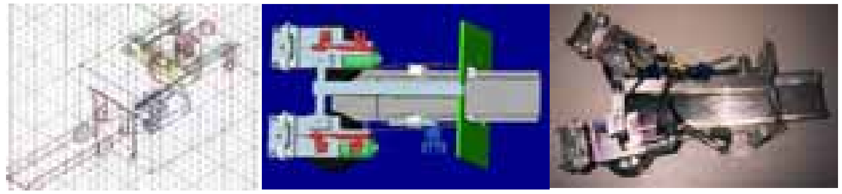
FUNdaMENTALS of Design

Topic 1

Design is a ***Passionate*** Process

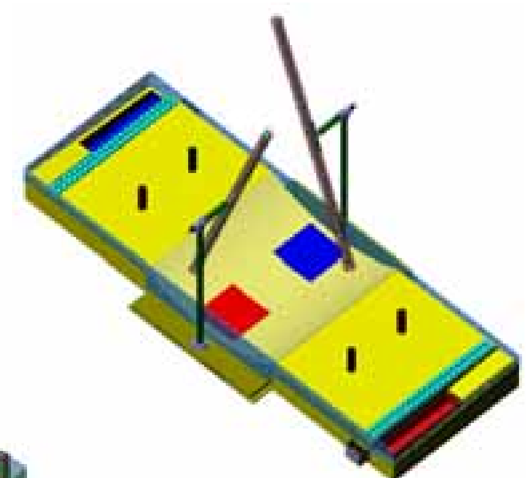
Topic 1

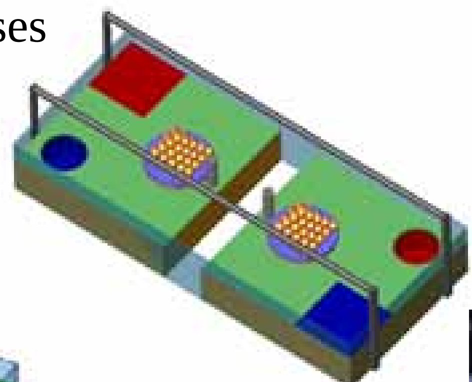
Design is a ♥*Passionate*♥ Process

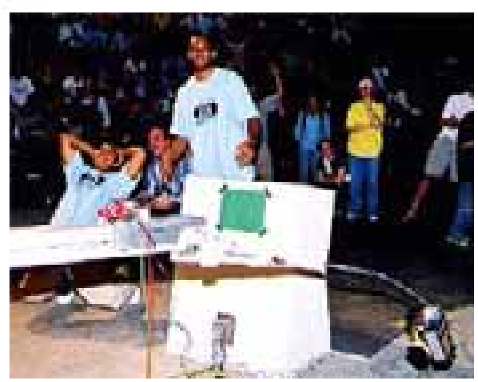


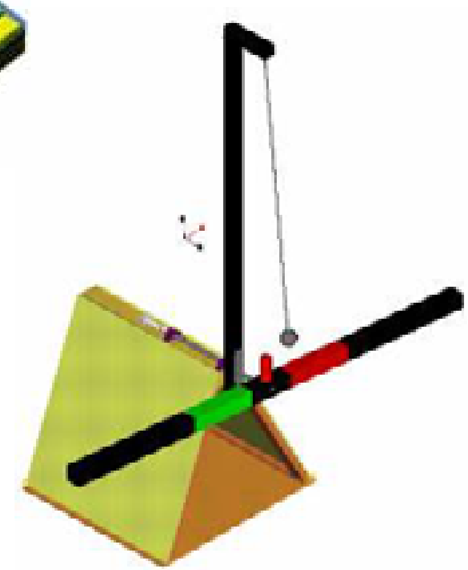
Topics:

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







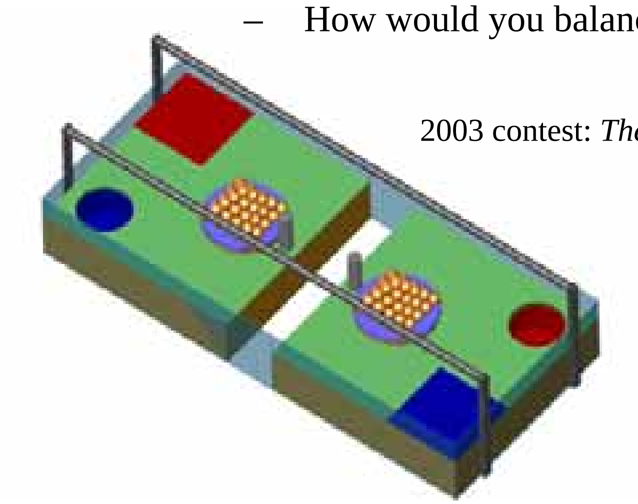


Design Contests

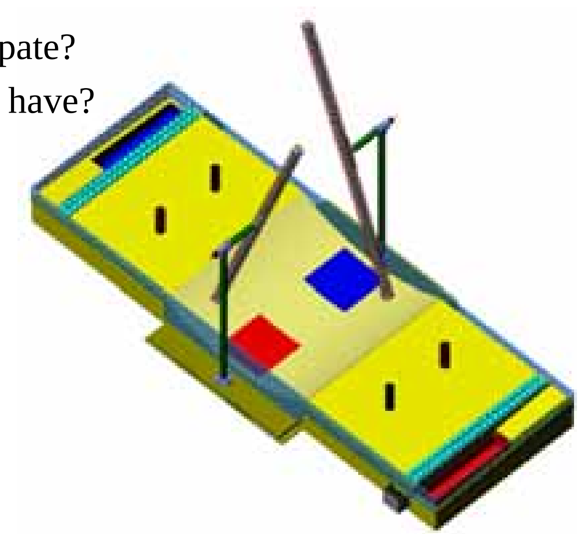
- Theme: Multiple ways to score (mass and motion)
- "Rules":
  - Only use materials in the kit and plus fasteners and adhesives
  - Machine must fit into starting zone (0.5m x 0.5m x 0.5m cube)
    - You can start with your machine engaged (wheels preloaded) to table features
  - "Score" is evaluated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

