Precision Product Design

Topic 1

Deterministic design process for precision products

"Rules" for each day of the week

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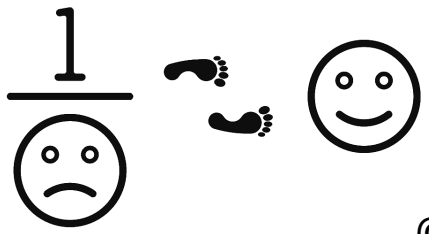

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Progression

Deterministic Design can be a common thread

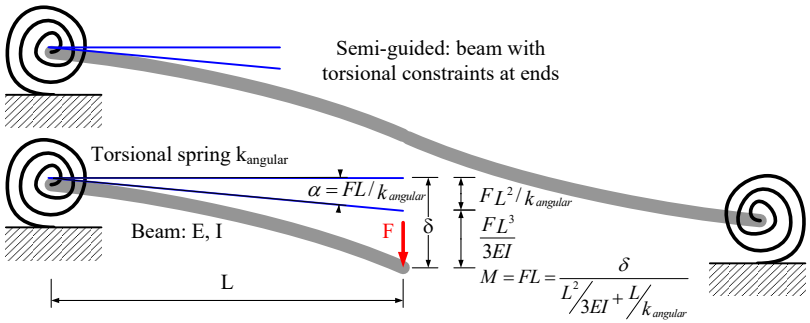
- SB: learn how you learn
- SM: learn to solve real problems
- PhD: learn to define problems
  - Qualifying exams: learn to think fast on feet
- Assistant Prof: learn to define an area of study
- Tenured professor: Learn how to start over :-)

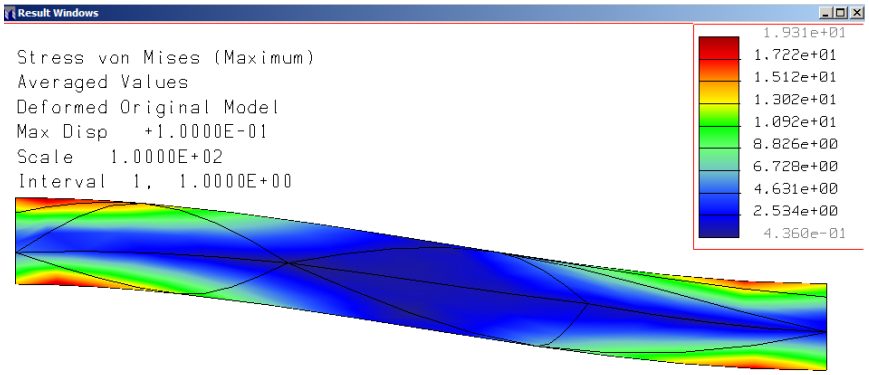
This class will help you learn to design machines ***right*** from the start ☺

- Like life being a bowl of cherries,
  - A machine is like a bowl of springs
    - Beware of misalignments (the pits!)

MOST overlooked thing in design: Everything has finite stiffness

- When a part wants to tilt, it has to deform the bearing & mount
  - They find an equilibrium position where each is feeling the same forces & moments
  - This adds loads to the bearings and structure and reduces life…





F=kx
(all the time and everywhere!)

- What's the equilibrium
  when you connect the springs?

Precision Product Design (*aka Deterministic Design*) Roadmap

Determine Functional Requirements

- Interfaces
- Loads
- Power flows (I/O)

Error Apportionment

Axis_error_apportionment_estimator

Develop Design

Stick Figures to describe strategies and concepts

Identify Structural Loops

Appropriate Analysis of elements

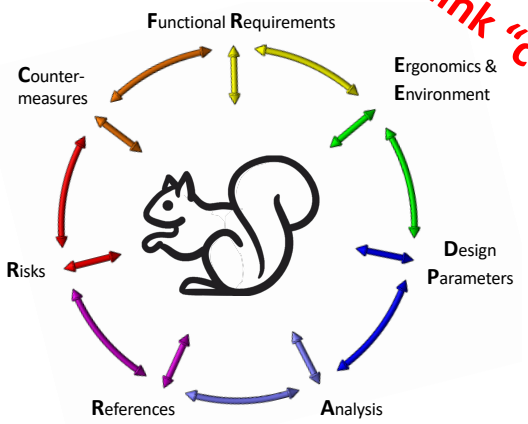
Error Analysis

Error_Budget_ Spreadsheet

Detailed design

Update & New Analysis

Intelligent design/testing of modules and lots of peer review
At each step of the way, think "coarse-to-fine" and FRDPARRC

