Modeling Yawning Contagion as a Reaction-Diffusion System: Emergence of Turing Patterns in Behavioral Contagion

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Abstract

When we see someone yawning, we often feel compelled to yawn ourselves - a phenomenon known as behavioral contagion in psychology. While one person's yawn acts as an activator that triggers yawns in others, we sometimes suppress the urge to yawn in situations like meetings, representing an inhibitor of this behavior. We formulated this yawning contagion as a reaction-diffusion phenomenon in an activator-inhibitor system and confirmed the emergence of Turing patterns. Our findings provide a theoretical framework for understanding and potentially controlling the spread of social behaviors in human populations.

Keywords: Reaction-Diffusion, Behavioral contagion, Yawning

1. Introduction

In this study, we use the "contagious yawning phenomenon [1]" as a starting point to analyze the phenomenon using a mathematical framework known as the reaction-diffusion phenomenon. The reaction-diffusion phenomenon is a model that forms the basis of a wide range of natural phenomena, such as chemical reactions and biological morphogenesis, and its importance is particularly demonstrated in Alan Turing's "Theory of Morphogenesis [2]." We uses the reaction-diffusion phenomenon to elucidate the mechanism of contagious yawning using a mathematical model and to open the possibility of applying it to natural and social phenomena.

When you see someone yawning, you are likely to yawn as well. In psychology, this reaction-diffusion phenomenon is called behavioral contagion [1]. Someone is yawning, which spreads and induces someone else to yawn. Factors that activate things like this are called activators.

On the other hand, when someone yawns in a meeting, and you are compelled to yawn, you might think, "I should not yawn here..." and hold back from yawning. Things that inhibit actions or reactions are called inhibitors. We describe the behavioral contagion of yawning as an activator and an inhibitor.

First, when someone is yawning, behavioral contagion makes you want to yawn, too. In other words, someone's yawning becomes an activator, making you want to yawn. Yawning induces yawning through behavioral contagion, so this is written as "yawn -> (+) yawn." Here, -> (+) indicates the reaction of an activator (a reaction that activates the behavioral contagion of yawning).

On the other hand, if someone is yawning, a reaction occurs to try to hold back to avoid being influenced. In this reaction, the "yawn" first activates the inhibitory factor "hold back a yawn." This is written as "yawn -> (+) hold back a yawn." When the inhibitory factor "hold back a yawn" is activated, it suppresses yawning, so this is written as "hold back a yawn -> (-) yawn." The greater the influence of this reaction, the more yawning is suppressed, and the less likely behavioral contagion will occur.

Alan Turing was one of the pioneers who focused on reaction-diffusion phenomena to understand natural phenomena. One of the biochemical reactions that interested him was the morphogenesis of living organisms. When an egg is fertilized, an organism takes shape through repeated cell division from a single fertilized egg. This process is called morphogenesis.

The shape of a fertilized egg is initially symmetrical. Still, after about a week, when the internal organs begin to form, the position and shape of the internal organs become asymmetrical. Turing was intrigued by the fact that the symmetry of the fertilized egg eventually breaks down, and various shapes emerge.

He formulated this phenomenon by considering it as a reaction-diffusion system. He then used the reaction-diffusion system to develop the change in the shape of a zygote, which has a symmetrical shape, to an asymmetrical shape as a change from a symmetric state, where the state is the same everywhere, to an asymmetric state, where the state differs depending on the location.

2. method

A reaction rule models the activation/inhibition system. The activation factor increases by X an autocatalytic reaction; that is, the amount of the activation factor X increases from X;

$$r_1 \colon X \xrightarrow[k_1]{} X, X.$$

Below we denote $k_1, \ldots, k_4$ as reaction coefficient. The inhibitory factor Y is produced from an activator X as follows:

$$r_2 \colon X \xrightarrow[k_2]{} Y, X.$$

The inhibition of X by inhibitor Y is:

$$r_3 \colon X, Y \xrightarrow[k_3]{} Y,$$

Note that in this reaction, Xonly decreases, $Y$and does not decrease. Finally Y, the disappearance is

$$r_4 \colon Y \xrightarrow[k_4]{} \emptyset,$$

where $\emptyset$ denotes the empty set. To summarize the above, the activation/inhibition system is based on the rewriting system [3], as follows:

$$r_1 \colon X \xrightarrow[k_1]{} X, X,$$
$$r_2 \colon X \xrightarrow[k_2]{} Y,$$
$$r_3 \colon X, Y \xrightarrow[k_3]{} Y, \mathrm{X}$$
$$r_4 \colon Y \xrightarrow[k_4]{} \emptyset.$$

2.1. Diffusion model

The above system does not include diffusion. Therefore, diffusion needs to be considered separately. Why does diffusion occur? If you drop a drop of ink onto clean water and stare at it for a long time, the ink that spreads across the surface will eventually dissolve into the water. No matter how long you stare at the water's surface with the ink dissolved, the ink will never return to its state when it is dropped back onto the water. In other words, diffusion is the process of homogenizing things.

The diffusion occurs between the cells x_i and x_j is $d = (x_i - x_j) \times D$, where D is the diffusion coefficient.

3. Result

Here, we consider a two-variable system consisting of 10 cells. However, the right side of the rightmost cell is connected to the leftmost cell. In other words, we consider the 10 cells connected in a ring shape. Then, we define $X$the initial state of and as follows:Y

$$X = [0, 10, 0, 10, 0, 10, 0, 10, 0, 10]$$
$$Y = [0, 10, 0, 10, 0, 10, 0, 10, 0, 10]$$

In each cell, the reaction proceeds according to the reaction rules the reaction coefficients are $k_1 = k_2 = k_4 = 0.001$and $k_3 = 0.005$. In the simulation, the state quantity is first updated by performing diffusion. Next, the state quantity is updated by applying the reaction rules in parallel. Then, the state quantity is updated by diffusion and then by the reaction rules, and this process is repeated.

