Teach yourself simple techniques for designing and conducting experiments by doing the following:

1. Make the paper helicopters described in the drawings for one of the three enclosed paper helicopter experiments. Then run the experiment and analyze it using the enclosed square plot, interaction plot and analysis of means.

2. Develop two other factors to vary in the design of a paper helicopter, design a 2×2 experiment similar to the one you ran in Step 1 above. If the two factors both have a natural middle value, add a center point to your design. Make the corresponding helicopters, perform the experiment, and analyze the results as in Step 1.

3. Design and conduct a similar experiment with a hobby.

    Example: We have baked two different kinds of potatoes at the same time and compared the taste. This experiment has only one factor – the kind of potato, not two as with these paper helicopter experiment. However, a one-factor experiment is still quite useful. From our potato baking experiments, we found we couldn't taste the difference between different varieties of standard potatoes, but we could taste the difference between yams and sweet potatoes.

4. Try to apply the ideas at work.

5. If you have questions about experimentation, or comments regarding this kit, feel free to contact

Productive Systems Engineering, (408)294-5779, fax: (408)294-2343, 751 Emerson Ct., San José, CA 95126.

Suggested reference:

Ron Moen, Tom Nolan, and Lloyd Provost, *Improving Quality through Planned Experimentation* (NY: McGraw-Hill, 1991)

Example: Hellstrand described a simple experiment that produced substantial economic results for SKF Company. As indicated in the following diagram, eight different ball bearings were made, one for each combination of three factors at two levels each, and were run to failure under several times the maximum rated load. These combinations and the hours to failure are indicated in the following diagram.

The results jump off the page:

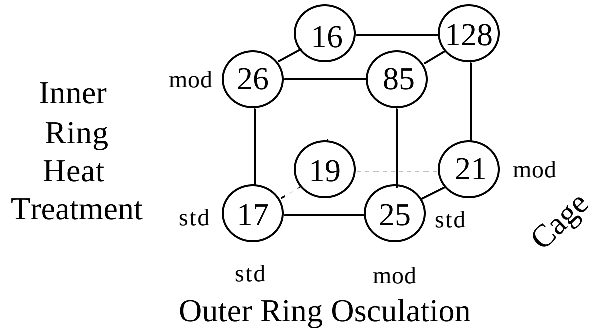
(1) A substantial increase in product life was achieved by combining the modified "inner ring heat treatment" with the modified "outer ring osculation."

(2) The difference between standard and modified cages was small or non-existent, at least in its impact on product life.

Both these effects are important: The first allowed SKF to produce higher quality ball bearings at lower cost; this not only affected the product under consideration, it exposed a previously unsuspected effect that opened up the possibility of similar improvements for a whole family of related products, thereby potentially contributing to the long-term competitive advantage of the organization.

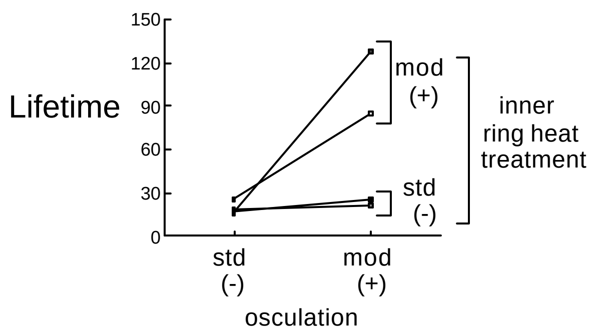
Another look at these results is provided in the accompanying "interaction plot," of lifetime vs. osculation, with two groups of lines, one group for each level of "inner ring heat treatment." When two factors combine to produce an effect that is different from the sum of the parts, it is called "interaction," and appears as lines that are not parallel in the interaction plot. Interactions are fairly common, and are a common reason for the failure of the "one-factor-at-a-time" approach to experimentation.

Some of the issues to be considered in experimentation are summarized in the "DoE (Design of Experiments) Planning Worksheet," provided on the following pages. This is followed by three simple experiments with paper helicopters that you can cut out, fold up, and run. The three do-it-yourself helicopter experiments are followed by a few further remarks on experimentation.



source: C. Hellstrand (1989), "The Necessity of Modern Quality Improvement and Some Experience with Its Implementation in the Manufacture of Roller Bearings," *Phil. Trans. of the Roy. Soc.*, **A 237**: 529-537

Figure 11.2 Interaction Plot for the Ball Bearing Experiment



source: S. Graves and T. Menten, (995) "Designing Experiments to Measure and Improve Reliability," ch. 11 in Ireson, Coombs and Moss (eds.) *Handbook of Reliability Engineering and Management* (NY: McGraw-Hill)

Enjoy these experiments, and open up a whole new approach to discovering interesting facts that can be economically very rewarding for you, your family and your organization(s).

DoE Planning Worksheet

date: __________

Experiment planned by: _________________________

phone: (____)____-______

Project / Business objective:

Background; why and how selected (Attach additional pages and/or cite other documents):

Technical goal of the experiment:
Narrative:

Categories:

To find something that works	____	Exploratory	____
To get something on target	____	or Confirmatory	____
To reduce variability	____		
To optimize a product or process	____		

Response variable(s), y:

Possible explanatory variables (factors), x:
(Mark "D"=design factors, "B"=blocking factors", "C"=measured covariates; all others may be considered in future experiments.)

Design factors for this experiment: *Other factors considered:*

Estimated budget	time	$
1. Experiment		
a. Initial set-up		____
b. Number of runs	____	
c. Cost per run	____	
d. Cost of runs (b*c)		____
e. subtotal (a+d)		
2. Clean-up and analysis		____
Total (1e+2)		____

Design factors	Low (-1)	center (0)	High (+1)	units	A priori guess of effect
1.					
2.					
3.					
4.					
5.					
Chunk-type factor a. b.					
Blocking variable(s)					
Covariates to be measured but not controlled					

Random variability

Between set-ups ______

Measurement error ______

total ______

Replication &

total number of runs ______

Method of randomization ______

Note: Is this an exploratory analysis in which the number of runs exceeds 8 or 16? If yes, have you considered either a smaller experiment or blocking this experiment so the first half can be analyzed as a complete experiment before the results of the second are available?

Experimental design selected:

Please attach a copy of the data collection form.

