INNOVATION

THEORY AND CONCEPT

Part II of Theory of Form
Self-Organizing Form by Entropy and Emergence

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Abstract

It has been assumed that form of biological entities is controlled by genetics. While the role of genetics in biological forms is undeniable, how genetics affect the form is not well understood. The adaptability and constant change of the form in the same individual suggest that genetics is only one of the factors that affects form. Here, we propose to look at the form from a different perspective, recognizing entropy and emergence as important factors in the creation of form. The entropy of the form is a "catalog" of all possible forms for each set of constraining factors. Emergence here is defined as the total of physical and chemical forces, internal or external, that act as constraints and skew the result of entropy towards higher probability forms. The constant change in the constraints by genetics, through the production of new proteins, together with entropy and emergence, results in a predictable self-organizing biological form.

Entropy

Entropy represents the probability of an even distribution of energy or molecules in a system. If the molecules are not in contact with any object, based on the laws of motion, they are likely to spread out. We can contain gas molecules in a box's corner by sealing the area (Figure 1A). As soon as we remove the confinement, the molecules will spread in the box. The probability that the molecules spread in the box is much higher than the probability of them staying in the same corner. Therefore, one can say the molecules go from low entropy (when they are concentrated in the corner of the box) to higher entropy (when they spread out in the box) (Figure 1). Entropy is not about a change in the system's total energy since, in both conditions, the system's total energy stays the same. However, the distribution of the energy in each condition is different. The configuration where the energy spreads out has the highest entropy. Low entropy means the energy is concentrated.

Entropy can be studied in a closed system where the influence of the surrounding environment is minimal, or in an open system where both the system and its surroundings act as one. We can measure the level of entropy of a system and its surroundings by measuring the probability of how energy can spread.

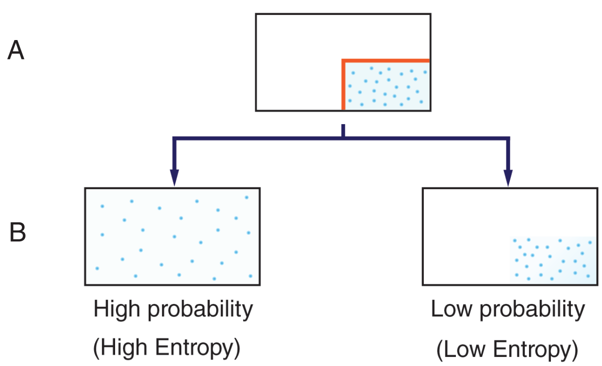

Figure 1: Entropy. *Assume we confine the molecules of a gas to the corner of a box (A). As soon as we remove the barrier confining them to that corner, the gas molecules escape in every direction and fill the whole box (B). In other words, the probability that they disperse in every direction is very high (high entropy), while the probability that the molecules stay together in the corner of the box after removing the confining barrier is very low (low entropy).*

Entropy of Form

We define the entropy of the form as the probability of different forms occurring under the same constraints. In other words, the form that is more probable under similar constraints has high entropy, while the form with less probability of occurring has low entropy. Understanding the entropy of a given form is very important since it argues that without any change in constraints, the form resulting from higher entropy would be the default form. If the probability for one outcome is higher than others, one can predict with high confidence what would be the resultant form.

Let's look at one example. Assume we have three balls that we drop on the floor. How many forms can these three balls create? Entropy of the form argues that some forms are more likely to occur than others. Here, the form is the result of each ball's position in space (Figure 2).

If the development of a form can have many outcomes, and almost all the outcomes have, more or less, a similar pattern, we can say that this pattern has a high probability of occurring or it has high entropy. Therefore, the entropy of the form is the number of different possible ways the units of the form can be distributed in space. In the above example, the triangular form has higher entropy than the linear form. The low entropy outcome, in the example being the linear arrangement of the units, will occur with a rare chance or can actively be produced if energy is invested.

