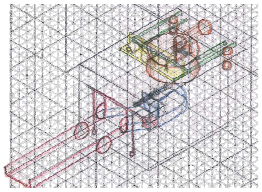
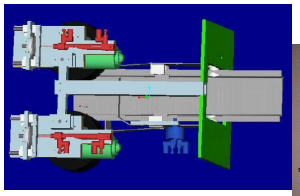
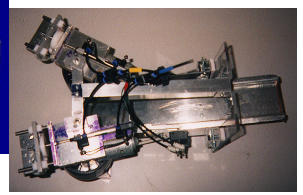
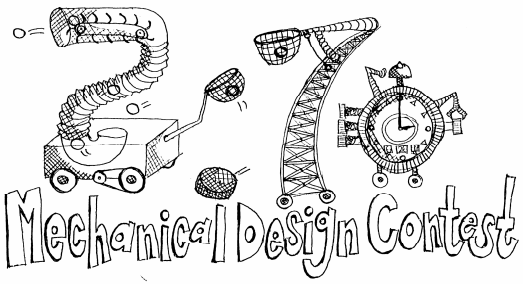
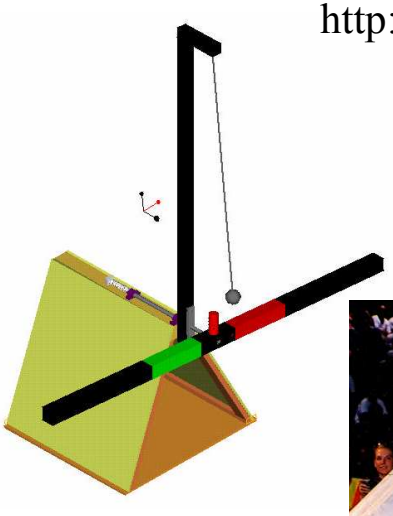
2.007 Design & Manufacturing I

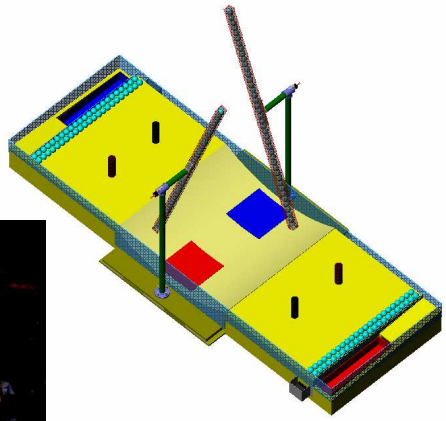
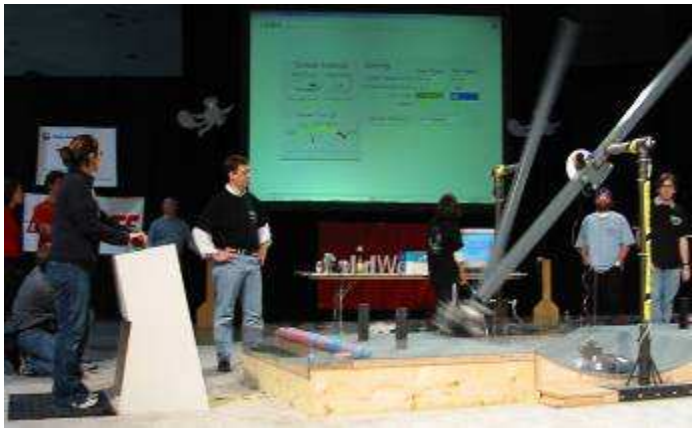
Design is a ♥*Passionate*♥ *Deterministic* Process

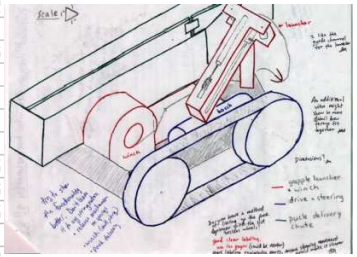
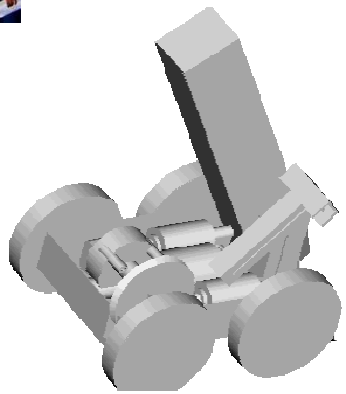
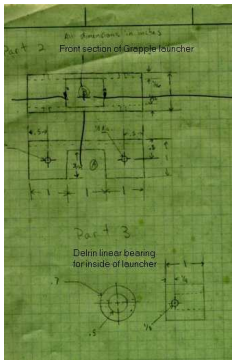


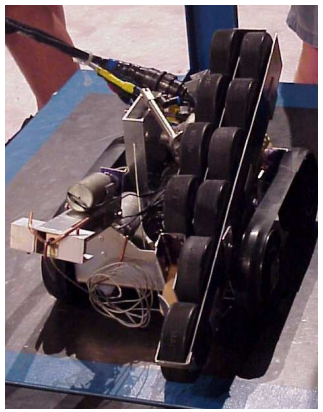
Prof. Alex Slocum
http://pergatory.mit.edu/2.007



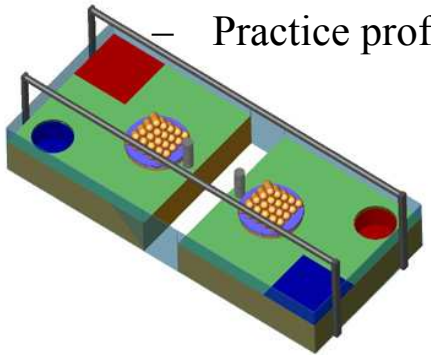
Hook launcher Model	
weight of hook (Kg)	0.05
muzzle velocity	9.4
Number of springs	2
d (draw)	0.095216
Winch model	
radius	0.05
mass	6
w (rpm)	55
torque	2.1
velocity	0.287833