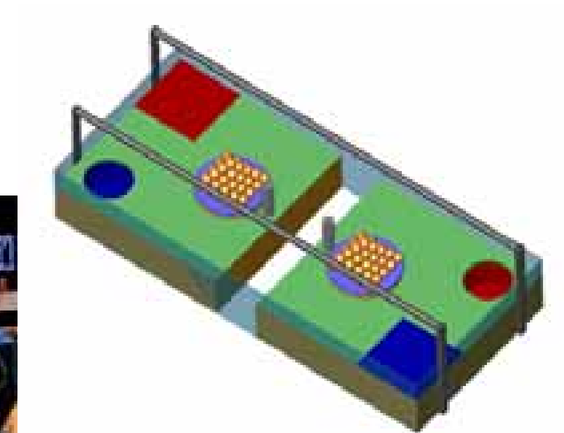


2002 contest: *The MIT & the Pendulum*

♥***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?

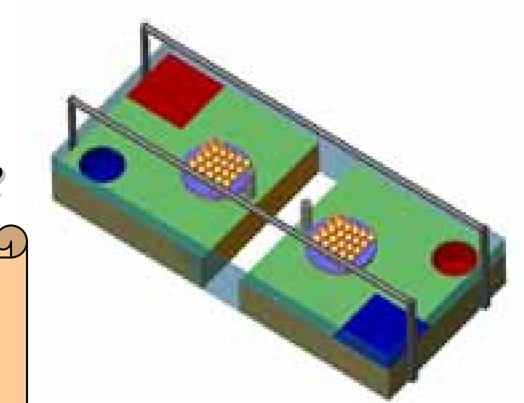
Ink-Blot milling machine by Peter How

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?'

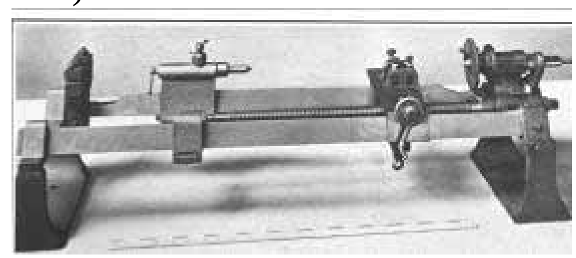
Avoid complexities and make everything as simple as possible

Remember the get-ability of parts

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

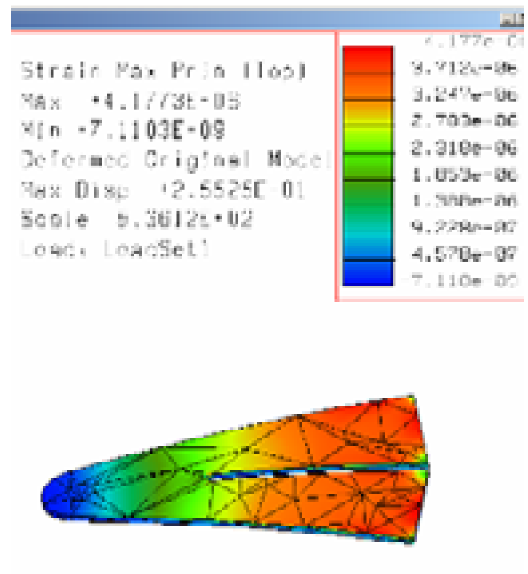
Maudslay's screw cutting lathe

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



♥Passion♥ *Best Engineering Practice*

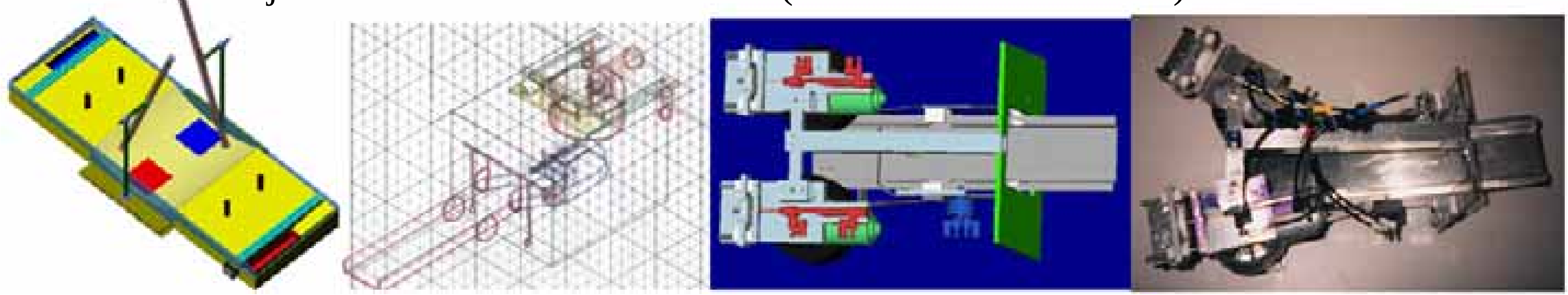
- Before we can talk about a process for design, we must consider the things the best designers do as they solve problems
  - *Best Engineering Practice* entails careful forethought and following standards
    - ***62.5 grams of prevention is worth a kilogram of cure!***
    - ***"Random Results are 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!