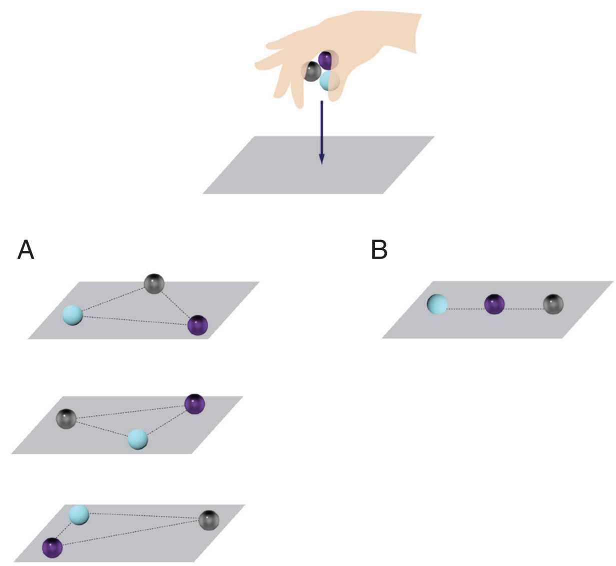

Figure 2: Entropy of form. *Form in this example is the arrangement of the balls on the floor. If we drop three balls on the floor, they can produce endless forms, with the overwhelming majority of them being a triangular arrangement (high entropy) (A). They may produce a linear form (B) on extraordinarily infrequent occasions (low entropy).*

Entropy of the Form and Disorder: a misunderstanding

Many may believe that the disordered forms have higher entropy. The higher the entropy of the form, the higher the disorder. However, the observer, not reality, defines order or disorder. For example, if we put the pieces of a broken plate in a bucket and then empty the bucket on the floor, the pieces of the plate can achieve many different forms (Figure 3). We may consider a specific pattern of broken pieces of the plate on the floor as our desired form. Depending on what specific pattern we have in mind, we may call this specific form the organized form (based on our pre-assumption) and all other configurations the disorganized forms, including the form of a plate. Based on this discussion, calling a specific form ordered or disordered does not add anything to studying the form. It is more meaningful to study the form regarding its probability and not a specific organization. For example, let's compare the probability of the broken pieces taking the pattern of a plate or not taking the pattern of the plate when we empty the bucket on the floor. It is obvious that the probability of the broken pieces producing the pattern of a plate is much lower than the probability of producing a pattern that is not a plate.

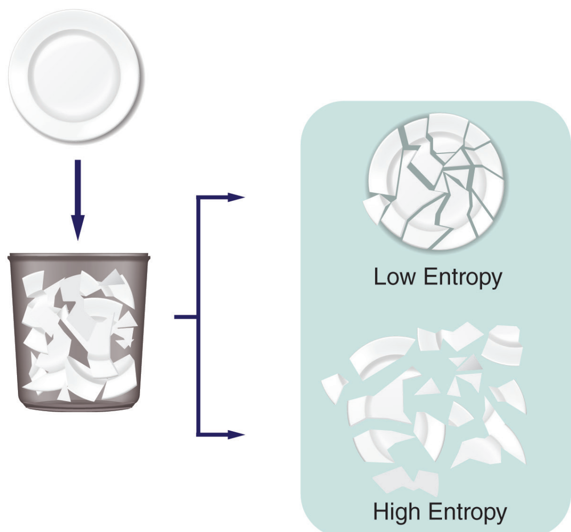

Figure 3: Entropy of the form does not represent disorder. *When we repeatedly drop the pieces of a broken plate on the floor, the pieces (units) of the broken plate can take an infinite number of positions in relation to each other. All configurations of the pieces on the floor have a probability of occurrence, including when they gather in the shape of a plate. We can categorize all the possible distributions of the pieces on the floor into two general patterns: one pattern is the shape of a plate, and the other pattern is anything but the shape of the plate. The probability of the broken pieces staying away from each other is much higher (infinity) than staying together as in the original shape of the plate (almost impossible).*

Entropy and Spontaneity of the Form

When we walk into a very crowded area, the probability of contacting other individuals is so high that contact occurs automatically and does not need an external push. Similarly, the probability that molecules of hot water will hit the molecules of the cup they are in, or the probability of molecules of a gas spreading in space, is so high that these events occur automatically or spontaneously. On the other hand, if you want to bounce back and forth and simultaneously walk in the crowd without touching any individual, you will need to hire a bodyguard to push the people away from you. In other words, you need to spend energy.

The events with lower entropy only occur spontaneously on rare occasions. Since the possibility for this occurrence is limited and rare (very low probability), it will require input and consumption of energy by the system. Spontaneity is one of the characteristics of events with high entropy.

