NOTE: Formulas for abstract skills are composed of outline capital letters, but Adobe Acrobat turns them into solid capitals.

Darwin’s Construction of the Theory of Evolution:
Microdevelopment of Explanations of Species’ Variation and Change

by Kurt W. Fischer & Zheng Yan

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The process of building new knowledge can seem mysterious, and microdevelopmental analysis shows great promise for unpacking some of that mystery (Dunbar, in press; Fischer, 1980b; Granott, 1998; Klahr, 2000; Werner, 1948). How do people bootstrap themselves and others to build new knowledge? Performing such analysis, however, requires obtaining detailed information about how people build knowledge and skill in real time. Tracking changes with assessments that are performed only at widely separated intervals – the norm in developmental research – makes the process seem mysterious. For knowledge that leads to conceptual revolutions, such as Charles Darwin’s theory of evolution by natural selection, the mystery appears deep and impenetrable.

Despite its obvious promise for illuminating the construction of knowledge, microdevelopmental research has been generally neglected (a state that this book will hopefully help to remedy). Collecting data can be difficult, requiring intensive commitments of time and energy. The person being observed may not learn or develop any new skill or understanding, making the effortful data collection useless. Even if the person does learn something new, studying important learning moments is difficult, because the most important kinds of learning are typically not recognized until after they are complete. Study of the building of culturally new, creative knowledge is frequently impossible, because the importance of the knowledge is not recognized until after it has been constructed.

Fortunately this mystery can be illuminated for the theory of evolution, because Darwin himself recorded in detail his construction of the theory of evolution as he was building it. The significance of these data is enormous, because evolution is obviously the most important new theory in biology in modern times. Darwin regularly recorded notes describing his thoughts and observations during the several years in which he first constructed the theory of evolution, thus
unknowingly tracing his own construction of the theory (Barrett, 1974; 1980; Barrett, Gautrey, Herbert, Kohn, & Smith, 1987; DeBeer, Rowlands, & Skramovsky, 1960). He recorded these notes for his own purposes, to further his research and theory-building. The notes were all written early in his adult life, between 1832 and 1839, the period when he constructed the theory; and they culminated in a series of notebooks specifically about “the transmutation of species” and related issues written between 1837 and 1839. Many years passed until 1859, when he finally published his earthshaking book, *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*. For Darwin, the process of initial construction of the theory was long, slow, and full of emotion and turmoil, reflecting the usual course for acquisition or creation of complex knowledge (Gardner, 1993; Gruber, 1973).

In his remarkable book *Darwin on Man*, Howard Gruber describes in detail Darwin’s creation of the theory of evolution. When I (Fischer) first read Gruber’s description shortly after its publication, the microdevelopmental process leapt from the page. It helped that Gruber himself had studied with Piaget and frequently used developmental concepts to inform his description. Still, I was surprised at how closely Darwin’s construction of the theory corresponded with the higher levels of development of abstractions beyond what Piaget and Inhelder called formal operations (Inhelder & Piaget, 1955/1958; Piaget, 1983). Darwin’s construction of explanations of variation and change in species amounts to a case study of adult skill development, unusual because of the novelty and importance of the knowledge constructed.

In 1980 one of us had presented the first formulation of development of levels beyond formal operations into early adulthood (Fischer, 1980b), an account followed by related models by others (Basseches, 1984; Case, 1985; Commons, Richards, & Armon, 1984; Kitchener & King, 1990). Gruber’s description of Darwin’s painstaking pathway to evolution fits the levels for abstract skills amazingly well (see also Keegan, 1989).
Processes of Building New Theory: Micro- and Macrodevelopment Together

Contrary to stereotypes about sudden creative insight, Darwin took a full eight years to develop his theory, building day by day a huge number of smaller skills about biological variation and adaptation that he eventually transformed through creation of the principle of evolution by natural selection. People commonly believe that creative new ideas come suddenly – as a kind of bolt from the blue or inspiration – but the evidence indicates that the process of creating new ways of thinking is long and slow, depending on lengthy processes of microdevelopment of component skills (Gruber, 1989). Parts of the novel knowledge system may come suddenly, such as solutions to single, well defined problems within the broader knowledge domain, but even those solutions have been prepared by lengthy cognitive work beforehand.

For new ways of thinking, such as evolution (or impressionism in painting or relativity in physics), a long and complex process of learning and thinking is required before a person can produce what is essentially a new point of view – a new way of looking at many problems, a new theory. Indeed, the gradualness of this construction is not limited to original creations but applies to any form of expertise dealing with richly textured problems. A rule of thumb is that becoming an expert in a new field requires five to ten years of skill construction, which combines many microdevelopmental processes with longer term cognitive reorganization of component skills (Ericsson & Charness, 1994; Gardner, 1993).

The construction of the theory of evolution by Darwin fits this model well, and analyzing it requires considering development as involving simultaneously both microdevelopment (change in understanding over a matter of seconds, minutes, hours, or days) and macrodevelopment (change over months and years), as skills are gradually constructed and reconstructed. Indeed, the time frame is less important to the distinction between micro- and macrodevelopment than the processes involved. Microdevelopment involves combining, differentiating, and reorganizing specific skills in particular tasks and contexts, as well as generalizing them. Macrodevelopment
begins with the many skill changes wrought by microdevelopment over an extended period and adds long-term changes in capacity and framework. For detailed analysis of actual skill construction like Darwin’s, there is no simple distinction between micro- and macrodevelopment but only a broader developmental analysis that subsumes both types of processes.

