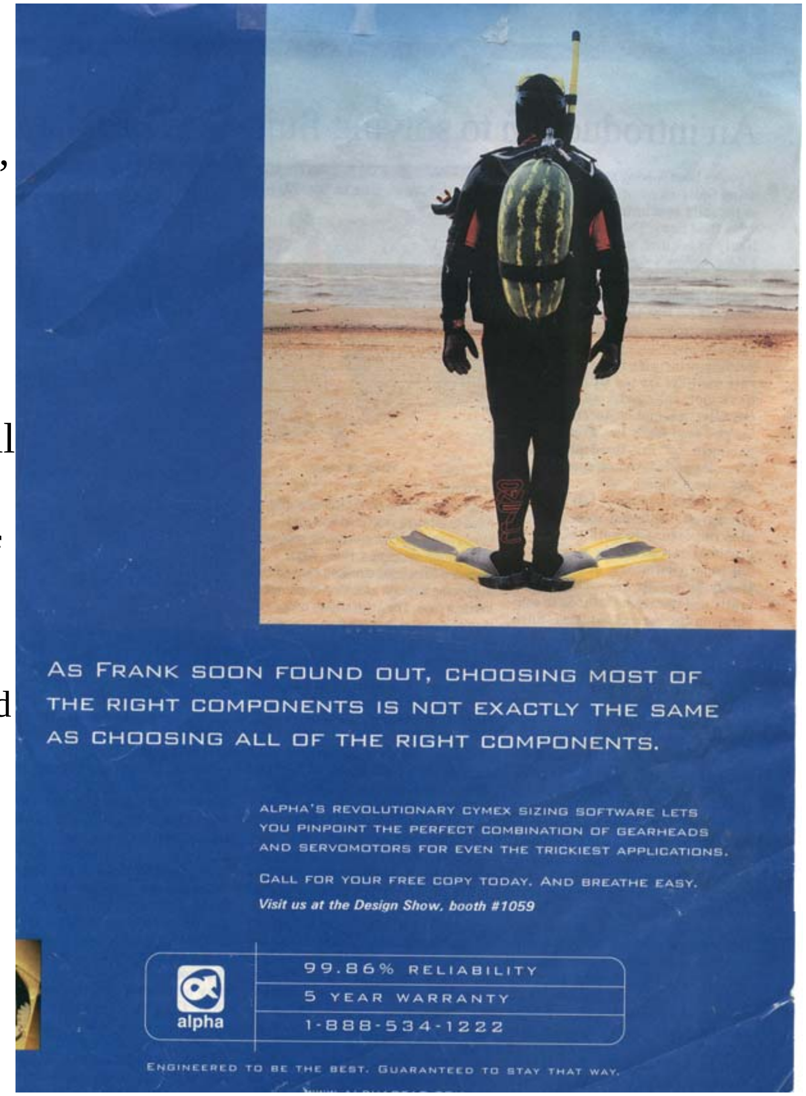
After the best ***components*** have been selected and sized, drawings are needed. These should be CAD solid models so the ***components*** can easily be added to the solid model assembly that represents your entire machine. At this point it is a good idea to do another *manufacturability review* and a final *safety review* prior to creating the part drawings that will be used to manufacture the *Bench Level Prototype* (BLP). The BLP is sometimes called the *alpha prototype* because it ideally will work just fine and require only minor modifications; however, at this point, enough time should still exist in your schedule to modify the BLP or retreat to one of your countermeasures if things go really bad.

Which ***components*** are ready to use out of the kit and which have to be modified or manufactured from scratch? Review the materials in your kit and their properties. Which materials might be good for which ***components***? Where might you use a composite of two different materials?

