INNOVATION

THEORY AND CONCEPT

Part I : Theory of Form Components of Self-Organizing Form

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Abstract

What is form? How are biological and non-biological forms created? What are the factors that affect biological form? Is our form predetermined with no opportunity for change or improvement? Why different species have different forms and why there is variability in the form for individuals of the same species? Are we fundamentally different from each other, or can the same universal rules explain variability even in the same individual over time?

In a quest to understanding biological form, we initiate our journey with a series of articles that establish a common ground for an overall theory of form. In Part I of this series, we define form in general (biological and non-biological) and focus on the common characteristics of biological forms, such as its building blocks, their organization, hierarchy, autonomy, and coordination over time. Unifying perspectives from different disciplines, we borrowed and redefined concepts and terminology that establish the foundation for the discussions that follow in Part II and Part III of Theory of Form.

Form

When describing a form (non-biological or biological), we describe a magnitude of material extended in different directions of space. Therefore, form has two different components: ***magnitude*** and ***direction***. Based on these characteristics, the form can be measured and compared mathematically. If we add the component of ***time*** to these two factors, then we can appreciate form modification over time.

Form of both non-biological and biological entities is constantly changing. If changes in the form are slow and prolonged, we can consider the form relatively ***static***, such as the form of a mountain. On the other hand, if the speed of change is fast, we can consider the form ***dynamic***, like the form of the wave. Biological forms are dynamic, but can be studied in short intervals of time as relatively static forms. Growth, aging, and adaptation are examples of biological form modification over time.

Creation of form is a gradual process

In both non-biological and biological worlds, form is not created instantly but gradually, unit by unit. The size of the unit of the form depends at which level we study the form. For example, we can study the biological forms at sub-atomic, atomic, molecular, cellular, tissues, organs, or the final form levels. The observer establishes the scale and defines the unit. For example, assume we study a biological form at the cellular level. In this case we define the unit of form in our study as the cell. How does this unit gradually transform into the final form? Arbitrarily, we can divide this gradual process into different stages, each with a specific form. For example, one cell gradually produces ten cells with a specific organization (one stage). Those ten cells create another 100 cells with a different organization (second stage). Then, those 100 cells create 1000 cells with much more complex organization (third stage), etc. In this article, we call each stage of form formation a ***micro-state***, while the final product is a ***macro-state*** (Figure 1). If form formation stops at any stage, that step is considered the final macro-state. During the development of the form, each micro-stage does not disappear but will function as a component of the next micro-state.

Since each micro-state has its own form, one can claim that the form is ***scale-dependent***. In other words, depending which micro-state we look at, the form can appear different. Based on the above discussion, the form at each micro-state can be defined by two factors: ***units*** that make up the form, and their interaction with each other or their surroundings, that define their ***organization***.

Units

At any magnification, we can assume the form is a block composed of smaller blocks or ***units*** (Figure 2). While some units may have a more straightforward organization, others have many levels of organization. As mentioned before, the observer studying the form determines the scale, which defines the size of the unit they will study at that particular scale.

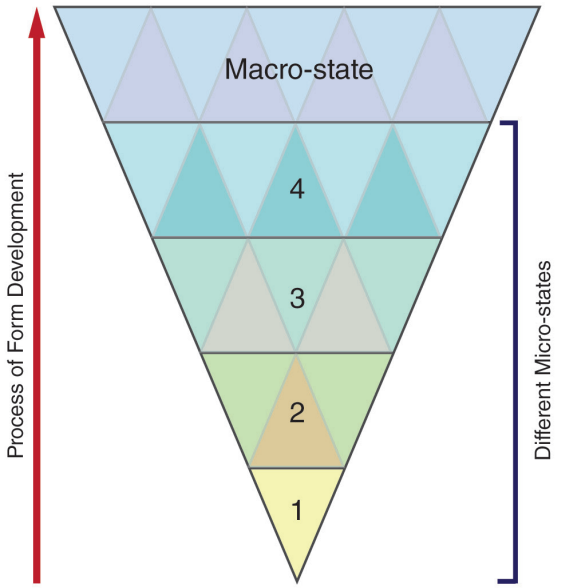

Figure 1: Development of form. *Development of form occurs during different stages. Each stage is called a micro-state (micro-states 1 to 4 are shown). The final shape is called the macro-state. As we progress toward the macro-state, the size and complexity of the form increases.*