Traditionally there has been a sharp distinction between macrodevelopment based on longitudinal assessment over long time spans such as years and microdevelopment or learning based on short-term changes. However, assessment only at widely separated intervals makes almost impossible the analysis of the constantly evolving process of constructing complex skills or knowledge systems. The approach that we take, called dynamic skill theory, shares with dynamic systems theory an emphasis on common processes of change across both short and long time courses. In addition, the recent surge of research on microdevelopment has convincingly demonstrated its power for analyzing short-term change and relating it to macrodevelopment, although researchers still disagree about the most useful tools for analyzing microdevelopment (Case & Okamoto, 1996; Dunbar, in press; Fischer & Bidell, 1998; Kuhn, 1995, Granott & Parziale, this volume; Siegler, 1996; van Geert, 1998).

Fundamental Variability of Skills

Understanding development of skills and expertise in an adult requires first recognizing the enormous variability in each individual in the complexity level of skill and understanding at different moments. This pervasive variability characterizes even single, coherent domains, such as understanding coral reef formation or analyzing the functions of the shapes of birds’ beaks (two domains where Darwin made important contributions). Much adult activity takes place at surprisingly low skill levels, while some activity occurs at high levels (Fischer & Granott, 1995; Granott, 1994). Low levels are common when a person encounters a novel or unfamiliar task or when a task is not challenging, requiring only low-level functioning (Fischer, 1980b; Fischer, Yan, McGonigle, & Warnett, 2000).
Even for long-term development, people evidence substantial variability, with the upper limit on skills varying as a function of contextual support, as illustrated in Figure 1 for optimal & functional levels in adolescence and early adulthood (Fischer, Rotenberg, Bullock, & Raya, 1993; Kitchener, Lynch, Fischer, & Wood, 1993). Assessments that support high-level functioning through priming and practice produce a high upper limit on performance, called the optimal level. Assessments that provide no such support produce a low upper limit, called the functional level. The gap between optimal and functional levels is termed the developmental range. The same person routinely produces skills that vary up and down within this range, showing a different “stage” depending upon whether the context provides support for high level functioning. Key components of support are familiarity with a task and immediate priming of its key components.

Optimal level commonly shows stage-like spurts in performance at specific ages, as illustrated in Figure 1, whereas functional level does not show systematic spurts. The four levels of abstractions emerge at approximately 10, 15, 20, and 25 years of age, respectively, for single abstractions (Ab1), abstract mappings (Ab2), abstract systems (Ab3), and systems of abstract systems (Ab4), which form principles. Before the development of abstractions, earlier levels of concrete representations develop and lay the foundation for abstractions, such as representational mappings (Rp2) and representational systems (Rp3), which emerge at approximately 4 and 6.5 years. Based on research on spurts in relevant skills, these ages of emergence appear to be relatively stable across people for familiar domains that are important to a person or that are facilitated by education (Fischer, Pipp, & Bullock, 1984; Fischer & Rose, 1994).

Darwin constructed the main tenets of his evolutionary theory when he was between 22 and 30 years of age, the period during which the two highest levels of abstract skills typically emerge.
Each of these levels will be explicated later in terms of development of Darwin’s thinking about variation and evolution.

In ordinary activities, people show great variability in skill level over short time periods, only occasionally functioning at their upper limit, and this variability is essential to the processes of construction of new skills. Contrary to the common cognitive image of people as scientists or philosophers functioning with high-level logic, people live in a practical world in which they routinely adapt their activities to fit the immediate demands of each situation (James, 1975; Peirce, 1878; Wittgenstein, 1953/1953). Much of the time, the tasks that people face do not require high-level skills. From an ecological perspective, low-level activity fulfills important adaptive functions for coping with simple, concrete realities, such as preparing dinner, eating, conversing about the day’s activities, and washing dishes. More complex, abstract activities such as explaining variations in species, diagnosing problems with a car engine, or analyzing the problems with political institutions have an important place in human cultures, although they are not required for most daily activities.

**Dropping to a Low Level to Build New Skills**

For both concrete tasks and abstract ones, construction of a new understanding (microdevelopment) starts with a sharp drop in the complexity level of skill, usually far below both functional and optimal levels. To build new skills or to change old ones to fit a new task, people must move their skill *backward* to a low level in a given domain in order then to gradually construct a higher level skill. Without this process of regression and reconstruction, skills remain stuck in old forms at a higher level that is adapted to a prior situation, not the new one that is required (Fischer et al., 1993). That is, staying at a high level fixes lower level skill components in old forms, while building new high level skills requires first reworking lower level ones by moving down to action at those lower levels and thus rebuilding components to eventually make possible the required new high level skills. That is, to adapt to new situations, people need to move down to a lower level so that they can reorganize their skills at that level for the new situation.
Granott (1993, this volume, 1998) has described compellingly how people produce these backwards transitions in order to adapt to new tasks and reconstruct their activities and understandings. Faced with a Lego robot for the first time, adults routinely regressed to egocentric sensorimotor actions that had many similarities to infants’ activities, failing to differentiate their own actions from properties of the robot. Granott found that even when adults seemed to have constructed a higher level skill for understanding a robot, minor changes in the situation produced regression once again, with a further need for new reconstruction. They thus showed repeated scalloping – building gradually to a higher level skill and then falling back down, building gradually again and once more falling back down, and so forth.