The diffusion coefficient with Y, $D\_X = D\_y = 0.0$, there will be no change from the initial state. Such a state is called an equilibrium state (equilibrium means "balanced"); in this reaction system, if the state $X = Y$ quantities of Y(and X) are equal, then neither $X$the state quantities nor $Y$the state quantities change.

Therefore, since the initial state holds in the corresponding cells $X = Y$, if there is no diffusion, it will remain in the initial state.

What happens if diffusion occurs when $D_x = D_y = 0.01$, the reaction is in equilibrium (state of equilibrium)? First, $X = Y$if we Xassume that the diffusion coefficients of $X$and are the same, then while $Y$and Ychange, they always $X = Y$ remain the same. In other words, the reaction is always in equilibrium. Eventually, diffusion Xwill Yhomogenize and the whole will reach equilibrium. This means that the diffusion coefficient is $D_x = D_y = 0.2, 0.3, \cdots$. Next $D_x = 1.0$ and $D_y = 0.001$, the diffusion coefficient $Y$for X, is more significant than $X$and Y are homogenized. On the other hand, if $D_x = 0.01$ and $D_y = 1.0$, then Turing Pattern like behavior appeared (Figure 1).

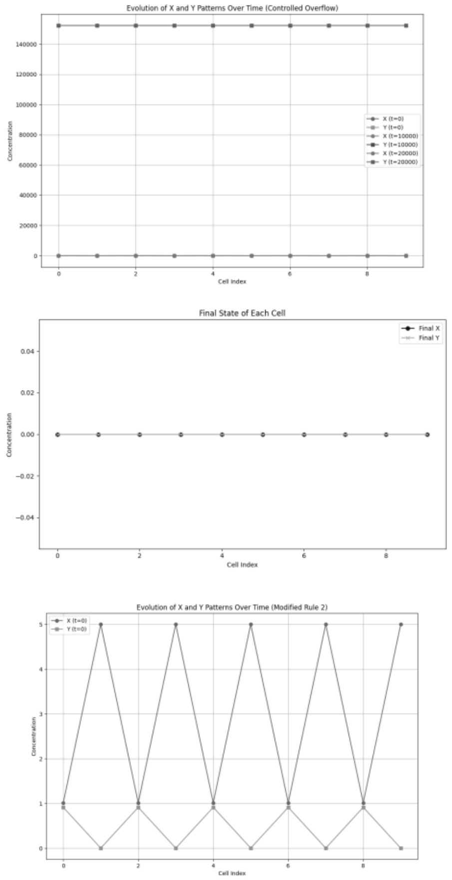

Figure 1 (Top) $Dx = Dy = 0.01$ (Middle) *Dx=1.0 > Dy=0.01* (Bottom) $Dy = 1.0 > Dx = 0.001$.

4. Discussion

Based on the preparations made in the previous Section, we can now specifically consider why a system's behavior in equilibrium changes due to diffusion.

$X$the diffusion coefficient of is Ylarger, the increase of is suppressed in the cell with the initial state of $(10{,}10)$, $X$and tends to increase in the adjacent cells $Y > X$due to diffusion. Eventually, every cell $X > Y$ becomes, $Y < X$and Xif there is no outflow of the state quantity from the cell, Xincreases while maintaining a homogeneous state.

X the diffusion of is Y slower than that of, then $(10{,}10)$ the amount of diffusion of $X$is greater $Y < X$ in the cell with the initial state of, $Y$and X increases. Since the diffusion of Y is faster, increases in the adjacent cells $Y > X$, and decreases. As a result, increases Xin the cell with X the initial state of, and decreases because the $(10{,}10)$of the adjacent cells X is suppressed. As a result, pattern of Y become larger and small quantities of X is formed.

This way, patterns can emerge by changing the diffusion rate even in a relatively simple reaction-diffusion system. In general, Turing pattern is stable for both time and space, however this model exhibits unstable for both (Figure 2).

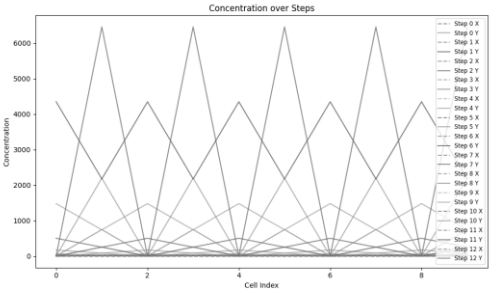

Figure 2. When Dy >> Dx, Turing pattern like behaviors appeared, however, the patterns are unstable and expanding as the time step increased.

As mentioned above, Turing discovered this mechanism and demonstrated it mathematically. The patterns that emerge from this mechanism are called Turing patterns.

After the proposal of Turing patterns, this mechanism was thought to be abstract, but Shigeru Kondo showed that the patterns on the surface of animals' bodies are Turing patterns.

The stripes of zebras and giraffes are fixed on the surface of their bodies. However, the spacing between the patterns on their body surface does not increase as they grow. Kondo wondered, "Perhaps the number of stripes increases as they grow?" Then, by observing a tropical fish (the imperial angelfish) that fulfills this condition, he showed that the stripes form a Turing pattern (Figure 3).

Figure 3. The Turing pattern on the surface of a zebra's body (Photograph by author)

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Authors Introduction

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