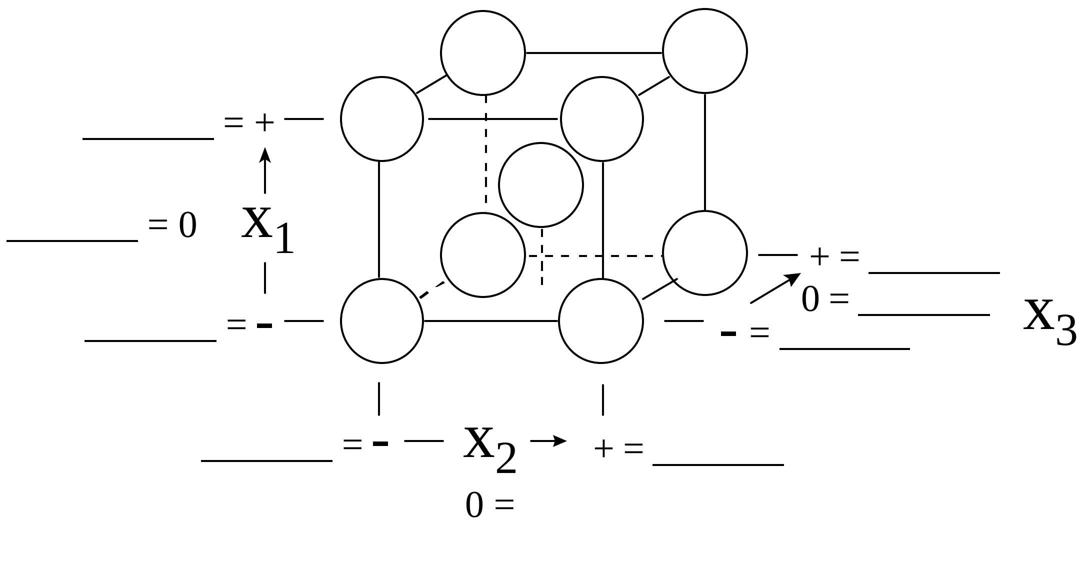
Planned method of statistical analysis

- Analysis of Means ____
- Control chart (against time) ____
- Yates algorithm ____
- Daniel (normal probability) plot of effects ____
- Effects / Interaction plots ____
- Square / Cube plots ____
- Regression analysis ____
- Other: ________________________________ ____

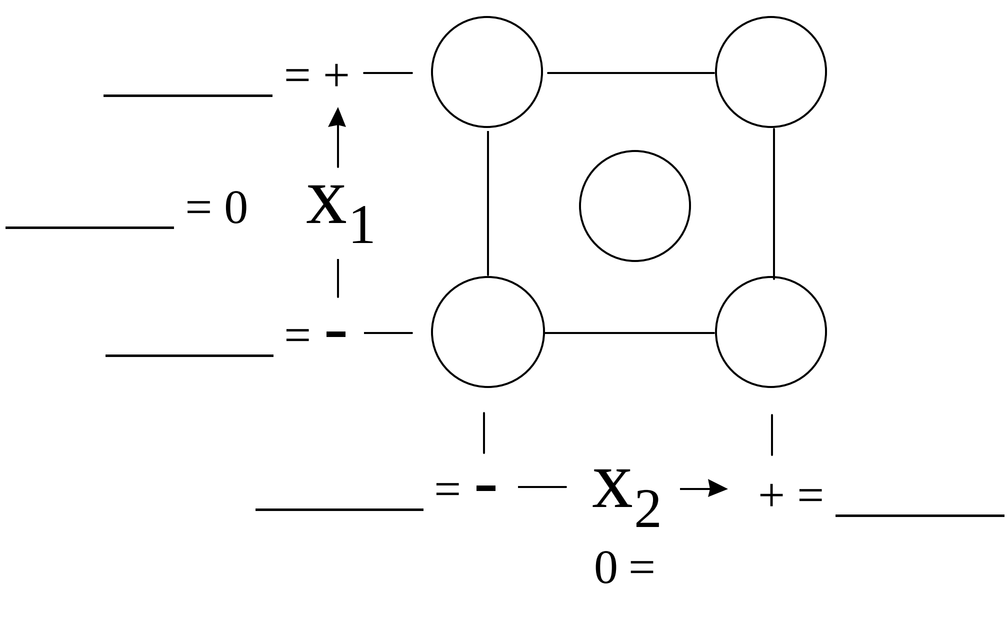
A single point can be added to a 2^3 to test for non-linearities.

This single point is called a “center point” (cp), and the resulting design is called “2^3+cp”.

If non-linearities are found, a 3-level design can be run to explore them further.

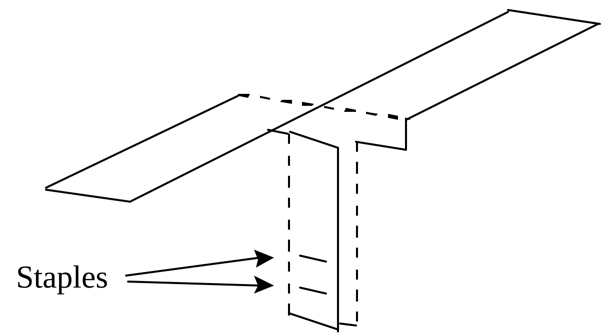


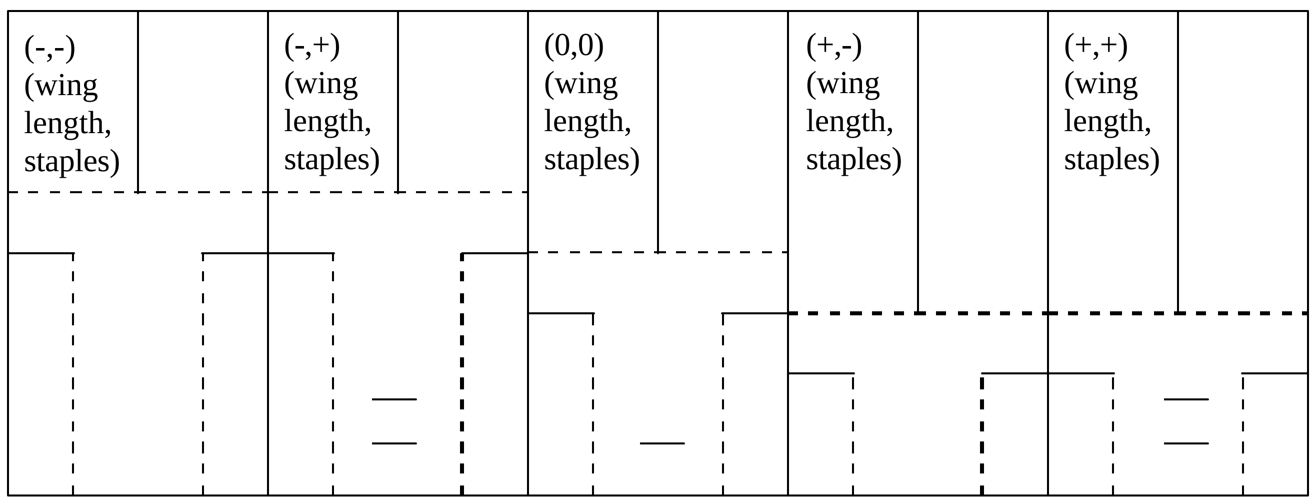
With only 2 factors, we get a 2x2+cp.