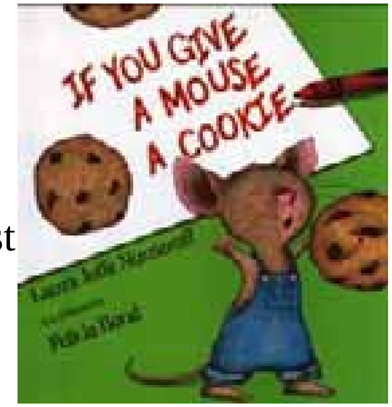
♥Passion♥ ***(Play, Sketch, Model, Detail, Build & Test)^N***

- Engineering is often a tactile, visual, verbal, cerebral, and physical activity:
  - Play with the table and the kit parts
  - Sketch ideas
  - Create physical and 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
- Students who follow *best engineering practice* create very impressive machines with just the correct amount of effort (and have time for a life!)

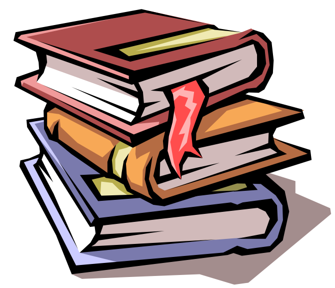


Alex Sprunt's machine was almost exactly like the solid model, and it worked "out of the box"!

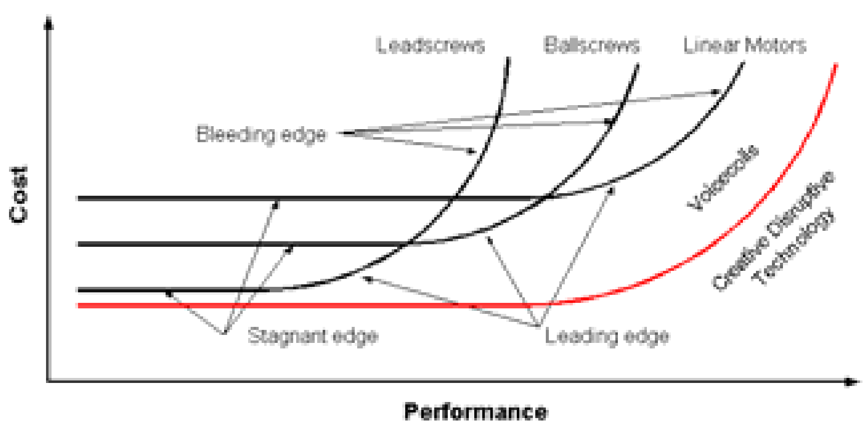
Deterministic Design

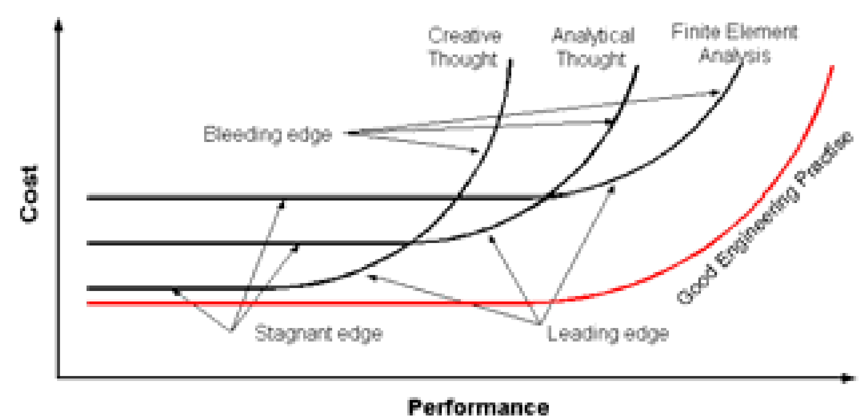


- Everything has a cost, and everything performs (to at least some degree)
  - If you spend all your time on a single tree, you will have no time for the forest
  - If you do not pay attention to the trees, soon you will have no forest!
  - You have to pay attention to the overall system and to the details
- 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!



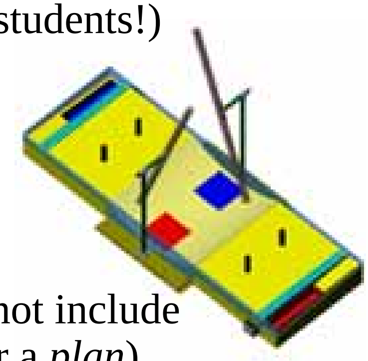
- Stay nimble (modular!) and be ready to switch technology streams
  - It is at the intersection of the streams that things often get exciting!
  - *"If you board the wrong train, there's no use running along the corridor in the opposite direction"* Dietrich Bonhoeffer



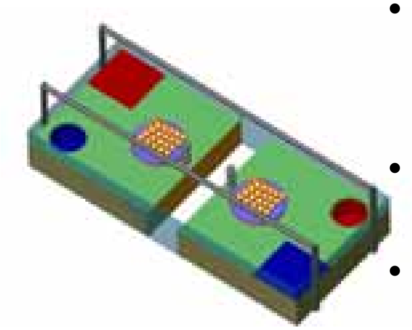


Deterministic Design: *Reverse Engineering*

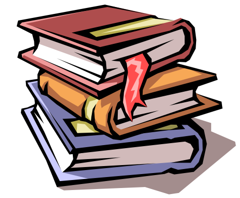
- How would you create a contest where the overall goals are:
  - The inertia of the machines is on the order of the inertia of the system
  - The system is SIMPLE to build and solid model (for the staff and the students!)
  - The contest can have MANY different possible winning strategies
    - Engineering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



