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 the **random number generator** on your calculator. Random number generators are not really random: straight out of the box, two calculators of the same make will usually produce identical "random" numbers. For your calculator to produce different random numbers than someone else's, you need to "seed" the random number generator with a unique initialization number. This is quite easy to do. On the Homescreen, type in any long number (use at least 10 digits), press the **STO→** key, select **MATH > PRB > 1:rand**, and then press **ENTER**. See below (but use your own number!).

```
2562895256→rand
        2562895256
```

In this project you will generate artificial earthquakes using a 5x5 grid of squares called the bingo box, the random number generator on your calculator, a pencil and an eraser. The squares of the bingo box are labeled with integers 1 through 25. As you generate the bingoquakes, you will record bingoquake sizes on a separate sheet of paper titled Raw Data.

In the project you will generate a sequence of random integers, each between 1 and 25. The random number will tell you which square to mark on the bingo box sheet. To generate a random integer from 1 to 25, go to the Homescreen and select **MATH > PRB > 5:RandInt(**. Then type in **1, 25)** and press **ENTER**. See below.

```
randInt(1,25)
                6
```

Now press **ENTER** a few more times and you will begin generating a sequence of random numbers. Try this now—your random numbers should be different than your partner's.

3. Procedure for Generating Bingoquakes

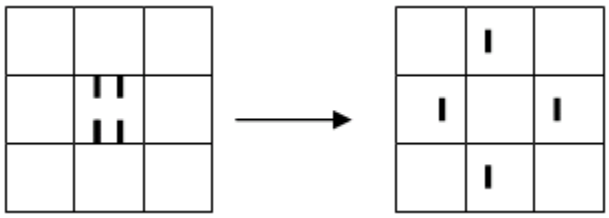
For this activity, you will need the Bingo Box and Raw Data sheets, and a TI calculator. It is best to have 1 person run the calculator and record on the Raw Data sheet, while the other person marks the Bingo Box.

1. Create a random number between 1 and 25 on the calculator.

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. Enter the size data into L1, and the reverse cumulative frequency data into L2. *Do not enter any data if the reverse cumulative frequencies are equal to zero. No 0's in L2!*

8. Frequencies of Earthquakes

a) On your TI-83/84, create a scatterplot of the (L1, L2) = (size, reverse cumulative frequency) data. There is no need to worry about setting up window dimensions, just correctly set up **Plot1** in **STATPLOT**, and then choose **ZOOM > 9:ZoomStat**. 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 bingoquakes 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) Using your TI calculator, calculate the best fitting power law regression through the (size, reverse cumulative frequency) = (L1, L2) data. What is the resulting equation? What is the correlation coefficient?

b) How well do the 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; maybe 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 L1 and L2. What will the scatterplot of these data look like if they are logged? To find out, go to the Homescreen and calculate the logarithm of list L1 and store it as list L3. Then compute the logarithm of L2 and store as L4. See below. (*Note: your list values will be slightly different than those displayed below)*.

```
log(L1)→L3
{0 .3010299957 …
log(L2)→L4
{3.799340549 3.…
```

a) Now make a scatterplot of the (L3, L4) logged data on your calculator. Again, just select the correct lists in **STATPLOT**, then choose **ZoomStat**. 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(size), log(reverse cumulative frequency)) data appear linear? Do the (size, 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(reverse cumulative frequency) = y = _____

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

reverse cumulative frequency = 10^{y} = _____

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 quake every _____ years.