Sixth Step: *Developing* ***Components***

- ***Modules*** are made from ***components***, ***sub-assemblies*** or ***machine elements***:
  - Words to describe what the ***component*** must do, and how it will work
    - Ideally in simple tabular form, like a FRDPARRC Table
  - Drawings
    - Initially a simple hand-drawn isometric will suffice
      - There may be many different ways of designing the ***component***
        - The process of ***strategy***, ***concept***, ***modules***, ***components*** can be applied again!
    - A solid model (part drawing) will eventually need to be created
  - Detailed engineering analysis
    - Motion, power, accuracy, stress, corrosion…
  - This is the super detailed phase of design



Sixth Step Example:
Components for the Reciprocating Paddle Module

Consider the FRDPARRC table opposite for developing ***components*** for the 2002 contest *The MIT and the Pendulum*. Once again, the FRS are kept at a high level where one *Functional Requirement* from the ***modules'*** FRD-PARRC table yields one *Design Parameter* (***module***) which is then distilled into the many *Functional Requirements* for the ***components*** for that ***module***. Hence FRDPARRC tables would have to be developed for ***components*** for the other ***modules*** such as the BotherBot

The *most critical component* should be selected for development first. In this case, the linkage is deemed to be the most difficult to develop. Chapter 4 focuses on the creation of linkages[1], but jumping ahead the first step in creating a linkage is to identify the *precision points*, which are the points that the output link (the *coupler*) are to pass through during its motion. In this instance, the tip should move up and down and back and forth about a ball diameter. At the same time, recognize that the simplest way to create reciprocating motion is to connect a link to near the outside edge of a wheel using a simple revolute (pinned) joint. If the base of the link is connected to another link or a sliding element which is then connected to the machine structure by a revolute joint, then rotation of the wheel will translate to a circular motion at the end of the link. The question becomes what is the relative amplitude of the vertical and horizontal motions for the two different design options? Which is the best? Can an elliptical motion of the end of the output link be obtained? Is this motion sufficient to collect the objects? Maybe it could bring an object part-way into the bin and then lift up, extend, come down, and pull the object the rest of the way back in?

Before doing the analysis for both ideas, start with the design that is easier to produce such as the design that just uses revolute joints. The general sequence of synthesis is sketch and build a simple physical model with which to play (if possible), or use classical synthesis techniques or a solid model to vary parameters and animate motion. Only one of these methods is deterministic: the others will help you to develop your analytical instincts.

1. Remember, the first milestone associated with this book's design exercises requires you to spend a day and read through the first 4 chapters!

Consider the simple model as sketched with its design parameters indicated as the variable dimensions shown. The position X_o, Y_o of the tip of the linkage can be determined from the design parameters (lengths a, b, c, d, X_b, Y_b, crank angle θ), and the results are shown on a spreadsheet.

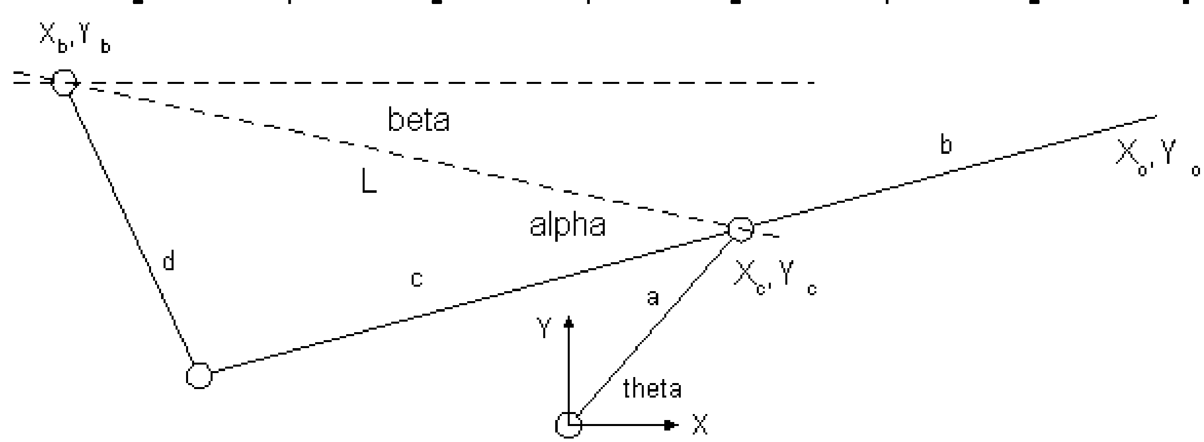
The figure, however, should reveal by inspection that the X direction travel of the tip will be equal to twice the length of the crank of length *a*. The vertical motion can be substantially larger because the angle of the crank is applied over the distance *b*. This means that the linkage could be rotated 90 degrees and the parameters optimized… In this case, a spreadsheet or MatLab script is very useful. There are also dedicated kinematic synthesis software packages available that can help to create linkages and also to provide important information about the accelerations in each of the links as well as joint forces.