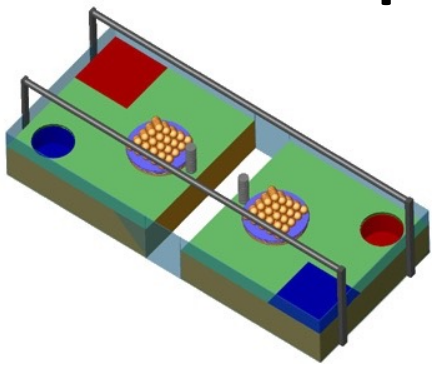


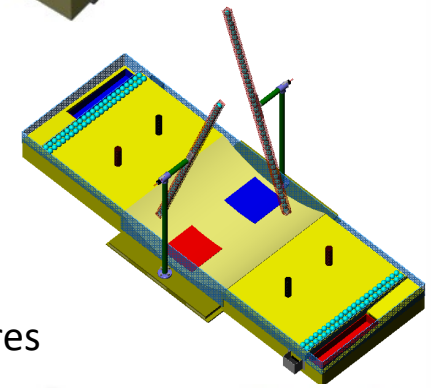
Rule 1: Nature Doesn't Give A Sh!T

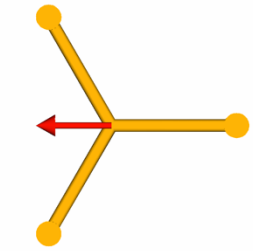
*so learn the **FUN**da**MENTAL* Principles (FPs)

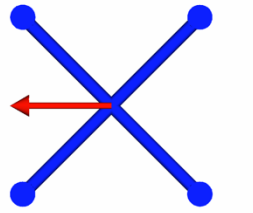
Some FPs

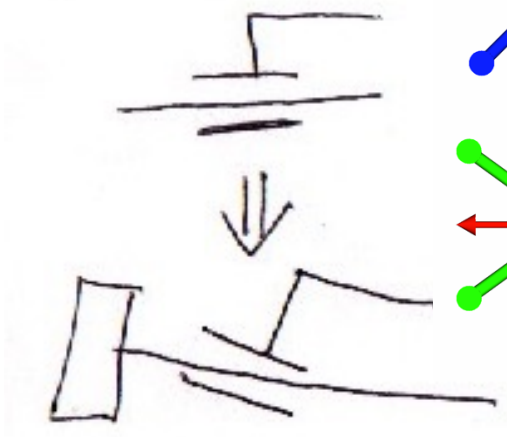
- Occam's Razor
- Newton's Laws
- Conservation of Energy
- Saint-Venant's Principle
- Golden Rectangle
- Abbe's Principle
- Maxwell & Reciprocity
- Self-Principles
- Stability
- Symmetry
- Parallel Axis Theorem
- Accuracy, Repeatability, Resolution
- Sensitive Directions & Reference Features
- Structural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

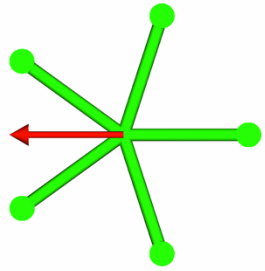


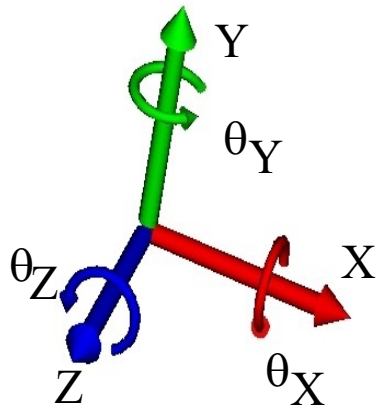












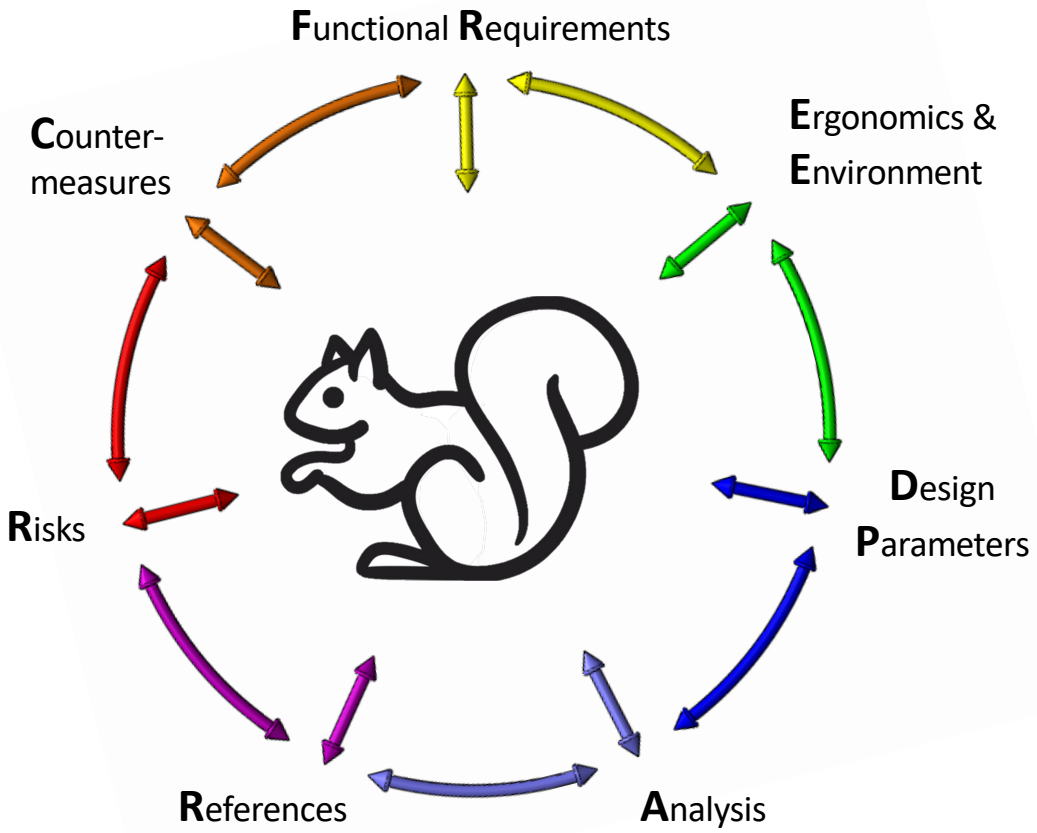
Rule 2: Apply FPs with Deterministic Design Circle:

