

Chapter 6 Project: A New Model for Earthquakes

Name _____

Name _____

1. Background:

Faults are approximately planar breaks in the Earth's crust and mantle. Crustal blocks moving quickly along a fault produce vibrations or waves, which radiate out in all directions away from the fault and fault blocks. What we experience in an earthquake is those vibrations along the surface of the earth. There are several non-traditional or new-wave explanations of fault behavior, all based on some form of randomness and unpredictability. This project focuses on one of these theories, known as **self-organized criticality**.

Faults are considered to be entities that have organized themselves into a critical state. Suppose a tiny amount of movement takes place along the fault. If the initial movement dies out, then a tiny earthquake is produced. If the initial movement propagates and grows and increases, a giant quake is produced. Despite many decades of scientific study trying to predict earthquakes, earthquakes have been found to be unpredictable; all predictors have failed to work. For more information about self-organized criticality in theory and in nature, read *How Nature Works* by Per Bak (New York: Springer-Verlag, 1996).

This project is designed to generate a population of artificial earthquakes, and to compare the model to real earthquakes. The earthquake generator is called a **cellular automaton**, but we prefer the name **bingo box**. The bingo box generates "bingoquakes."

2. Pre-project preparation

Before you begin, make sure that your group has the following papers:

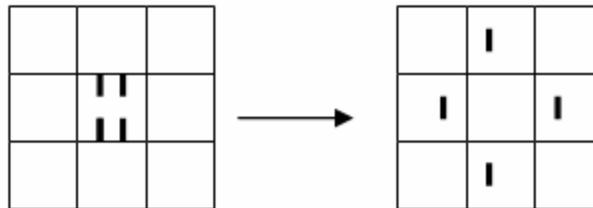
- "Bingo Box" ... 1 copy
- "Raw Data" ... 1 copy
- "Group Summary Data" ... 2 copies
- "New Madrid scatterplot" ...2 copies

This project will make use of a **random number generator**. Consult your calculator manual and/or ask your instructor about generating random numbers. Alternatively, you can use two dice of different colors. In this project you will generate artificial earthquakes using a 5x5 grid of squares called the bingo box, the random number generator, a pencil and an eraser. The squares of the bingo box are labeled with integers 1 through 25. The random number will tell you which square to mark on the bingo box sheet. As you generate the bingoquakes, you will record bingoquake sizes on a separate sheet of paper titled Raw Data.

3. Procedure for Generating Bingoquakes

For this activity, you will need the Bingo Box and Raw Data sheets, and a random number generator. It is best to have 1 person run the random number generator and record on the Raw Data sheet, while the other person marks the Bingo Box.

1. Create a random number between 1 and 25.
2. With the soft pencil, put a tick mark in the corresponding square on the bingo box.
3. Repeat steps 1 and 2 above until one of your squares has 4 tick marks. This is the start of a bingoquake.
4. Erase the 4 ticks marks and put 1 tick mark in the square above, 1 in the square below, 1 in the square to the right, and 1 in the square to the left. If a tick mark lands outside of the bingo box, it just disappears.



5. If **another** square now has 4 tick marks (acquired from the erased square), erase that square and distribute the tick marks. Repeat until all the “4s” are used up (there are no more squares with 4 tick marks).
6. Keep track of how many squares you erase in one sequence (since you last generated a random number). The number of squares you erase in one sequence is the size of your bingoquake. If you erased 3 squares in a series, then your bingoquake is size 3.
7. Record the size of your bingoquakes on the Raw Data sheet **as you create them**: your first bingoquake, your second bingoquake, your third, and so on. Stop when you have created 50 bingoquakes, UNLESS your last bingoquake was one of your top 3 bingoquakes in size. If so, create another bingoquake; don’t end on a big one.
8. If a square acquires more than 4 tick marks, just erase 4, and leave the rest.

4. Compiling your data

After generating 50 bingoquakes and recording their sizes on the Raw Data sheet, you will need to complete the Group Summary Data sheet. In the frequency column, record the total number of bingoquakes that you generated of each size. In the reverse cumulative frequency column, record the total number of bingoquakes that were of that size or greater. *For example, the reverse cumulative frequency for size 12 bingoquakes is the total of all bingoquakes of size 12 and larger.*

Why compute reverse cumulative frequency, and not just use the actual frequency of each bingoquake? The cumulative frequency produces a nice decreasing sequence of numbers, and it smoothes out the frequency distribution. Also, the plain frequency data for some bingoquake sizes may have 0 (zero) events of that size. That would cause problems when taking logarithms of those numbers, because the log of 0 is not defined.

