INTRODUCTION

A Recipe for Change

Life has remarkable transforming powers. Through billions of years of evolution, elementary forms are transformed into the complex creatures of today. Over nine months a nondescript egg turns itself into a human being. During a few years a flailing baby becomes a walking, talking, and reasoning adult. And over ten thousand years, human societies are transformed from small tribal communities into the complex cities and civilizations of today.

It is tempting to think that this transformative property of life depends on a single underlying mechanism. Yet when we look, we see four very different mechanisms at play. All the creatures on our planet are thought to have arisen as a result of individuals competing for survival and reproduction over many generations, through the process of Darwinian selection. Quite a different mechanism underlies the development of an egg. As a fertilized egg goes through repeated rounds of division, patterns are built up in the embryo by cells signaling and responding to each other in various ways. Development is about patterning within a growing embryo rather than competition for reproductive success. Yet another mechanism underlies learning. As an animal interacts with its surroundings, neural connections in the brain are modified. Some connections are lost or weakened while others are formed or strengthened, allowing new relationships in the environment to be captured. Learning is all about modifying neural interactions and connections. Finally we come to cultural change. Humans interact within social groups, leading to advances in tools, artifacts, and knowledge. Culture is a social phenomenon that depends on how we as humans behave and interact.

There is no obvious commonality among the operations of these various processes. They all seem to happen in completely different ways: evolution by differential reproductive success, development by cell proliferation growth and patterning, learning by changes in neural connections, and cultural change through human interactions.

It seems strange that Nature should have come up with four entirely different transformation mechanisms. Just as physicists strive for a "theory of everything," one that brings together its fundamental theories, so you might expect biologists to be seeking a unified theory for living transformations; a theory that encompasses evolution, development, learning, and cultural change. Some attempts at unification have been made in the past. Ernst Haeckel, a keen follower of Darwin in the nineteenth century, proposed a direct relationship between evolution and development. He thought that as an embryo develops, it reenacts its evolutionary history. Thus, human embryos would pass through a fishy stage, a reptilian stage, and so on, as they grow in the womb. This idea, however, was later shown to be misguided. A more recent attempt at bringing together evolution and learning was Gerald Edelman's theory of "neural Darwinism." In the 1980s Edelman proposed that neural patterns in the brain are selected for during learning in a way that parallels natural selection. This idea, however, has been heavily criticized. It seems that a unified explanation of diverse living transformations is fraught with difficulties.

Perhaps Nature really has four completely different ways of transforming itself and we should look no further. I believe this view is mistaken. In this book I want to show that recent advances in our scientific understanding have given us access to a unified picture of how living systems transform themselves, from the origins of bacteria to the creation of an artistic masterpiece. For the first time, we can begin to see a common set of ingredients and mechanisms underlying life's transformations.

Why should finding common ingredients matter? After all, studies on evolution, development, learning, and culture seem to have so far moved along quite happily without concern for overarching similarities. What do we gain from viewing them collectively? Suppose you compare the way ice melts with how water boils. These processes differ in many ways: the first involves a solid turning into a liquid around zero degrees centigrade, while the second involves a liquid turning into a gas at one hundred degrees. Yet these two transitions can also be seen to have many features in common, for both involve a change in the strength and energy of interactions among water molecules. They are different manifestations of the same underlying process. This unifying perspective gives us a deeper understanding of what is happening than what we perceive by simply viewing each transition in isolation. In the same way, looking at the common elements behind different living transformations can help us to understand the essence of each process, while also giving us a broader overview of events.

Such an approach is perhaps reasonable for evolution, development, and learning as they are all subjects of intense scientific investigation. It might, however, seem a little far-fetched to extend this approach to cultural change. We tend to think of human creativity and culture as being so complicated and special to us that science can have little to say about them. But when it comes to looking at living transformations as a whole, we see that science plays a dual role. On the one hand, science provides a source of knowledge about the world and our place within it, and thus frames our culture. On the other hand, science is a product of culture, the result of humans working collectively over many years to make sense of the world around them. It is only when we look at all types of living transformation together that we can get a clear view of this dual aspect of our outlook, of how science both frames our culture and is framed by it. We then gain not only a broader understanding of how cultural change is brought about, but also a better understanding of how it is related to our biological past.

Why has it taken so long to arrive at this collective viewpoint?