MANY designers are ADHD & CDO…

Design circle helps organize thoughts as you think about…

Seven primary colors of the Rainbow

Seven factors designers should know



Fear Not your Inner Shiny Squirrel Hunter

(Make sure to wear your CDO armor)

Creatabelitivity
Alex Slocum
2020.12.20

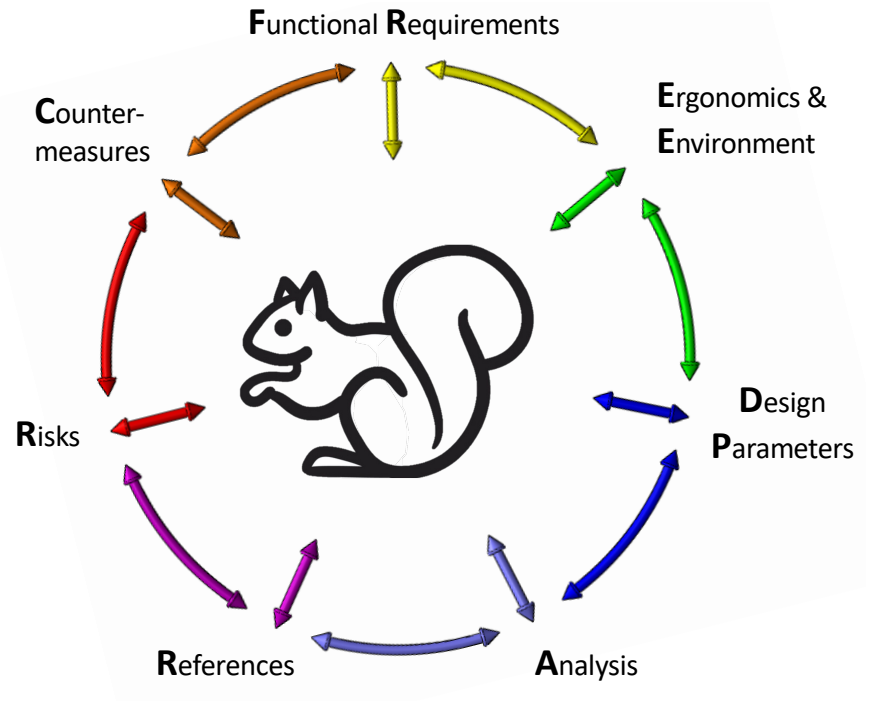
Many a process for "creative" design
And for everyone there is one that's fine
Beware rigid structure some would impose
Real creative people will run away from those

Many creative people are ADHD
LOOK, A SHINY QUIRREL THAT'S FREE
And many are Compulsive Disorder Obsessive
Worry not about these labels that are repressive

With life's pressures and expectations to fill
It's so easy to seek that magic fix and cure all pill
Healthy diet and exercise a mind needs for support
Physician prescribed medication one can later resort

Every person's mind is a blessing
And with it no one else should be messin'
It matters not the order in which design is done
Catalyzed by creative passion, just do it all and have fun

Functional **R**equirements and **D**esign **P**arameters we must meet
Ergonomics, **E**nvironment, **A**nalysis and **R**eferences make them sweet
And for every **R**isk there is a **C**ountermeasure to make sure all are fine
Please make sure all seven are addressed for *Precision Product Design!*



Paula do Vale Pereira who in 2.70 2020 suggested add a squirrel to the core of the circle of design

Deterministic Design FREEDPARRC

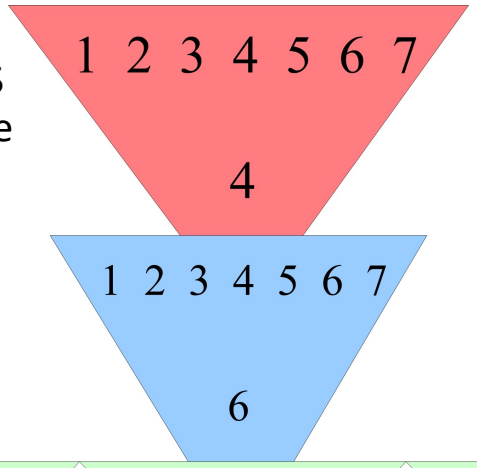
- Create a table of FUNCTIONS that need to be accomplished
  - It can include specifications, but generally words preferred
  - List just the major ones to start…
    - Do not fret over discovering everyone to start
    - The table can be appended (peeling the onion)
  - Its important to use the table as a catalyst to get moving!
    - Ideas will catalyze more ideas and table amendments…
    - List approaches that come to mind as you begin to fill out the table…