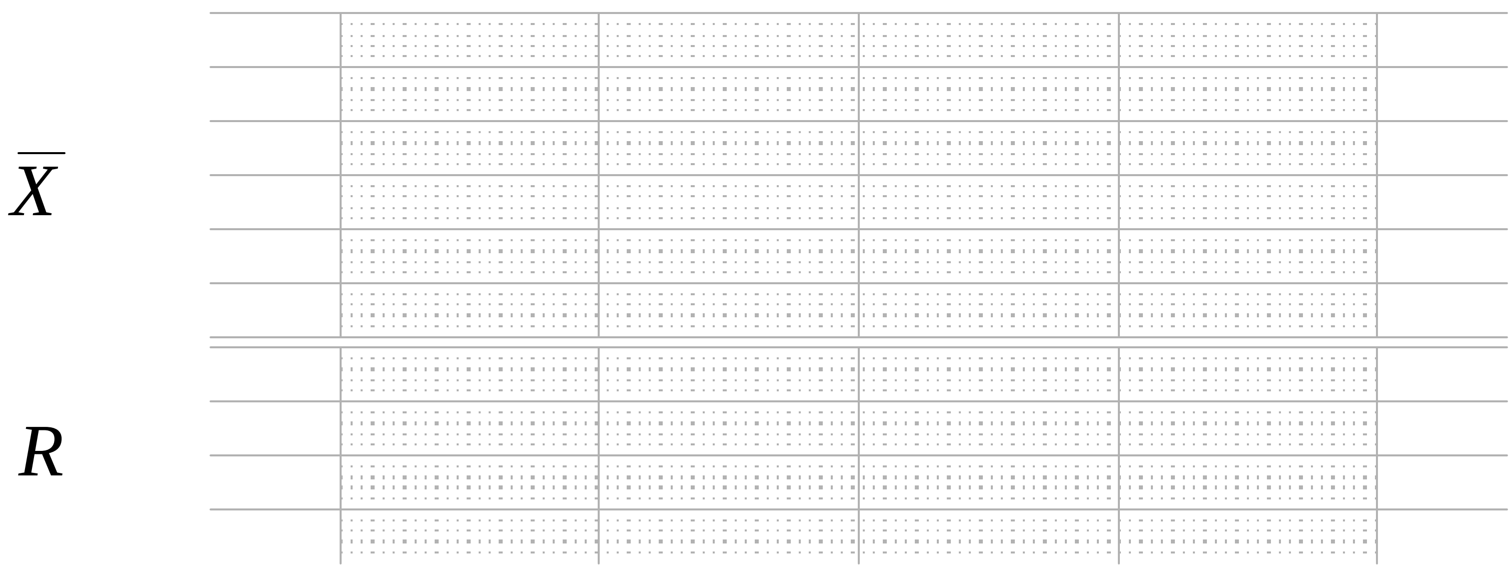
Experiment I

wing length (3/8, 4/8, 5/8 of total length)
by staples (0, 1, 2)

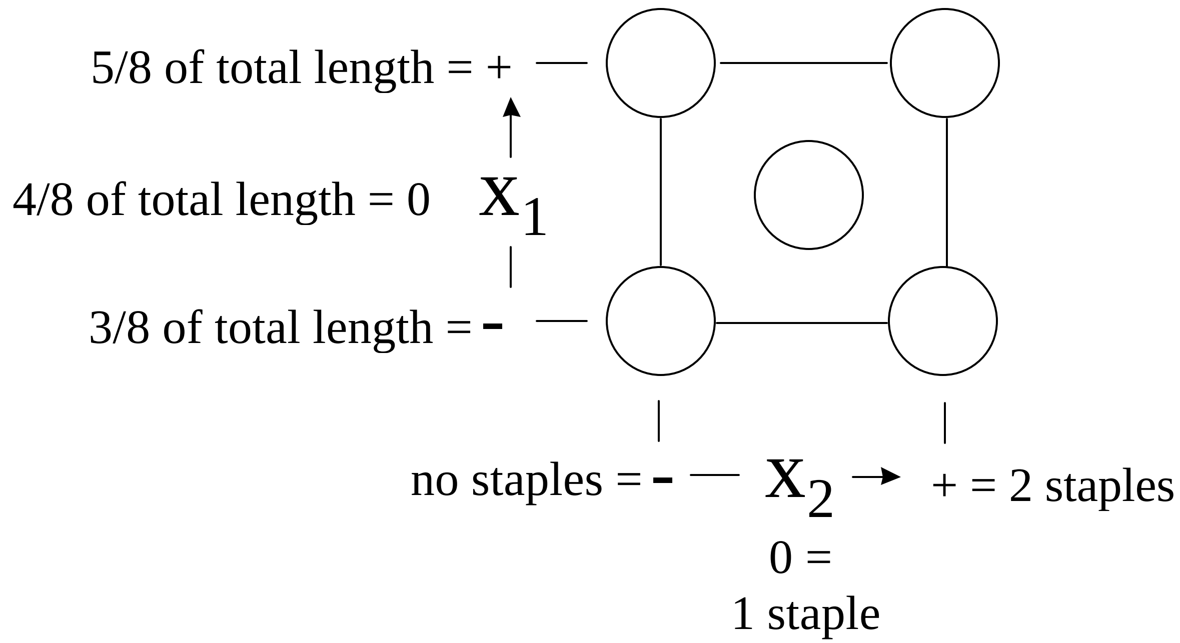




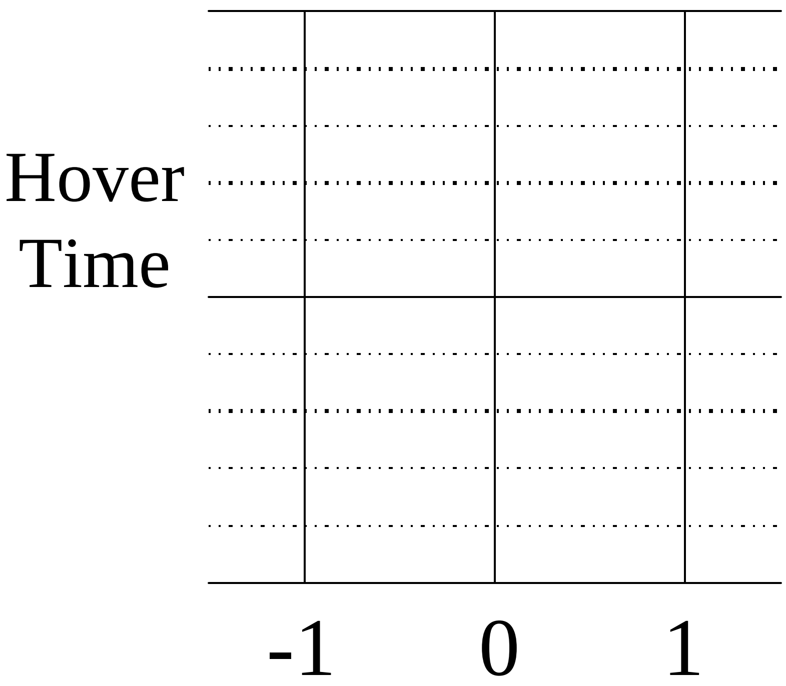
$X_1 =$		-	-	+	+	0
$X_2 =$		-	+	-	+	0
data	1					
	2					
	3					
	4					
	5					
sum						
average						
range						
notes						