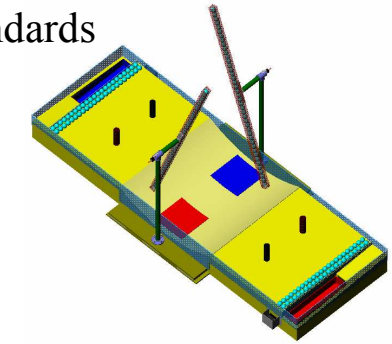







Course Objectives

- Use a fun contest to catalyze learning a ***process*** of design, based on the scientific method, to combine creative thinking with engineering principles (physics) to turn ideas into robust reality:
  - Identify a problem (opportunity!)
  - Use fundamental principles & appropriate analysis and experiments to select & develop ideas
  - Generate & create strategies for solving the problem
  - Generate & create concepts for implementing the selected "best" strategy
  - Break the concept into modules and develop the most critical module first
  - Complete the detailed design of the modules and manufacture, test, and debug them
  - Integrate modules and test, debug, and modify the system as needed
  - Document the results (close the design loop)
  - Become familiar with fundamental design principles, machine elements, and manufacturing and assembly techniques
  - Learn to assess risk, resort to countermeasures when risk becomes too great, and manage projects to be "on-time" and "on-budget"
  - Practice professionalism, be safety conscious, and maintain high ethical standards

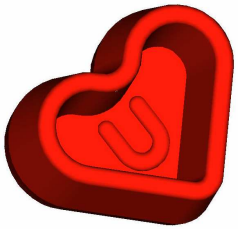




2.70/2.007 History

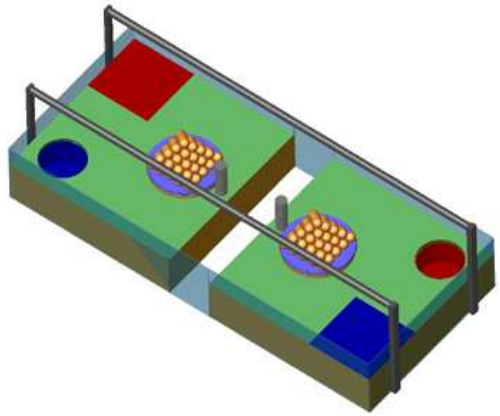
- 2.70 was started in the late 1960's by Prof . Robert Mann as a "design and build course
  - Prof Dave Wilson took it over and Woodie Flowers became the head TA
    - Woodie became a professor at MIT and assumed responsibility for 2.70 for the next 15 years
  - Prof. Flowers evolved the course into a design/build/final "contest" celebration
    - 2.007 became a large class that many across MIT took, as the only pre-requisite was 8.01
  - Prof. Harry West took over 2.007 and made it even more popular
    - Prof. West partnered with Prof. Shimizu at Tokyo Institute of Technology to create the International Design Contest, and Prof. West ran 2.70 for 10 years
- Prof Slocum took 2.70 over in 1995
  - Undergraduate assistants were asked to help with the transition
  - "Customer feedback" (former students' opinions" were used for a process of continual improvement
  - Solid modeling (Pro/ENGINEERING) was added as the drawing package
  - Enrollment number were soaring and too often students did little "real engineering" and more trial and error which was expensive in terms of time and resources
  - Mechanics of solids (2.001) and mechanical engineering tools 2.670 (solid models and basic machining) were added as perquisites to 2.70 which then became 2.007
- In 2.004, Prof Nam Suh and Neil Pappalardo started the Pappalardo Textbook Series in Mechanical Engineering, and Alex started writing FUNdaMENTALS of Design textbook for 2007
  - FUNdaMENTALS of Design is now offered online for free for all the world
    - Over 10,000 copies have bee downloaded since Jan 2007

♥Passion♥ LOVE to Create

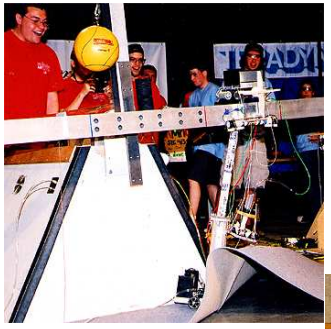


"Enthusiasm is one of the most powerful engines of success. When you do a thing, do it with all your might. Put your whole soul into it. Stamp it with your own personality. Be active, be energetic, be enthusiastic and faithful and you will accomplish your object. Nothing great was ever achieved without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

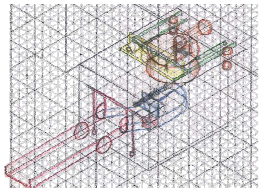
Ralph Waldo Emerson

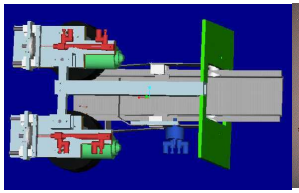


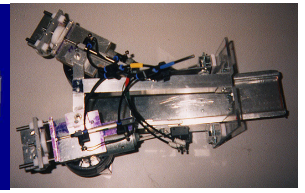
- Use ♥*Passion*♥ as a catalyst to make ideas become reality:
  - Never stop asking:
    - "Is this really the best I can do"
    - "Can the design be made simpler"
  - Create, never stagnate
    - Do you see machines in ink blots?