Strategy	**FR** Functional requirements	**DP** Design Parameters	**E&E** Ergonomics & Environment	**A** Analysis	**R** References	**R** Risks	**C** Counter-measures

Deterministic Design: *Coarse-to-Fine:*

Strategies *Concepts* *Modules* *Components*

- *Deterministic Design:* Everything happens for a reason
- *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

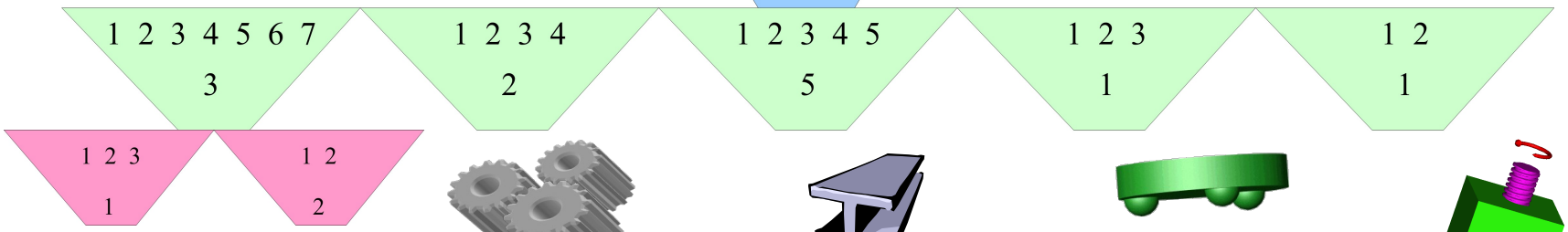


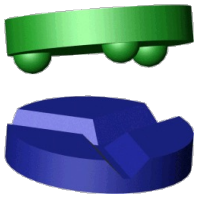
Strategy: Overall approach to accomplish the goal

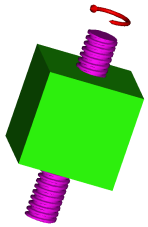
Concept: Design to implement the strategy

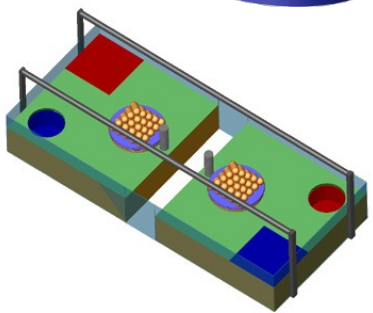
Module: A major part of the design that executes a certain function

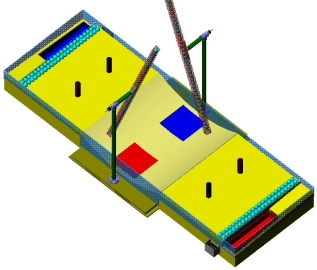
Component: An individual element











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

Compare to “Six Sigma”

- Process to help evaluate efficiency and assess complex systems
  - Goal is 99.99966% of end products perform within required tolerance limits
- 6σ involves *five* stages (DMAIC) for continuous improvement
  - Define (Problem definition)
  - Measure (Quantify)
  - Analyze (Root cause analysis)
  - Improve (Implement)
  - Control (Process control)
- More detail:
  - https://mantec.org/six-sigma-benefit-manufacturers/#:~:text=The%20Six%20Sigma%20Methodology%20comprises,it%20ideates%20new%20process%20solutions.

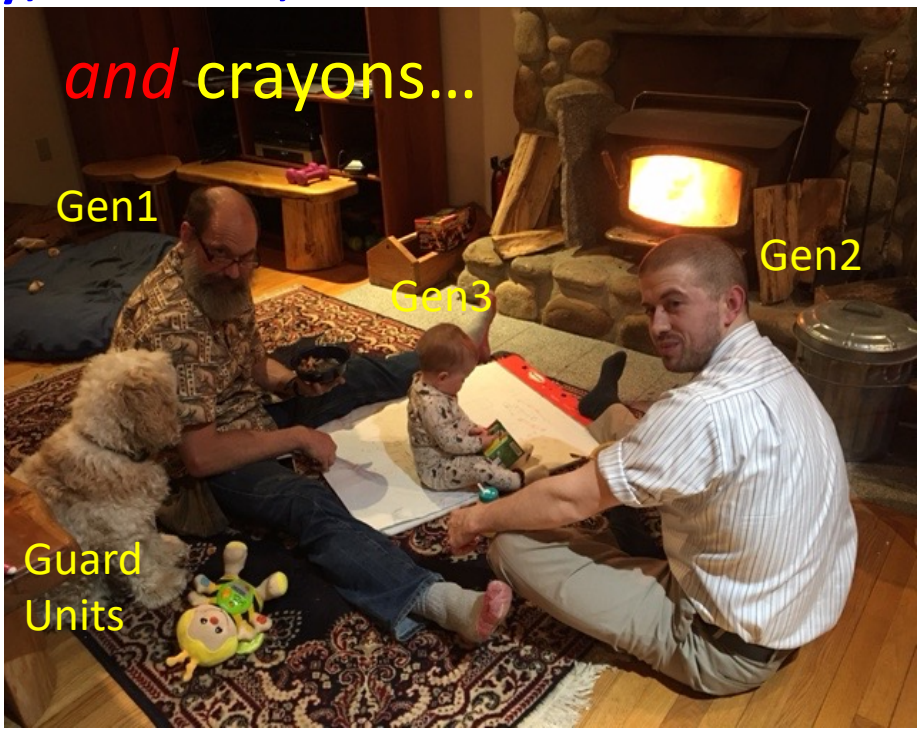
Rule 3: Teamwork!