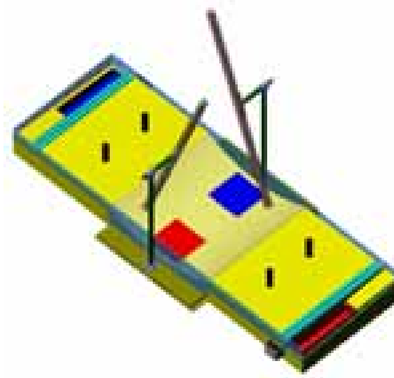
Deterministic Design: *Disruptive Technologies*

- 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

∰

Will Delhagen & Alex Jacobs

2001's ***Tiltilator!***

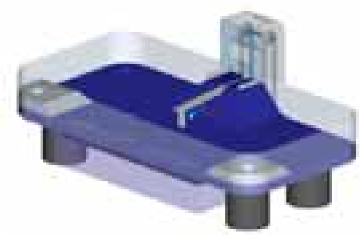


Kevin Lang

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

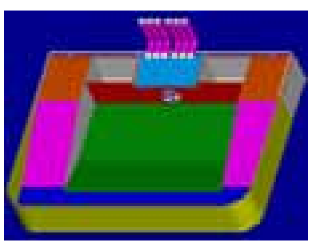
Hyoseok Yang

☺



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

Sami Busch

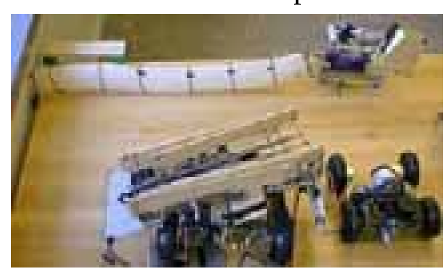


1996's ***Niagara Balls!***

Tim Zue

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

Colin Bulthap



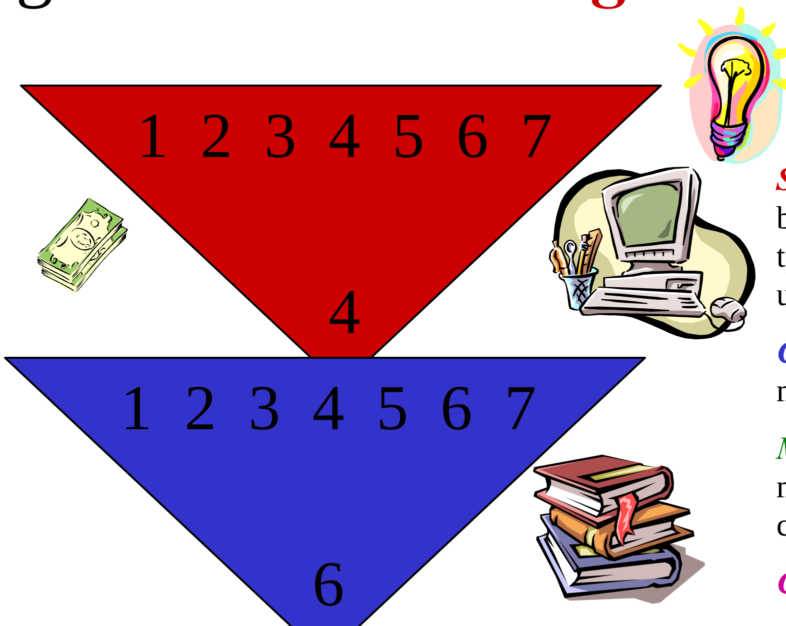
1998's ***Ballcano!***

David Arguellis

1999's ***MechEverest!***

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

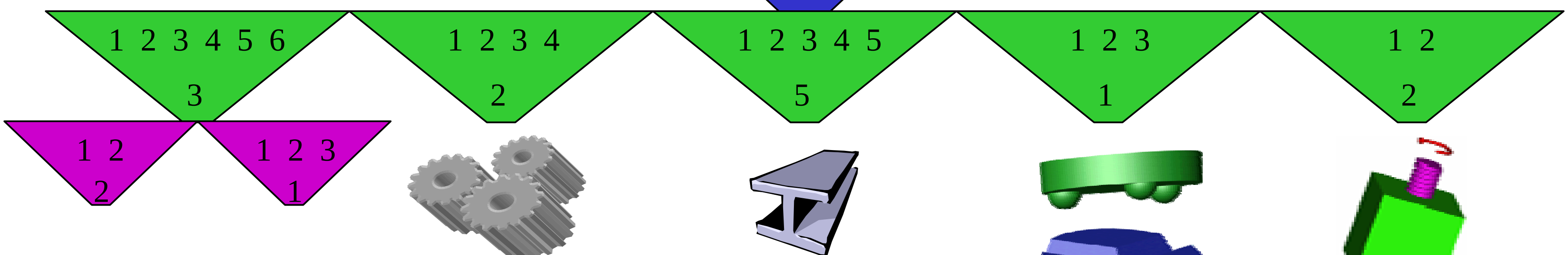


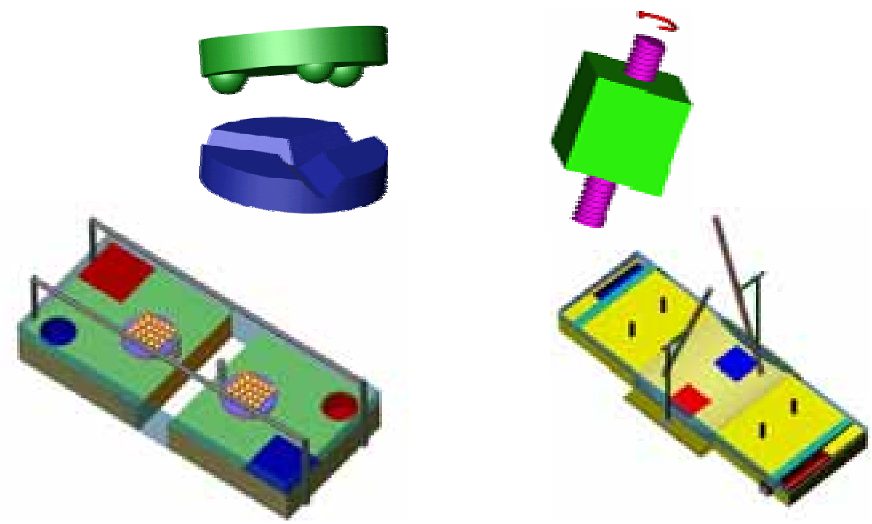
Strategy: Plan or tactics to score but there may be many different types of machines that could be used

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

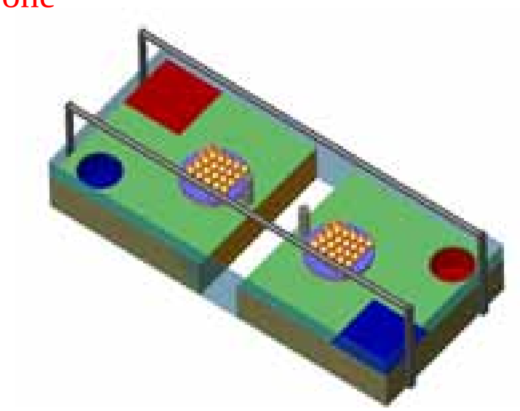




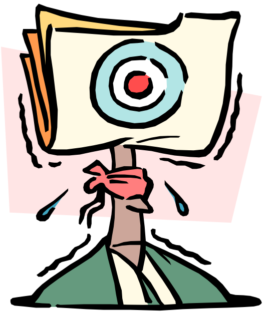
- It is OK to iterate…
  - A *goal* is to never have to backtrack