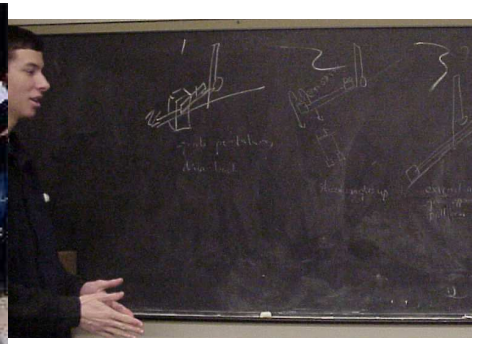


Ink-Blot milling machine by Peter How









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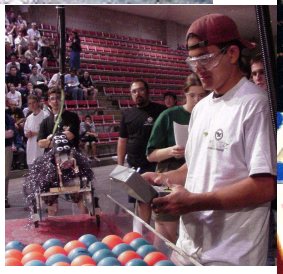

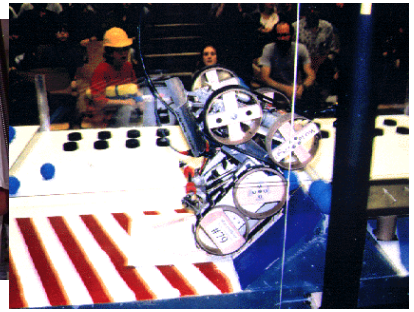

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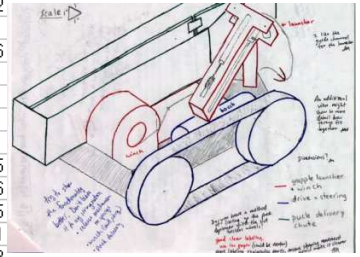
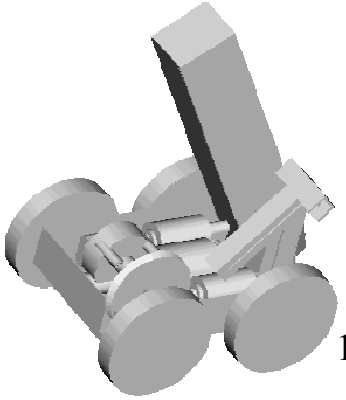
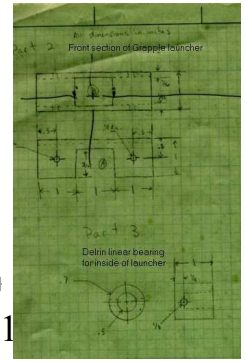
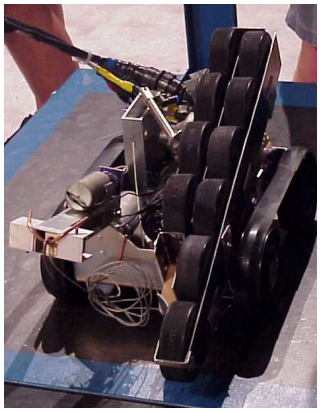


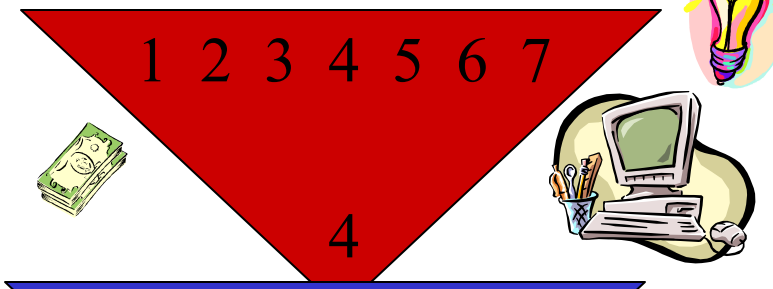


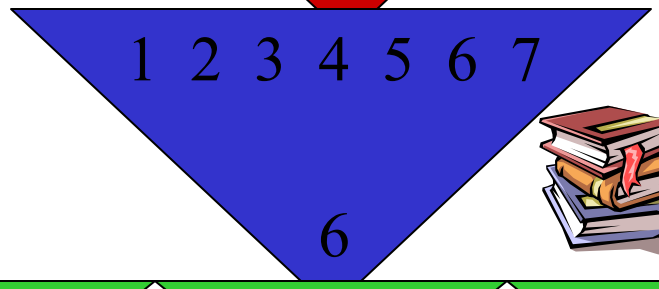




Deterministic Design: *Funnels:* ***Strategies*** *Concepts* *Modules* *Components*

- 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



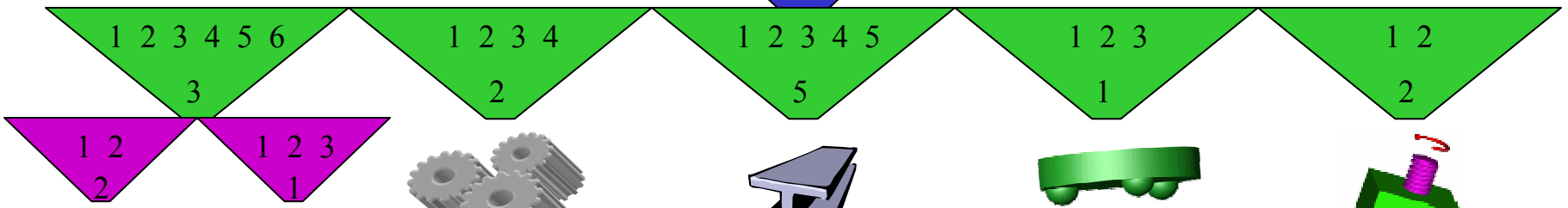


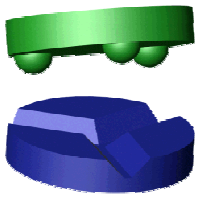
Strategy: Plan or tactics to score but there may be many different types of machines that could be used

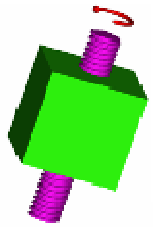
Concept: An idea for a specific machine that can execute a strategy