In other words, if the energy of the system does not change, some forms are spontaneous while others are less likely to occur. Please note that spontaneity of a form does not mean that no energy is required for the creation of that pattern. It just means that in a system under a certain amount of energy with similar constraints, one pattern has more probability than the others to occur without the need for additional energy.

Going back to the broken plate example, the possibility of broken pieces on the floor forming a pattern that is not a plate is higher than forming the pattern of the plate. Therefore, in this article the pattern that is not the plate is considered the spontaneous pattern. Similarly, there are many ways that rocks in a mountain can be arranged to produce a recognizable mountain structure. However, it is almost impossible that they will arrange so that they take a shape of the head of a USA president. Therefore, under those conditions, the shape of mountain as we are all familiar with, is considered as having high probability or being spontaneous. An energy-consuming effort by an artist is required to increase the probability of creating the organized shape of Mount Rushmore, against all odds. This specific pattern is not considered spontaneous.

Entropy and Randomness of the Form

While randomness is part of entropy, entropy is not the measure of randomness. Randomness describes the probability of distribution. If the probability of all possible outcomes is equal, the possibility of the appearance of each outcome is considered random. While at very high magnification of the form, the units may have a similar probability of appearing at different locations, and therefore, their position is random, at lower magnification, not all the possible forms of micro-state have the same probability of occurrence. This decreases the randomness of the form (Figure 4).

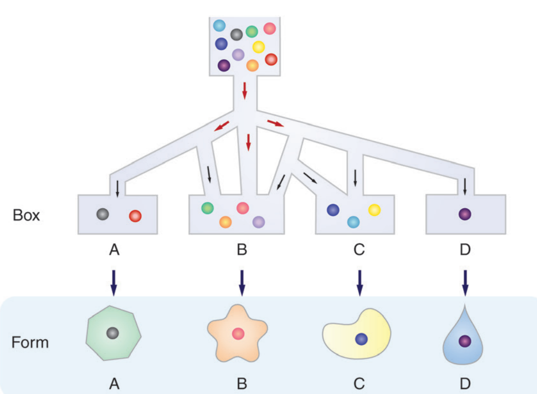

Figure 4: Randomness and Entropy of the form. *In the above experiment, balls (units) collected in the basket randomly take one path leading to one of the boxes A to D. When a ball gets to a box, regardless of which ball arrived, the box automatically creates a form (forms A through D). While the unit distribution is random, at the level of form, probabilities arise, with some forms having a higher probability of appearing than others. In this example, form B is more likely to occur than the other forms. Therefore, the probability of creating forms A to D is not random. One can say form B has higher entropy than form D. In this figure, the balls' paths represent constraints that limit how the units can move and interact with other units.*

In this example, if we increase the number of paths that a ball can enter box B, the probability for form B to occur increases even more. Similarly, if we increase the number of units, the probability for form B to occur also increases. This is important since the increase in the units of the form (in this example, the balls) does not equally increase the number of all forms. In other words, increasing the available units of form does not increase the diversity of the micro-states (forms A through D). However, it can change the probability of one form occurring over another. Therefore, entropy does not necessarily result in randomness of form.

Based on the above discussion, we can conclude the following. First, in the presence of certain constraints (physical and chemical influencing factors), countless patterns of distribution of units can produce a certain number of forms. If the majority of the patterns of distribution result in creation of one form, this would be considered the default form, or the form with the higher entropy in the presence of those constraints. Second, if the constraints change, for example as the form evolves from one micro-state to another, new constraints appear and the entropy of the form for that microstate also changes. Third, at each micro-state, some forms have higher entropy than others. Still, when that microstate evolves to the next, a new "catalog" of forms is created with different entropy that does not allow the comparison of the entropy of form from one micro-state to another. Therefore, entropy of form can only be studied at each micro-state, not between micro-states.

Entropy of Form, Mass Form, and Functional Form

As we discussed above, different constraints change the entropy of the form. That is why each micro-state has its own entropy. The presence of the new constraint changes the organization of the units and therefore, represents the new functional form. Based on the concept of encapsulation (discussed in Part I of Theory of Form), the functional form of one micro-state becomes the mass unit for the next micro-state and its new functional form. Hence, we can have multiple mass and functional forms, as the biological form evolve.

