

CHAPTER 6

Dynamic Systems Theories

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Dynamic systems is a recent theoretical approach to the study of development. In its contemporary formulation, the theory grows directly from advances in understanding complex and nonlinear systems in physics and mathematics, but it also follows a long and rich tradition of systems thinking in biology and psychology. The term *dynamic systems*, in its most generic form, means systems of elements that change over time. The more technical use, *dynamical systems*, refers to a class of mathematical equations that describe time-based systems with particular properties.

DYNAMIC SYSTEMS THEORIES

In this chapter, we present a theory of development based on very general and content-independent principles that describe the behavior of complex physical and biological systems. The application of dynamic systems to development process is relatively new, emerging in the past 20 years. However, in many ways it is a modern continuation of a long tradition; accordingly, this chapter begins with a brief historical review of two strands that form the intellectual heritage for dynamic systems theories: theories (and empirical studies) of develop-

mental process and general systems theories. We present a tutorial of dynamic systems principles and show how they may be used to yield a deeper understanding of the processes of change. We show how these ideas can be used to help us understand developmental process as: (a) a conceptual guide, (b) a program for research, and (c) a basis for formal theory. Finally, we consider the relation between dynamical systems approaches to development and other theories of development.

Throughout the presentation, both in the historical heritage of studying developmental process and in dynamics systems theory itself, two themes will recur:

1. Development can only be understood as the multiple, mutual, and continuous interaction of all the levels of the developing system, from the molecular to the cultural.
2. Development can only be understood as nested processes that unfold over many timescales from milliseconds to years.

The value of dynamic systems is that it provides theoretical principles for conceptualizing, operationalizing, and formalizing these complex interrelations of time, substance, and process. It is a metatheory in the sense that it may be (and has been) applied to different species,

ages, domains, and grains of analysis. But it is also a specific theory of how humans gain knowledge from their everyday actions (e.g., Thelen & Smith, 1994).

Intellectual Heritage: Developmental Process

[T]he induction of novel behavioral forms may be the single most important unresolved problem for all the developmental sciences. (Wolff, 1987, p. 240)

What do we mean when we say that an organism “develops”? Usually, we say that it gets bigger, but always we mean that it gets more complex. Indeed, the defining property of development is the creation of new forms. A single cell and then a mass of identical cells are starting points for legs, livers, brains, and hands. The 3-month-old infant who stops tracking a moving object when it goes out of sight becomes an 8-year-old child who can read a map and understand symbolically represented locations, and, later, an 18-year-old student who can understand and even create formal theories of space and geometry. Each of these transitions involves the emergence of new patterns of behavior from precursors that themselves do not contain those patterns. Where does this novelty come from? How can developing systems create something from nothing?

Understanding the origins of this increasing complexity is at the heart of developmental science. Traditionally, developmentalists have looked for the sources of new forms either in the organism or in the environment. In the organism, complex structures and functions emerge because the complexity exists in the organism in the form of a neural or genetic code. Development consists of waiting until these stored instructions tell the organism what to do. Alternatively, the organism gains new form by absorbing the structure and patterning of its physical or social environment through interactions with that environment. In the more commonly accepted version, the two processes both contribute: Organisms become complex through a combination of nature and nurture. For instance, the guiding assumption of developmental behavior genetics is that the sources of complexity can be partitioned into those that are inherent, inherited, and absorbed from the environment. But whether development is viewed as driven by innate structures, environmental input, or a combination of the two, the fundamental premise in the traditional view is that “information can preexist the processes that give rise to it” (Oyama, 1985, p. 13).

But if the instructions to develop are in the genes, who turns on the genes? If the complexity exists in the environment, who decides what the organism should absorb and retain? The only way to answer these questions is to invoke yet another causal agent who evaluates the information, whether genetic or environmental, and makes decisions. Some clever homunculus must be orchestrating a developmental score while knowing how it must all turn out in the end. This is a logically indefensible position; it says that novelty really does not develop, it is there all along. Postulating an interaction of genes and environment does not remove this logical impasse. It merely assigns the preexisting plans to two sources instead of one.

In this chapter, we follow a different tradition. We agree with Wolff (1987) that the question of novel forms is the great unanswered question. And we also concur that the traditional solutions—nature, nurture, or interaction of both—are sufficient. The tradition we follow, that of *systems theories of biological organization*, explains the formation of new forms by processes of *self-organization*. By self-organization we mean that *pattern and order emerge from the interactions of the components of a complex system without explicit instructions*, either in the organism itself or from the environment. Self-organization—processes that by their own activities change themselves—is a fundamental property of living things. Form is constructed during developmental process (Gottlieb, Wahlsten, & Lickliter, Chapter 5, this *Handbook*, this volume; Oyama, 1985).

Dynamic systems offers general principles for formalizing ideas of biological self-organization in ways that are extraordinarily useful for understanding developmental process and for conducting experimental research. In this chapter, we apply these principles most specifically to perceptual, motor, and cognitive development in infants and early childhood (e.g., Jones & Smith, 1993; Thelen, 1989; Thelen & Smith, 1994; Thelen & Ulrich, 1991). But the theme of the developing organism as a holistic, self-organizing system has appeared many times before in biology and psychology. Before we describe and apply dynamic principles, we situate our systems theory in the wider perspective of systems thinking in development. Toward this goal, our review is selective and thematic, rather than exhaustive. Readers are referred to excellent reviews by Ford and Lerner (1992), Gottlieb (1992), Gottlieb et al. (Chapter 5, this *Handbook*, this volume), Oyama (1985), and Sameroff (1983).

Lessons from Embryology: Form from a Formless Egg

A baby's first step or first word is a dramatic example of new behavioral form. But no example of developmental novelty is as compelling as the emergency of an embryo from the initial state of a seemingly homogeneous and formless single cell, the fertilized egg. And no other aspect of development seems so completely "genetic" in the strict unfolding of species-typical structure.