- Aesop's Fables: *The Bundle of Sticks*
- Teams are critical!
- Individuals are critical!
- Solve Challenges with PREP process
  - Individuals then think and write/sketch ideas in notebooks
    - Including apply PREP to identifying problem to be solved!
  - Notebooks traded and everyone reviews each others work and writes constructive comments…
  - THEN brainstorm!

Exercise: Use PREP to develop what the Seven terms mean for your project

❤Passion❤ Rule 4a: Never Stop Being a Kid!

- YES you CAN have family, career, creative fun!



"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**

Rule 4b

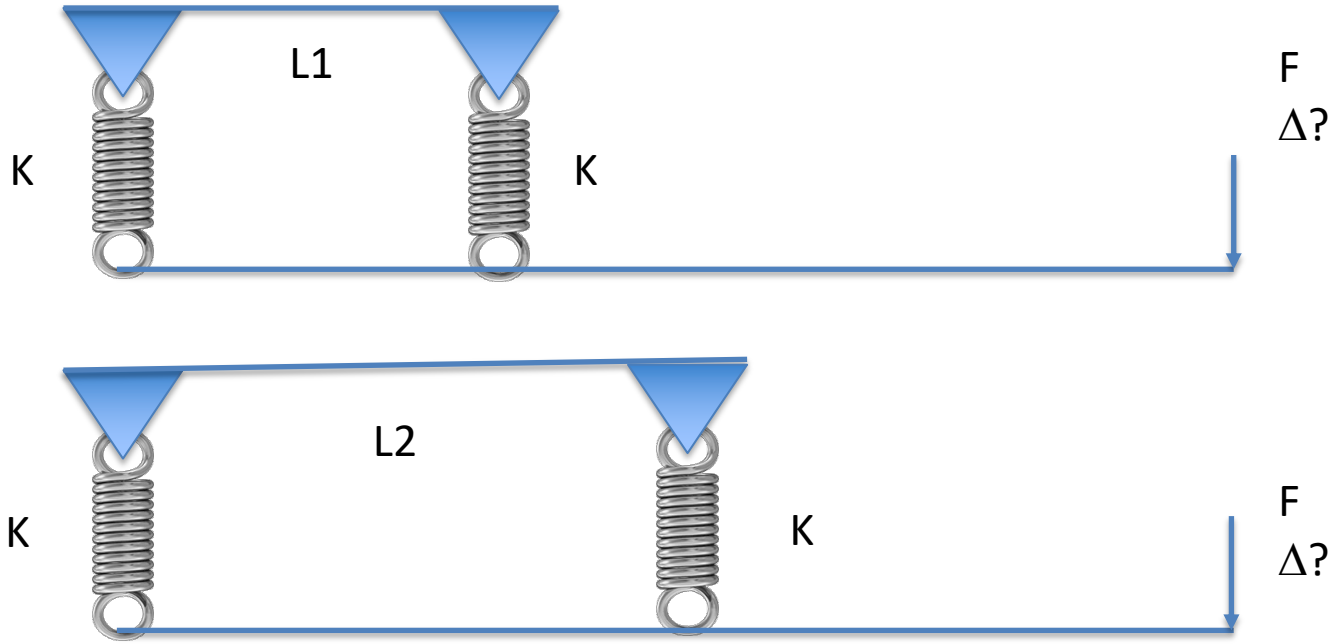
- Kids of all ages *exercise*….to stay healthy and smart!
  - Better blood flow to brain….
  - Do it with friends, family
  - Never too young
  - Never too old

Rule 5: Be Prepared….

- Maintain library of things, processes, analysis …
- Constantly cycle through what you see applying FREEDPARRC to assess it…
- Update library…
- Be ready to do quick analysis to check reality claims:
  - What happens to these springs when their ends are clipped together?
  - What are the forces on the mounts?
  - Anything else?

Now in 2D…

- What is the “tilt stiffness”?



Rule 6: In General, Never Generalize!