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

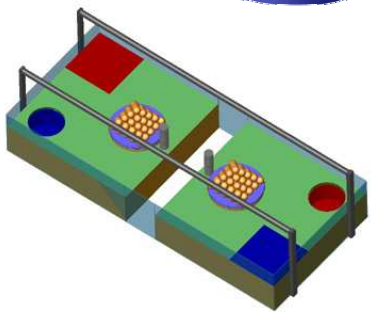
Component: An individual part

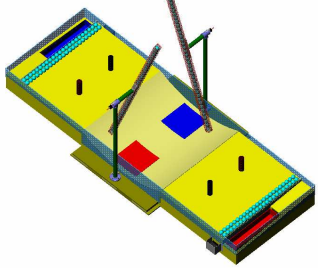


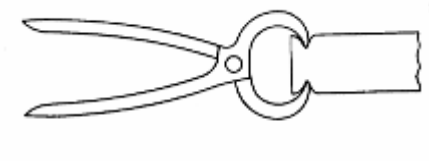




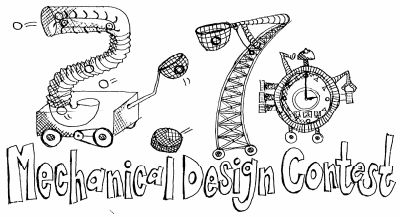
- It is OK to iterate…
  - A *goal* is to never have to backtrack
    - A good engineer, however, knows when its time to let go…

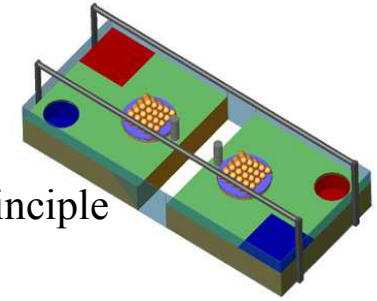






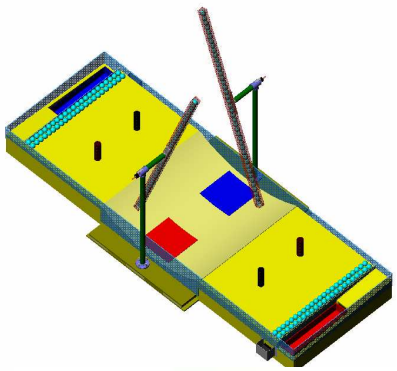
2.007:
*FUN*da*MENTAL* Principles

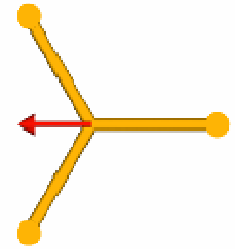


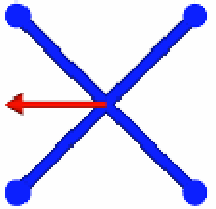


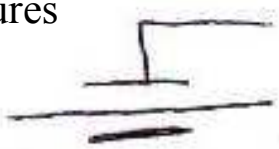
Topics

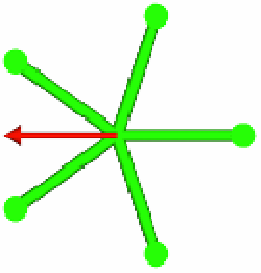
- Occam's Razor
- Saint-Venant's Principle
- Golden Rectangle
- Abbe's Principle
- Maxwell & Reciprocity
- Self-Principles
- Stability
- Symmetry
- Parallel Axis Theorem
- Accuracy, Repeatability, Resolution
- Sensitive Directions & Reference Features
- Structural Loops
- Free Body Diagrams & Superposition
- Preload
- Centers of Action
- Exact Constraint Design
- Elastically Averaged Design
- Stick Figures