To create a form, we need accumulation of units over time, which is why the form is not created instantly. As long as more and more units are added to the form, it will continue to develop. At very high magnification, for example at the atomic and molecular level, the differences between biological and non-biological forms disappear. At this level, the source of material for the fabrication of form is external. None of the biological or non-biological forms can create their basic atoms. However, when we define the units of the form at lower magnification, such as cells, which are a specific organization of molecules, those units can be fabricated internally, especially in the case of biological forms. Cells are not brought to the body externally but fabricated internally, even though all required elements were brought to the body externally.

Organization

Form, on one hand, is the outcome of gathering of units, and on the other hand, is a reflection of the ***organization*** of these units. The organization of units is the result of interactions between units or between units and their surroundings. In biological forms, units, such as cells, have extensive interaction with each other both in space and time. This interaction defines their organization and ultimately the form, which reflects the specific position of units in space and time.

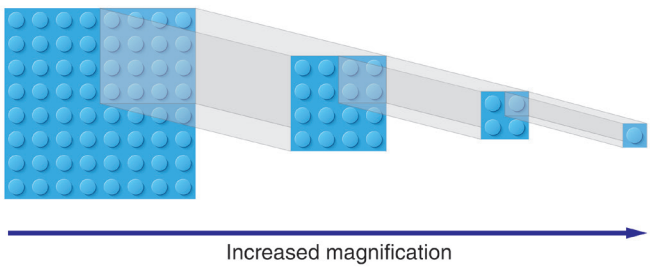

Figure 2: Units of the form. *The form can be considered as one large square, each composed of smaller squares which are considered the form's unit at that scale. The size of units can be different depending at which scale we look at the form.*

Mass form and functional form

Based on this discussion, part of the form represents merely the presence of the materials (units) that compose that form. Depending on the size of the unit we are studying, part of the form just represents the mass of the subatomic particles, atoms, molecules, collection of molecules, and so on. If we remove the organization of the units, what form will these materials have? Please pay attention, we cannot completely take all organizing and influencing forces out of our study, and there will always be some basic factors that affect the arrangement of the units. However, at lower magnification we can study the form in the presence or absence of a specific organization. In this article, the form that the material adopts in the absence of a specific organization, is referred to as ***mass form***. For example, if we drop an assembled jigsaw puzzle where pieces have a certain relation between them, we will create a pile of pieces without any specific organization. The shape of this pile of pieces (mass form) is now affected by other physical factors such as gravity (Figure 3).

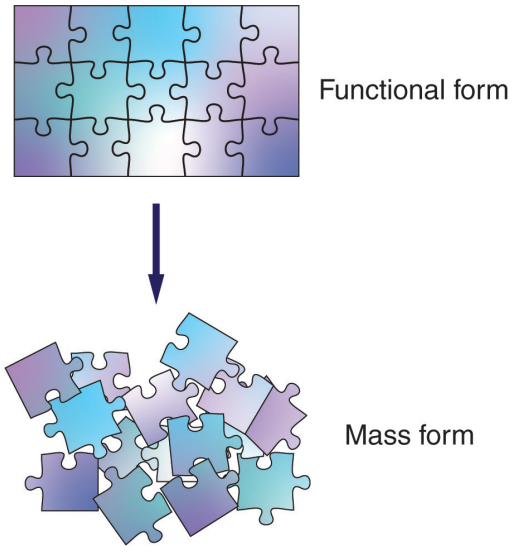

Figure 3: Mass form. *Assume we assemble a jigsaw puzzle. If we drop the puzzle on the floor, its pieces will generate a random shape regulated by physical laws. This form is representative of the collective shape of its units, which based on their physical structure will adopt a particular position in space (mass form). However, this form does not reflect a specific organization between units anymore or the form's function (functional form).*

On the other hand, the part of the form that reflects the organization between units is referred to as the ***functional form*** (Figure 3). We called this form functional since in biological forms, the organization usually produces specific properties with functional importance for the form. If the form is made from several micro-states, depending on which stage we look at, we can observe different functional forms. Each level of organization of micro-state becomes part of the organization for the next micro-state level. For example, cells create connective tissue, muscles, nerves, and skeleton, which interact to produce another level of organization, such as an organ. Each higher level of an organization depends on the existence of a lower-level organization (Figure 4).