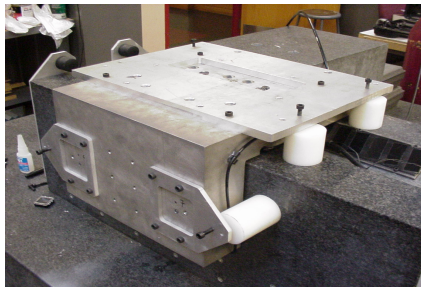
- Usually when you generalize, you are wrong…
  - To avoid falling into this trap, try to use what you know will not work, and learn from it…
- Again, apply FREEDPARRC to assess it…

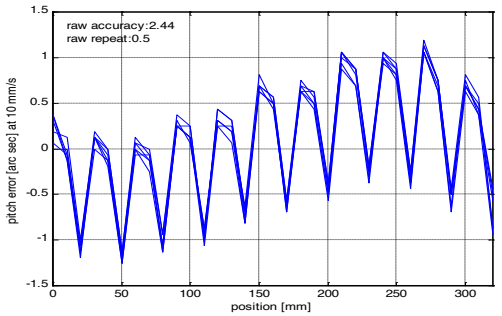
Rule 7:
Reciprocity rules!

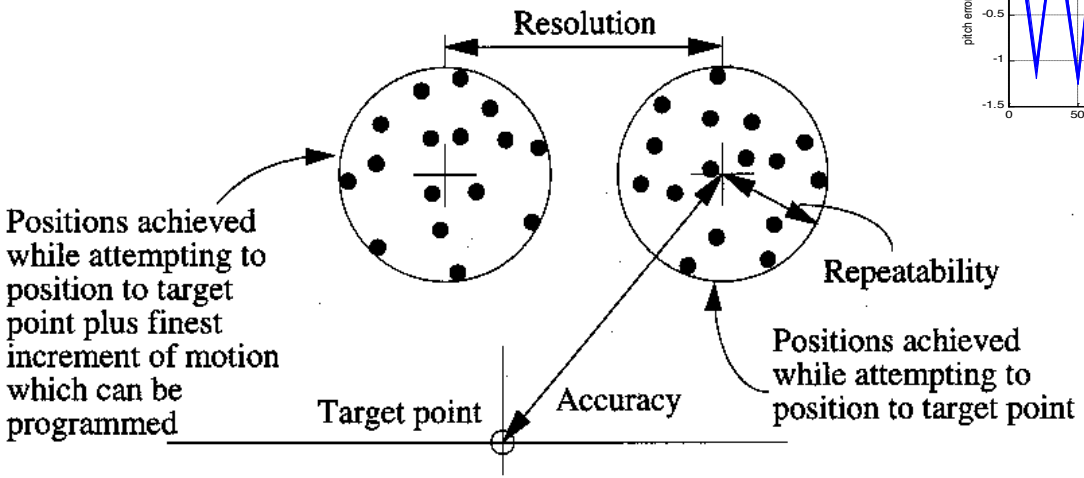
For each of the teams in this class, can the ”problems”… yield solutions for the others?

Errors: What are you trying to achieve?

- Anything you design and manufacture is made from parts
  - Parts must have the desired accuracy, and their manufacture has to be repeatable
- *Accuracy:* the ability to tell the truth
  - Can two machines make exactly the same part?
  - Are the parts the exact size shown on the drawing?
- *Repeatability:* the ability to tell the same story each time
  - Can the machine make the exact same motion each time?
  - Are the parts all the same size?
- *Resolution:* the detail to which you tell a story
  - How fine can you adjust a machine?
  - How small a feature can you make?
- How do these affect the design process?







Error types

- *Geometric errors* are errors in the shape of the parts from which the machine is made and inaccuracies in how they are put together, e.g., :
  - Systematic (squareness of axes) and random (bearings)
- *Thermal errors* are errors due to expansion of elements, e.g., :
  - The machine has an aluminum structure and steel bearing rails…
  - The machine is built in a controlled environment and used in an old building with no temperature control
- *Load induced errors* are deflections of the machine, e.g., :
  - Weight of a part, the machine's own weight as it moves, cutting forces…
- *Process errors* are errors in the process itself, such as sagging print material, or the kerf on a waterjet
- … (Others?)

Error Apportionment: A Precision Hunting License

- Before a designer starts sketching ideas, find the level of goodness required of each axis and the components
  - Saves a lot of time thinking about ideas that are not likely viable
- *Key Philosophy: IF then the "hardest" error can be accommodated, the rest are sure to follow…*

Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes. By Alex Slocum, last modified AHS 2014.04.09								
Enter numbers in **BOLD,** Results in **RED**								
Number of axes, N	**3**							
Total allowable error, dtot (microns)	**100**	what the customer wants from their machine						
				Apportion of error within each axis (amount allocated to each of X, Y, Z directions) to be determined by sensitive directions				
				Bearings (fb)	Structure (fs)	Actuator (fa)	Sensor (fs)	Cables (fc)
Source of error	Factor (f)	Apportion of error (dtot/f)	Apportion of error per axis	1	0.1	0.2	0.2	0