History and Form

On the face of it, war and chess are very different. War involves people fighting and killing each other, while chess has two people peacefully sitting at a board pushing some pieces of wood around. Yet, in spite of such obvious differences, these activities are closely related. First they are connected in history. The origins of chess can be traced back to the game of chatrang played in Persia in the fifth to sixth centuries, which in turn may have derived from the Indian game of chaturanga. Like modern chess, chatrang was a game for two players with thirty-two pieces on a board of sixty-four squares. Each player had an army comprising two elephants, two horses, two chariots, and eight foot soldiers. These were based on the main fighting units of the time and were the predecessors of bishops, knights, rooks, and pawns in modern chess. There was also a king and minister (equivalent to the modern queen). The aim was to capture or trap the opponent's king. The game illustrated how one army could overcome and outflank another through strategy and cunning. Chatrang was as much a war game in its time as computer war games are today.

There are other ways in which chess can be related to war that do not depend on knowing their historical links. Both can be seen to be highly competitive, involving opponents trying to overcome each other. Both are territorial, with each competitor trying to occupy or control regions. They both involve attempts to eliminate or capture elements of the opposition. And there is a strong strategic element of cooperation within each side, with units supporting each other when mounting an attack or maintaining a defense. War and chess have a similar form as well as being connected in history.

These two ways of relating chess to war, through history or form, are themselves related. Similarities in form, such as competition and territoriality, reflect the origins of chess as a game that mirrors war. Not all features of war, however, are mirrored by chess. Elements such as the physical death of humans are not a part of chess; nor is consideration of varying layouts of land or environmental conditions. Chess is always played with the same arrangement of squares and perfectly controlled initial conditions, and notions such as weather or visibility don't enter into the game. Chess is not simply a mirror of war; it is an abstraction of war that captures a particular set of elements. It is these essential features that provide the similarities in form.

The various transformations of life may also be related through history or form. It is thought that life on Earth originated about 3.8 billion years ago, and by 3.5 billion years ago our planet was populated by a diverse collection of single-celled creatures. At this stage of evolution there were no complex many-celled organisms. These evolved later, during the last billion years or so, through the process of development from fertilized eggs. Development, the transformation of eggs into multicellular organisms, arose long after evolution started, just as the game of chess arose many years after wars had begun to be fought.

Similarly, learning arose after development. The first multicellular creatures to develop on our planet were hardly able to learn. They did not have brains that allowed new relationships in their surroundings to be captured. Complex nervous systems started to evolve later. This happened through changes in the way embryos developed. Part of the development of some creatures became dedicated to the formation of brains with connecting nerve pathways. With that came the ability of an organism to learn from its surroundings, an ability that is now shared by many of our cousins, from slugs and dogs to chimpanzees. Learning came after development, just as development came after evolution.

The final type of living transformation to arise was cultural change. As humans spread over the earth in social groups, learning how to domesticate and exploit other creatures for their own benefit, they generated a food surplus. This excess, together with the human capacity to learn and innovate, allowed societies to support and develop a range of human specializations, such as builders, soldiers, artists, teachers, and administrators, leading to the formation of elaborate cultural systems. Civilizations only began to emerge within the last ten thousand years, long after the ability to learn first arose. So, cultural change is much more recent than any of the other processes.

The historical relationships seem clear—first came evolution, then development, then learning, and finally cultural change. This time sequence reflects the dependence of each process on its predecessor. The ability of eggs to develop into multicellular creatures arose through the process of evolution. The ability to learn depends on the prior development of a complex nervous system within an embryo. And cultural change is only possible because of the learning capacity of humans. The historical chain reflects a sequence of dependence.

While historical relationships seem straightforward, things are much trickier when we come to relationships of form. Are there fundamental similarities among these various transformations, or does each process operate according to entirely different principles? Attempts to identify similarities in form have been singularly unsuccessful in the past, largely because of two main types of mistake.

One type of error has to do with confounding the familiar with the fundamental. As humans, we are all familiar with the idea of designing and making things, like clothes, furniture, and houses. It therefore seems natural to use the notion of *making* as a general model for how living transformations occur. A tree or frog could arise through making just as a watch is made by a watchmaker. Instead of a human we would need a more powerful divine maker to do the work, but the principle of an external agent being responsible for the design and construction would be the same. This notion of an external agent or divine maker has a long tradition and became embedded in many religions. With the benefit of scientific hindsight we can see where the problem with this explanation lies. The ability of humans to design and create things is a complex feature that arose much later than evolution. Using the notion of making as an overall explanatory principle is employing a complex outcome to account for itself. We only fall into this trap because as humans we are so familiar with making, not realizing how this complex process itself rests on a whole series of other transformations.