Emergence

As discussed above, If the units in the mass form are organized in a certain way due to appearance of new constraints, they produce a functional form. In this article, the process of organizing the mass form into a functional form is called Emergence. This organization produces specific patterns for the form that do not exist if the units are not organized (Figure 5). Similarly, this specific organization produces certain properties or functionality of the form, which would not exist if emergence was not organizing the units. For example, the rigidity of the skeleton emerges from a specific organization of cells and their activity, matrix production. However, one bone cell alone cannot produce the rigidity of the skeleton as would a group of cells, their matrix, and their network of activities.

Importantly, each unit of the form can be the product of emergence from much smaller units. For example, the bone cell, as a unit, emerges from the specific organization of macromolecules and basic elements, and it has particular properties that do not exist at the level of macromolecules alone. This reasoning, of course, extends to the limit of our detection systems. For example, DNA as a macromolecule has specific characteristics that none of the individual nucleic acids that compose the DNA triple helix have. These properties allow DNA to be used to preserve information, but none of the nucleic acids alone can be used to transfer information. Sometimes during emergence, the units lose their original properties. For example, the gas atoms oxygen and hydrogen combine to make liquid water molecules.

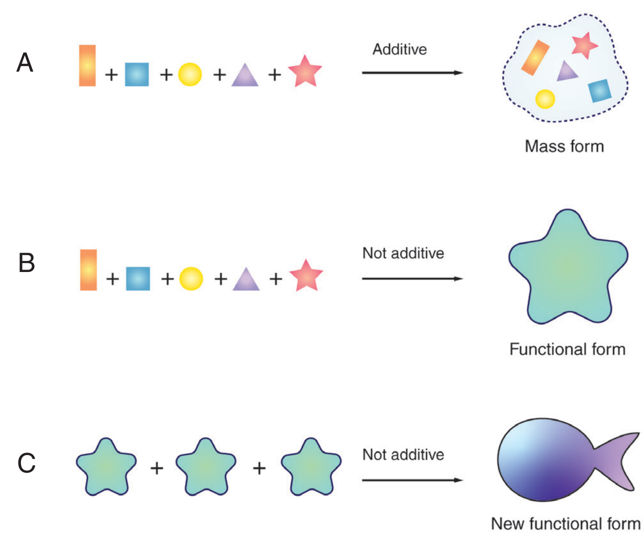

Figure 5: Emergence of functional form. *Mass form is an additive form of all its units without a specific organization (A). In contrast, the functional form reflects the emergence of a new organization of its units (B). Therefore, the functional form has specific new characteristics or functionality that did not exist in the individual units before introducing new constraints. The functional form of this micro-state (in B) becomes the units for the next micro-state organized into a new functional form (C).*

Constraints

In this article the total of physical and chemical factors, internal or external, that affect the position of the units of form in space and in relation to each other at a specific time, are considered constraints. The purpose of this article is not to concentrate on these constraints and their mechanism of action but to recognize their overall effect in the development of a biological form at different micro-states. These constraints include osmotic pressure, diffusion, the density of biological matter, the elasticity of biological matter, gravity, temperature, electric charges, hydrophobic and hydrophilic bonds, enzymatic activities, and many more. These constraints constantly change as gene expression introduce new variables to the system that

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change cell proliferation, differentiation, matrix synthesis, and apoptosis. The form at each micro-state is the result of interactions between biological materials and their constraints. As the constrains gradually change from one micro-state to next, the role of entropy decreases, and form becomes more affected by emergence and therefore, as we explain later, becomes more predictable.

Intra Micro-state and Inter Micro-state Differences of Form

Based on this discussion, one can argue that entropy is mostly a micro-state phenomenon since it explains form at each microstate in agreement with the constraints of that micro-state. However, emergence mainly explains the development of the next micro-state due to new constraints and, therefore, it is an inter micro-state phenomenon. That is why the entropy of form in one micro-state cannot be compared with the entropy in the next micro-state since they represent different conditions of evolving forms.

Emergence and Trajectory of the Form

Both biological and non-biological forms may develop through different stages where one micro-state evolves into the next by emergence. The trajectory, in this article, is defined as the path of development of one micro-state into another. Therefore, the trajectory of form is a property of emergence, not entropy. While some forms develop in a few stages (lower number of micro-states), other forms have a higher number of micro-states, which means the development of form occurs in many stages.