    - A good engineer, however, knows when its time to let go…

Deterministic Design: *Schedules*

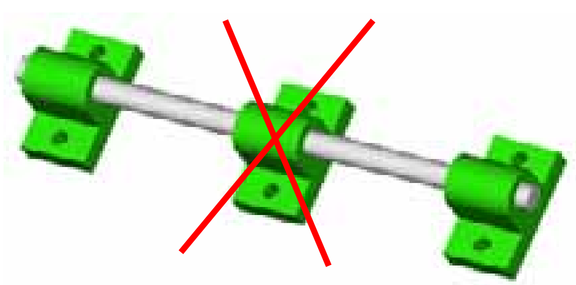
- Time is relative, but you will soon run out of it if you keep missing deadlines!
  - No matter how good your ideas are, their value decays exponentially with every day they are late
    - Once a customer starts buying a product, if the manufacturer maintains diligence, you will find it extremely difficult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



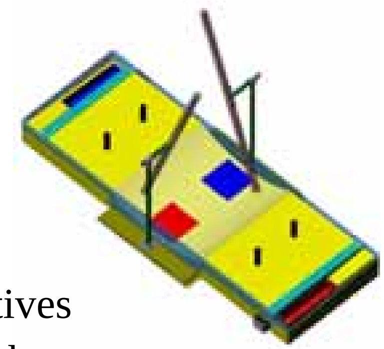
Deterministic Design: *Risk Management*



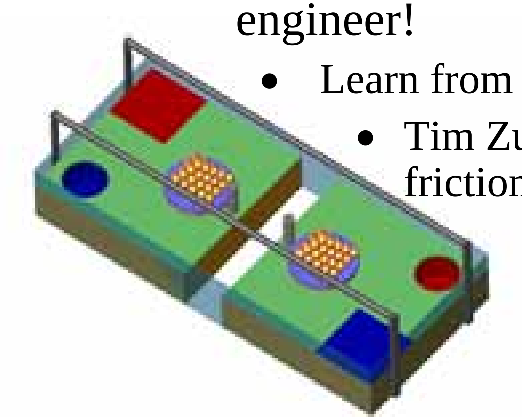
- The key to deterministic design is risk management
- For every idea, risk must be assessed
  - Ask yourself which ideas and analysis (physics) are you most unsure of?
    - Which element, if defined or designed wrong, will neutralize the machine?
  - For every risk identified
    - Estimate the probability 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: *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!

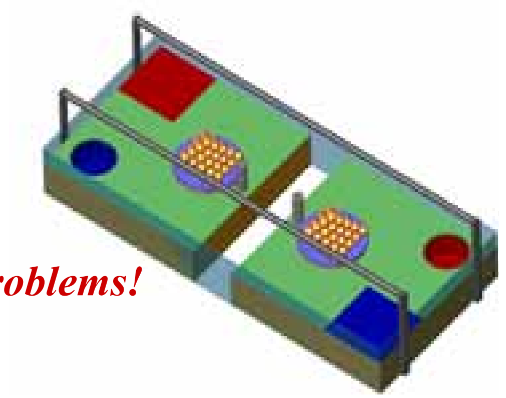


Systematic Organization of Ideas: *FRDPARRC*

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!