One can also make a simple bench level experiment using Lego™ Technic™ blocks, which allow you to move the connection points and feel and see the difference in performance. You can also create a solid model and then vary the angle θ and observe the motion on the screen. Ideally, one would use a linkage design software tool that would give forces and velocities and accelerations.

Once you have engineered the other ***components*** with a similar passion for detail and accuracy, you can complete the solid model of the ***module*** and make sure that it still fits within the overall confines of your machine. Then you can create part drawings directly from the solid model, make the parts and assemble and test a BLP of your most critical module. Voila, you have removed the greatest element of risk from your concept and you can proceed with the development of the other ***modules***.

Sixth Step Example:
*Components for the Reciprocating Paddle **Module***

Functional Requirement's **(Distilled from Module's DPs)**	Possible design Parameters	Analysis	References	Risk	Counter-measures
Linkage	**1)Revolute joint linkage** 2)Revolute & prismatic linkage	1)4-bar synthesis & force analysis 2)Trigonometry & force analysis	Freshman physics, Chapter 4 of this book	1)Too simple motion 2)Complexity	1)Use option 2, or a paddle 2)Make one single center linkage
Paddle	**1)Bent sheet metal** 2)Welded truss	**?**	**?**	**?**	**?**
Bearings	**1)Nylon** 2)Metal pins				
Actuator	**1)Screwdriver motor** **2)Piston**				



What else?…

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Patterns from the Process:

RepeatsRepeatsRepeatsRepeats

From first struggling with ***strategies***, to creating ***concepts***, to minding ***modules***, to cranking ***components***, each step of the design process, as well as the overall process, follows the time-tested scientific method:

- Examine the problem (opportunity!) and create a hypothesis to solve it.
- Design and conduct experiments.
- Analyze the data until you thoroughly understand it.
- Develop conclusions and modify the hypothesis accordingly.
- Honesty, integrity, professionalism, and ethics are the foundations for success!

This process can occur in analytical, physical, or hybrid modes, and in essence is what the sequence of FRDPARRC tables helps a designer to implement. At every step in the development of your machine, always think of as many solutions as possible. This is why it is so important to FIRST carefully think of the functions that must be accomplished; henceforth, different designs can be thought of to provide the required functions and you will meet all of your customer's goals.

As you investigate different ideas in finer and finer detail, physics makes us go back and redefine earlier functional requirements, which is exactly why it is so important to move all aspects of the design forward as a wave progressing from **Coarse**-to-fine. Unforeseen mounting issues for a ***component***, may require a change in the size of a ***module***, which may require you to alter the ***concept***, but hopefully it will not change the ***strategy***.

IF YOU EVER FIND YOURSELF THINKING "GEE, I HOPE THIS WORK..." Then do not lock in on the idea until thoroughly investigated using the scientific method:

- Functional Requirements (Problem)
- Design Parameters (Hypothesis)
- Analytical model (Hypothesis)
- References (Background research)
- Risks
- Countermeasures
- Physical models (Experiments):
  - Sketch models
  - Bench Level Experiments (BLEs)
  - Bench Level Prototypes (BLPs)
- Final design (Conclusions)

