LIVING ON THE EDGE
CHAOS, ORDER & COMPLEXITY
A Working Analogy for Natural Selection

Background

One of the most common objections to the theory of evolution by natural selection arises when people observe the extraordinary complexity of living organisms. In 1802,the theologian William Paley argued, in his much repeated thought experiment, that if one stumbles on a watch on the ground - a highly complex device - then surely, someone must have made it (and dropped it!). Obviously, it must be the product of intelligent design, rather than just somehow forming naturally from the soil. He extends this argument to all complex structures in nature, including living organisms, suggesting that all life had to be made by a creator, or "intelligent designer". Many people find it very difficult to accept that the processes of random mutation, even with non-random selection, could ever fashion complex life.

This is indeed a critical challenge to the idea of natural selection. Part of the process of natural selection involves random events (**mutation**), but the other part of the process is **selection**, which is a *non*-random process (often forgotten by critics of the process). At first glance, it is indeed hard to imagine how any series of random events could ever produce complex, orderly systems. However, if we can show that random events, interacting according to orderly (non-random) rules, can produce orderly patterns, then we must seriously question the universal validity of Paley's argument, and conclude that, at least in principle, complex living systems could indeed arise by natural selection.

The purpose of this activity is to examine and model both orderly and random systems, and their interactions. The activity includes a "Chaos Game" used to demonstrate that highly complex objects can and do arise from surprisingly simple interactions of these systems.

The Complexity of Life

There can be little argument that LIFE is COMPLEX. The incredibly complex structure and behaviour of living things is well known to everyone. But can we explain exactly what it means to be "complex"?

- What is complexity?
- Is it a good thing, a bad thing, or does it matter?
- How are orderly (predictable) rules and chaotic (unpredictable) behaviour related to complexity?
- Are complex patterns and behaviours only produced by complex relationships and processes?

For each item or question below, discuss with your partners, and be prepared to respond during the general class discussion. Record your answers (in your notebook) to all items if so directed by your teacher.

Part I: Order and Chaos

We can begin to answer and understand the significance of these questions by considering and investigating "order" and "chaos", both independently and when they are in close interaction.

What is ORDER?

1. Brainstorm and list several everyday examples of VERY ORDERLY arrangements (*systems*). For example, a checkerboard is a highly orderly "system".

2. What everyday object is used to "continuously count" units in a highly orderly fashion?

3. Which school subjects are most devoted to the systematic analysis of orderly processes? Explain.

4. How might the word "RULE" be associated with orderly systems?

5. Draw something which you are sure is highly ordered.

6. What is the key feature of a system which does NOT have order?

What is CHAOS?
7. Define the term *random*.

8. State (and list) several examples of very CHAOTIC (random) processes.

9. Draw something which is very CHAOTIC.

10. Brainstorm several everyday uses of chaotic processes. Think of instances in which we prefer objects or behaviours to be random. For example, lottery corporations would have a very difficult time running a fair lottery draw if the winning numbers were not picked by a random process.

Comparing ORDER & CHAOS
In order to appreciate *Complexity*, we must first understand the properties (and the advantages and disadvantages) of orderly and chaotic systems. To do this, we need to compare some well known examples of such systems. We'll get to living systems a little later.

Orderly Systems:
COMPUTERS and AUTOMOBILES are both examples of highly orderly systems. They (usually) behave in very *predictable* ways.

Chaotic Systems:
A shuffled DECK OF CARDS and the roll of a pair of DICE both illustrate very chaotic systems. They tend to behave in very *unpredictable* ways.

Using the above as examples, assess the advantages/successes and disadvantages/failures of these systems:
11. Which systems are most "reliable"? Which systems do we "count on" to perform the same way every time?

12. Why is it essential to begin each card game with a shuffled deck? What would be the response to the same hand being dealt repeatedly?

13. If you drop a shuffled deck of cards and then pick the cards up, do they still behave the same way? Is this true of a laptop computer? This is a "thought experiment" - Please do NOT actually conduct this trial with your classroom computer or microscope (or your personal computer, either!)

14. Based on your answer to number 13, which type of system generally is more sensitive to change? Which type of system remains unaffected by such change?

Examples of ORDER and CHAOS in NATURE:
Order: The Laws of Physics - try to name a few. These are the unshakable "rules" of the universe. They are completely predictable, non-random "truths". No event has ever been observed that contradicts these fundamental relationships.

Chaos: The universe is composed of fluids - gases and liquids - that are composed of particles in kinetic molecular motion. This completely random "jiggling" of molecules is beyond prediction - what Niels Bohr might have called "God Playing Dice" at the molecular and subatomic level.

Part II: Complexity
We have seen that orderly and chaotic systems have very different properties. In many ways, they seem opposite and may appear to be "incompatible". It is also apparent, however, that most systems in the real world are neither "perfectly orderly" nor "totally chaotic". This adds a further set of questions to our list for consideration:

- Can a system be orderly and chaotic at the same time?
- What happens when ORDER & CHAOS meet?
- Is there a continuum from totally orderly to totally chaotic? What does something "halfway between" look like?
- Are systems that combine order and chaos interesting or useful?