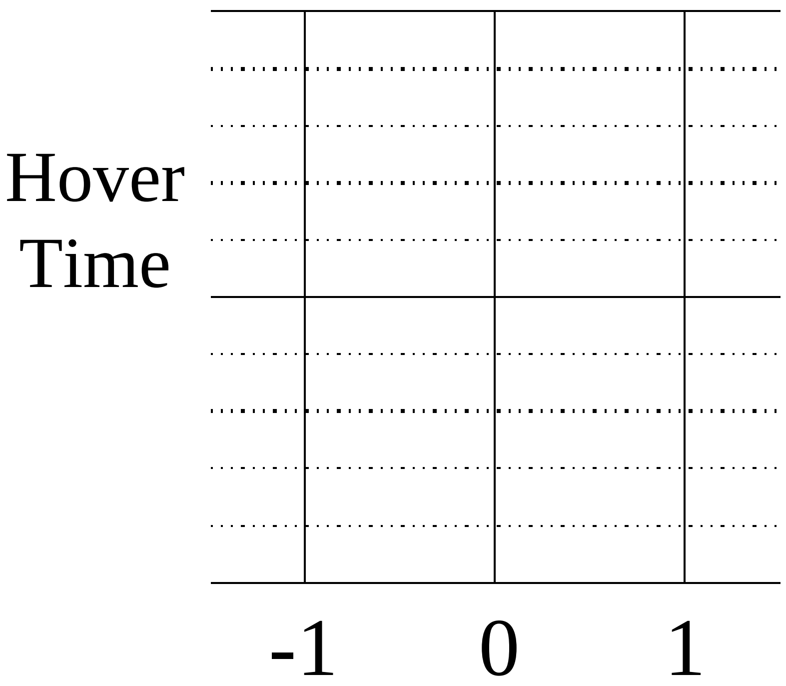


Wing length


5/8 of total length = +
4/8 of total length = 0
3/8 of total length = -
X_1
no staples = -
X_2
+ = 2 staples
0 =
1 staple

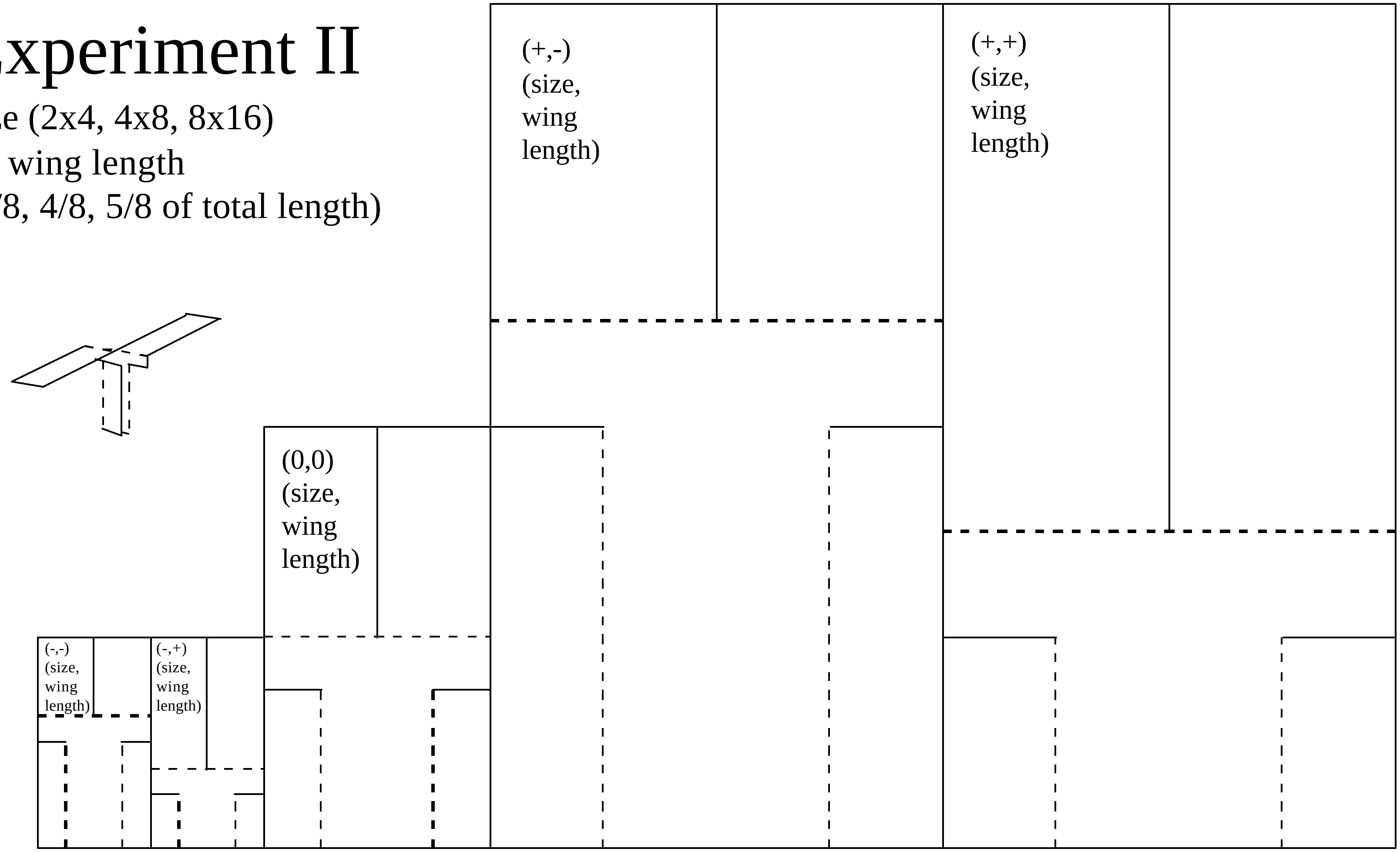
Interaction Plots





Experiment II

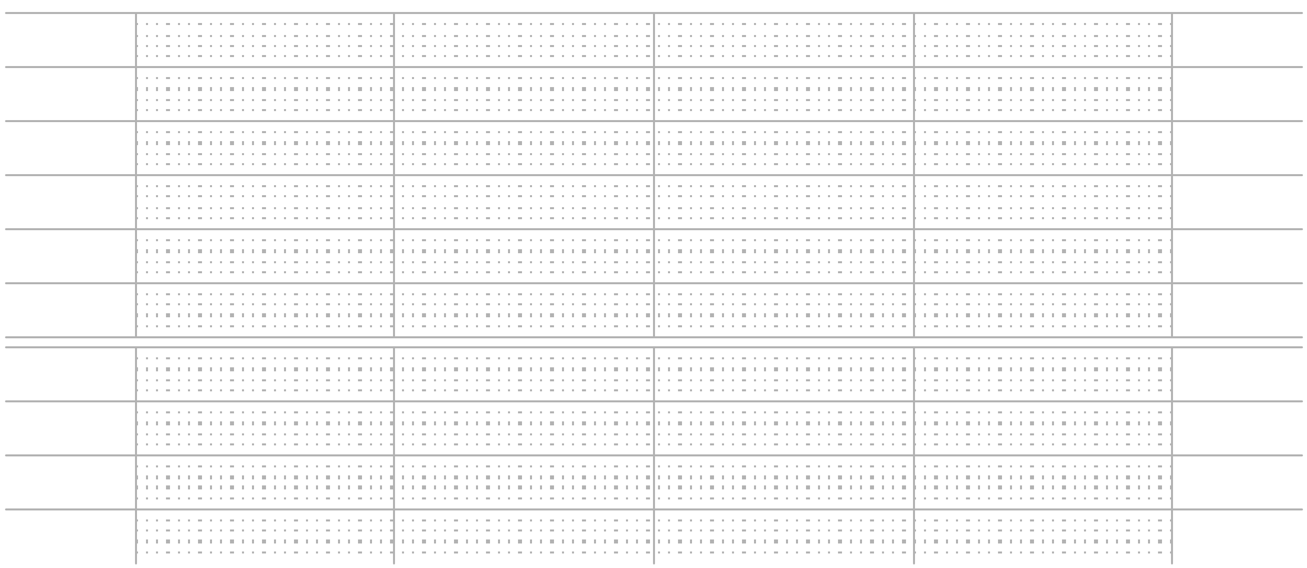
size (2x4, 4x8, 8x16)
by wing length
(3/8, 4/8, 5/8 of total length)