For well over a century, biologists have studied this transformation of a single sphere into an intricate, three-dimensional organism with beautifully formed organs and well-differentiated tissue types. During the past few decades, however, researchers have made significant advances toward understanding the "impenetrable black box" (Marx, 1984a, p. 425) of this developmental process.

What is now abundantly clear is that embryonic development is an intricate dance between events in the nucleus—the turning off and on of particular gene products—and what one writer has deemed "mundane" biophysical principles in the cell body and surface (Marx, 1984b, p. 1406). Consider how animals get their basic body plans—the specific parts and organs that emerge in orderly time and space dimensions in the first days and weeks of life. Formation of the body pattern occurs when the fertilized egg has divided to about 10,000 cells. By this time, although the cells look like an undifferentiated heap, they are already marked in positions that predict distinct body locations. They have become a founder group of cells.

It is now well established that what appeared to be a homogenous founder cell or group of cells actually contains various and subtle gradients of substances, which form a very general "prepattern" of the structure that will emerge (Wolpert, 1971). These gradients and patterns, in turn, often arise from the "mundane" effects of gravity, the mechanical effects of molecular structure in the cell and at its surface (the pushing and pulling of particular molecules and crystals), or the regulated amplification of small local fluctuations in physiology or metabolism (Cooke, 1988; Gierer, 1981). Even more remarkable, is that once some initial prepattern is formed, the regulating genes in the nucleus are themselves switched on and off by these changing physical and mechanical events outside of the nucleus. Thus, once the initial generalized body fates are determined, the course of more refined tissue and organ differentia-

tion is equally bidirectional between nuclear processes and other cellular events.

During embryogenesis, cells divide, change character, move, and organize themselves into larger collectives of tissues, organs, and organ systems. The process is highly dynamic; that is, the cell and tissue movements themselves are sources of order and complexity. As groups of cells arising from different local gradients move and come into contact, their new positions further change their character, a process known as *induction*. What is especially relevant to our account here is that no single cell itself gives the signal that this region will become a neural tube or limb bud. Rather, it is the group of cells, acting as a collective and within a particular position in the larger collective that determines their ultimate fate. No one cell is critical, but the history and spatial and temporal dimensions of the collective are. Development is constructed through process:

The pathways of induction and determination involve a historical series of milieu-dependent gene expressions that are coupled to those mechanical and mechanochemical events that actually govern the achievement of form and pattern. At any one time, there is interplay between the place, scale, and size of bordering collectives, and various inductive molecular signals not only maintain the pattern so far established but also transform it into a new pattern. (Edelman, 1988, p. 26)

This picture is much different from one that casts the genes as the puppeteer, pulling the right strings at the right time to control the ensuing events in the cells. In a dynamic view, we consider the marionette and the puppeteer as affecting each other equally. Or, more accurately, we do away with the puppeteer and the marionette altogether: *What is important is the relationships among the strings as they pull and then become slack.*

Embryologists have been among the pioneers in using dynamic systems both formally and metaphorically to model developmental processes. Most notable was the preeminent developmental biologist C. H. Waddington. Waddington's primary interest was the genetic influence on tissue differentiation in the embryo, the emergence of sharply distinctive tissue types—bones, muscles, lungs, and so on—from a single cell. Although a geneticist, he was also a thoroughgoing systems theorist. Waddington (1954) couched developmental process in explicitly dynamic terms: "We can still consider development in terms of the solutions of a system of simulta-

neous differential equations” (p. 238). Especially in his later writings, Waddington described embryonic change in the language of attractors, bifurcations, open systems, stability, catastrophes, and chaos (Waddington, 1977). Figure 6.1 is one of his depictions, in three dimensions, of the multidimensional space subdivided into a number of regions, such that trajectories starting anywhere in one region converge to one certain end point, while those starting in other regions converge elsewhere (Waddington, 1957, p. 28). The figure shows how the gradients established in the egg, through time-dependent processes, become stable, differentiated tissue types. Waddington was especially intrigued by the self-stabilizing nature of development, depicted on his now classic “epigenetic landscape” shown in Figure 6.2. The landscape represents a developing system, where time runs toward the reader, and where the depth of the valleys is an indication of stability (the ball, once in a valley, is hard to dislodge). From an initial undifferentiated

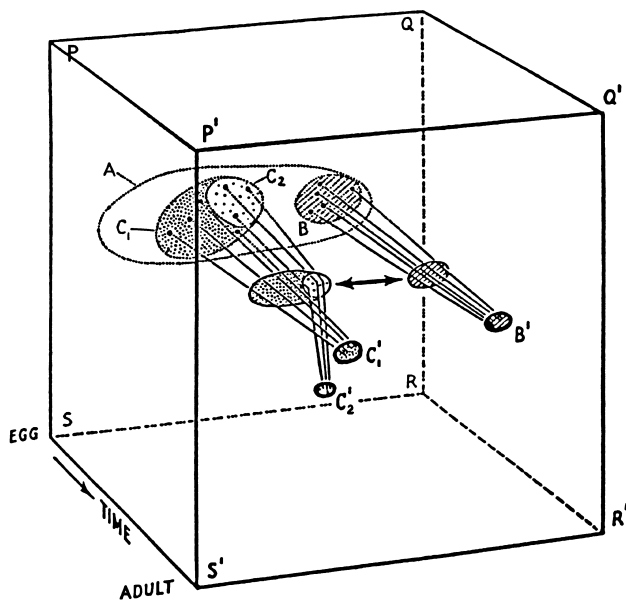


Figure 6.1 Waddington's phase-space diagram of development. Time runs along the z-axis, from plane PQRS at the time of fertilization to P'Q'R'S' which is adulthood. The other two dimensions represent the composition of the system. The diagram shows how the egg, which has continuous composition gradients becomes differentiated into specific tissues. Some areas in the state space act as attractors, pulling in nearby trajectories. *Source:* From *The Strategy of the Genes: A Discussion of Some Aspects of Theoretical Biology* (p. 28), by C. H. Waddington, 1957, London: Allen & Unwin. Copyright 1957 by Allen & Unwin. Reprinted with permission of Mrs. M. J. Waddington.