It took many generations of scientists to overturn this misconception. A key step was Darwin identifying a simple mechanism (natural selection) that could account for the diverse creatures on our planet. Instead of requiring a divine maker, the evolution of life proceeds inexorably from the way organisms reproduce and interact with their environment. The struggle to establish this viewpoint left a lasting legacy. It established a major divide between our notions about human activities (design and creativity) and the way we think about biological processes such as evolution. These are very different things that we compare at our peril.

We can illustrate another type of error in the search for similarities in form by returning to our game of chess. Take the following conversation between a teacher of chess and a novice pupil:

> **Teacher:** "This piece, the knight, is like a horse because it is able to jump over other pieces."
> **Pupil:** "So, where are its legs?"
> **Teacher:** "It doesn't need legs because the player can make it jump."
> **Pupil:** "How does the player do that?"

Teacher: "By taking the horse and lifting it over the other pieces."

Pupil: "But if the player does the jumping, what is the point of having a horse?"

The misunderstanding arises because the pupil is taking the similarity between a chess piece and a horse too literally. Horses and knights are related only in an abstract or symbolic way. Indeed, it is possible to learn the rules of chess without ever mentioning horses—simply learning the way the knight moves is enough. The game would be exactly the same game if knights looked like teapots instead of horses—all that matters is the nature of the moves they make. Comparisons between knights and horses, if taken too literally, may be a distraction, a misguided analogy that confuses rather than helps.

This type of mistake has repeatedly cropped up in comparisons of different types of living transformation. A case in point is Ernst Haeckel's idea that a fertilized egg reenacts its evolutionary history as it develops. There is no doubt that the way an egg develops is connected with the process of evolution, for it is through evolution that the process of development has arisen. But in trying to take this relationship too far, with development literally repeating the path of evolution, Haeckel ends up missing the mark. He fails to achieve the right level of abstraction and winds up making false and unhelpful comparisons. Edelman's ideas about the brain operating according to Darwinian principles have similarly been criticized for trying to draw too close a comparison among distant processes.

To determine common principles we need to be working at the right level of abstraction. This can only be achieved by having a reasonable understanding of what we are comparing. War and chess can only be compared in a meaningful way after we appreciate what each entails. We don't have to be chess experts or know how to command an army, but we do need an overall idea of how board games and military encounters operate. This allows us to understand both the similarities and the differences between the activities. War and chess are both territorial, but we also understand that there are numerous differences in what a territory means in each case. In war, territory involves land, while in chess it refers to a region of the board.

In the same way, to get at common principles that underlie living transformations we need a broad understanding of how each works. And this has only recently become possible because of advances in our scientific knowledge, particularly in the fields of development and learning. Previous comparisons have been hampered by our not knowing enough about each process, leading us to confound the familiar with the fundamental or to make the wrong types of abstraction. How might we now proceed to address this issue?

Life's Creative Recipe

The sixth-century Chinese art critic Xie He came up with six ingredients that he thought were important for defining the quality of a painting. Roughly translated, these are vitality, brushwork, natural form, color, composition, and copying. All of these aspects, with the exception of color, are illustrated in *Persimmons* (fig. 1), a painting by the thirteenth-century monk Mu Qi. The six ingredients are not completely independent of each other. The vitality of Mu Qi's painting comes partly from the lively brushwork. Similarly, the composition depends on an arrangement of fruits that may have been copied. Rather than providing a set of independent features, Xie He was highlighting some key interacting ingredients that he thought would be helpful in appreciating paintings. Others might come up with a different list of ingredients, so whether or not we like Xie He's choice depends on the extent to which it helps us organize our knowledge

The same applies to the way we organize our ideas. There are many ways of presenting our understanding of processes like evolution, development, learning, and cultural change. In this book I will present a particular viewpoint that emphasizes some overarching features. I will highlight seven key principles that underlie processes from the evolution of bacteria to the workings of our brain. There is nothing mysterious about the number seven here; it is simply that the principles naturally fall into seven categories, just as Xie He found it convenient to define six principles involved in painting.