Does the number of micro-states affect the diversity of the form? If different micro-states can evolve into similar macro-states, then the diversity of the form does not change significantly (Figure 6, Example 1). But, if micro-states can change the trajectory of the form, then increasing the number of micro-states could diversify the form (Figure 6, Example 2).

Since biological forms have many micro-states, forms with high probability in one micro-state still converge to produce similar forms in the next micro-state and keep the form divergence under control while allowing normal variability. Without this mechanism, the trajectory of the forms could change significantly, and any minor defect in the form in one micro-stage could propagate into a significant malformity at the last macro-state. But this mechanism automatically removes minor deformities without affecting the final macro-state, producing a self-correcting mechanism for the form.

Emergence of Predictable Forms

Does entropy and emergence make the form unpredictable? On the contrary, the forms that result from entropy and emergence are predictable. As an example, let's look at the shape of water drops. The form of a water drop is affected by many factors, including forces of gravity and surface tension. The force of gravity tends to flatten the liquid drop and spread it out until its surface becomes horizontal. Gravity is acted against by surface tension, which works to maintain the drop in the form of a sphere. We know that the gravitational force on the water drop depends upon the mass of the liquid drop, which is proportional to its volume. On the other hand, the surface tension depends upon the surface area of the water drop. Therefore, gravity plays a more significant role in determining the shape of large drops, which causes the drop to become more flattened, while surface tension is more prominent in the case of a small drop, which gives the drop a spherical shape. If no other constraints are introduced to the system, the shape of the water drops based on their size is predictable. In this discussion, other factors, such as adhesion forces, are ignored (Figure 7).

Predictability is not limited to simple forms, and entropy and emergence can produce predictable complex forms. If we add soap to water, in response to the interaction between the hydrophilic head and hydrophobic tail of the soap molecules, the complex shape of a micelle spontaneously forms (Figure 8).

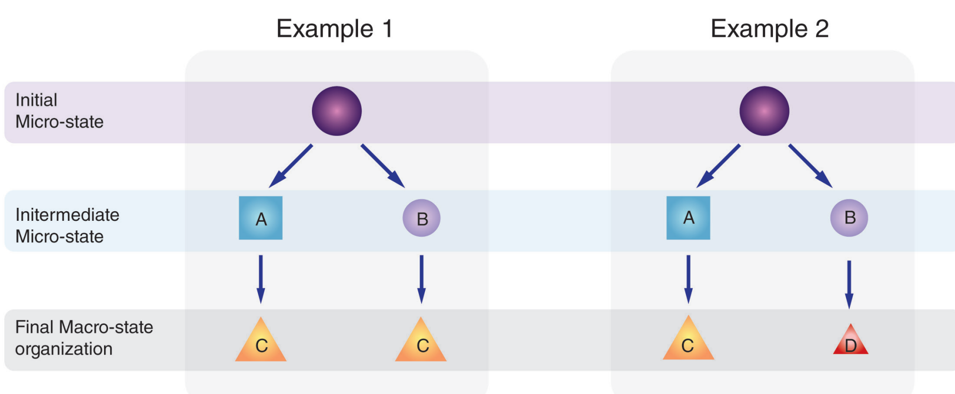

Figure 6. Emergence and trajectory of the form. *In this example, two different forms are developing in 3 stages. In the first example (example 1), a change in the intermediate micro-state (micro-state A and micro-state B) does not change the shape of the final macro-state (C). Therefore, the form trajectory does not diversify. In the second example (example 2), different intermediate microstates (A or B) change the possible form of the final macro-states (C or D) and, therefore, diversify the form trajectory.*