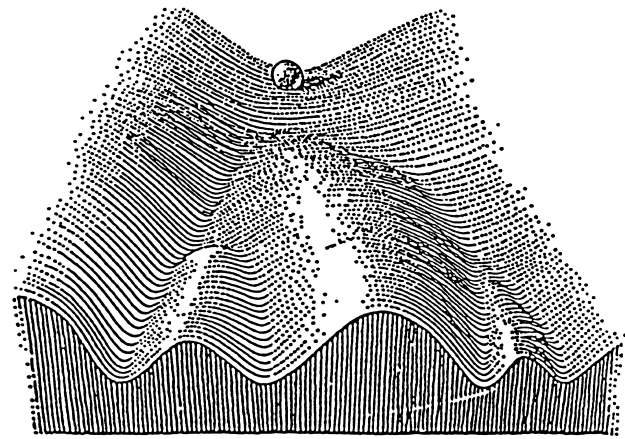


Figure 6.2 Waddington's classic epigenetic landscape. The path of the ball is the developmental history of part of the egg, showing the increasing stability of the developing tissue types. *Source:* From *The Strategy of the Genes: A Discussion of Some Aspects of Theoretical Biology* (p. 29), by C. H. Waddington, 1957, London: Allen & Unwin. Copyright 1957 by Allen & Unwin. Reprinted with permission of Mrs. M. J. Waddington.

state (the ball could be anywhere on the landscape), development creates hillocks and valleys of increasing complexity. As development proceeds, the tissue types become separated by higher hills, signifying the irreversible nature of development. However, the pathways down the landscape also show buffering; that is, development proceeds in globally similar ways despite somewhat different initial conditions, and despite minor perturbations or fluctuations along the way. In his last book, published posthumously in 1977, Waddington called the epigenetic landscape an “attractor landscape” (p. 105). He asked, “How do we find out the shape of the landscape?” He suggested: “So what we should try to do is to alter it, slightly, in as many ways as possible and observe its reactions. We will find that the system resists some types of changes more than others, or restores itself more quickly after changes in some directions than in others” (Waddington, 1977, p. 113). Similarly, in our version of a dynamic systems account, probing the system's stability is also a critical step.

Since Waddington, theorists and mathematicians have offered numerous dynamic models of morphogenesis, the emergency of form (see, e.g., Gierer, 1981; Goodwin & Cohen, 1969; Meakin, 1986; Tapaswi & Saha, 1986; Thom, 1983; Yates & Pate, 1989, among others). The common features of these models are initial conditions consisting of very shallow gradients, differential mechanical factors such as pressures or adhesions

in the cells, or both. The gradient or force fields are represented by one of several classes of differential equations, which express change as a function of time. Some sets of equations involve lateral inhibition, which allows a small local activation to become enhanced and form the node of a pattern. When the equations are solved for variety of parameters, complex spatial patterns are generated, which may consist of cycles, multiple peaks and valleys, and even fractals (complex scale-independent patterns). Combining two or more gradients with different rates of change and coupling their interactions can lead to highly complex patterns, including stripes, columns, and so on: “[V]ery complex real patterns may arise on the basis of elementary field-forming mechanisms and their combinations” (Gierer, 1981, p. 15).

One of the most delightful and fanciful of these models of pattern formation is that of the mathematician J. D. Murray, who provides an elegant model of the ontogeny of mammalian coat patterns: “How the leopard got its spots” (Murray, 1988, 1993). Think about your last visit to the zoo and the remarkable range of coat markings you saw: The complex spots and stripes of zebras, leopards, and giraffes; the simpler stripes of skunks and badgers; and the softly shaded patterns of some ungulates. Murray shows how a *single* mechanism, modeled by a simple nonlinear equation of the developmental process, can account for all the variations in coat markings. The equation is of the reaction-diffusion type, where an initial gradient of some chemical (the morphogen) can take on particular rates of reaction combined with varying rates of diffusion in a close surface. The interactions between the chemical reaction and its rate of diffusion are highly nonlinear, meaning that sometimes the reaction proceeds in a stable manner, but, at other values, the reaction is unstable and no pigment is formed. This nonlinearity leads to either a smooth or a patch-like pattern of reaction products on the surface. Critical factors include the reaction rates; when the process is started, presumably under genetic control; and then, only the geometry and scale of the initial gradient is believed to be some substance that activates melanin (pigment) production in melanocyte cells in the skin surface during early embryogenesis.

The power of Murray’s simple model is illustrated in Figure 6.3, which shows the results of the simulations of the equation with set parameters, changing only the scale of surface of the body over which the chemical

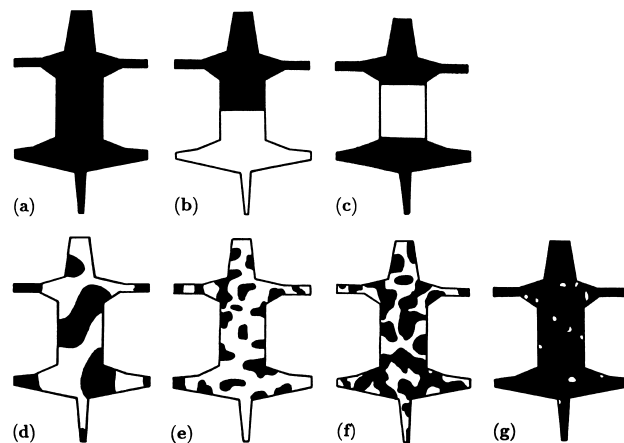


Figure 6.3 The effect of body surface scale on the patterns formed by a reaction diffusion mechanisms for mammalian coat coloration. A single mechanism can account for diverse coat patterns, depending on the parameter values in the equations. *Source:* From *Mathematical biology* (2nd ed., p. 445), by J. D. Murray, 1993, Berlin, Germany: Springer-Verlag. Copyright 1993 by Springer-Verlag. Reprinted with permission.