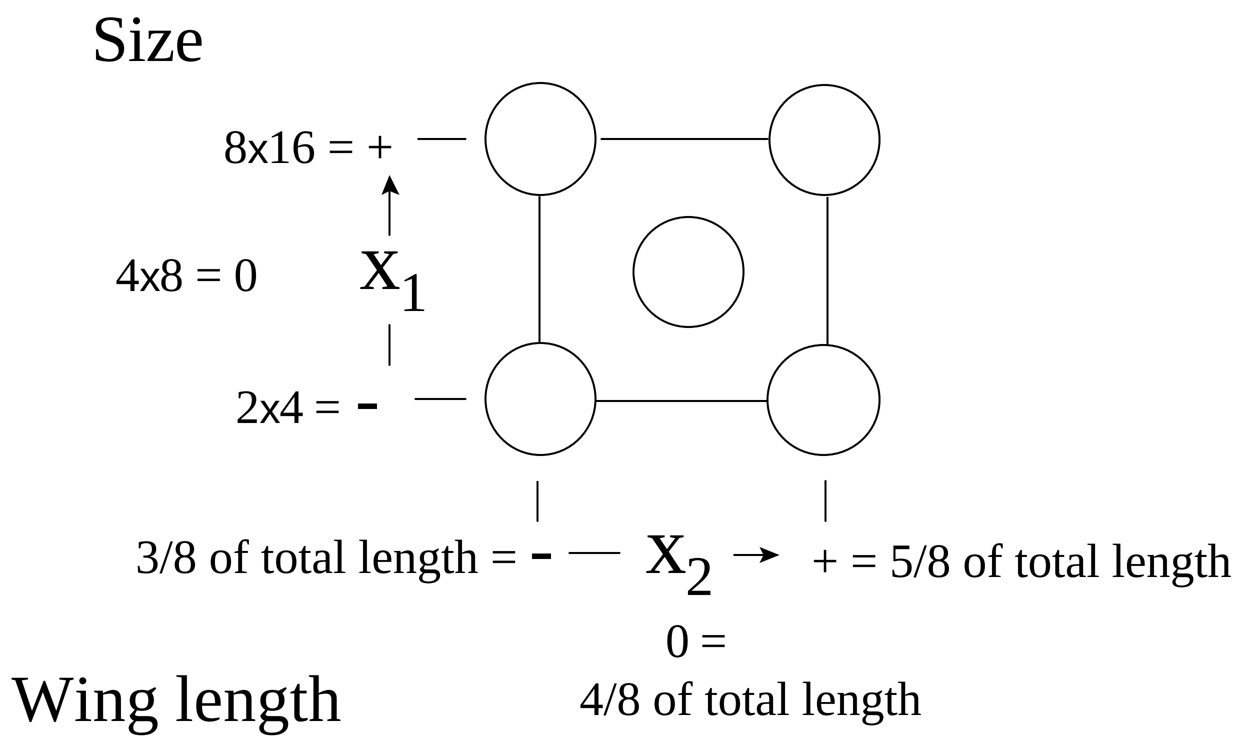


	$X_1 =$	-	-	+	+	0
	$X_2 =$	-	+	-	+	0
data	1					
	2					
	3					
	4					
	5					
sum						
average						
range						
notes						