One of the best ways to investigate the above questions is to play a simple "game" in which a "strict rule" is applied to a series of totally random events. This can be accomplished by playing the "Chaos Game".

Activity: Playing the Chaos Game - following rules and rolling dice

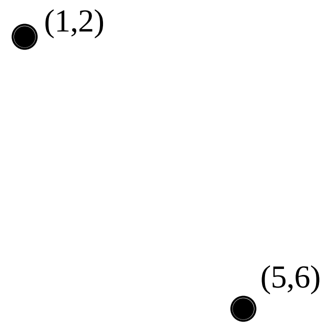
For this activity you will need:

- sheet of blank paper
- ruler
- one die (singular of dice)
- pen or pencil

<u>The Chaos Game Rules</u>:

The Board: Draw three points on a blank page as shown in **Figure 1**. The points should be well spaced out (use the entire page) and form the vertices of a roughly equilateral triangle. The three corners (vertices) should be labeled (1,2) (3,4) and (5,6) respectively.

Figure 1. The Chaos Game Board (much reduced):



How to play:

1. Mark a small dot anywhere on the paper.

2. Roll the die.

3. Mark a second dot on the paper **EXACTLY HALF WAY** between your first dot and the vertex indicated by the number on the rolled die.
   For example: if you roll a three, go half way **in a straight line** from your first dot to the (3,4) vertex, and place another dot at this location. DO NOT CONNECT ANY DOTS.

4. Roll the die again. Mark a third dot on the paper **EXACTLY HALF WAY** between your LAST dot and the vertex indicated by the rolled die. (Isn't this fun?)

5. Repeat step 4 over and over. Isn't this a fun game?

6. Bored? - keep going. Bored silly? - keep going as your pencil becomes a stub :-)

7. After you have put at least three dozen dots on the page, answer the discussion questions below.

Discussion Questions:

8. What aspect of this game is controlled by an orderly process?

9. What aspect of this game is controlled by a chaotic process?

10. What pattern, if any, is formed after this "system" operates for many "generations" (many dots)?
    Your teacher will show you with a sample "print out" of the results of playing the Chaos Game precisely for many thousands of iterations. (Your teacher mindlessly played this game at home for countless hours just so you could see the results - science teachers do things like this in their spare time.) As an alternative, you may be shown, or have a chance to operate, a computer program which does the mindless repetitions described above, something computers do very well.

11. Would you describe this pattern as orderly, random, or complex? Explain.

12. This type of structure is called a *fractal*, and is described as being infinitely detailed. Explain.

Analysis:

Life can be described as living on the edge (or the boundary) between order and chaos. Life is indeed complex. Use these questions to consider the ways in which the Chaos Game models the formation of complexity in nature:

13. Is the final product of the chaos game simple or complex?

14. Are most structures in nature simple or complex?

15. The "rule" in the Chaos Game was to move (in a straight line) half the distance to the randomly chosen vertex.
    Move = d/2

    a. Is this equation highly complex in mathematical terms?

    b. If you were shown the final product of the Chaos Game (called a Sierpinski Triangle), would you have guessed the mathematical equation behind the object could be so simple?

    c. Would you have thought that you could produce an object like this by using a dice roll as part of your "graphing method"?

16. Would you describe the following formulae as highly complex or relatively simple?
    V = d/t   F = ma $E = mc^2$

17. While you may find the laws of physics to be "complicated", their equations are certainly simple when compared to the fine (detailed) structure of cell organelles, circulatory systems, the structure of a fern frond, or the topography of mountain ranges.

    a. Do these more complex structures "obey" the laws of physics?
    b. What chaotic processes are involved in the formation and activities of cells, circulatory systems, ferns and mountain ranges?

18. Is a snow flake or frost pattern random, highly orderly (predictable), or complex?

    a. What chemical properties (rules) of water molecules influence the formation of ice crystals?
    b. What random conditions influence the formation of ice crystals?

19. Examine a cauliflower or broccoli flower. Is there any similarity between its form and that of the Sierpinski triangle?

20. Consider the rules of the Chaos Game. What do you think might have happened if part way through the game your "dot" was grabbed and relocated 1 meter from your last position? If you had kept playing the game, describe what would have happened.

21. How does this characteristic of the Chaos Game model homeostatic mechanisms?

22. In what way is the "rule" similar to the genetic code or protein structure?

23. In what way are the dice rolls similar to the process of "random mutation"?

24. Consider the list of biological "objects" below, and answer the questions which follow:
    The pattern of branching and leaf shape in trees (such as maple or pine)
    The pattern of blood vessels in an adult human
    The arrangement of petals in a flower
    The arrangement of bracts in a pine cone.

    a. Are these structures highly predictable? As they grow, can you predict exactly how each structure will develop? Are they all identical?
    b. Are these structures recognizable? Do they share the same complex patterns?
    c. Could random forces and "rules" of nature produce these beautiful features?

25. Brainstorm and consider other objects or patterns in nature that seem to have an apparently complex structure.