Yan (1998) found similar backwards transitions when graduate students learned how to use a computer to do simple statistical analyses over four class sessions as part of a course (Fischer et al., 2000). The students developed backwards to single representations (not all the way to actions) and then gradually built new more complex skills. For example, Figure 2 shows this process of repeated scalloping in the skills of one student in her first class session. She began at a low level, moved up to a higher level as she solved one subtask, moved down again to a lower level with a new subtask and then built up to a higher level for it, and so forth. Note that she demonstrated only representational systems (Rp3) as her highest skill, even though other evidence showed that she commonly used higher levels of abstraction when appropriate in class. Similar patterns of skill levels obtained for other students too. Because the computer task required only representational systems and perhaps occasional single abstractions, people used skills at those levels, not superfluous higher ones.

The microdevelopmental process of repeating skill construction with variations (scalloping) pervades learning of new skills. These recurring growth spurts are similar to the circular reactions
that pervade young children’s activities, as they repeat an activity many times with the apparent
goal of mastering it (Baldwin, 1894; Piaget, 1936/1952; Wallon, 1970). Similarly Darwin showed
repeated reconstruction of understanding as he built the theory of evolution – rediscovering, for
example, the principle of natural selection repeatedly until finally he could generalize it to become a
central building block of his theory. At several separate places in his notebooks he described the
core principle of evolution by natural selection, but the early versions did not stick with him. Instead
he seemed to lose the significance of the principle and then had to invent it again later.

Granott and her colleagues Fischer and Parziale (1999) also describe how people bootstrap
their activities during microdevelopmental regressions to low-level skills, using a process called
bridging, in which they establish a target shell to guide their efforts to learn a task or solve a
problem. In bridging, people function at two levels simultaneously – the (low) level at which they
perform a new or problematic task and the (higher) level of a bridging shell to mark the kind of skill
they seek to build. The shell includes empty slots, like algebraic unknowns, to be filled in through
activities with the task. In Granott’s study of lego robots, for example, one dyad used a shell based
on the concept of “reaction.” Framing the robot as producing a reaction, they set up a shell that
initially had two unknowns – the input that caused the reaction and the change in activity that came
from the reaction. Typically a shell is based on prior knowledge about related tasks, linking the
known and the new and thus facilitating understanding the new. Teachers, mentors, or friends can
provide a bridging shell (Case & McKeough, 1990; Dunbar, in press; Ericsson & Charness, 1994;
Rogoff, 1993), and people often provide shells for themselves.

Solving novel tasks seems to require bridging shells to guide the creation of new
knowledge, as when Darwin sought a naturalistic explanation for variations and changes in
species. In the early part of his voyage on the Beagle, he used concepts from geology as bridging
shells – for example, the theory of formation of coral reefs. Later he used some of his own earlier
conceptions, such as the theory of coral reefs, as bridging shells for his later work. Through many
such microdevelopmental processes of building specific skills to solve specific problems, he gradually laid the foundation for the macrodevelopmental transformation of his thinking through the integrative principle of evolution by natural selection. Within each shorter period he built many individual understandings through microdevelopmental processes, with the long-term result being construction of a novel, revolutionary framework for understanding variation and change in living things. Each of the following four sections outlines some of the microdevelopmental changes through which Darwin built specific understandings at each of the four skill levels, ultimately leading to the macrodevelopmental construction of the theory of evolution.

**Darwin’s Starting Point: The Social Context of Understanding Variations**

Like all scientists, Darwin began with the viewpoints of his time, which he learned from his highly educated family and at school. Many scientists were studying nature, and their study was structured by a Christian belief system concerning creation, a nearly universal belief in a narrow interpretation of the Biblical account of creation: The Earth and its inhabitants were the products of a Creator, who made the world in six days about 6000 years earlier. One purpose of much science was to document and catalogue the marvels of physical and organic nature in order to demonstrate the supreme intelligence and necessary existence of the Creator, who devised such intricate and perfect structures and creatures. Eventually, Darwin built a different view, showing how the imperfections and irregularities found everywhere in living organisms indicate that the design of nature was achieved not by an omniscient inventor but by a groping evolutionary process. He began, however, with the standard scientific view of his time.

In 1831-32, before the 22-year-old Darwin began his major scientific work during his voyage as the naturalist on the British naval ship H.M.S. Beagle, he thought of the world in terms of the conventional religious beliefs of his day: There were two separate worlds, the Physical World of rocks, minerals, gases, and the like, and the Organic World of plants, animals, and human beings. God created the two worlds separately, on different days during the week of creation, and they
remained separate in their fundamental nature. He created the two worlds in perfect balance, with each creature having a specific place and role in the physical world. There was no fundamental interaction between the two worlds beyond the fit that God had ordained, no basic change in one caused by the other.

Each of these concepts – the physical world and the organic world – required a minimum of a Level Ab1 single abstraction, a skill level that sustains the formation of intangible concepts, such as consistency, justice, physical world, or organic world (Fischer, Hand, & Russell, 1984).¹ The concept for physical world, denoted by the skill structure \textit{WORLD PHYSICAL}, involves nonliving materials, such as rocks, soil, water, and air. The concept of organic world, denoted by the skill structure \textit{WORLD ORGANIC}, involves living things, such as plants, fish, and farm animals. The concept of Creator was also a single abstraction at its simplest, \textit{CREATOR DIVINE}, involving a notion of God not simply as a (concrete) king sitting on his throne in the skies, but instead as an intangible agent who somehow created the physical and organic worlds. Starting with these relatively simple abstractions, Darwin and his peers could build up more complex skills, such as understandings about relations between the Creator’s actions or intentions and properties of the physical and organic worlds. However, at their simplest and by themselves, the concepts of physical and organic worlds required only two single abstractions. These concepts represented the primary starting point for Darwin’s eventual creation of the theory of evolution by natural selection.