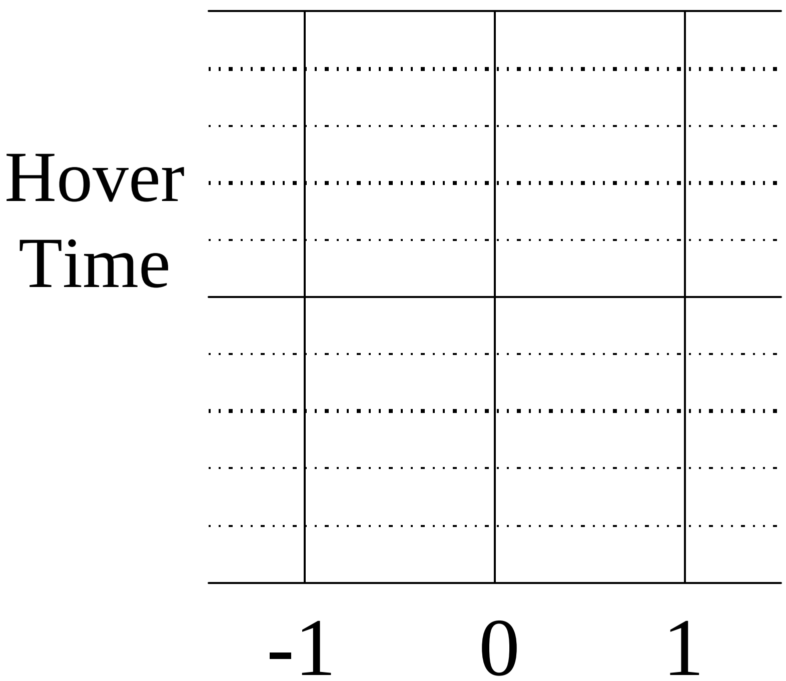
$\bar{X}$

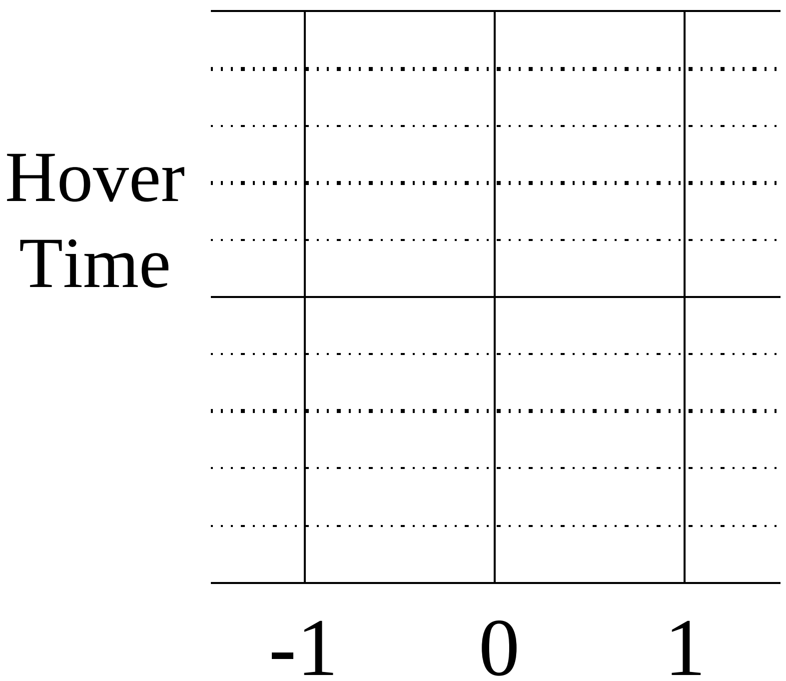
R




Size
8x16 = +
4x8 = 0
X_1
2x4 = -
3/8 of total length = -
X_2
+ = 5/8 of total length
0 =
4/8 of total length
Wing length

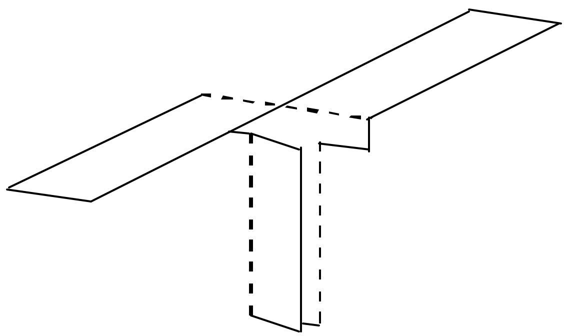
Interaction Plots

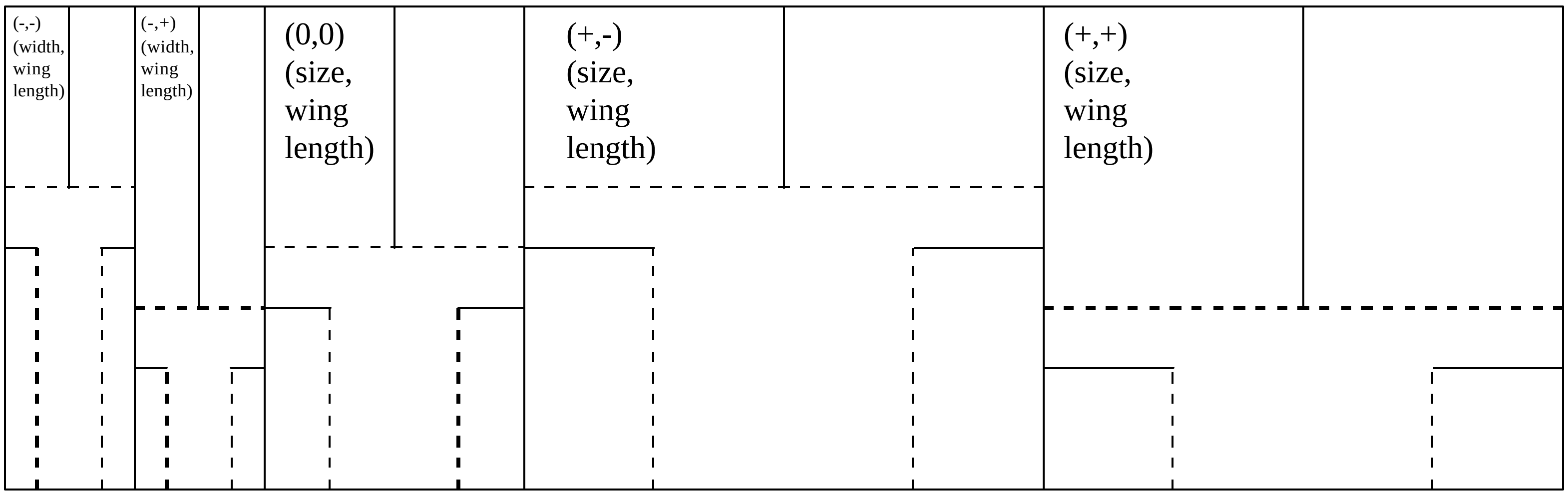




Experiment III

wing length (3/8, 4/8, 5/8 of total length)
by width (1/4, 1/2, 1 of total length)



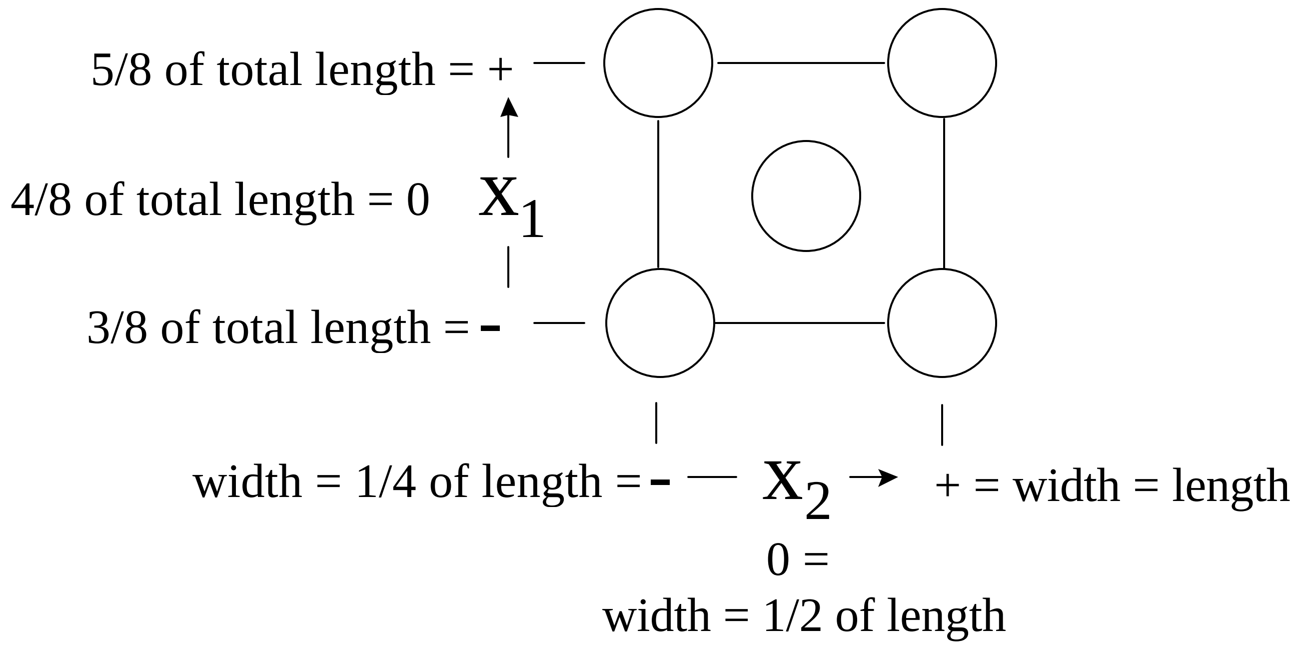


	$X_1 =$	-	-	+	+	0
	$X_2 =$	-	+	-	+	0
data	1					
	2					
	3					
	4					
	5					
sum						
average						
range						
notes						