Submit 1 copy of the Group Summary Data sheet to your instructor and **keep 1 copy** for your group. Your instructor will total all of the reverse cumulative frequencies from the entire class, and return these data to you for use in Part II below. In the meantime, proceed with Part I.

PART I

5. The Bingo Box as a Critical System

One goal of the bingo box was to create a model system that showed **criticality**; a tiny "blip" would produce nothing, and the next identical blip would produce a giant event. Did the bingo box show critical behavior? How long (in terms of number of blips/random numbers) did it take for the bingo box to reach criticality?

6. Foreshocks

A foreshock is an earthquake that precedes another earthquake, and is generated by movement along the *same fault*. With real earthquakes, a foreshock can't be a small earthquake, because every earthquake is preceded by a small earthquake (usually very small). A foreshock has to be substantial in size.

a) With bingoquakes, let's make the rule that the foreshock has to be at least half as big as the main shock. Using this rule, determine if the largest bingoquakes had foreshocks. Find your 5 largest bingoquakes on the Raw Data sheet. What was the size of the bingoquake **immediately before** those bingoquakes? Fill in the table with this information.

size of largest bingoquake	size of quake just before large bingoquake

b) What percentage of the largest bingoquakes have foreshocks according to the "twice as big" rule? Show work.

c) You've analyzed your data for foreshocks, now let's apply that analysis. Suppose you have a bingoquake of size 3, you've recorded that bingoquake, and now you're ready to resume play. But before you resume play, you must answer the question: is that size 3 bingoquake a foreshock to a larger bingoquake, just another bingoquake, or is it the case that you can't tell in advance? Explain briefly.

7. Seismic Gaps

A seismic gap is a lack of any substantial earthquakes on a fault before a big earthquake on that fault. Seismic gaps, like foreshocks, are thought to be **precursors** to big earthquakes. The thinking is that, without any substantial earthquakes, stress continues to build until finally a big earthquake occurs. We can test this theory with the bingo box model.

a) Let's define a **bingogap** for our bingo box as *at least* three very small bingoquakes in a row (either size 1 or 2, in any order). Circle all the bingogaps on your Raw Data sheet. How many bingogaps do you have in your bingoquake catalog?

b) What is the size of the next bingoquake following a bingogap? Make a list below. Do bingogaps (as defined above) precede large bingoquakes? And therefore can bingogaps be used to **predict** large bingoquakes? Discuss your answer.

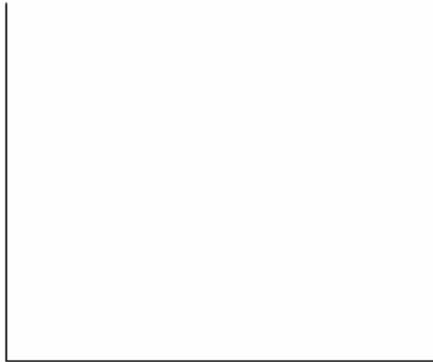
c) Geologists with the Bingoquake Bureau are saying that big bingoquakes should be *followed* by bingogaps! Explain why you would expect bingogaps *after* a big bingoquake.

PART II

Before beginning this section, obtain from your instructor the Class Summary Data sheet. Go to www.statcrunch.com and log in (if you have not previously logged in, you must register). Enter the size data into the first column (**var1**), and the reverse cumulative frequency data into the second column (**var2**). *Do not enter any data if the reverse cumulative frequencies are equal to zero. No 0's in var2!* Make sure there are the same number of rows of data. Re-label the two columns “size” and “RCF” by highlighting the column headers, backspacing, and then typing in the new labels.

8. Frequencies of Earthquakes

a) Create a scatterplot of the (size, reverse cumulative frequency) data. Select **Graphics > Scatter Plot**, select size for the **X Variable** and RCF for the **Y Variable** from the pull-down menus, and then go directly to **Create Graph!** Make a “thumbnail” sketch of the scatterplot below. Label axes.



Real faults show a **characteristic pattern** of the sizes of earthquakes. Along a fault, there are many small earthquakes, some medium sized earthquakes, and just a few large earthquakes. No matter which fault geologists look at on earth, they always see this same pattern of many small, some medium, and a few big earthquakes.

b) Inspect your scatterplot. Do bingquakes show the same characteristic pattern of frequency distribution as real earthquakes? Explain briefly.

c) Can you think of another natural phenomenon, or system with objects or things or events, that has many small events/things, some medium sized events/things, and a few large sized events/things? Please describe briefly. *Sorry, but you can't use auto accidents or other phenomena that were mentioned in the Chapter 6 Science in Depth article.*

9. Power Law Regression

a) To determine the best fit power law regression, we must (1) transform the data by logging, (2) find the best fit linear regression through the transformed data, and (3) calculate the best fit power law regression using a small bit of algebra.