The general skill levels for Darwin’s construction of the theory of evolution by natural selection are outlined in Figure 3. Abstractions develop through four main optimal levels, indicated in the lefthand column. The skill structures in the table are defined broadly to emphasize Darwin’s

¹[Editor: This note could go in Figure 3 instead of in the text.] Each set in abstract skills is designated by words in outline capital letters, with the main set or agent indicated by larger letters and the categories or subsets indicated by smaller letters. A skill structure is delimited by brackets, and relations between sets are denoted by lines or arrows. Level Ab1 skills involve single sets, Level Ab2 mapping skills are denoted by a single line relating sets, Level Ab3 system skills by a two-headed arrow between sets, and Level Ab4 by a two-headed double-line arrow between sets. Words in lower case letters next to a line or arrow define the relation. Further explanation of skill structures and notations can be found in several sources (Fischer, 1980a; Fischer & Rose, 1994).
general conceptions about how the organic and physical worlds interact. Here in the text, on the other hand, the skill structures are defined more specifically with concepts about the organic and physical worlds that Darwin actually used, such as death of an animal (organic world) or growth of a mountain (physical world). In skill formulas large words in capital letters denote abstract concepts, while small words below or above the large ones denote specific characteristics or subsets of those concepts. Lines and arrows denote relations between abstractions that are characteristic of different levels.

Insert Figure 3 about here.

At age 22 as Darwin was about to begin his work on species variation and evolution, he was not limited to these simple concepts, these single abstractions about variation in the world, but he already had more sophisticated skills. Based on the norms for emergence of levels of abstraction, he could use skills involving relations between abstractions (abstract mappings and systems), especially for familiar topics and in supportive contexts. The capacity to construct abstract systems coordinating several abstractions typically emerges at about age 20, while that for coordinating such systems in terms of general principles does not usually emerge until age 25 (Fischer & Rose, 1994; Kitchener et al., 1993). In some domains, he was already sophisticated about biology and geology, and he used these areas of high-level skill to provide microdevelopmental bridges to help him construct understandings of species variation and evolution. During the voyage of the Beagle his capacity to construct and understand principles for coordinating abstract systems emerged and developed. Late in the voyage and in the following three years, he vividly demonstrated this capacity in his extensive discussions in his notebooks about principles for making sense of variations and adaptations across species.
The first break in the existing point of view about variation and evolution came from geologists, who were finding it difficult to reconcile large classes of geological facts with the Biblical stories of creation and the flood. In particular, the Principles of Geology, published by Darwin's mentor Charles Lyell in three volumes between 1830 and 1833, demonstrated that the geological time scale was much longer than 6000 years. The publication of Lyell's books was a crucial event in Darwin's life. In December of 1831 Darwin sailed on the Beagle to help with its mission of charting the coastal geology of South America and making various other scientific and navigational measurements. He took along Lyell's first volume to read and use as he studied geological formations and organic life in the many locations he visited during the five-year voyage, including the Galapagos Islands that he later made famous for its variety of species.

During the several years following publication of this landmark geological work, many scientists came to agree with Lyell's conclusions about earth's physical changes, including that the time elapsed since creation of the physical world was much more than 6000 years. The consensual interpretation became that God had created a set of universal natural laws that accounted for the geological changes. The geological changes characterized the physical world, however, and were not seen as implying anything about changes in the organic world. Acknowledging that natural laws operate on rocks was vastly different from acknowledging that they operate on human beings. A common argument was that the Earth was created first and then some time later, the Creator made plants, animals, and people. Here is where the analysis of Darwin's thinking about evolution begins.

A central idea from geology that pervaded Darwin's work on evolution was gradualism: Universal natural laws produce gradual change in small amounts, but over long periods of time, the small changes add up to make enormous changes (Keegan, 1989). In geology, small, gradual changes combine to create powerful qualitative changes, such as strata of soil and even mountains.
and seas. In biology, Darwin gradually applied the same principle, eventually extending gradualism to explain enormous changes in the organic world over long periods.

Darwin assimilated Lyell’s geological principles during the voyage of the Beagle and made extensive field observations in many locations in South America. Gradually he began to recognize that there were important interactions between the physical world and the organic world. In constructing his new skills for understanding organic and physical variations, he built on his earlier understandings of two kinds of interactions – the death of defective or deviant creatures, and selective breeding of animals and plants by people. Each of these skills he built through a series of microdevelopmental steps.

Regarding the death of deviant organisms, when an animal, plant, or person has a major physical defect, that organism will usually die or fail to reproduce. A sparrow born with defective wings, a deer with part of a leg missing, a monkey that is blind, or a cactus with no chlorophyll will quickly die in their natural environments. Because of the nature of the physical world in which particular organisms live, major physical defects lead to death. Darwin understood that in this way the physical world acts on the organic world to eliminate deviants, a skill structure denoted as \[ \text{WORLD}\overset{\text{deviant}}{\text{REQUIRE}}\overset{\text{DEATH}}{\text{ORGANISM}} \]. This skill was a Level Ab2 abstract mapping relating characteristics of the physical world (requirements for survival) to characteristics of the organism (death from deviance from requirements), as shown in Figure 3. The relation of the two worlds also required a differentiation of the organic world into two distinct types, deviant and normal (not shown in Figure 3), \[ \overset{\text{ORIGINISM}}{\text{DIFFER}}\overset{\text{ORIGINISM}}{\text{DEVIAN}} \], a distinction that proved later to facilitate Darwin’s use of the concept of natural selection.