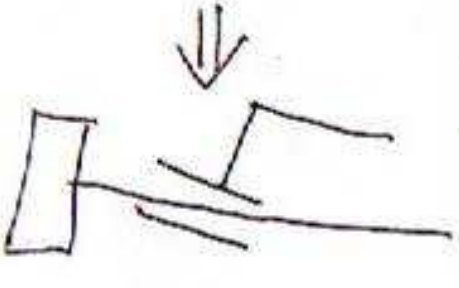


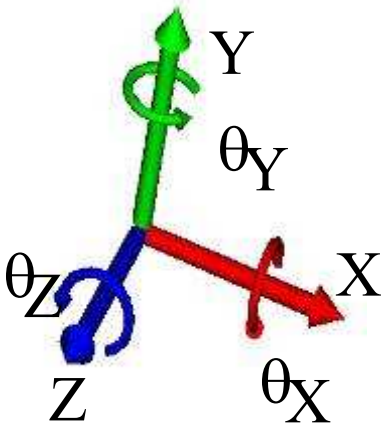


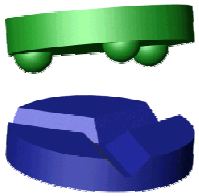




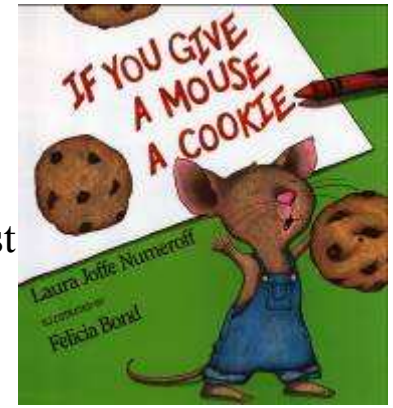




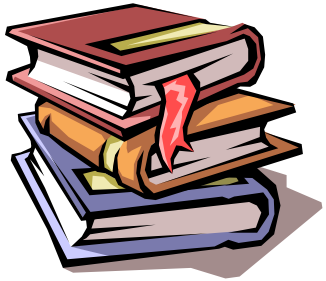


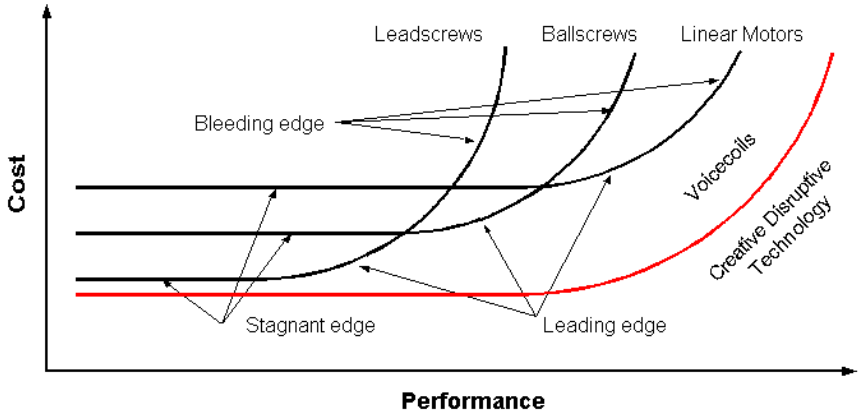


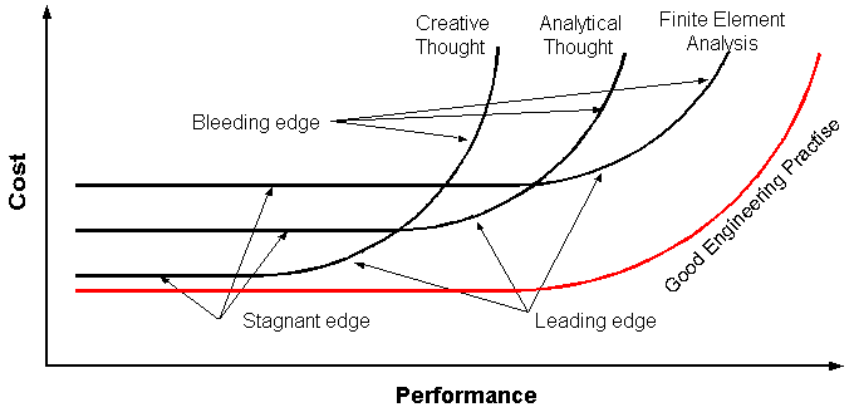
Deterministic Design



- 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

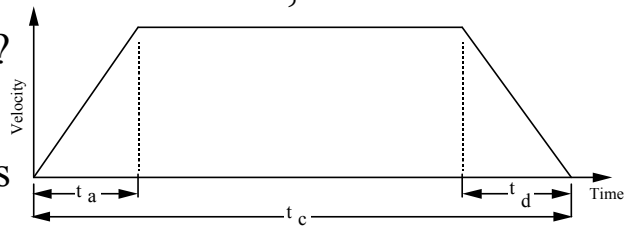


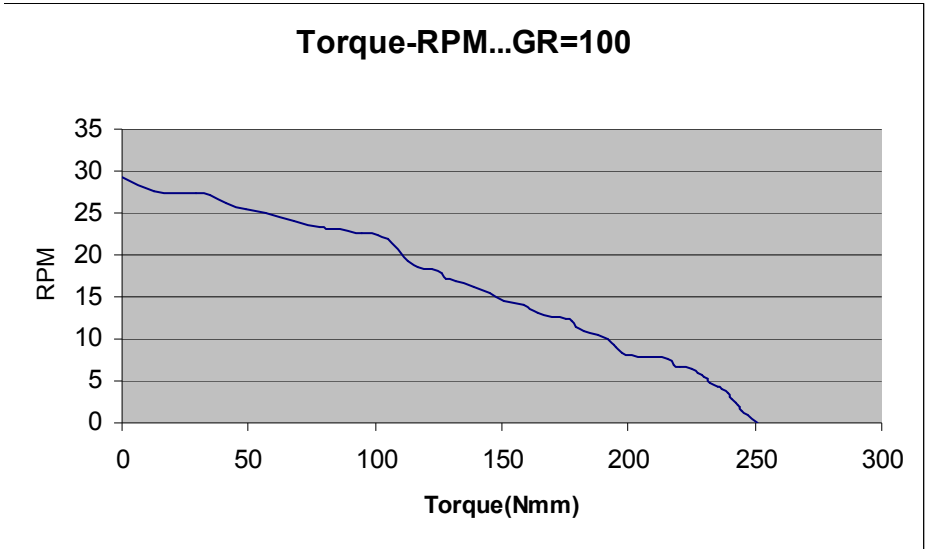




Design Spreadsheets
Example: DC Brushed Motors:

- Use the *Matched Inertia Doctrine* to find the "optimal" transmission ratio
- Motor power rate should be > load power rate
- With an obtainable transmission ratio, determine:
  - Will the wheels slip?
  - Move times
  - Battery requirements
- Play "what-if" scenarios with the spreadsheet *Gearmotor_move.xls*