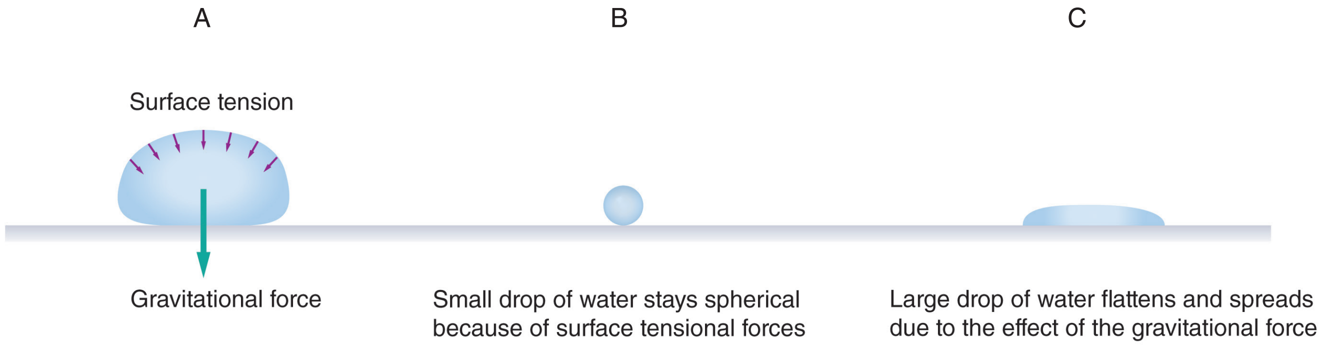

Figure 7: Form is controlled by physical and chemical laws. *Both surface tension and gravitational force play a role in the form of a drop of water (A). A small drop of water stays spherical due to tensional forces (B), while the shape of a larger drop of water on a hard surface is flattened due to gravitational force (C).*

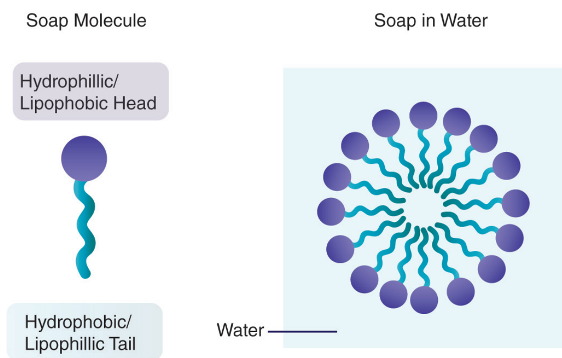

Figure 8. Emergence and predictability of complex forms. *If we add soap to water, the interaction between the hydrophilic head and the hydrophobic tail of the soap spontaneously creates a complex micelle form that can be explained by the physical and chemical properties of both soap and water molecules. This process is an example of a predictable complex form created by emergence.*

Similar to non-biological forms, biological forms have a significant level of predictability. For example, proteins, which are the main products of the genetic machinery and play a fundamental role in the creation of biological forms, as discussed in Part III of the Theory of Form, have a predictable form due to entropy and emergence. Proteins are made up of folded polypeptide chains composed of amino acids. Based on the folding of these chains, protein structures can be described in four primary forms (Figure 9).

Protein synthesis and folding exemplify the process of emergence and the predictable creation of complex biological forms. The primary protein configuration is simply the linear structure of amino acid chains. The secondary structure is the result of hydrogen bonds between adjacent amino acids, which can cause the protein to fold as either helix (alpha-helices) or sheets (b-pleated sheets) depending on whether the hydrogen bonds are intra-strand or inter-strand between adjacent segments of that polypeptide chain. The tertiary structure is the more compact 3D structure. This folding happens spontaneously based on the pattern of polar and non-polar amino acids in the protein chain. In an aqueous

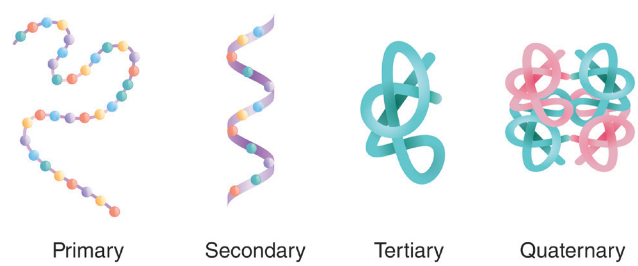

Figure 9: Spontaneous formation of complex protein forms by emergence. *Proteins are made up of amino acids. The chemical and physical interactions between different amino acids and their surroundings produce four forms of functional proteins: primary, secondary, tertiary, and quaternary structures, corresponding to different micro-states of protein folding.*

environment, hydrophobic molecules, such as the non-polar amino acids, are found predominantly in the interior of the protein structure. In contrast, polar amino acids are mostly found in the external portion of protein structure (Figure 10). The quaternary structure is found in proteins composed of two or more interacting polypeptide chains.