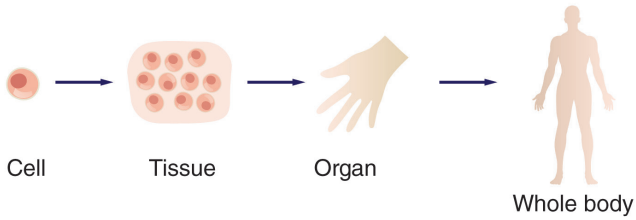

Figure 4: Functional form. *Functional form represents the organization between units of the form at that micro-state. For example, the organization of cells at different micro-states produce a unique multicellular form, such as a human. The final shape of a human is not just a blob of material stuck together but highly organized units at that macro-state performing different functions.*

When it comes to biological forms, one can argue that functional form does not stop at the level of the multi-cellular organism but continues to the level of a population of multi-cellular organisms. For example, a flock of birds has a shape that a simple gathering of birds cannot explain, and the same happens with a school of fish or colony of ants or human society. All these shapes can only be explained due to specific interactions between units, which would be the birds, fish, ants, or humans. Therefore, we can look at the form of human gatherings (their society) as a continuation of form development.

General characteristics of evolving biological forms

Both biological and non-biological forms may demonstrate all or some of the following characteristics during development of their form. However, here we are focusing on biological forms.

Encapsulation and hierarchy

During the development of the form, micro-states do not disappear but will function as a component of the next micro-state and, finally, part of the final macro-state. In other words, each micro-state still exists as the next micro-state emerges. The previous micro-state becomes a building block of the next micro-state. In this article, we call this phenomenon ***encapsulation*** (Figure 5).

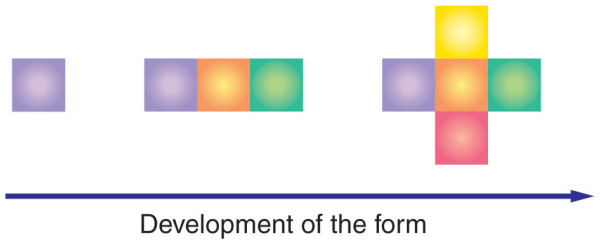

Figure 5: Encapsulation. *During the development of the form, each micro-state becomes the building block for the next stage. Each colorful block represents a micro-state.*