• • •

Example: Error Apportionment Spreadsheet

	A	B	C	D	E	F	G	H	I
1	**Axis_error_apportionment_estimator.xls**								
2	To apportion errors between types and axes. By Alex Slocum, last modified AHS 2014.04.09								
3	nter numbers in **BOLD,** Results in **RED**								
4	Number of axes, N	**3**							
5	Total allowable error, dtot (microns)	**100**	what the customer wants from their machine						
6					Apportion of error within each axis (amount allocated to each of X, Y, Z directions) to be determined by sensitive directions				
7					Bearings (fb)	Structure (fs)	Actuator (fa)	Sensor (fs)	Cables (fc)
8	Source of error	Factor (f)	Apportion of error (dtot/f)	Apportion of error per axis	1	0.3	0.2	0.2	0
9			*Based on linear sum of errors*						
10	Geometric, fg	1.00	40	13	8	2	2	2	0
11	Thermal, ft	1.00	40	13	8	2	2	2	0
12	Load-induced (deflection), fl	0.50	20	7	4	1	1	1	0
13	Process, fp	0.00	0	0	0	0	0	0	0
14			*Based on Root Square Sum of errors*						
15	Geometric, fg	1.00	67	38	36	11	7	7	0
16	Thermal, ft	1.00	67	38	36	11	7	7	0
17	Load-induced (deflection), fl	0.50	33	19	18	5	4	4	0
18	Process, fp	0.00	0	0	0	0	0	0	0
19			Average (expected case) of Sum and RSS						
20	Geometric, fg	1.00	53	26	22	7	4	4	0
21	Thermal, ft	1.00	53	26	22	7	4	4	0
22	Load-induced (deflection), fl	0.50	27	13	11	3	2	2	0
23	Process, fp	0.00	0	0	0	0	0	0	0

Apportionment

- Each axis has the major elements of bearings, structure, actuator (including the servo), sensors, and cables.
- The error allotted for an axis must now be divided up amongst these components
- The apportionment factor must be entered based on experience or an educated guess.
  - E.g., for most machines cables do not pull much and the axis is stiff so a small amount of error is allotted.
  - For a wafer stepper, it's a different story…

Apportionment

- in order to set the apportionment factor, for each error type the designer has to rely on experience
  - Or better, educated guess because design is iterative- (just trying to reduce iterations!).
- This factor can be from 0-1 or 0-10 or any range, just be consistent and the spreadsheet will normalize.
  - The factor is a measure of how difficult it will be for the designer to create a machine to not exceed allowable error of the type.
  - On a scale of zero to 1, a 1 means *this will be a challenging error so give me all I can have*.

Apportionment

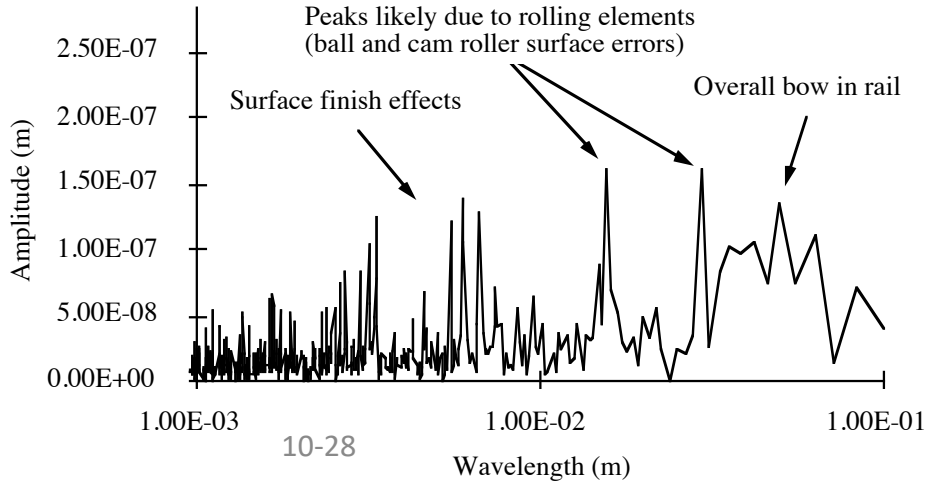
- The spreadsheet this calculates how much error of each type is allotted *per axis*.
  - Should axes far away from the tool point get more error?
    - Perhaps but then they also have more space for components…
    - The apportionment method can be customized by designers to suit their needs and style…
- It does this based on linear sum of the errors, root square sum, and average of linear sum and root square sum.
- Rarely do all the errors all linearly sum to be as bad as possible (it perhaps depends how badly your design ancestors have sinned?).
  - Usually some are + and some – so some cancellation occurs.
  - Rarely are you so lucky that they combine as RSS.
  - Hence the expected value to design with is the average of the SUM and RSS.