dynamics occur. As the body is scaled up over 50,000 times (presumably, from a mouse to an elephant), a regular series of patterns emerges: The solid color of very small animals, then the simple bifurcations and the more elaborate spottings, and, again, the nearly uniform coat of large animals. (Indeed, very small and very large mammals are more likely to have solid coats.) In real animals, small random variations in the initial gradient would lead to the noticeable individual variations in coat pattern. The important fact is that the *dynamics* of the reactions create the pattern.

Embryologists and theoreticians of morphogenesis show how, during development, extraordinarily complex structural patterns can arise from very simple initial conditions in dynamic systems. The patterns that result are not specifically coded in the genes. Although all leopards are spotted and all raccoons have striped tails, there is no dedicated gene for spots on the leopard or striped tails for raccoons. Structural complexity is constructed during development because living systems with particular chemical and metabolic constraints spontaneously organize themselves into patterns. In such systems, the issue of “what causes what to happen” is particularly thorny. When all parts of the system cooperate, when a group of cells only takes on a particular fate in the context of its position among other cells, it is simply not feasible to ask whether this structure or this behavior is “caused” by genes or by

environment. Through experimentation and modeling, the efforts of embryologists are directed toward a deep and detailed understanding of process.

The implications of embryology for theories of psychological development are profound. Often we find ourselves searching for the “cause” of development, or the essential structure that makes some behavior—language, walking, number concepts—what it is. Thus, much developmental research has been directed toward discovering invariants—the programs, stages, structures, representations, devices, schemas, or modules—that underlie performance at different ages. A good part of this search is directed toward which invariants are “innate” (present at birth), which are “genetic” (hard-wired into the system by natural selection), and which, by analogy to genes, “determine” developmental outcome (e.g., Gelman & Gallistel, 1978; Spelke, Breinlinger, Macomber, & Jacobson, 1992). But embryology teaches us that the genes do not—in and of themselves—determine developmental outcome. Genes are essential elements in a dynamic cascade of processes. Understanding the development means understanding that cascade.

The Mountain Stream Metaphor

The larger lesson from embryology for psychology is this: the stable regularities we see in developed organisms—the phenomena we seek as psychologists to explain—might not have specific causes that can be demarcated and isolated but rather may be understood only as a dynamic cascade of many processes operating over time. This idea challenges the usual notions of science that we understand by analysis, by isolating *things*—ingredients and components—until we arrive at the essential *stuff*. Explanations in terms of complex and cascading processes as opposed to explanations in terms of a list of parts is difficult even for scientists (see Chi, Slotta, & de Leeuw, 1994). Accordingly, we offer a metaphor that may seem at first far afield, but we hope that thinking about it explains process as the cause of structure.

The metaphor is of a fast-moving mountain stream. At some places, the water flows smoothly in small ripples. Nearby may be a small whirlpool or a large turbulent eddy. Still other places may show waves or spray. These patterns persist hour after hour and even day after day, but after a storm or a long dry spell, new patterns may appear. Where do they come from? Why do they persist and why do they change?

No one would assign any geological plan or grand hydraulic design to the patterns in a mountain stream. Rather, the regularities patently emerge from multiple factors: The rate of flow of the water downstream, the configuration of the stream bed, the current weather conditions that determine evaporation rate and rainfall, and the important quality of water molecules under particular constraints to self-organize into different patterns of flow. But what we see in the here-and-now is just part of the picture. The particular patterns evident are also produced by unseen constraints, acting over many different scales of time. The geological history of the mountains determined the incline of the stream bed and the erosion of the rocks. The long-range climate of the region led to particular vegetation on the mountain and the consequent patterns of water absorption and runoff. The climate during the past year or two affected the snow on the mountain and the rate of melting. The configuration of the mountain just upstream influenced the flow rate downstream. And so on. Moreover, we can see the relative importance of these constraints in maintaining a stable pattern. If a small rock falls into a pool, nothing may change. As falling rocks get larger and larger, at some point, the stream may split into two, or create a new, faster channel. What endures and what changes?

Process accounts assume that behavior patterns and mental activity can be understood in the same terms as the eddies and ripples of a mountain stream. They exist in the here-and-now, and they may be very stable or easily changed. Behavior is the product of multiple, contributing influences, each of which itself has a history. But just as we cannot really disentangle the geologic history of the mountain from the current configuration of the stream bed, we also cannot draw a line between the real-time behavior and the lifetime processes that contribute to it. Likewise, there is no separation of the patterns themselves from some abstraction of those patterns.

The mountain stream metaphor depicts behavioral development as an *epigenetic process*; that is, truly constructed by its own history and system-wide activity. This is a venerable idea with a long history in developmental theorizing.

Epigenesis in Developmental Psychobiology

No one understood a systems approach more deeply than a group of developmental psychobiologists working largely in the 1940s, 1950s, and 1960s, especially T. C.

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Schneirla, Daniel Lehrman, and Zing-Yang Kuo, whose tradition is carried on today most eloquently by Gilbert Gottlieb (Gottlieb et al., Chapter 5, this *Handbook*, this volume). These biologists used the word *epigenesist* to describe the process of behavioral ontogeny (see Kitchener, 1978, for discussion of the various meanings of the term *epigenesist*). Their vision is best understood as a contrast with the prevailing scientific thought about behavior and its change, and, in particular, the recurrent issue of nature versus nurture.