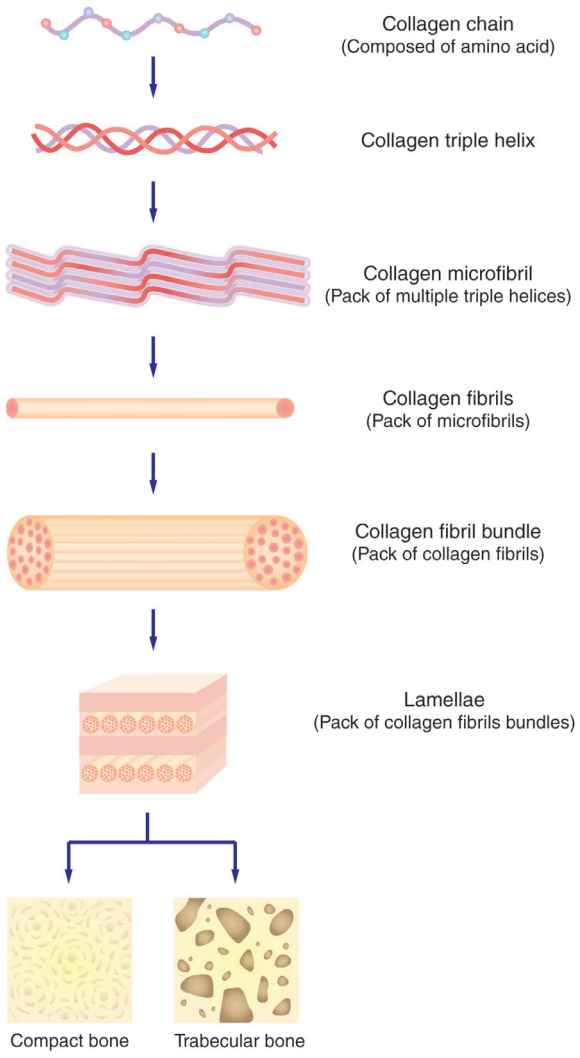

Figure 6: Hierarchical organization of form. *The molecular structure at different magnification levels creates a different micro-state and organization that produces a different form. The final form depends on the organization of these molecules and not the original shape of the molecules. In this example, collagen, one of the main structural proteins in our body, shows different levels of organization from a collagen chain to its grouping into a triple helix, which is packed to form a collagen microfibril which in turn is organized to make fibrils. Multiple fibrils form a bundle that can be organized into packs called lamellae. These building blocks can be used to produce different shapes, for example, trabecular or compact bone.*

This is important since, as we increase the magnification of our study, we can see the form and its original micro-states. However, it should be emphasized that not all the original micro-states are recognizable in the final form. In the case of biological form, cell differentiation, proliferation, and matrix synthesis may change some of the characteristics of the original micro-states. Due to this encapsulation effect, a hierarchy appears in the organism (Figure 6), as the form evolves.

Hierarchy, in turn may cause a ***fractal form*** to be created where similar patterns are repeated at different scales. Fractal form reflects the application of similar physical and chemical laws at different scales. It should be emphasized that fractal form can be observed in both biological forms, such as pattern of vessels at different magnification (Figure 7), or some non-biological forms, such as snowflakes.

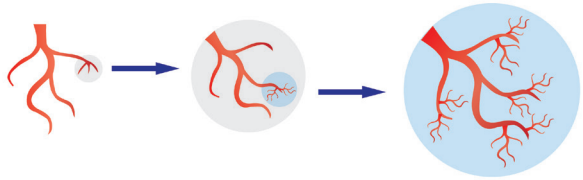

Figure 7: Fractal form. *Blood vessels are an example of a fractal structures where similar patterns are observed at different scales of the form, from lower to higher magnification.*

Feedback

At each micro-state, the interaction between units and their surroundings guides the creation of the next micro-state, which can act as a new surrounding for the previous micro-state exerting either a positive or negative feedback. Hierarchy in the organization of micro-states, allows any positive feedback to have exponential effects. In other words, in biological forms, small positive feedback can quickly create a significant effect in the form. The feedback is not just from the "bottom up" but also from "top to bottom". The larger micro-state creates

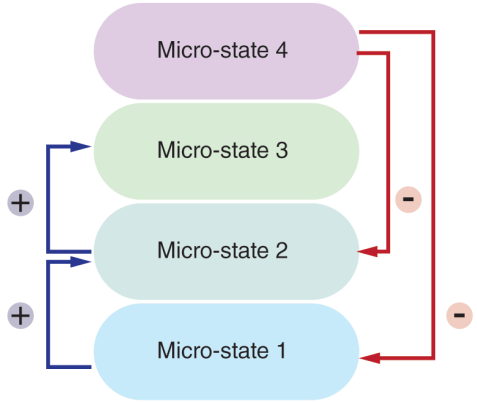

Figure 8: Positive and Negative Feedback. *This schematic shows an example of positive and negative feedback between micro-states. In this example, lower micro-states (1 and 2) exert a positive feedback on the next micro-state, while the more developed micro-state (micro-state 4) controls the growth of this signal by putting restrictions on lower micro-states (micro-state 1 or 2).*

a downward restriction or boundaries for the operation of the smaller micro-states (Figure 8). For example, different cells together create the tissue, and then the tissue regulates and coordinates the function of each cell.

Diversification

Form does not progress as one micro-state. As the size of the form increases, different micro-states are forming at the same time in different areas of the form. While these micro-states affect each other, they are more or less independent. Since the properties of these micro-states differ, we call this ***diversification*** (Figure 9). The number of diversified areas of form increases significantly as the size and complexity of the form increase.