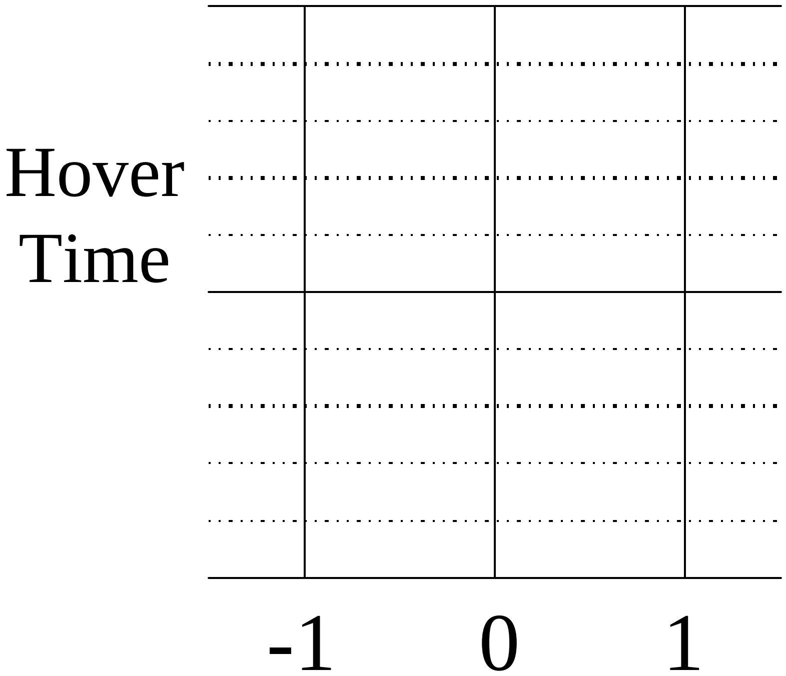
$\overline{X}$

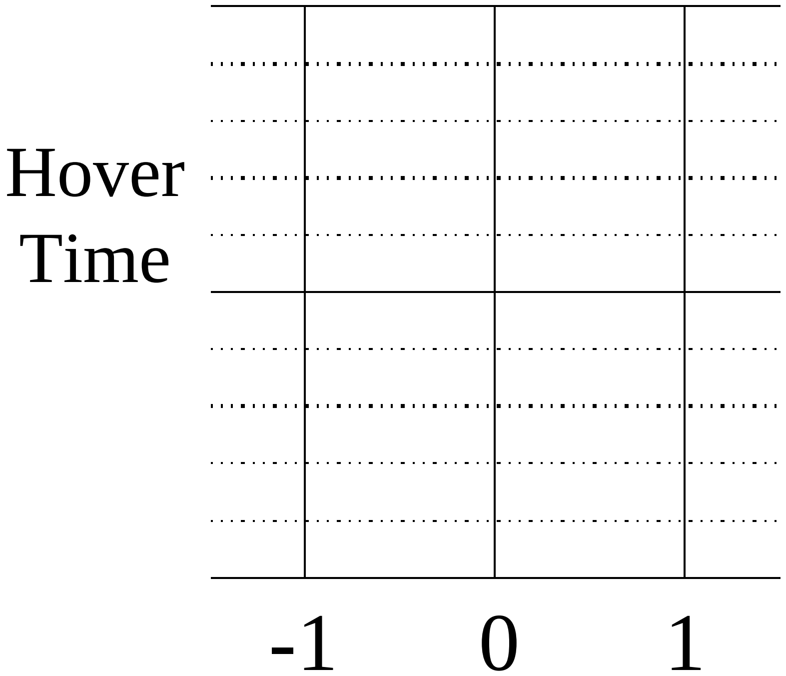
R

Wing length


5/8 of total length = +
4/8 of total length = 0
X_1
3/8 of total length = -
width = 1/4 of length = -
X_2
+ = width = length
0 =
width = 1/2 of length

Interaction Plots





Factor

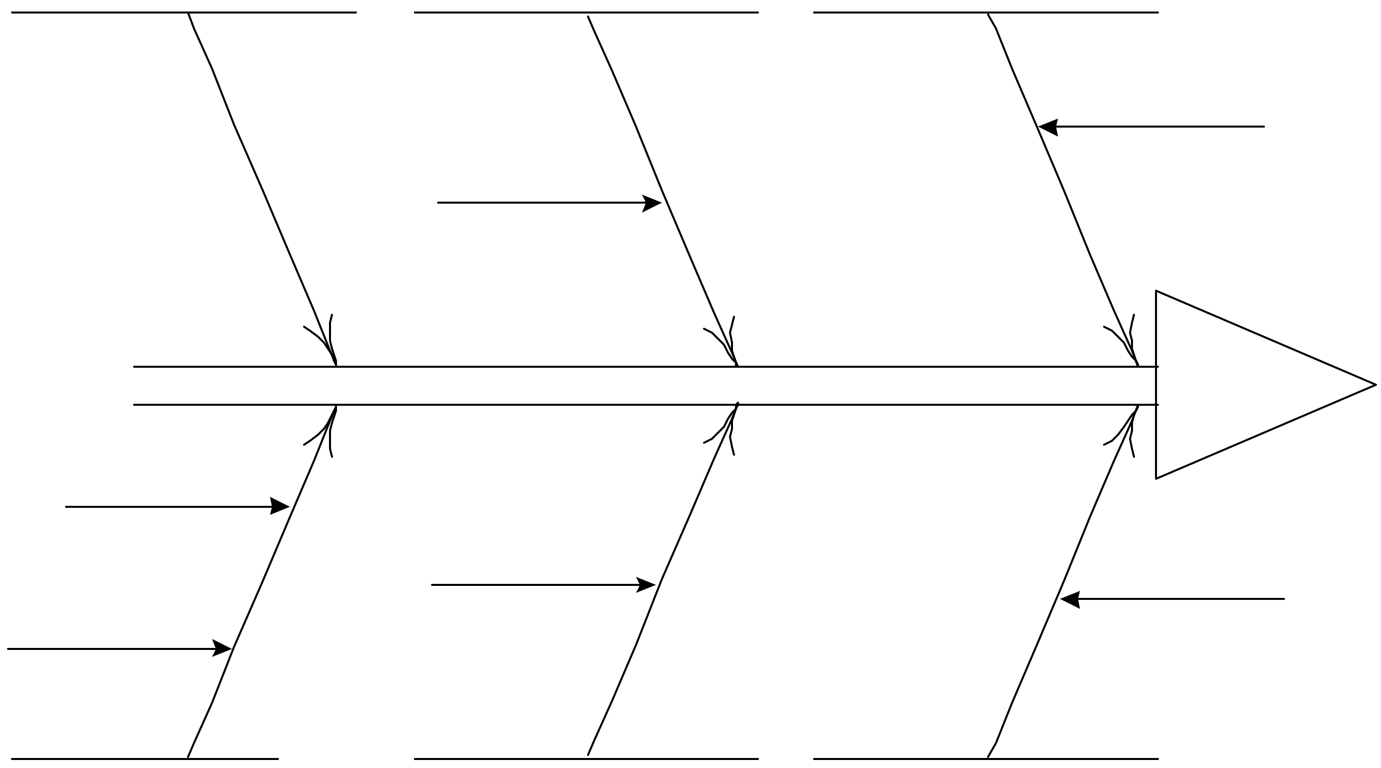
Definition: A variable to be *manipulated* in an experiment