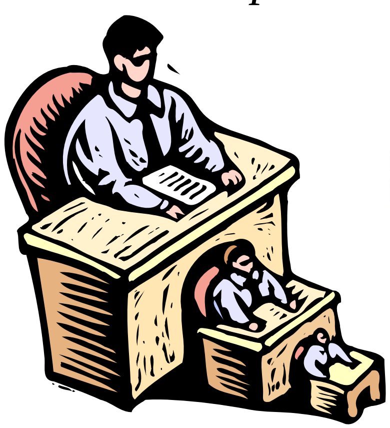
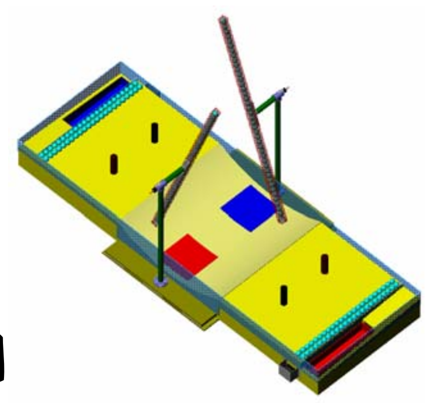
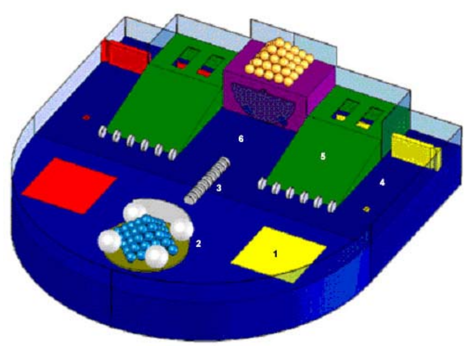
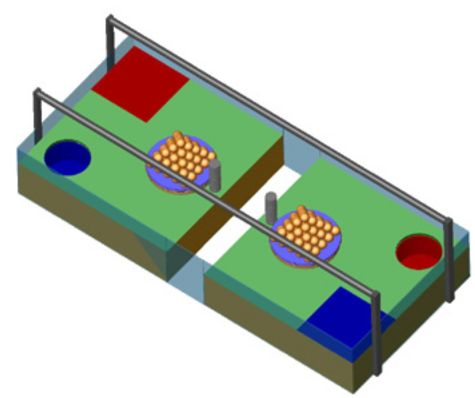
As you become experienced, these steps will all become second nature, just like snowboarding in the glades where you must stay double alert in order to dodge the trees; however, beware that familiarity can breed contempt and your competitors will have no mercy with your market share. Design can be a fun game, as long as you understand that the rules of physics give no quarter. So never grow old and tired or emulate a terminal tuber. Play mind games with everything you encounter. Twist it, pull it, push it in whatever sequence is required to make problems become opportunities.

As you design, keep an eye out for the patterns of the process. Build *passion* into your design. *Practise* using different tools and methods. Be careful of the amount of *precision* required from the design. Observe *patters* that occur in the design and the design process. *Oscillate* (be random), *observe* (experiment), and *organize* (by systematic) and have fun!

Take a step back and look at what you have done so far. What patterns and processes can you see that you have developed? Which ones are most efficient? Which ones lead to the creation of the greatest ideas? Continual self assessment is a very important part of life! Create or stagnate!

Patterns from the Process: *Repeats* *Repeats* *Repeats* *Repeats*

- Notice how each ***Strategy's*** Functional Requirements will each generate one or more ***Design Parameters (Concepts)…***
  - Notice how each ***Concept's Functional Requirements*** will each generate one or more ***Design Parameters (Modules)…***
    - Notice how each ***Module's Functional Requirements*** will each generate one or more ***Design Parameters (Components)…***
- Executing a systematic design process can help you develop a ***rapid design reflex:***
  - Rapidly and effectively solve design problems with a minimum of floundering!
- *As you take more and more trips around the sun, the design process and a rapid design reflex becomes hard-wired into your bio-neural-net!*

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Topic 1 Study Questions

Which suggested answers are correct (there may be more than one, or none)? Can you suggest additional and/or better answers?