In those decades, North American psychology was dominated by learning theorists. As is well known, the goal of these experimental psychologists was to elucidate the general laws of behavior as animals are shaped by experience. Behaviorists used a variety of experimental animals such as rats and pigeons, but they believed that the principle of training and reinforcement applied to all species, including humans. Development, according to behaviorist theories, consists of the animal's reinforcement history. The radical environmentalism of behaviorists is captured in a statement from a critical essay by Lehrman (1971):

Also basic to what I here call the "behaviorist orientation" is the idea that scientific explanations of, and statements of scientific insights into, behavior *consist* of statements about how the experimenter gains control over the behavior, or about how the actions of the subject can be predicted by the actions of the experimenter. (p. 462)

Although learning continues to be an important aspect of developmental accounts, especially in explaining the socialization of children (Bandura, 1977), learning theories have lost favor as general developmental theories. In part, this is due to their inability to explain species differences and to provide satisfactory accounts of cognitive and language development. Equally troubling is that learning alone does not tell us how novelty arises.

In the 1950s and 1960s, a view of behavior became popular that strongly opposed pure learning theories. *Ethological theories* came from the European school associated with Konrad Lorenz and his students. Lorenz's work was seminal in reorienting psychologists to the role of species-typical behavior and animals' adaptations to their environments. And although ethologists such as Lorenz considered learning to be important, learning always was placed alongside behavior deemed innate or instinctive. According to Lorenz (1965), that distinction between innate and learned was of primary importance in understanding behavior and its development. Indeed,

Lorenz believed that behavior could be broken up into elements that were wholly innate and elements that were learned, although the focus of ethologists' studies was most often on the innate parts. The form of a behavior—for example, particular courtship calls or displays, or, in humans, facial expressions—was believed to be "hard-wired" and not acquired. Lorenz called this class of movements "fixed action patterns" because they were believed to emerge without specific experience. The object and orientation of these displays may be learned during ontogeny. Geese, for instance, instinctively follow objects on which they become imprinted, but they learned to follow Lorenz instead, if he substituted himself for the mother goose at the appropriate time.

The epigeneticists, in contrast to both learning theorists and ethologists, campaigned to eliminate altogether the question of learned versus acquired. They were especially critical of what they considered the vague and ill-defined meaning of such terms as *innate* or *instinctive*. Lehrman's statement in 1953 is as eloquent and relevant today as then:

The "instinct" is obviously not present in the zygote. Just as obviously, it is present in the behavior of the animal after the appropriate age. The problem for the investigator is: How did this behavior come about? The use of explanatory categories such as "innate" and "genetically fixed" obscures the necessity of investigating developmental *processes* to gain insight into actual mechanisms of behavior and their interrelations. The problem of development is the problem of the development of new *structures* and activity *patterns* from the resolution of the interaction of existing ones in the organism and its internal environment, and between the organism and its outer environment. (p. 338)

In his book, *The Dynamics of Behavior Development: An Epigenetic View*, Kuo (1967) presented a particularly clear statement of developmental process from a systems view. Kuo emphasized that behavior is complex and variable and takes place in a continually changing internal and external environment. The behavior we observe is an integral part of the total response of the animal to the environment, but there are differentiations—or patterned gradients—of response among different parts of the body. He wrote:

Ontogenesis of behavior is a process of modification, transformation, or reorganization of the existing patterns of behavior gradients in response to the impact of new en-

vironmental stimulation; and in consequence a new spatial and/or serial pattern of behavior gradients is formed, permanently or temporarily (“learning”) which oftentimes adds to the inventory of the existing patterns of behavior gradients previously accumulated during the animal’s developmental history. (Kuo, 1970, p. 189)

During the life span, new patterns are selected from among the range of potential patterns:

Thus, in every stage of ontogenesis, every response is determined not only by the stimuli or stimulating objects, but also by the total environmental context, the status of anatomical structures and their functional capacities, the physiological (biochemical and biophysical) condition, and the developmental history up to that stage. (Kuo, 1970, p. 189)

In his call for an integrated developmental science, Kuo (1970) exhorted scientists to study “every event that takes place under and outside the skin” as part of the behavioral gradient, and not to look just at global measures of organism or environment: “[W]e must take quantitative measures of stimulative effects of every sensory modality, and make qualitative analyses of the interactions of the component parts of the environmental context or complex” (p. 190). Kuo’s extraordinary vision, fashioned from his work as both an embryologist and a comparative psychologist, did not have a direct influence on the mainstream of child psychology, which became enraptured with Piaget (1952) at that time, and later with Bowlby (1969) and attachment theory. Nonetheless, a broad systems view has continued with a group of comparative developmental psychobiologists who have conducted exquisite and detailed studies of the intricate interrelated mechanisms of offspring, parents, and environment in early life. These include Gilbert Gottlieb, Jay Rosenblatt, Lester Aronson, Ethel Tobach, Howard Moltz, William Hall, Jeffrey Alberts, Patrick Bateson, Meredith West, and others. Gerald Turkewitz has been a pioneer in continuing the Schneirla-Kuo tradition in human infancy studies.

One hallmark of this comparative work is minute and detailed understanding of the experiential context of the developing organism, including factors that are not necessarily the apparent and obvious precursors to a particular behavior, but may indeed be critical contributors. “Experience may contribute to ontogeny in subtle ways,” Schneirla wrote (1957, p. 90), and also in ways that are nonspecific. Small effects of temperature, light,

and gravity, at critical times, for instance, can cascade into large developmental differences. Nonobvious and nonspecific factors are important considerations in a dynamic systems view as well.