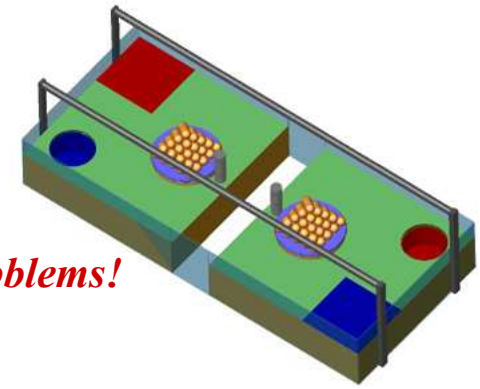
Gearmotor_move.xls		
To estimate inertia of gearmotor and find system optimal transmission ratio		
By Alex Slocum		
Last modified 8/22/03 by Alex Slocum		
Enters numbers in **BOLD**, Results in **RED**		
Motor (torque and speed are NOT at absolute max values, but rather at max efficiency)		
Rotor mass, Mr (grams, kg)	**10**	**0.0100**
Diameter, Dm (mm, m)	**15**	**0.0150**
Mength, Lm (inches, m)	**12**	**0.0120**
Number of drive motors, Nm	**2**	
Nm Motors' rotary inertia, Jmotor (kg-m^2, g-mm^2)	**5.63E-07**	**563**
Motor operating efficiency, etamotor	**50%**	
Max motor torque, gammax (m-N-m, N-m)	**8**	**0.008**
Max motor speed, wmax (rpm, rad/s)	**13500**	**1414**
Motor speed at maximum efficiency, wmaxeff (rpm, rad/s)	**11500**	**1204**
Steepness S (N-m-s/rad)	**5.659E-06**	
Planetary Transmission		
Planet carrier assembly mass Mplanet, (grams, kg)	**2.1**	**0.0021**
Planet carrier outer diameter, Dpod (mm, m)	**20**	**0.0200**
Planet carrier inner diameter, Dpid (mm, m)	**10**	**0.0100**
Number of stages, Nstage	**3**	
Efficiency per stage, etastage	**90%**	
Planetary total rotary inertia, Jplanets (kg-m^2)	**3.94E-07**	
Output shaft mass, Mouts (grams, kg)	**4**	**0.0040**
Output shaft diameter, Douts	**4**	**0.0040**
Output shaft rotary inertia, Jouts (kg-m^2)	**8E-09**	
Total Nm planetary transmissions' rotary uinertia, Jtrans (kg-m^2)	**8.04E-07**	
Transmisssion efficiency (includes car wheels), etatrans	**66%**	
Car		
Mass of car, Mcar (kg)	**4**	
Diamter of wheel, Dwheel (mm, m)	**75**	**0.0750**
Max car acceleration, acar (m/s^2, g)	**0.98**	**0.10**
External loads, friction... Fext (N)	**0**	
2Wd or 4WD, Nwd	**2**	
Coefficient of friction wheel-to-ground, mu	**0.2**	
Optimal Transmission ratio by Matched Inertia Doctrine		
Optimal transmission ratio, ntrans	**64**	
Confirm: Number of stages = # required to achieve desired ntrans	**yes**	
Actual transmission ratio to be used, ntranactual	**64**	
Actual equivelent linear inertia of motor and tranny, mtrans (kg)	**4.0**	
Total actual sysetm equivelent inertia, Mtotal (kg)	**8.0**	
Power rates		
Motors' total power rate, PRmotor	**187.41**	
Load power rate, PRload	**3.86**	
System goodness (should be >1): PRmotor/(4PRload/etatrans)	**7.96**	
Motion Results		
Start-to-stop travel distance (must be>Xaccel), Xdes (m)	**1.5**	
Max. potential tractive effort (even mass distribution), Ftraction (N)	**3.92**	
Max. motor tractive effort (even mass distribution), Ftractive (N)	**17.92**	
Can wheels slip?	**yes**	
Maximum theoretical car speed vmaxpot (m/s)	**0.83**	
Car speed at max motor η, vmaxeff (m/s)	**0.71**	
"Steepness", slinear (N-s/m)	**-4.73**	
Time to accelerate to speed at max motor η, taccel (seconds)	**3.22**	
Taylor series approx. time to accelerate to speed at max motor η	***3.89***	
Distance travelled during acceleration to max speed, Xaccel (m)	**1.48**	
Time to travel 1/2 desired travel distance, tohtd (seconds)	**1.75**	
Total travel time, ttotal (seconds)	**3.49**	
Approx. travel time (no velocity limit, Taylor series approximation)	**3.49**	
Battery Requirements		
Estimated maximum power draw from batteries, Pbat (W)	**8.43**	
Estimated maximum energy draw from batteries, Ebat (J=N-m)	**29.5**	

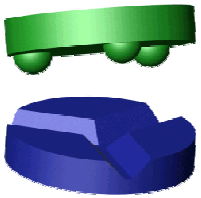
Deterministic Design: *FRDPARRC*

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

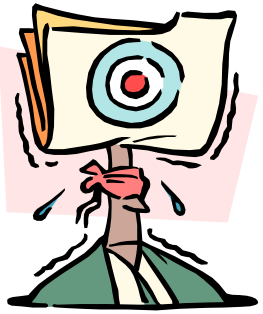
- To actually use the FRDPARRC Table:
  - Create one actual table that becomes your development roadmap
  - Dedicate one sheet to each FR/DP pair

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

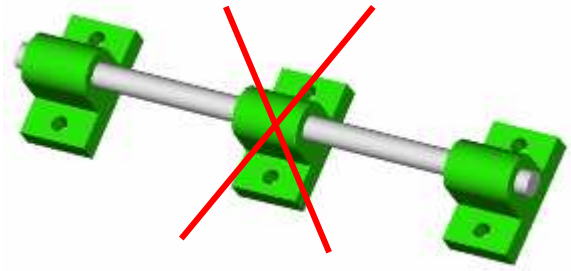


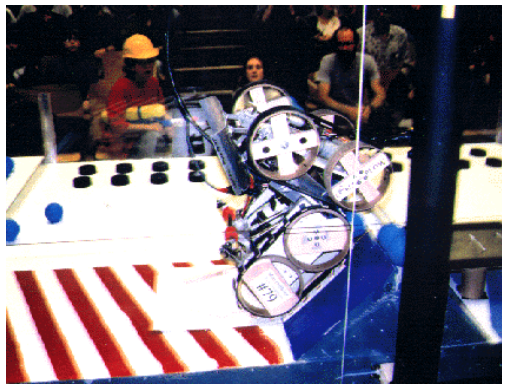


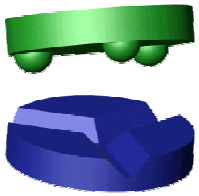
Deterministic Design: *Risk Management*



- 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!