Before Darwin’s theory, scientists interpreted this relation between the physical world and the organic world in a way that required no change in the conception of two separate worlds. Since the Creator had devised all creatures to fit their particular environmental niche, deviants would naturally die. There was still no true interaction between the physical and organic worlds.
The second understanding that Darwin built on was selective breeding of animals and plants (which he later studied himself in a hobby of selectively breeding pigeons). Within the organic world, when breeders wanted pigeons with a particular characteristic, such as large chests to provide more meat for eating, they would selectively breed several generations of pigeons with larger chests and thus produce offspring with large chests. In general, people (a special part of the organic world according to the Christian framework) could produce major changes in desired characteristics through such selective breeding, $\text{PERSON} \xrightarrow{\text{select}} \text{ORGANISM} \xrightarrow{\text{breed}} \text{ORGANISM} \xrightarrow{\text{changed}}$. This kind of human selection eventually proved to be a useful bridge to help Darwin think about inheritance and natural selection in evolution. In this way his skills for understanding both deviant organisms and selective breeding served later as bridging shells to guide his construction of skills for analyzing evolution by natural selection.

On the Beagle voyage, Darwin’s interest at first was in geology, and his first major step toward conceptualizing the pervasive interaction between organic and physical worlds involved geological formations – coral reefs – which commonly form large rock-like barriers in the ocean in the vicinity of islands or continental coasts. During the voyage, Darwin confirmed Lyell’s observations and hypotheses about coral reefs, and gradually began to build his theory of coral reef formation and evolution, which by the end of the voyage, he had built into a broad theory that is still valid today. The theory built on the observation that corals, which are living organisms that live in huge colonies, actually construct the reefs through their shells, with the colonies creating massive rock formations.

In its simplest form, this concept involved a Level Ab2 mapping of the organic world of the coral onto the physical world of ocean reefs: Changes in the organic world of corals produce changes in the physical world of reefs, $\text{ORGANISM} \xrightarrow{\text{change}} \text{CORAL} \xrightarrow{\text{world}} \text{REEF}$. This simple conception neglected any back-and-forth relation between the organic and physical worlds, focusing only on one dimension of the relation between coral organisms and physical reefs in the ocean, but still it
established a clear link of organic world affecting physical world, moving beyond the separation that pervaded common belief. Of course, Darwin moved rapidly beyond this simple conception to a sophisticated analysis of the interplay of influences in the formation of coral reefs.

Central Theme: Relations among Variations in Organic and Physical Worlds

By the end of the Beagle voyage, Darwin had constructed a sophisticated multi-dimensional theory that went beyond Lyell’s ideas to explain both the formation of coral reefs and their evolution over long geological time periods. This theory also presaged the theory of evolution by natural selection, with its dynamic interaction of physical and organic worlds along multiple dimensions. Of course, Darwin did not recognize these connections initially but had to gradually construct understandings of the sophisticated interactions embodied in species’ variation and evolution. His new skills involved several dimensions of variation in organism and world and thus required Level Ab3 abstract systems, which typically emerge for optimal level at about 20 years of age (Fischer & Rose, 1994).

The coral-reef theory specified variations in land masses, sea floors, water depth, sunlight under water, reef height, and coral growth. Corals grow only in relatively shallow, sun-lit waters, and each generation of organisms builds its hard skeleton on the foundation of skeletal remains laid down by preceding generations. As land masses rise over hundreds and thousands of years, the floor of the sea nearby slowly recedes, making the water deeper and lowering a reef under more water. To stay close enough to the surface of the sea to obtain the sunlight they need to survive, new corals must grow on top of the skeletons of dead corals, and thus coral reefs slowly form on top of previous generations of corals.

Dealing with the several dimensions and components of coral reef variation and evolution required several related abstract systems. In one skill, the lowering of the reef into deeper water (because of subsidence of the sea floor) leads gradually to death of the old coral and growth of
new coral on top, which in turn produces a higher reef. Another part of
the dynamic interaction in coral reef formation is that the depth of the ocean floor varies with the
height of the land mass nearby (two aspects of the physical world). The ocean floor lowers as an
island rises in the Pacific Ocean or as mountains grow on the western coast of South America,

\[
\text{DEEPER NOW} \xrightarrow{\text{match}} \text{HIGHER NOW} \\
\text{SEAFLOOR} \xleftrightarrow{\text{LAND}} \text{LESS BEFORE} \xrightarrow{\text{LOWER BEFORE}}
\]

Consequently coral reefs tend to form where there has been a visible upwelling of land and a corresponding drop in the ocean floor.

The interaction between ocean floor and upwelling of land involves a relation of compensation or match, in which the rising of the land corresponds to the dropping of the ocean floor. The interaction between coral growth and reef formation also involves a correspondence, but one that involves adaptation, a central process in evolution. The corals adapt to the changing light conditions relating to ocean depth. Such nonobvious correspondences and adaptations were essential to Darwin's work on geological and biological evolution, grounding his many later achievements in biological explanation: Variations in the organism involve adaptations to variations in the physical world where the organism lives. Coral reefs adapt to sinking ocean floors by growing to heights that keep them at the right depth from the surface in order to obtain the sunlight that they need to grow. This kind of adaptational argument became central in Darwin's theory and research.