Interactions of amino acids, ruled by their physical and chemical properties during the process of emergence, result in different protein forms with distinct solubility and functions:

Figure 10: The tertiary structure of proteins. *The 3D form of a polypeptide chain is created spontaneously by emergence due to a favorable reaction between an aqueous environment and non-polar and polar amino acids. The protein spontaneously fold so that the non-polar amino acids are located internally in the protein structure, while the polar amino acids are found in the external portion of the protein structure*

globular, fibrous, and membrane proteins. Globular proteins are spherical in shape and soluble in water, which makes them marginally stable and suitable for motion. Fibrous proteins have a linear, insoluble structure, and have a structural role. On the other hand, membrane proteins are associated with the cell membranes (Figure 11), where they play essential functions in signaling or trafficking across membranes.

it evolves based on internal and external constraints. This is particularly important in biological forms, where genetics constantly introduces new components to the form (proteins) allowing fast changes based on the need for organization, until the end of the biological entity. As we discussed above, while the components of the protein structure are dictated by genetics, the form of proteins is the result of entropy and emergency. The role of genetics in self-organizing biological forms is discussed

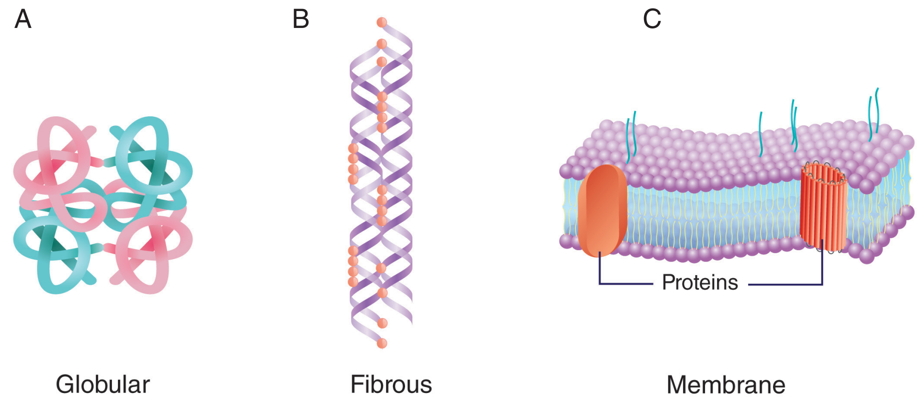

Figure 11: Different forms of proteins are created by emergence. *Through the emergence process, the final macro-state of protein folding results in Globular (A), Fibrous (B), or Membrane (C) protein forms. These three groups of proteins have different shapes, solubility, and function.*

in detail in Part III of Theory of Form.

Self-Organizing Form: A General Rule in Nature

While entropy, by default, produces the more probable form at each micro-state, emergence through physical and chemical constraints gives a defined organization and function to that form. Therefore, no control center dictates the form. In other words, form is not similar to a statue created by an artist based on a planned design. At each micro-state, forms evolve based on the interaction between entropy and emergence. Therefore, while this form is predictable, it is not pre-determined. In a pre-determined form, the plan of creation of form would unravel in time, regardless of the interaction of units with their constraints. We would just need to wait for the form to gradually achieve its final macro-state. This concept of pre-determine form has two serious flaws: first, the inescapable final shape, if part of a preordained plan, one day it will reach its final form; and second, the fact that the plan can go forward regardless of events in its surroundings.

In this article, the process of form creation, following entropy and emergence principles, is called the self-organizing form. Self-organization means that at each stage of development of the form, based on constraining factors, the form evolves into a new form without a central control regulating the process. In the self-organizing form, the interaction between the form and its surroundings defines the trajectory of the form, which can change and evolve as time progresses. Self-organizing form never reaches its final shape, and time will define how

The self-organizing form can be observed at any place in the universe. We can recognize rivers, volcanos, mountains, stars, and anything in this universe because of their different material (units) and their particular organization that confers a specific form. None of these forms are created based on a specific plan of an external or internal designer. While there may be some differences in the details of the shape of rivers based on geographical variables, they represent similar dynamic forms due to similar physical laws that dictate their form. Nobody has planned the shape of rivers, but they share significant similarities no matter where in the world they are located.