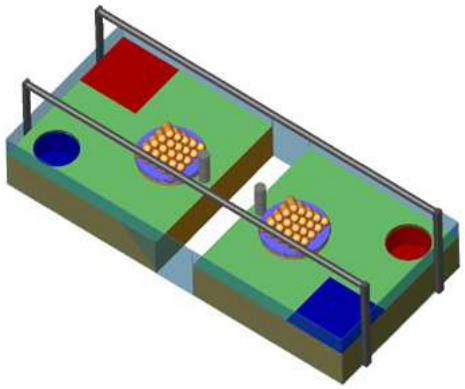


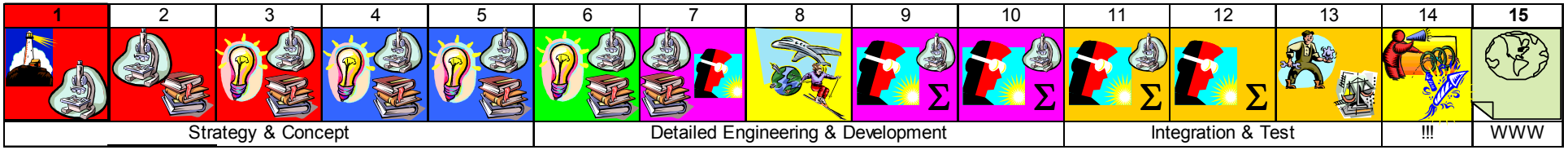




Deterministic Design: *Schedules*

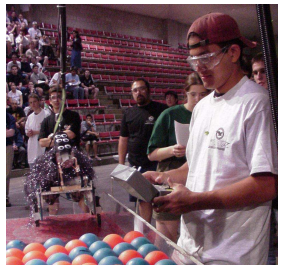
- Time is relative, but you will soon run out of it if you keep missing deadlines!
  - No matter how good your ideas are, their value decays exponentially with every day they are late
    - Once a customer starts buying a product, if the manufacturer maintains diligence, you will find it extremely difficult 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…

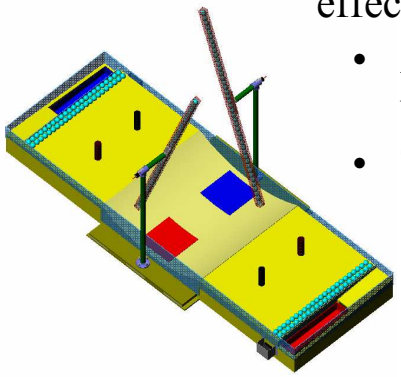


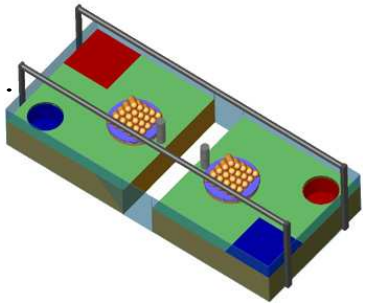


Teamwork: *Individual Thought*

- Individual thought is often the most creative
  - Do leisurely things (e.g., long walks) that you know inspire creative thought.
  - Look at what other people have created
    - Look in your home, stores, www, patents
  - Get out of traffic and take alternate routes
  - Sketch ideas and the ideas' principal components
  - Cut out the principal components and pretend they are modular elements
    - Like toy building blocks, try different combinations of components to make different products
  - Pit one idea against another and imagine strategies for winning
    - Take the best from different ideas and evolve them into the best 2 or 3 ideas
- Update the FRDPARRC table and create a *Milestone Report* or *Press Release* for your favorite ideas
  - The FRDPARCC Table (ONE DP per FR) and a large annotated sketch makes an effective infomercial
    - A random person should be able to read your *press release* and fully understand your idea without your having to explain it to them
    - These sheets will be shared with your teammates in the next stage…







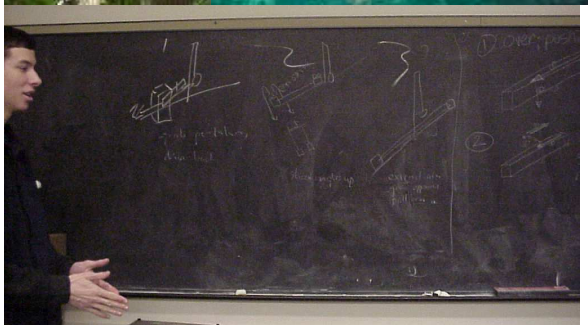
Teamwork: Peer Review Evaluation Process (*PREP)*

There is no such thing as just an individual, however,

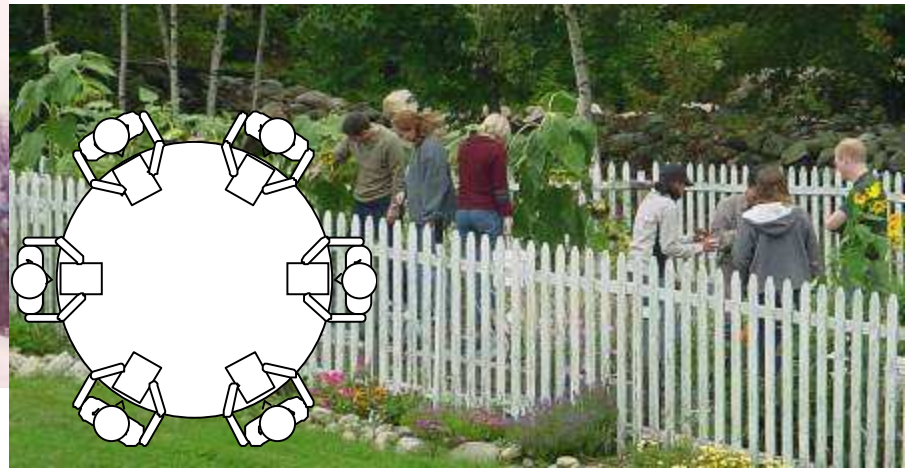
- Teams are made up of individuals

Any design process must make the best use of resources: ***individuals*** and ***teams:***

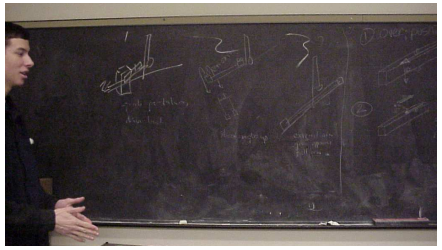
- Give individuals pride of ownership:
  - Encourage individuals to privately think & create on their own, and make them realize that their thoughts will be considered
  - Encourage individuals to privately & constructively evaluate the work of others, and make them realize that their opinions will be considered
- Maximize the efficiency and effectiveness of teams and reduce apathy:
  - Do not have brainstorming meetings unless everyone is PREPared
    - Individuals must have thought of ideas and reviewed each other's ideas before the meeting
    - Peer pressure will help correct non-performers and nay-sayers and thus reduce apathy
    - It takes motivated individuals to make the JUMP to start the design process with:



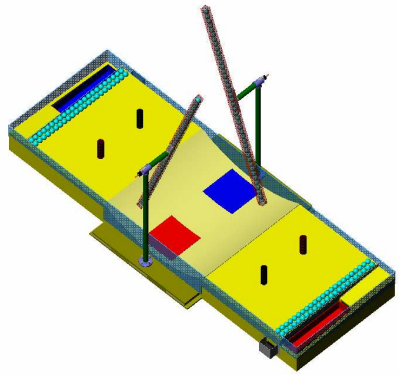
♥Passion♥ ***♥Passion♥***



Teamwork: *Group Brainstorming*

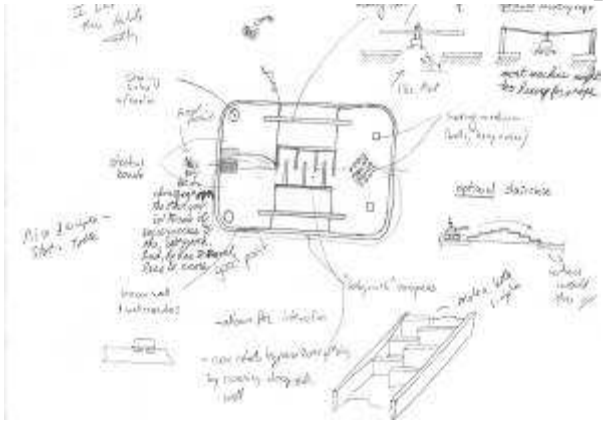


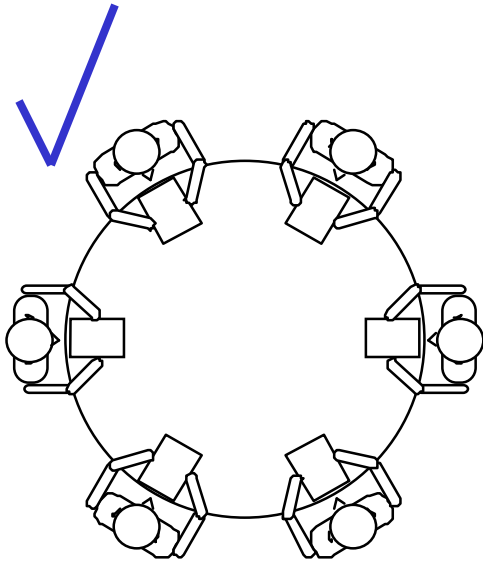
- Brainstorming helps teams solve personal creativity deadlocks and help to ensure something hasn't been overlooked
- Initially let everyone voice their suggestions, then distill ideas
- Group personality factors must be considered:
  - Shy individuals getting run over
  - Aggressive individuals always driving
- An individual's personality often has nothing to do with creativity
  - Careful to avoid conflicts over the issue of who first thought of the idea
  - The people in the group must be willing to take praise or scolding as a group
  - NO pure negatives, only observations with suggestions for improvement:



- ~~"That design sucks!"~~

- "I see a low pressure region that can be alleviated by making it blue"

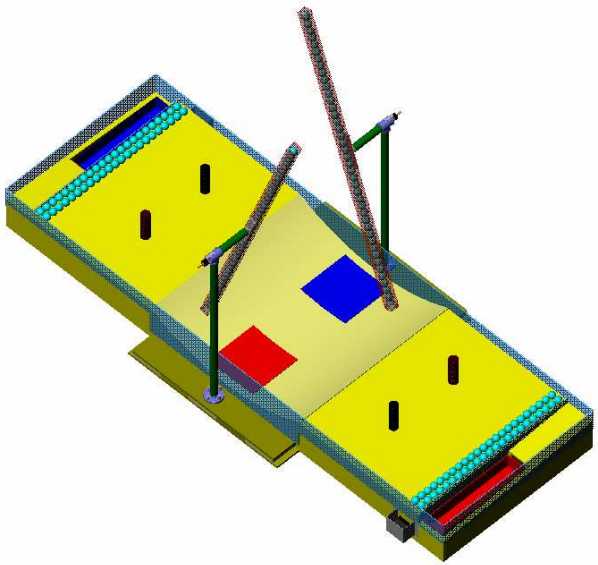




Teamwork: *Comparing Designs*

- There are many systematic methods available for evaluating design alternatives
  - The simplest method is a linear weighting scheme:
    - You may want to use the list of FRs as the evaluation parameters
    - Apply a relative importance weight to each evaluation parameter
    - Pick one design as a "baseline" (all zeros), and compare the rest (+ or -)
    - Easiest to use provided user bias can be minimized
    - When you find the "best" design, look at other designs that have higher weights and see how those characteristics can be transferred to the "best" design to make it even better!
  - A "Pugh" chart is similar, except that it does NOT use the weighting column!
    - A linear weighting scheme (a series of +, -, 0 wrt a baseline design) will give equal weighting to attributes

	Weight	Titling Table	Peace Circle	Tilting Beam
Scoring variation	3	0	-1	0
Dynamic motions	2	0	0	1
Crowd appeciation	1	0	0	0
Manufacturability	1	0	1	0
Transportability	1	0	1	0
Scalability	2	0	0	0
Base for storage	1	0	1	0
		0	0	2



Design: *It Never Stops*

- Physically experimenting with the hardware while thinking about all possible variations can produce many creative ideas
  - Sketching, drawing, and solid modeling are powerful creativity catalysts
  - Much has been done by others: Learn from others' failures and successes
  - Writing down your thoughts and dreams can help you to see solutions
  - Analysis can identify areas of high (low) sensitivity and rapidly ascertain feasibility
  - Ideas can evolve rapidly when they are compared to others

- ***Stay Psyched and Passionate!***
- ***Never Stop!***