Along with the coral-reef theory, Darwin also began to build an interactive view of variations across species. During the Beagle voyage, he made extensive notes about the many animals and plants he saw and the many specimens that he collected. His notes describe, for example, the variations in species that he saw from island to island in the Galapagos. The notes were concerned primarily with cataloguing, classifying, and describing what he had seen; but he also began to attempt seriously to explain his observations.
One key example involved the adaptations of the beaks of the many species of Galapagos finches to their feeding habits. For finches – and eventually, Darwin saw, for other organisms – the physical and organic worlds were intimately related. Darwin observed that each species of finch had a type of beak that fit its needs for obtaining the kind of food it ate. For example, small tree finches have small thin beaks that are effective for catching the insects that they eat, while woodpecker finches have large thick beaks that fit the needs of hammering holes in wood.

Darwin found similar adaptive matches everywhere he looked, and he described and explained many such adaptations throughout his long career as a biologist. Birds’ and bats’ wings are adapted to the kinds of flying that they need to do in their species’ specific niche. Monkeys’ legs and arms are adapted to the kinds of locomotion that they use in their niche. Many earlier scholars had noted some such matches and marveled at God’s creation of such matches, but Darwin built a framework for analyzing the matches in order to understand adaptation and evolution. This pattern of adaptive match became an essential building block for the theory of evolution by natural selection.

Once Darwin had built skills for complexly relating the organic world of coral to the physical world of reefs, the organic world of finches’ beaks to the physical world of food sources, and other explanations of variations among species, he could use these skills as microdevelopmental bridging shells to guide his construction of the broader theory of evolution. Darwin began to realize that organisms undergo physical and behavioral changes that allow them to adapt to variations and shifts in their environments. Also, from fossil finds, he knew that some species had changed dramatically over time, and others had died out completely. Here was another piece of the picture, skills that related changes in species over time. For example, he hypothesized that all the species of Galapagos finches might have come from one species that happened to fly to the island,
reproduced, and then changed over time to take on many different forms.

With many pieces of the puzzle in hand, Darwin now struggled to construct a theory that would explain all that he had learned. How and why did these adaptations and eliminations of species take place? As he searched for solutions, he used the coral-reef theory, the examples of adaptive variation, and other analyses to support building broader explanations of adaptive variation.

Resolution: Principles for Unifying and Explaining Systematic Variations

As the Beagle voyage came to an end in 1836, Darwin continued to work toward finding a principle to coordinate and explain his many observations of species variation and adaptation. In his microdevelopmental struggle Darwin created not only successful explanations but also ones that failed. He labored mightily, for example, with concepts of multiple creation, as well as multiple extinction. What if God had created new species several times, not just once, with each creation producing animals and plants especially adapted to particular environmental niches? What if somehow many organisms had died out at one particular time, as described in the Biblical story of the flood? He was struggling to construct a principle that would tie together the many adaptive variations into a coherent whole and explain them. That is, he was striving to build a Level Ab4 skill, a system of abstract systems integrated in terms of a broad principle, as shown in Figure 3.

All Darwin’s first attempts at creating a general principle to explain variation and adaptation proved unsatisfactory. One of the principles that he tried was hybridization – that interbreeding between species somehow produced new species – but for this and other processes of inheritance he was at a major disadvantage because of the virtual nonexistence of genetic knowledge in his lifetime.

Despite the failure of these first attempts at principles, some of them turned out to be productive mistakes. Although the explanations failed in themselves, they sometimes created
useful bridges that helped Darwin in his later work. One particularly interesting principle that he tried in 1837 and abandoned was monad theory, which provided important concepts for his eventual success in building the theory of evolution by natural selection (Gruber, 1981). A monad is a hypothetical entity that Darwin considered to explain multiple creations and extinctions. At some historical point, a monad (like a small germ cell with a fixed life span) comes into existence, engendering a new species. The species reproduces and radiates into many distinct species, inhabiting different parts of the physical world. Eventually, however, the life span of the monad is reached, and all species coming from the monad become extinct.

Darwin considered monad theory briefly because it could perhaps explain the exuberant radiations of new species as well as the massive extinctions that fossils seemed to show. For example, if the original species of Galapagos finch was a monad, then over time it would engender new species for different niches in the islands through the process of growth along a monadic tree, 

\[
\text{monad tree}
\]

\[
\begin{array}{c}
\text{FINCH X1} \\
\text{ORGANISM} \\
\text{FINCH X2} \\
\text{change over time} \\
\text{FINCH X3}
\end{array} \rightarrow
\begin{array}{c}
\text{WORLD} \\
\text{NICHE A} \\
\text{WORLD} \\
\text{NICHE B}
\end{array}
\]

That is, the first finch species would change over time into several new species that fit into different niches.