Our seven principles, or ingredients, and the way they work together define what I call *life's creative recipe*. It is this recipe that lies at the root of how life transforms itself. The evolution of diverse organisms, the development of an egg into an adult, an animal learning of new relationships in

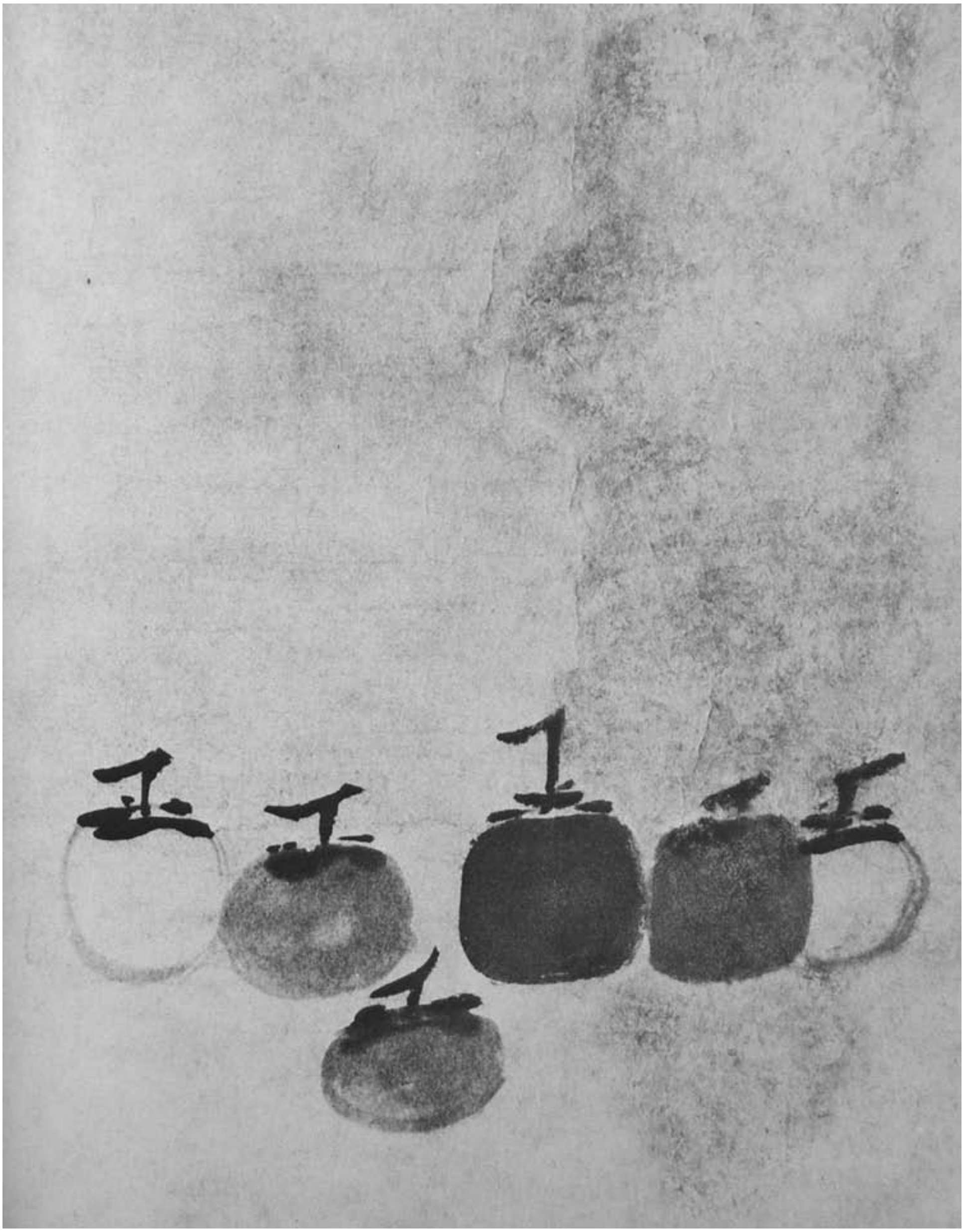

Figure 1. *Persimmons*, Mu Qi (active 1269). Daitokuji, Kyoto.

its environment, and the attainments of human culture are all different manifestations of life's creative recipe. They all depend on the way a common set of basic ingredients work together. Like Xie He's criteria for paintings, the ingredients of life's creative recipe are not independent. We will see how they interact and feed off each other. Rather than being completely separate aspects, they provide a series of connected vantage points that together allow us to see a common form behind living transformations. We will also see how they are related in history. As with war and chess, the story of life involves an interplay between history and form.