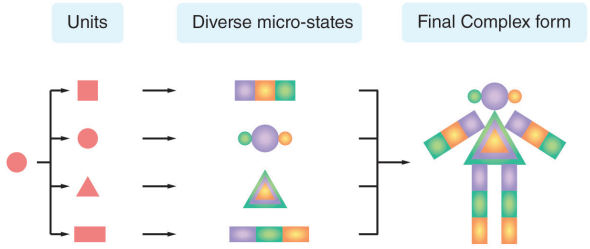

Figure 9: Diversification. *As complex biological forms develop, different micro-states start to appear, creating different outcomes in different areas of the form. The final form is a collection of all these diversified micro-states.*

Autonomy

Diversification of micro-states, gives some independence to different parts of the form. In other words, each path of diversification has some ***autonomy*** in its development. This gives the form significant adaptability. The creation process of form can continue in other areas even though one area of the creation of form has been interrupted. This can explain why malformities usually are localized to one area of the form, not all.

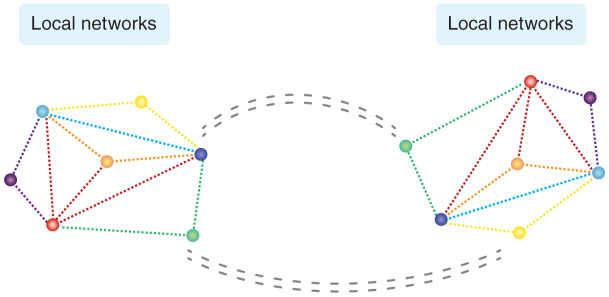

Figure 10: Networking. *Interactions between similar and diversified micro-states in different locations produce another level of organization into networks. Different color circles illustrate diversified micro-states. These localized networks automatically act as macro-environments for adjacent networks and create a more extensive network representing the whole form. (dashed lines represent interactions between networks).*

Networking

Each diversified micro-state interacts with adjacent or far micro-states and creates a network of positive or negative feedback that adds to the organization of the biological form (Figure 10). Endocrine and paracrine factors produced in the body are examples of networking.

Centralization

While at the beginning of form development, any micro-state has equal value in the creation of form, very soon, the size and complexity of the form causes a micro-state to gain a role as an organizing center that establishes coordination between different micro-states. At this stage, the form of each micro-state can no longer develop in complete autonomy, and the organizing center keeps the coordination between different parts of the form, in short and long term. For example, the central nervous system at the beginning develops among other components of the form without control over any other components. However, for different components of the form to act as one, very soon the central nervous system, through hormones and the peripheral nervous system, plays a significant role in coordination of the growth and development of different parts of the body (Figure 11).

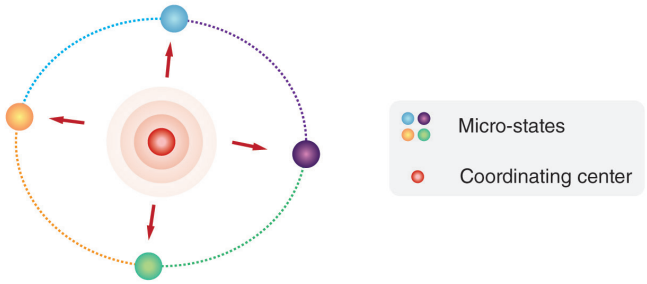

Figure 11: Centralization coordinates form development. *During the development of the form, as different micro-states develop at the same time in different locations, the need for coordination arises so the organism can perform vital functions. Different color circles illustrate different micro-states developing independently until a micro-state assumes the role of organizing center, playing an important role in the evolution of form by keeping the coordination between different parts of the form.*

Summary

In our theoretical analysis of biological and non-biological forms, some underlying commonalities, rules, and concepts arise that help explain how simple units organize into micro-states, how micro-states diversify, and establish networks under central coordination giving rise to continuously evolving complex forms. In Part II of Theory of Form we will discuss the importance of Entropy and Emergence as two main factors in the creation and evolution of form.

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