Darwin knew that this principle was extremely speculative. Although he was publicly circumspect about speculation and careful always to present concepts in terms of the empirical evidence for them, in private he freely searched for concepts to explain species variation and adaptation. Before long, he rejected monads, but in the meantime the idea had given him a powerful new tool. When he thought about how monads might grow new species, he began to draw tree diagrams to capture the radiation of species. Although he eventually concluded that monads do not exist, he kept the idea that species radiate into new species in tree- and bush-like patterns over long periods of time.
Darwin's notebooks show that he created this tool, the tree of evolutionary change, as a result of his brief efforts to use monads to create a principle to explain multiple creations and extinctions. His work on coral reefs also served as a bridging shell to this tool, as when he said in his notebook, “the tree of life should perhaps be called the coral of life, base of branches dead, so that passages cannot be seen” (Gruber & Barrett, 1974, p. 143). Once again, microdevelopment occurs through bridging, in which a shell created for one set of skills (monad theory or coral reef theory, respectively) can be adapted to support construction of another set of skills (evolution by natural selection).

In late 1838 and early 1839 Darwin gradually worked out the solution, the theory of evolution by natural selection. In an important event in 1838, he read Thomas Malthus’ *Essay on Population*, which argued that every species, including human beings, is capable of reproducing itself at a much greater rate than its physical surroundings can support. Darwin had encountered this idea in earlier years, reading scientific descriptions of the superfecundity of species. During his travels on the Beagle, he had seen many examples of species reproducing excessively and competing for resources.

During several months of intense microdevelopmental construction, Darwin put together all the concepts to build the principle of evolution by natural selection: The high rate of reproduction, he realized, leads to competition for the means to survive and reproduce – a struggle for existence – which in turn results in natural selection of the species members who fit the requirements of the physical world.

Even with this important realization, however, he did not simply build the principle one day. Over several months he seemed to understand it several times based on what he wrote in his notebooks, but he was not quite able to sustain the new skill and make it work consistently. By early 1839, he had built and rebuilt the skills for the principle so frequently that he could sustain the
principle as a generalization across many domains, and the theory of evolution came into existence.

The notebooks and other records show that repeated reconstruction and eventual generalization occurred for a number of key components of Darwin’s framework. For example, the concept of the tree of life receded for some time after its first flowering, so that despite the evidence in his notebooks Darwin himself eventually attributed it to some time after 1844 (Autobiography, pp. 120-121, cited in Gruber & Barrett, 1974, p. 117).

The principle of evolution by natural selection requires a Level Ab4 skill that systematically relates various abstract systems involving variations in organisms and their physical worlds. For example, Galapagos finches’ beaks are well adapted to their particular environmental niche because the finches evolved that adaptation through natural selection. The first finches to migrate to the islands were not specifically adapted to the niches there, and through selection their descendants gradually evolved adaptations specific to distinct environmental niches (A and B in the formula).

This is the essence of the evolutionary principle. The characteristics that organisms possess show variations, which are somehow inherited. Darwin did not know about genetics, which had not yet been discovered, but he knew that people could practice selective breeding (artificial selection) with animals and plants, like pigeons, dogs, cows, and wheat. Because of the high rate of reproduction, organisms compete for limited physical resources, such as food, water, and shelter. Natural selection occurs because those that compete more successfully are more likely to survive and reproduce, passing on their inherited characteristics to their offspring. Evolution will thus occur as a matter of course through the mechanism of natural selection.
Note that a number of factors contribute to evolution (including many more than those explicitly mentioned on this page) and they are coordinated through the principle of evolution by natural selection. Darwin’s and other scientists’ specific skills involve not just one principle of evolution, but a number of related principles dealing with variation, adaptation, competition, inheritance, and much more. Darwin spent the rest of his scientific life elaborating principles by which the factors of evolution worked in diverse domains, and other scientists continue that endeavor today. The whole of 20th-century biology is built on the foundations of Darwin’s evolution by natural selection, which he constructed initially over a period of eight years between 1831 and 1839.

A Note on Socioemotional Repercussions of Darwin’s Theory

This essay focuses on microdevelopment in Darwin’s construction of the theory of evolution, but there is another story that needs to be mentioned – the socioemotional side of Darwin’s efforts. Emotions and social relationships played a central role in Darwin’s efforts from start to finish. He began with the traditional Christian view of creation, and he knew that many people, including his mother and other family members, would be upset by the new view that he was creating. Just as he was reaching a stable formulation of the principle of evolution by natural selection in 1838, he had a vivid dream of being executed. He knew that his theory would be bitterly attacked when it was published and that his life and the lives of his family might be endangered. That seems to be the main reason that he delayed publishing his theory of evolution from 1838 to 1859. Another powerful story to be told is how socioemotional forces shaped Darwin’s developmental pathways.

Along with these anxieties, Darwin was simultaneously excited by the theory and methods that he was creating to understand species variation and change. He made it his life’s work to build not only the theory of evolution but a wide range of branches of biology that are informed by it. Even in the twenty-first century, it is hard to find a part of biology that was not shaped powerfully by Darwin’s projects. In constructing these many scientific achievements, Darwin embodied the
processes of circular reaction and bridging – repetition of problem-solving over and over with variations, and use of skills from past successes as bridging shells for new problems. From 1838 until his death in 1882, Darwin worked on dozens of projects that not only elaborated the theory of evolution but applied it to a wide range of topics, ranging from barnacles to human facial expressions. These later works were important in themselves, each elaborating new explanatory principles for a domain of science. They were also essential to the eventual success of the theory, making evolution ever more difficult to dismiss. Without them the grand theory of evolution would have been less powerful, less creative, and less successful (Gruber, 1981).