(1). Under **Data > Transform data**, type in **log10 (size)** and then press **Transform**. Be sure to use log10 in this calculation. Logarithms of the sizes are stored in a new column. Repeat for reverse cumulative frequency.

(2). Under **Stat > Regression > Simple Linear**, choose log10(size) for the **X Variable** and log10(RCF) for the **Y Variable**. Go straight to **Calculate**. What is the equation of the linear regression? What is the correlation coefficient?

(3). Using the values for the slope and the y-intercept from the linear equation, calculate the best fit exponential equation through the un-transformed data. Show steps. What is the resulting equation?

b) How well do the original data fit a power law relationship? Explain.

10. Comparison to Computer Generated Results

The software program Maple® was programmed to run a 5 x 5 bingo box for 1 million iterations (hundreds of thousands of bingoquakes) to see what the frequency distribution of bingoquakes would look like for a very large set of data. Perhaps the small data set for the class (500-1000 bingoquakes) is not adequate. This simulation was

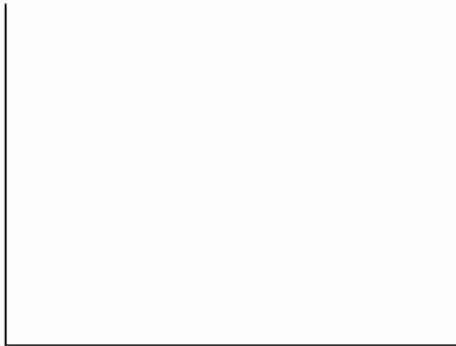
run 30 different times, to see whether the results are reproducible, and to see how much variation is obtained between simulations.

The best fitting power law relationship between size and reverse cumulative frequency for the Maple bingo box experiment has an average exponent of -3.22 . The exponent ranged from -3.42 to -3.05 . How do the Maple numbers compare with the class's bingo box result?

11. Comparison with Real Earthquake Data

The attached scatterplot shows annual data for earthquakes in the New Madrid seismic zone around Missouri for the period 1816-1983. The independent variable is the logarithm of size (also known as the magnitude), and the dependent variable is the logarithm of reverse cumulative frequency. In other words, the data are graphed with the x and y values pre-logged. To better understand this graph, return to the class bingoquake data stored in StatCrunch. What will the scatterplot of the logged data look like?

a) Using StatCrunch, make a scatterplot of the transformed data. Select **Graphics > Scatter Plot**, select $\log(\text{size})$ for the **X Variable** and $\log(\text{RCF})$ for the **Y Variable** from the pull-down menus, and then go directly to **Create Graph!** Make a thumbnail sketch below. Label axes.



We know that when $(\log(x), \log(y))$ data appear linear, then the original (x, y) data will have a power law shape. Do the $(\log(\text{size}), \log(\text{RCF}))$ data appear linear? Do the $(\text{size}, \text{reverse cumulative frequency})$ data have a power law shape? Discuss.

b) Now return to the attached scatterplot of the earthquake data from the New Madrid seismic zone. Recall that in the plot of New Madrid earthquakes, the x and y values have already been logged. Will the un-transformed New Madrid data (that is, size and reverse cumulative frequency) fit a power law model? Explain your answer briefly.

12. The Big One

a) The New Madrid scatterplot can be used to determine the frequency of occurrence of earthquakes of any severity. Let's start with a moderately small earthquake. From the graph read off the y value when the magnitude equals 3.0. *Estimate as closely as possible.*

$$\log(\text{reverse cumulative frequency}) = y = \underline{\hspace{2cm}}$$

To find the reverse cumulative frequency, simply take the y value and find 10 to that power:

$$\text{reverse cumulative frequency} = 10^y = \underline{\hspace{2cm}}$$

Your last answer is the approximate number of earthquakes per year of magnitude 3.0 or greater along the New Madrid fault zone.

b) Magnitude 8 earthquakes took place in the New Madrid area in the winter of 1811-1812. How often do quakes of that magnitude or greater occur? Repeat the calculations above to find the approximate number of earthquakes per year of magnitude 8.0 or greater along the New Madrid fault zone. *Hint: You will need to extend the regression line.*

c) Express the frequency of New Madrid quakes of magnitude 8.0 or higher in the form:

$$1 \text{ quake every } \underline{\hspace{2cm}} \text{ years.}$$