It has taken several years for me to arrive at this viewpoint. I first began thinking about these issues when writing a previous book, *The Art of Genes*. The focus of that book was on development, but it also drew on other processes, such as evolution and art. I related these processes to development through history or analogy. But their many similarities also made me wonder about the possibility of more fundamental connections. These ideas started to crystallize further after I finished writing the book and became familiar with ideas in computer science through my scientific research. I came across an insightful essay written in 1990 by computer scientist Christoph von der Malsburg, in which he identified three basic principles that were common to self-organizing systems. His main emphasis was on brain function and development, but he also noted the importance of these principles for evolution. Reading his ideas led me to take a fresh look at the foundations of biological thinking, particularly in the light of what has been discovered in recent years.

I proceeded to strip down the theories in each area of biology to their bare essentials and then reexamine them afresh, looking at what they might have in common. Of course if you look hard enough you can always find trivial things in common among any set of processes. The surprising result, though, was that the commonalities that emerged were not superficial, but went to the very heart of each process. They defined the core interactions that led to transformations in each case. I had arrived at a deeper and more unified way of seeing living transformations: different manifestations of a common creative recipe.

To convey the meaning of life's creative recipe we need to understand how it applies to each type of living transformation. We will begin with evolution (chapters 1 and 2). Evolution is the parent of all other transformations and provides us with our first clear view of how life's creative recipe works. We will then take a look at development, at how a microscopic egg can turn itself into an oak tree or a human child (chapters 3 to 5). It is only since the 1980s that we have begun to get a firm grip on how this takes place. By drawing on this knowledge we will see that in spite of many differences, the principles of development show some striking similarities to those of evolution. It is the same creative recipe but dressed in a different guise. We then turn to learning, first looking at how organisms like slugs and weeds respond to changes in their surroundings (chapter 6). These basic response mechanisms provide some of the key ingredients for learning. By looking further into how learning works, we will see that it is founded on the same creative recipe as evolution and development (chapter 7). The same recipe helps us understand how animals learn to act, recognize, and interpret their surroundings, providing the basis of human intelligence and creativity (chapters 8 and 9). All of these instances of learning are embedded in evolution and development, showing how one form of life's creative recipe may frame another (chapter 10).

We then turn to cultural change (chapters 11 and 12). This is arguably the most complex of living transformations, yet paradoxically it is the one that we feel most familiar with as we are all active participants in society. We may identify many well-known factors involved in cultural change, such as human creativity, charismatic individuals, power struggles, economic developments, and changing environments. This is the domain of history, sociology, and economics, and we may feel there is little to be learned from biology. But life's creative recipe allows cultural change to be viewed from a broader perspective. Instead of seeing it as an isolated process that separates humans from their animal relatives by an unbridgeable gulf, we will see that it is connected to other processes in both form and history. Cultural change is a fourth manifestation of life's creative recipe, one that is built upon and incorporates the other three.

Conveying such a viewpoint requires maintaining a broad perspective, while also giving scientifically rigorous explanations. This means that I have not shirked from going into scientific details where necessary, although I always aim at explanations that are accessible to a wide audience. I would encourage readers with little or no scientific background to keep going if they encounter tricky passages, as the key concepts should sink in as they are repeatedly encountered. I hope that readers with more scientific backgrounds will also have much to gain from this book by seeing areas of science treated from a fresh and unifying perspective. Some may feel that areas familiar to them are dealt with in a very selective way. Such selectivity is inevitable in the effort to cover many disciplines and the connections among them, so I hope these readers will forgive my many omissions.

To help convey my viewpoint, I do not keep human creativity at a distance from the scientific story but use it as a recurring theme throughout the book. I often use paintings to illustrate principles, subjects, or ideas I touch upon. The paintings provide visual entry points, and they also serve to remind us of the many perspectives through which we may view things. The artistic and scientific themes eventually come together toward the end of the book. We then see that evolution, development, learning, and culture form a grand cycle, a series of related transformations through which life's creative recipe comes to look back on itself.