Conclusion: Development of Deep Understanding

Micro- and macrodevelopmental analysis of Darwin’s construction of the theory of evolution illuminates how new knowledge is constructed. Darwin gradually built his skills for analyzing variation and change in organisms in relation to variation and change in the physical world. The entire sequence required eight years for the full formulation of the theory, with many microdevelopmental fits and starts along the way. He even built important concepts, such as natural selection and the tree of life, and then could not sustain them and had to build them again. In the long term, Darwin moved from the level of simple abstractions about the Organic World, the Physical World, and the Creator through three further levels of coordinating and differentiating abstractions until he could unify them all in terms of the principles of evolution by natural selection.

In building many distinct abstract skills for particular biological problems, such as the formation of coral reefs and the adaptation of finches’ beaks, he built new knowledge by using some of his previous skills to form bridging shells. This repeated bridging construction in microdevelopment allowed him eventually in macrodevelopment to formulate broad principles that incorporated the earlier skills as special instances. For example, the theory of coral reefs had the formal structure of evolution implicit in it, specifying how coral organisms adapted to long-term changes in the physical world (lowering of the ocean floor) and simultaneously changed the
physical world through their own activities (forming coral reefs). Darwin used this theory to bootstrap his later work, seeing the evolution of species as a tree of evolutionary life, similar to corals growing upward in the ocean on top of their ancestors.

Eventually, and gradually, he created the broad principles of evolution, the deep understanding that subsumed coral reef theory as a specific case. None of the general principles themselves were realized in one moment, but Darwin constructed and reconstructed them until they became stable skills that he could use consistently and explain to other scientists, as Howard Gruber describes eloquently in his insightful book *Darwin on Man*.

### List of Figures

Figure 1. Developmental Range for Abstract Skills

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### References


Figure 1. Developmental Range for Abstract Skills

Skill Level

Ab4
Ab3
Ab2
Ab1
Rp4
Rp3
Rp2

Age in Years
8 12 16 20 24 28

Single Abstractions
Abstract Mappings
Abstract Systems
Principles
Optimal Level
Functional Level
Figure 2. Learning a Statistics Operation

Participant 07, Session 1

(Yan, 1998, 2000)
Figure 3. Development of Darwin’s Theory of Evolution (1831-1839):
A General Overview

<table>
<thead>
<tr>
<th>Level</th>
<th>Skill</th>
<th>Major Events</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ab1. Single Abstractions</td>
<td>[ \text{WORLD} \quad \text{ORGANIC} ] or [ \text{WORLD} \quad \text{PHYSICAL} ]</td>
<td>From adolescence: Musings about creation &amp; species; Separation of organic &amp; physical worlds.</td>
<td>Before 1831</td>
</tr>
<tr>
<td>Ab2. Abstract Mappings</td>
<td>[ \text{WORLD} \quad \text{deviant} \quad \text{WORLD} \quad \text{ORGANIC} ]</td>
<td>Physical world eliminates deviant organisms.</td>
<td>1831 - 1836</td>
</tr>
<tr>
<td></td>
<td>[ \text{WORLD} \quad \text{breed} \quad \text{WORLD} \quad \text{ORGANIC} ]</td>
<td>People selectively breed animals and plants for desired characteristics.</td>
<td>1831 - 1836</td>
</tr>
<tr>
<td></td>
<td>[ \text{WORLD} \quad \text{reef} \quad \text{WORLD} \quad \text{ORGANIC} ]</td>
<td>Voyage of Beagle: Mastering Lyell’s <em>Principles of Geology</em> &amp; collecting observations.</td>
<td>1831 - 1836</td>
</tr>
<tr>
<td></td>
<td>[ \text{WORLD} \quad \text{ORGANIC} \leftrightarrow \text{WORLD} \quad \text{PHYSICAL} ]</td>
<td>Beginning of coral reef theory: Corals vary with changes in physical world.</td>
<td>1835 - 1837</td>
</tr>
<tr>
<td>Ab3. Abstract Systems</td>
<td>[ \text{ORGANIC} \quad \text{reef} \quad \text{WORLD} \leftrightarrow \text{WORLD} \quad \text{ORGANIC} ]</td>
<td>Final coral-reef theory: Coral reefs grow as corals adapt to changing ocean depths by growing upward to reach light.</td>
<td>1835 - 1837</td>
</tr>
<tr>
<td></td>
<td>[ \text{ORGANIC} \quad \text{match} \quad \text{WORLD} \leftrightarrow \text{WORLD} \quad \text{ORGANIC} ]</td>
<td>Variations in Galapagos species match species characteristics with physical niche.</td>
<td>1835 - 1837</td>
</tr>
<tr>
<td></td>
<td>[ \text{ORGANIC} \quad \text{time} \quad \text{WORLD} \leftrightarrow \text{WORLD} \quad \text{ORGANIC} ]</td>
<td>Many species show systematic change over long time periods.</td>
<td>1835 - 1837</td>
</tr>
</tbody>
</table>

Continued
## Figure 3 continued

<table>
<thead>
<tr>
<th>Level</th>
<th>Skill</th>
<th>Major Events</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Struggling with idea of multiple creations.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inadequate process of evolution: Monad theory, branching tree.</td>
<td>1837</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hybridization (instead of natural selection).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emergence of theory of evolution by natural selection (heredity, variation, natural selection).</td>
<td>1838 - 1839</td>
</tr>
</tbody>
</table>


Note: Skill structures in this table emphasize relations between physical and organic worlds in the various phases of Darwin's work. The structures in the text diagram the actual skills, specifying the components from physical and organic worlds that Darwin actually coordinated.