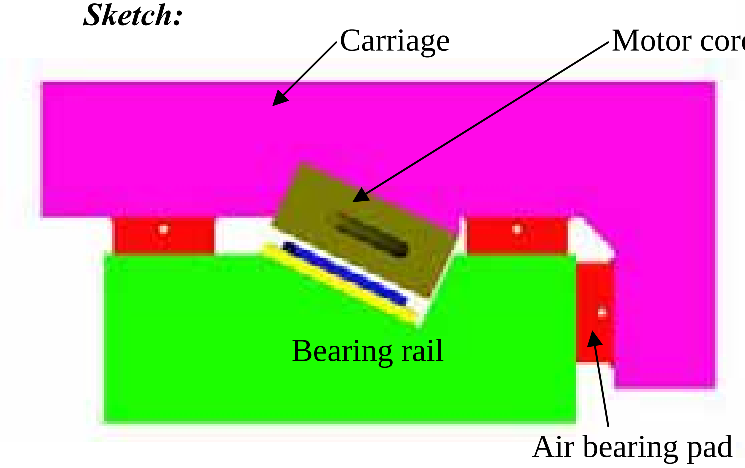
FRDPARRC Example: *A Precision Linear Motion System*

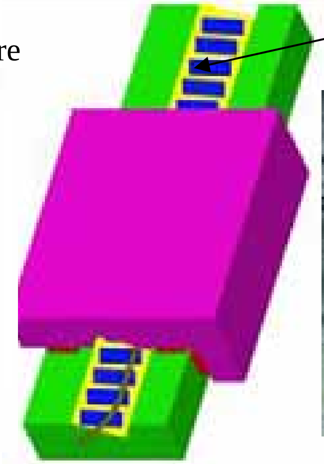
FRDPARRC Sheet Topic: Precision Low Cost Linear Motion Stage

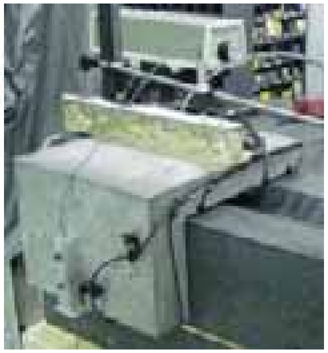
Functional Requirement (Event) Preload air bearings for minimal cost

Design Parameter (description of idea) Preload air bearings using magnetic attractive force of motor, so air bearings need only ride on two 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

$$F_V = F_{magnets} \sin\theta \qquad \frac{F_V}{F_H} = \frac{A_V}{A_H} = \tan\theta$$

$$F_H = F_{magnets} \cos\theta \qquad \theta = \arctan\left(\frac{A_V}{A_H}\right)$$

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

Design is a Series of Steps Blended Together

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

Explore

- – ***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

Experiment

- – ***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!

Create

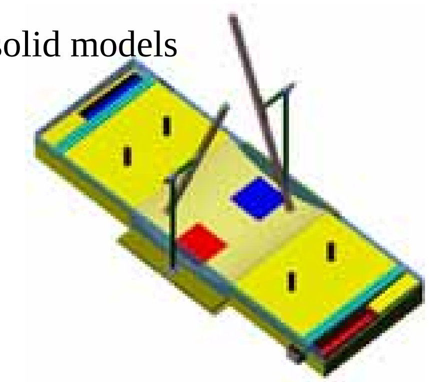
- – ***Fourth Step:*** Create ***concepts,*** specific ideas for machines, to implement the best ***strategies,*** using words, analysis, and sketches
  - Use same methods as for ***strategies***, but now sketch specific ideas for machines
  - Often simple experiments or analysis are done to investigate effectiveness or feasibility
  - Select and detail the best ***concept***…

Detail

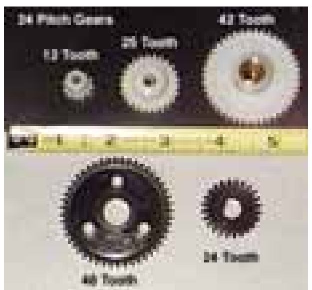
- – ***Fifth Step:*** Develop ***modules,*** using words, analysis, sketches, and solid models
- – ***Sixth step:*** Develop ***components,*** using words, detailed analysis, sketches, and solid models

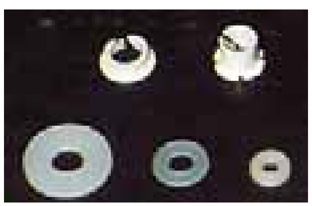
Build & test

- – ***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*



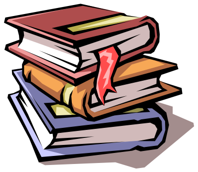


- Before even thinking about potential solutions to a problem, one has to first take stock of the available resources:
  - What time is available?
    - When is the project due?
    - How many person-hours a week can be spent on the project?
    - What are the hours of operation for support facilities (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.efunda.com/home.cfm
    - Look at other machines
    - 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….?

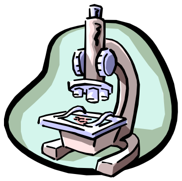
Second Step: Understanding the *Problem (Opportunity!)*

- 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

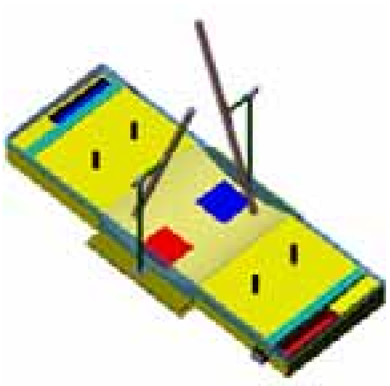
- Study a problem and then define it in terms of its energy storage and dissipative elements, and its geometry and materials:
  - ***Simple physical models***
    - Physically play with the kit and contest table: Let the hardware talk to you….
    - A *sketch model* made from simple materials enables you to play with the problem