Hunting License

- We now have an idea of the dimensional performance requirements for the primary elements in the system.
  - E.g., by the numbers, you can see what kind of bearings you are most likely to be able to use…
- Now create concepts with stick figures… sketches…. Quick estimates….
  - First order estimates (by hand or spreadsheet) determine if the most challenging axis can be designed using elements you would like to use…
    - E.g., determine if bearings you would like to use and structure sizing you are thinking of… are feasible
    - *Then the rest of the axes are likely achievable and so proceed with further development of the concept*

Example: Appropriate Elements

- The below also depends on loads and application… but as a starting illustration point:
  - Positioning Ability:
    - 100 microns: Sliding, rolling, flexure, fluid, air, magnetic (most anything)
    - 10 microns: Rolling, flexure, fluid, air, magnetic
    - 1 microns: Rolling (special) flexure, fluid, air, magnetic
    - 0.1 Microns: flexure, fluid, air, magnetic
  - Straightness of motion
    - 100 microns: Sliding, rolling, flexure, fluid, air, magnetic (most anything)
    - 10 microns: Sliding, Rolling, flexure, fluid, air, magnetic
    - 1 microns: Sliding, Rolling (special) flexure, fluid, air, magnetic
    - 0.1 Microns: Sliding, flexure, fluid, air, magnetic

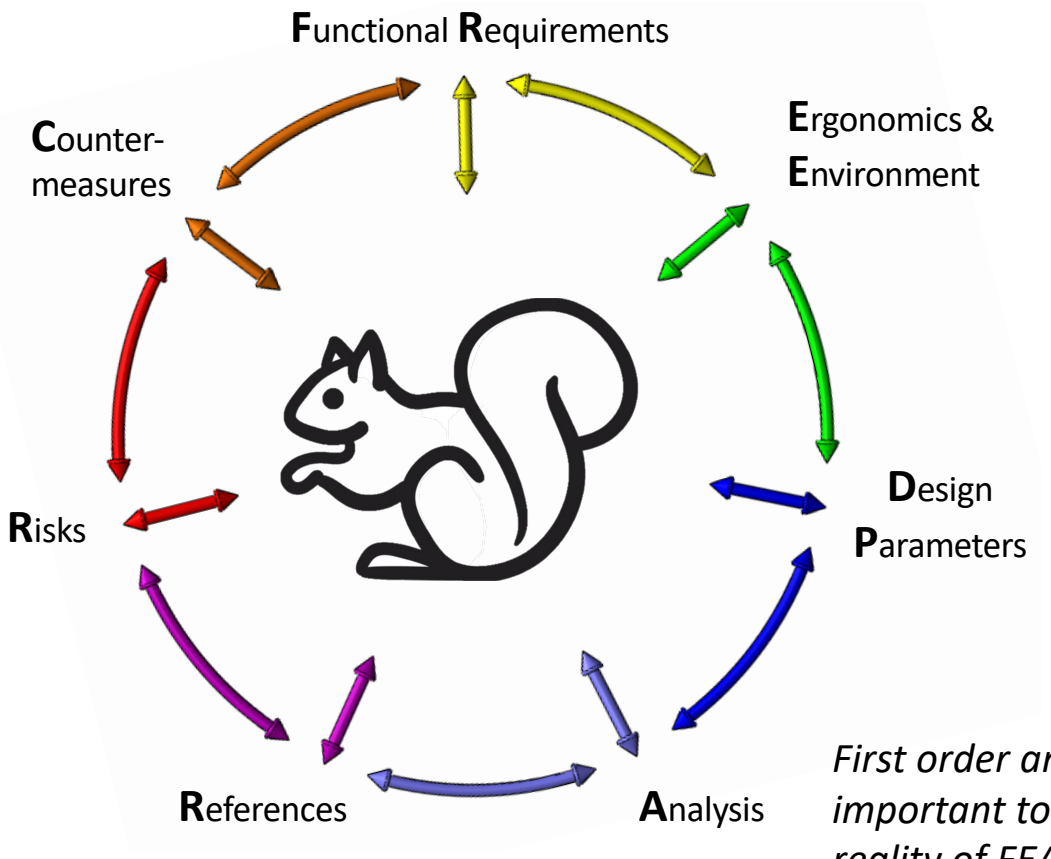


Next steps…

- Apportionment-based first order analysis allows you to start filling out some details for strategies/concepts…
  - Strategies/concept selection can be done rationally …
- Next details involve more refined error budgeting:
  - Assign coordinate systems and then to estimate the error motions in the elements and stiffness of connections.

Seven things to remember when hunting errors…

As you identify them as risks, what is the physics and what are the countermeasures?



First order analysis important to gauge reality of FEA!

Note on RMS v RSS

- The Root Mean Square (RMS) of a set of errors (deviations) from an average (mean) value of a set of values from a measurement for example is:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \delta_i}$$

  - RMS represents possible error in each of N measurements
  - It gives an estimate of how far each measurement is from the mean (average) of all the samples.
- The Root Square Sum (RSS) of a set of errors (uncertainties) is:

$$RSS = \sqrt{\sum_{i=1}^{n} \delta_i}$$

  - RSS is used for when you are combining sources of errors
  - The RSS does not include the term of dividing by the total number of errors combined.
  - The RSS is for uncorrelated errors, it does not take into account the sign of the error.
  - It is akin to how does one combine the X, Y, and Z errors to get the diagonal resultant.
- For error apportionment estimates at initial stage of design,
  - Sum of errors (assumes all are positive) is truly worst case (pessimistic)
  - RSS is best possible case (optimistic)
  - RMS would give very optimistic estimate (too much hope)
  - Expected value of average of Sum and RSS is realistic