A beautiful example of developmental analysis in the systems tradition of Schneirla and Kuo is the work of Meredith West and Andrew King on the ontogeny of bird song. West and King’s studies on song learning in the cowbird, a brood parasite, have uncovered subtleties and variations in the developmental process that raise questions about a more simplistic earlier view: Song learning was either directed by an innate template or learned by imitation of other singing males. First, they found an overwhelming effect of context on both the learning and the performing of songs—for example, males’ being housed with females during rearing affected their song content. Even though females do not sing, they exert social influence on males that are strong enough to override any specific sensory template (King & West, 1988). The mechanism appears to be females’ selective responses (by brief wing-flicking movements) during the time when males are learning song. The female cowbird helps shape the male song by her response. Furthermore, experience with cowbird females is essential for appropriate male mating behavior. When male cowbirds were raised with canaries, they sang to and pursued canaries rather than females of their own species. But this preference was not a rigid imprinting, as the old ethologists would have maintained. When these canary-housed cowbird males were housed with cowbird females in their second season, they reversed their preference.

From this and other evidence, West and King conclude that song development is highly multiply determined and dynamic in the sense of being continually constructed in time and space. An animal’s species-typical environment of rearing and its own actions in that environment are as “inevitable [a] source of influence as are an animal’s genes” (West & King, 1996). And because these dynamic processes are so interactive and nonlinear, fundamental properties disappear when they are disrupted. For example, experimental perturbations to the expected rearing conditions, such as placing animals in isolation or injecting them with hormones, may have both dramatic and subtle cascading effects. Such manipulations often illuminate the interactions in the system, but they must be interpreted with great care. These insights raise cautions about interpretations of experiments with infants and children because the interaction between the experimental manipulation and the

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normal, everyday experiences of the subjects are often unknown. A dynamic systems approach suggests that these contextual factors and their time functions are the critical aspects of performance and development.

Recent research by Goldstein and West (1999; Goldstein, King, & West, 2003) strongly illustrates this point. This work concentrates on the development from the sounds children make *prior to language* to those that may be considered *speech* sounds. Prelinguistic vocal development or “babbling,” long thought to be driven exclusively by articulator maturation (e.g., Kent, 1981), takes on new significance when studied from a dynamic systems perspective. When caregivers and infants are studied together as they interact in real time, vocal development shows multicausality and interdependency of timescales. Mothers react in consistent ways to the babbling of even unfamiliar infants, and as babbling becomes more speech-like it more strongly influences mothers’ responding (Goldstein & West, 1999). Infants are sensitive to the reactions of caregivers and to their sounds, changing the amount and acoustic form of their babbling in response to changes in the form and timing of their caregivers’ behavior (Goldstein et al., 2003).

In the Goldstein et al. (2003) study, mothers of 8- to 10-month-old infants wore wireless headphones, allowing them to receive instructions from an experimenter. When mothers responded (by smiling, moving closer, and touching) contingent to their infants’ vocalizations, the infants’ babbling incorporated increased voicing and faster consonant-vowel transitions, which are developmentally more advanced forms of production. In contrast, the infants of yoked control mothers, who received the same amount of social stimulation but without contingency, did not change their babbling. Infants must therefore recognize that their sounds produce a change in the environment in order for their sounds to change.

By manipulating caregiver-infant interactions in real time, multiple causes and timescales of vocal development become evident. The mechanisms that create vocal development are not restricted to the infant, but rather the system of caregiver and infant. Patterns of vocalizations are created by the interaction of multiple forces, including the articulatory apparatus, visual and auditory perceptual systems, and learning mechanisms. These components regulate and are regulated by caregiver availability and responsiveness. Vocal development is not an infant ability, but an emergent property of caregiver-

infant interaction in that the vocal learning process is created by social interactions. Because developmental advances in babbling change the ways that caregivers react to their infants (Goldstein & West, 1999), setting the stage for new learning to occur, moment-to-moment social interactions are probably linked to the months-long stages (Oller, 2000) that reliably describe the first year of vocal development. From a dynamic systems view, maternal behavior and infant sensory capacities interact to generate the development of more advanced infant behavior. Thus, the patterns of interaction between caregivers and infants are a source of developmental change.

Contextual and Ecological Theorists

The tradition of the embryologists and the epigeneticists emphasized self-organization from multiple processes both in the organism and between the organism and its environment. The focus is on relationships among components as the origins of change, rather than a set of instructions. Such a view naturally turns our attention to the physical and social settings in which infants and children are raised, and it requires as detailed an understanding of the context as of the organism situated in that context. Existing developmental theories can be placed on a continuum as to whether they are more concerned with what is in the child’s head or with the specific and changing details of the environment. Piagetian, cognitivist, and information-processing accounts of development, for instance, pay little attention to the particular nature of the physical and social worlds of children. The goal of these approaches is to understand general qualities of mind and how they develop. Because the processes are assumed to be universal adaptations to the world by human brains, it is immaterial, for instance, whether a child learns transitive inference from playing with sticks on the ground, or in a structured school, or by observing groups of people talking and acting. The focus is on the individual as the basic unit of analysis, in the sense that individuals all have common structures and processes above and beyond their differing experiences.

For theorists at the other end of the continuum, a person’s experiences in context and culture are not just supportive of development, but are the very stuff of development itself. At this end of the continuum, we group developmentalists who are working in the tradi-

tion of James Mark Baldwin, John Dewey, and Kurt Lewin; more recently, A. R. Luria and L. S. Vygotsky; and who are labeled as *ecological, contextual, or cross-cultural* theorists. In addition, some versions of *life-span* perspectives (e.g., Baltes, 1987) also have strong epigenetic and systems assumptions. All these views are well represented in this *Handbook*, this volume, in the chapters by Overton (Chapter 2); Valsiner (Chapter 4); Gottlieb et al. (Chapter 5); Rathunde and Czikszenmihalyi (Chapter 9); Bradtstder (Chapter 10); Shweder et al. (Chapter 13); Elder, Bronfenbrenner, and Morris (Chapter 12); and Baltes, Lindenberger, and Staudinger (Chapter 11). Although there are many versions of contextualism (see reviews by Dixon & Lerner, 1988; Ford & Lerner, 1992), they share certain assumptions about development, and these assumptions overlap with many features of a dynamic systems approach. First and foremost is the quest to eliminate the duality between individual and environment, just as the epigeneticists endeavored to erase the boundaries between structure and function.