One may ask, if the laws of physics are the same worldwide, why do we have different forms? The difference in the form exists because the materials that comprise the form and the conditions in which the physical laws express themselves are different. The final form will have similar characteristics as long as the materials and physical conditions are the same. The final form represents the response of those materials to the physical laws without need for an external designer. For example, a change in the magnitude of the wind or rain can significantly affect a dune form. In addition, as the dune grows, the angle that the sand makes with the wind changes. Therefore, the growing dune will have two areas: one in the direction of the wind, and one away from the wind, which molds the dune's form differently. Based on these constraints, a self-organizing process produces a predictable form of dunes.

Time and Self-Organizing Forms

Emergence is the pillar of self-organizing form that acts in the framework of time. If forms were instantaneous (no time spent in their creation), the concept of micro-states would not be necessary. Form would reach its final shape immediately. However, both non-biological and biological forms are progressive, and evolve during the lifetime of each entity. Based on this concept, there is not a single form for any biological and non-biological entity, each entity has many forms, many micro-states. Depending on the time frame of our study, we can pause the process of the developing form, and evaluate the relation between units at that particular time or micro-state. This form could be stable only if no further interaction between units and between units and their constraints occur. However, the universe is not static, and as long as the universe exists, the form is constantly exposed to changes and continues to self-organize accordingly.

A Note on Studying the Variability of the Form

Form progresses through different micro-states that become part of a larger micro-state by encapsulation (Part I of Theory of Form), giving rise to the final macro-state. This observation raises a very important question: at what scale should we study the variability of form? In other words, at what micro-state should we compare different forms, especially biological forms?

As we increase the magnification of the microscope to study an organ, tissue, cell or organelles of cells, we are walking reverse in the creation of the form and we can see its original micro-states. As we focus our microscope, we lose the organization of the larger gathering of the cells into tissues, and we can see the effect of the entropy at one micro-state before emergence into the next micro-state. However, at lower magnification, we can observe the general order between different components of the form that arise by emergence (Figure 12). This is important especially when we study the form of different species.

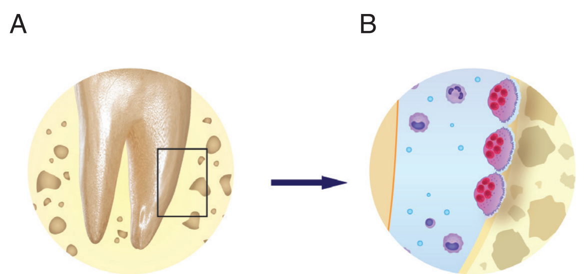

Figure 12: Scale-dependent complexity. *If we look at the tooth and its surrounding alveolar bone at lower magnification (A), we may not recognize the complexity of the organization that can be observed at higher magnification (B). One can say that the structure in "A" mostly represent emergence into a much later micro-state, while in "B" we can appreciate the interaction of entropy and emergence at very earlier micro-states.*

If we are studying the form of related species, the distinction mostly appears at the level of macro-states. Evaluating the form at micro-states, smaller than organs or tissues would not be as fruitful, especially in species that are related to each other. The inter-species variability can best be captured at the level of macro-states.

If the DNA of two multi-cellular organisms is the same and they produce similar proteins at a similar time in similar amounts under the same constraints, they can produce with high probability an identical form at the macro-state level, but not at an earlier micro-state level where entropy creates numerous possibilities. Therefore, the difference between two completely similar forms, for example identical twins, should be studied at a smaller micro-state level where the entropy effect can be observed in more detail.

Due to this complexity of the form, two biological structures that could seem identical at low magnification, do not look the same at higher magnification. In fact , the details demonstrate significant variability at different levels of the form, where we can see the effect of entropy on the form.

Summary

Entropy and emergence are the main factors in the creation of self-organizing form. When studying form if it important to define the scale, as entropy and emergence's footprint may be clear at different magnifications, or micro-state versus macro-state. In addition, variability is also scale dependent as two biological structures that could seem identical at low magnification do not look similar at higher magnification. Finally, we discussed the concept of time in self-organizing of both non-biological and biological forms, that allows form to change and evolve in response to its surroundings. In the context of the discussions of Part I and Part II of Theory of Form, we are now ready to dissect the role of genetics in self-organizing biological forms in Part III of Theory of Form.

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