Examples:

Qualitative:
- * Different vendors
  - - Gulf, Standard Oil brands of gasoline
- * Different colors
- * Different operators, shifts, machines
- * Different procedures

Quantitative:
- * Length, weight, temperature, pressure, percent concentration of a certain reagent
- * Table or file size in a computer set-up

Make a Cause-and-Effect Diagram of Hover Time



(*Memory Jogger*, pp. 24-29)

1. Brainstorm possible factors (e.g., with a cause-and-effect diagram)

   * Power of brainstorming:

   Dr. Noriaki Kano (Science University of Tokyo), a leading expert in quality and productivity improvement, asked:

   What is the biggest obstacle to improving quality and productivity?

   answer:

   Arrogance.

   i.e., the perception that we already know all that is worth knowing about a particular issue.

   It's not what I don't know that hurts me
   so much as what I do know that ain't so.

   * Brainstorming is:
      - Antidote for arrogance
      - Team building

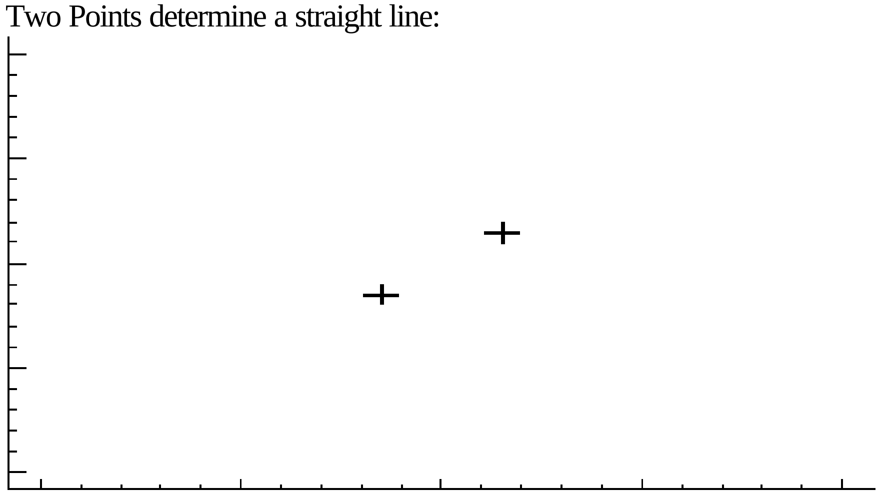
2. Pick the likely most important 2 or 3 factors.

3. Pick 2 levels for each factor (possibly with a center point)

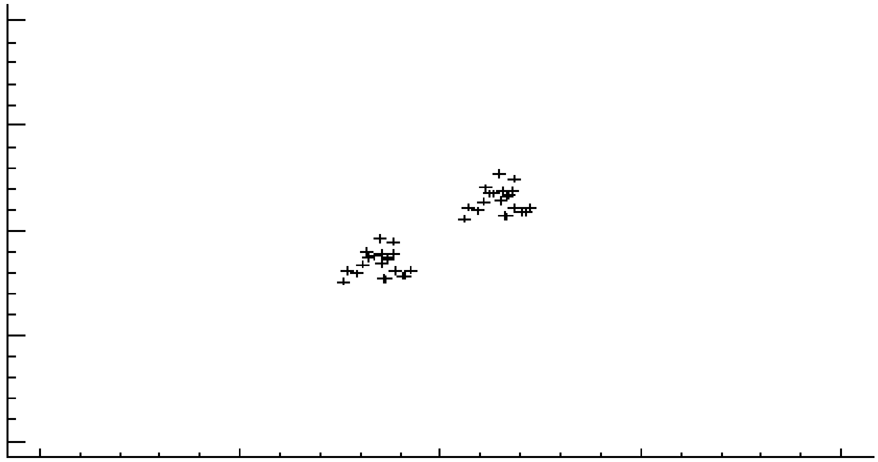
4. Label a square or a cube plot with the factors and levels.

Selecting Levels

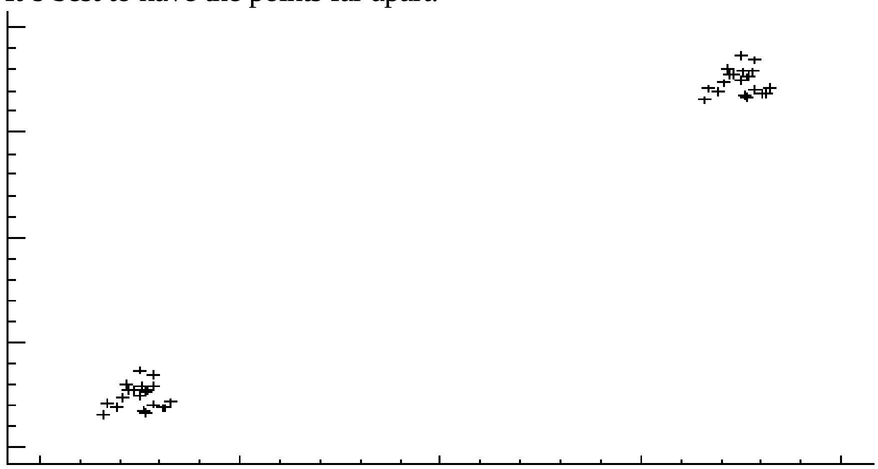
Two Points determine a straight line:



If the line is determined with “fuzz”:



It’s best to have the points far apart:



General Rule:

Experiment with two levels.

Exceptions:

1. Each experiment takes a long time, e.g., agricultural experiments where the natural cycle time is often six months or several years.

2. Nominal variables, e.g., different vendors, shifts, machines.

   a. With no information on which might be "best" and "worst," or
   b. After "best" and "worst" have been tested and have shown a difference, and you want to experiment with others.

3. The factor is likely to be highly non-linear
   ➔ Hedge with a center point.

4. To fit a specific non-linear model.

Be Bold:

Off-line quality control:

- Pick levels as far apart as feasible
- If you expect major non-linearities, add a center point; if you find non-linearities, then add points to estimate quadratic effects.

Keep it Simple:

Think in terms of a series of simple, quick experiments.

One can sometimes learn more from a more complicated experiment. However, especially with people who have not done many experiments, more complicated experiment are more likely to encounter problems in execution and are more likely to be killed by organizational politics and shifting priorities.