All developmental theorists would acknowledge that humans and other living beings can be described over many levels of organization from the molecular and cellular, through the complex level of neural activity and behavior, and extending to nested relationships with the social and physical environments (e.g., Bronfenbrenner, 1979). And all developmental theories also view these levels as interacting with one another. The deep difference between contextualism and more individual-centered approaches is that the levels are conceptualized as *more* than just interacting; instead, they are seen as integrally fused together. Behavior and its development are melded as ever-changing sets of *relationships* and the history of those relationships over time. Thus, as mentioned earlier, we must discard our notions of simple linear causality: That event A or structure X *caused* behavior B to appear. Rather, causality is multiply determined over levels and continually changing over time.

Systems ideas have radical implications for the study of mind. For example, the idea that knowledge is emergent and that human behavior is socially constructed in task and history is beautifully illustrated in Hutchins' (1995) recent study of navigation. Navigation in modern navies is achieved via a complex system of interactions among a large number of people and measuring devices. These interactions are shaped and maintained by the culture of military practice and language, but also by

the geography of large ships, the measuring devices, the psychology of individuals, and the encountered tasks. No one element alone does the navigation. Hutchins' analysis, based on both participant observation and computer simulation, shows how all these elements matter—how the smartness of navigation teams emerges, depends on, and is constrained by the physical components, traditional roles, and culture. Navigation teams *are* smart. Their activity is event-driven and goal-directed. The navigation team must keep pace with the movement of the ship and must maintain progress. When things go wrong, there is no option to quit and start over; the right decision must be made at the moment. Hutchins' work shows how these decisions are distributed over the interactions of individuals—none of whom knows all there is to know about the problem. Nor is the optimal system one in which the problem has been logically divided up into mutually exclusive parts and assigned to individuals in a perfect division of labor. Rather, navigation teams are characterized by partially redundant and sometimes rapidly changing patterns of interactions and information flow. The intelligence sits in the patterns of interactions in the whole and has properties quite unlike those of the individuals who comprise that whole.

At the end of his book, Hutchins (1995) reflects on the meaning of culture and socially distributed cognition for cognitive science:

The early researchers in cognitive science placed a bet that the modularity of human cognition would be such that culture, context, and history could be safely ignored at the outset and then integrated in later. The bet did not pay off. These things are fundamental aspects of human cognition and cannot be comfortably integrated into a perspective that privileges abstract properties of isolated individual minds. (p. 354)

General Systems Theories

We have described theoretical approaches to development at different levels of organization, from embryological to societal. These approaches are based on common assumptions about systems' complexity and the multiple interrelated causes of change. However, the characteristics of developing organisms emphasized in these views—self-organization, nonlinearity, openness, stability, and change—are not confined to biological systems. They are also found in complex physical systems such as chemical reactions, global weather changes, mountain streams, clouds, dripping faucets—

wherever many components form a coherent pattern and change over time. The principles of dynamic systems formulated by physicists and mathematicians to describe the behavior of such complex physical systems may also be the best way to study and understand developing organisms.

Kurt Lewin and Dynamic Force Fields. One of the earliest explicitly dynamic formulations of development was Kurt Lewin's (1936, 1946) topological *field theory* of personality development. Lewin was unabashedly antireductionist. How, he asked, can psychology present all the richness of human behavior as the novelist, but "with scientific instead of poetic means" (Lewin, 1946, p. 792)? Referencing Einstein's theoretical physics, Lewin (1946) proposed:

The method should be analytical in that the different factors which influence behavior have to be specifically distinguished. In science, these data have also to be represented in their particular setting within the specific situation. A totality of coexisting facts which are conceived of as mutually interdependent is called a *field*. (p. 792)

According to Lewin, a given physical setting has meaning only as a function of the state of the individual in that setting. Conversely, individual traits do not exist outside of the setting in which they are displayed. Lewin called these fields of interactions *life spaces*—fields of forces with varying strengths. People move dynamically through this force field, depending on their location in the space, their needs, and previous history. Forces may compete, conflict, overlap, or sum, depending on the person's disposition and the environment. Learning—and development—consist of finding a pathway or discovering a new niche in the life space. And as children carve new pathways, they actually create yet new parts of the space to explore, a process of self-organization.

Lewin depicted this developmental dynamic as shown in Figure 6.4. Life spaces at different points in development are represented by layered force fields, with different zones for varying degrees of "attraction" to those fields. The parameters of the life space have several dimensions: Size of the space, degree of specificity, separation between reality and "irreality" or fantasy, and the influence of psychological processes across time. The life space of a younger child is more limited and less differentiated, and it is influenced more by the immediate

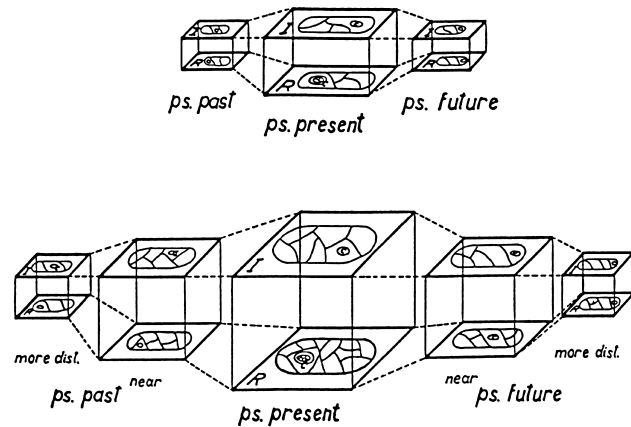


Figure 6.4 Lewin's psychological space (ps.) landscapes, depicted as layered systems of force fields with R = "reality" and I = "Irreality," and showing the connection between the motivational forces in the past, present, and future. The top panel depicts a life space of a young child; the bottom, that of an older child. Source: From "Behavior and Development as a Function of the Total Situation" (p. 798), by K. Lewin, in *Manual of Child Psychology*, L. Carmichael (Ed.), 1946, New York: Wiley. Copyright 1946 by John Wiley & Son. Reprinted with permission.

past and projects more into the immediate future than the more expansive space of the older child. Waddington's 1977 illustration of a phase-space diagram of development, shown in Figure 6.1, is remarkably similar to Lewin's in identifying preferred region and depicting development as a progressive drift through this space.