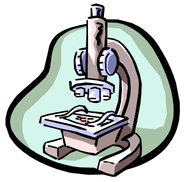


  - ***Simple drawings***
    - A simple hand-drawn isometric figure helps you to pattern the problem into your bio neural net
    - A simple solid model can also be very useful, particularly when later seeking to test your solid model solution on the problem



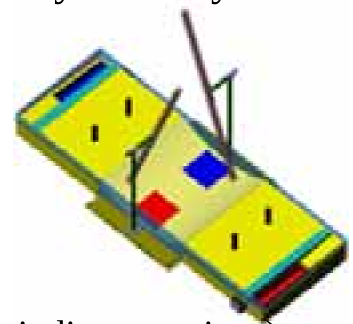
  - ***Physics: First-Order-Analysis***
    - Words to describe the physics
    - Simple analysis with guestimates of realistic numbers (spreadsheets)
  - ***Words*** (in a table or bulleted list) to describe what problem must be solved
    - What must be accomplished? (e.g., tip a balance…*functions*, *events*)
    - What are the constraints? (e.g., rules, cost, size, time)





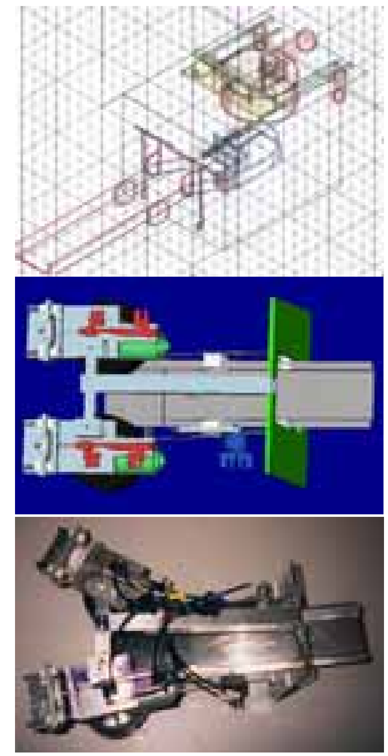
Third Step: *Developing* ***Strategies*** ***Concepts*** ***Modules*** ***Components***

- 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

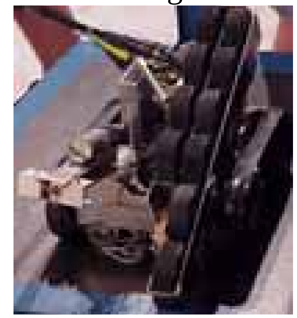
Alex Sprunt's 2.007 machine development



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

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	**?**	**?**	**?**	**?**

David Arguellis

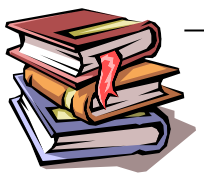


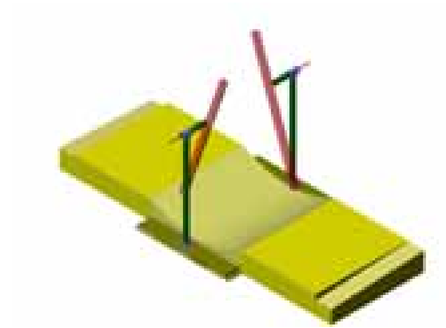
1999's ***MechEverest!***

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

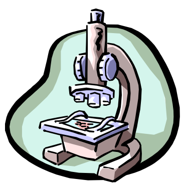
- A ***concept*** is a specific vision of how one could actually accomplish the ***Strategy***:
  – Words to describe what the concept must do, and how it will work
    - Ideally in simple tabular form, like a FRDPARRC Table

  – 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)**

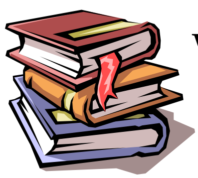


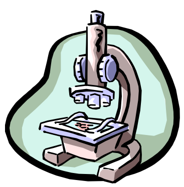
  – The design engineer needs to take care to propose a concept in just enough detail to be assured that it could indeed be implemented
- Example: ***Concepts*** for ***Gather pucks and balls and deposit in goal*** *Strategy*
  – ***Concept A*** for ***Strategy*** 1: Drive around picking up pucks and balls 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

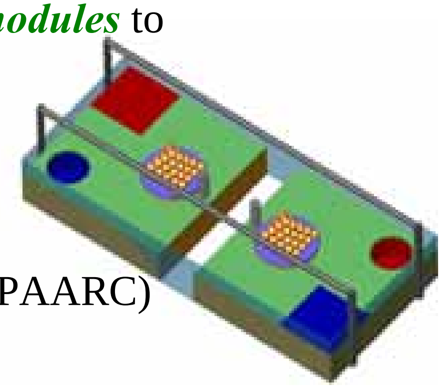
Fourth Step Example:
Concepts for the Knock Down Balls Strategy

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**	**?**	**?**	**?**	**?**

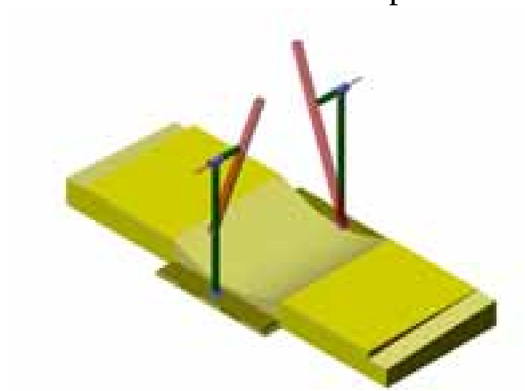
Fifth Step: *Developing* ***Modules***







- 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

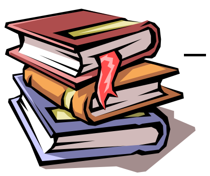


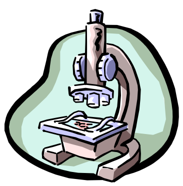
Fifth Step Example:
Modules for the Harvester Concept