1. Cost vs. performance curves can philosophically be used to help you determine when to switch technologies, or possibly identify the need for a disruptive technology:
   True
   False
2. Deterministic design is based on the philosophy of:
   Determining the minimum cost method to bring the product to market on time and within budget.
   Never assume anything, and therefore never do anything without using analytical models, tests, or experience to justify a design decision
3. When considering cost verses performance curves, the *stagnant* (trailing) edge is where considerably more performance could be obtained for not much more cost, and thus the design (or the people in charge of it) is ripe for *evolution*
   True
   False
4. When considering cost vs. performance curves, the *leading* edge is where a balance has been achieved between cost and performance, and thus the design (or the people in charge of it) are *right on target* (for the moment):
   True
   False
5. When considering cost vs. performance curves, the *bleeding* edge is where huge amounts of effort are being poured into a project with very little return, and thus the design (or the people in charge of it) is ripe for *revolution:*
   True
   False
6. The design of a new machine is best accomplished by first developing a design strategy followed by creation of many design concepts to realize the strategy:
   True
   False
7. A *strategy* is a basic approach to solving a problem, yet there are still many different actual machines that could be constructed to execute the strategy:
   True
   False
8. A *concept* is a basic approach to implementing a strategy, yet there are still many different actual components that could be selected when detailing the design:
   True
   False
9. A *module* is a quasi independent unit of a machine (or concept), such that the module can be independently developed and tested, and then brought together with other modules to complete the machine:
   True
   False
10. The *most critical module* is the module that if it doesn't work, could eliminate the chance of your finishing the machine on-time and on-budget:
    True
    False
11. To minimize risk, the *most critical module* should be developed first:
    True
    False
12. Aesthetics and ergonomics are not related to machine performance and therefore can be put off until the technological heart of the machine has been developed:
    True
    False
13. Six-sigma programs can enable a manufacturing organization to identify and overcome design problems by utilizing enhanced manufacturing methods:
    True
    False

14. Six-sigma programs require sensitivity analysis of the entire design and manufacturing process to identify the primary variables that affect quality and performance, and then to focus efforts on correcting those problems:
    - True
    - False
15. Unless a machine is designed so people will want to use it, it will probably not be successful:
    - True
    - False
16. Human factors standards can play a critical role in defining work envelopes and thus may also have a critical impact on the machine's technological detail:
    - True
    - False
17. Safety features are not related to machine performance and therefore can be put off until the technological heart of the machine has been developed:
    - True
    - False
18. Unless a machine is designed so people feel safe using it, it will probably not be successful:
    - True
    - False
19. Safety standards can play a critical role in defining work envelopes and thus may also have a critical impact on the machine's technological detail:
    - True
    - False
20. The best way to minimize design time is to:
    - Form a team, brainstorm to generate solution ideas, form sub teams to evaluate the different ideas, gather together again and resolve differences and select the best idea
    - Form a team, agree on the problem, individually generate strategies, individually review each others' ideas, and then brainstorm to select the best solution strategy
    - It does not matter so long as the team is motivated to solve the problem
    - Use statistical models to enable the achievement of *six-sigma* (6σ) quality
21. The relative amounts of time spent on bringing a design from the "we need a ...." to the "watch this demo of the alpha prototype" are typically:
    - 1/3rd time on developing strategies and concepts, 1/3rd time on detailed engineering, and 1/3rd time on build-test-tweak
    - 1/4 time on developing strategies and concepts, 1/4 time on detailed engineering, and 1/2 time on build-test-tweak
    - 1/2 time on developing strategies and concepts, 1/4 time on detailed engineering, and 1/4 time on build-test-tweak
22. Information in catalogs and advertisements is always correct and hype-free because the vendor has much more experience and always is most concerned with the interest of the customer:
    - True
    - False
    - I want to buy the bridge for sale in Brooklyn
23. *FUD* is a marketing principle utilized by salespeople to emphasize:
    - Free Unconditional Delivery
    - First Uniform Design
    - Functional Uniform Distribution
    - Fear, Uncertainty, & Doubt

Areas for reflection on design process AFTER the entire book has been used over the course of the development of a machine[1]:

1. What FUNdaMENTAL principles (Topic 3) did I find to be particularly valuable, and what principles do I now know that I could have used more effectively?
2. What do I now know that I didn't know before this term about the processes that engineers use to create new designs?
3. What lessons have I learned about organizing my design efforts?

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1. Ask suggested by Prof. Sandy Campbell and Prof. Warren Seering

4. What lessons have I learned about the processes for making parts for my design?
5. What have I learned about good design practice?
6. What would I look for when evaluating someone else's design?
7. What elements of the process did I do well?
8. What elements of the process would I do differently next time; how would I do them?