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**	**?**	**?**	**?**	**?**

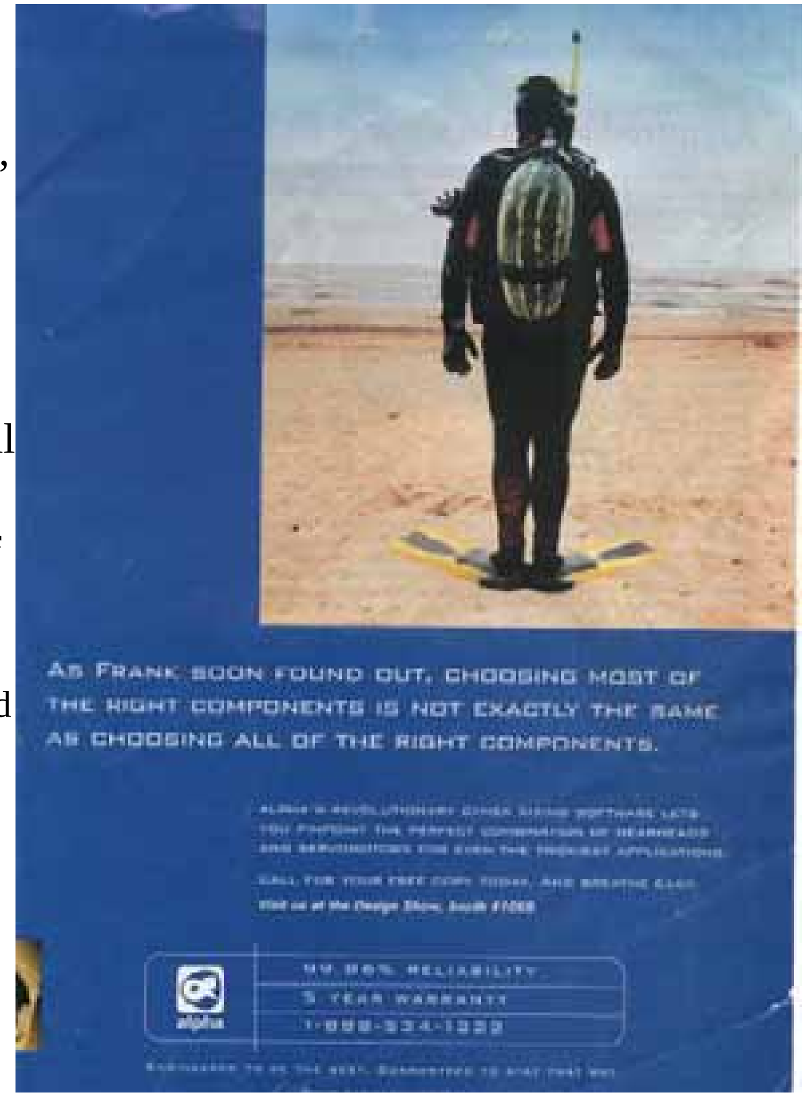
Sixth Step: Developing ***Components***

- ***Modules*** are made from ***components***, ***sub-assemblies*** or ***machine elements***:





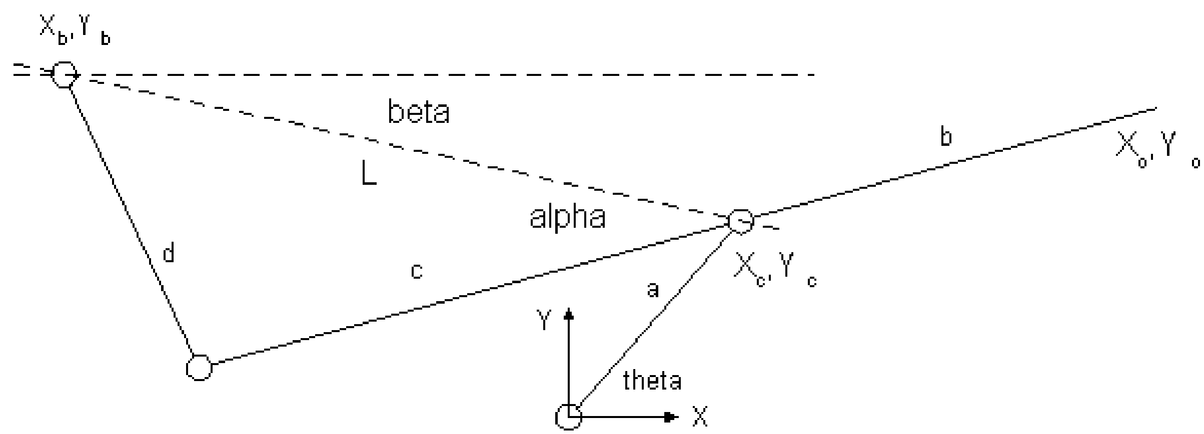
  - Words to describe what the ***component*** must do, and how it will work
    - Ideally in simple tabular form, like a FRDPARRC Table
  - Drawings
    - Initially a simple hand-drawn isometric will suffice
      - There may be many different ways of designing the ***component***
        - » The process 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:

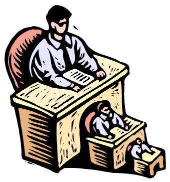
Components for the Reciprocating Paddle Module

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?…

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!*