Systems Theory as Metaphor. Kurt Lewin's dynamic concepts were rich, but vague and difficult to operationalize. His ideas were poorly matched to either the mechanistic flavor of North American experimental psychology during the 1950s and 1960s, or to the mentalistic assumptions of Piagetian developmental psychology, and his impact on child psychology was little felt during those decades. Systems thinking about development underwent a small renaissance in the late 1970s and early 1980s, however, and these versions were much more explicitly tied to the new sciences of complexity in physics, math, and biology. Two authors, Ludwig von Bertalanffy, a biologist, and Ilya Prigogine, a chemist, were especially influential in this renewal.

Ludwig von Bertalanffy (1968) has usually been credited with originating "General Systems Theory." Since the 1930s, he has heralded an antireductionist

view of biological systems (von Bertalanffy, 1933). The dominant trend in all the sciences, from chemistry to psychology, was to isolate smaller and smaller elements of the system, but von Bertalanffy felt that understanding would come, not from these separate parts, but from the relationships among them. So, while animals are made of tissues and cells, and cells are built from complex molecules, knowing the structure of the molecules even in the greatest detail cannot inform us about the behavior of the animal. Something happens when complex and heterogeneous parts come together to form a whole that is more than the parts. The system properties need a new level of description—one that cannot be derived from the behavior of the components alone. These systems principles, in turn, are so universal that they apply to widely diverse beings and entities:

We can ask for principles applying to systems in general, irrespective of whether they are of physical, biological, or sociological nature. If we pose this question and conveniently define the concept of system, we find that models, principles, and laws exist which apply to generalized systems irrespective of their particular kind, elements, and “forces” involved. (von Bertalanffy, 1968, p. 33)

von Bertalanffy provided dynamic equations to illustrate these principles: Wholeness or self-organization, openness, equifinality (self-stabilization), and hierarchical organization. In his discussion of systems applications to psychology, von Bertalanffy was especially critical of “homeostasis” models of mental functioning, especially the Freudian assumption that organisms are always seeking to reduce tensions and seek a state of equilibrium. Rather, organisms are also *active*; as an open system, they live in a kind of disequilibrium (what we will call dynamic stability) and actively seek stimulation. This disequilibrium allows change and flexibility; the idea that too much stability is inimical to change recurs in many developmental accounts (e.g., Piaget, Werner) and is an assumption we also find essential for understanding development.

The Nobel chemist Ilya Prigogine was the second principal contributor to systems theory and an eloquent popularizer as well (see, e.g., Prigogine, 1978; Prigogine & Stengers, 1984). Prigogine was primarily interested in the physics of systems that were far from thermodynamic equilibrium. Recall that, in Newtonian thermodynamics, all systems run to disorder. The energy of the universe dissipates over time. The universe increases in

entropy, and, as Prigogine puts it, the “arrow of time” runs in only one direction—toward disorganization. But many systems, and all biological systems, live in thermodynamic nonequilibrium. They are thermodynamically open: They take in energy from their environment and increase their order—the arrow of time is at least temporarily reversed. Development is a premier example of a progressive *increase* in complexity and organization. Such systems take on special properties, including the ability to self-organize into patterns and nonlinearity or sensitivity to initial conditions. Again, it is critical that such systems are inherently “noisy,” for order arises from such fluctuations. In equilibrium systems, the noise is damped out and the system as a whole remains in equilibrium. In nonequilibrium systems, in contrast, fluctuations can become amplified and overtake the organization of the whole system, shifting it to a new order of organization.

A number of developmentalists immediately recognized the relevance of these explicit systems principles for age-old, yet still critical, issues in developmental psychology. Sandor Brent (1978), for instance, saw in Prigogine’s formulations of self-organization potential solutions for the questions of the origins of complexity and shifts from one developmental stage to more advanced levels. Moreover, Brent believed that ideas of nonlinearity could explain the seemingly “autocatalytic” aspects of development, where one small transformation acts as the catalyst for subsequent, accelerating changes.

Brent’s discussion is strictly theoretical. Arnold Sameroff (1983) tied the new systems ideas more concretely to developmental phenomena. Sameroff has long been interested in developmental outcomes of children at risk, particularly in the failure of linear models to predict pathology from antecedent conditions. In an important and influential paper, Sameroff and Chandler (1975) documented the persistently puzzling finding that some children with very serious risk factors around birth, including anorexia, prematurity, delivery complications, and poor social environments, suffered no or little long-term consequences, while others sustained serious effects. Simple cause-and-effect or medical models of disease must be supplanted with a thoroughgoing organismic model, according to Sameroff, where “Emphasis on a wholistic, actively functioning entity that constructs itself out of transactions with the environment is derived from the properties of biological development” (1983, pp. 253–254).

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Adoption of such a systems model, with its assumptions of wholeness, self-stabilization, self-organization, and hierarchical organization, has implications for every aspect of developmental psychology, according to Sameroff. For instance, theories of socialization must become thoroughly contextual, because the notion of open systems means that the individual is always in transaction with the environment. Biological vulnerability or risk, in this case, does not exist in a vacuum, but within the rich network of a more or less supportive family and community culture. Outcome is a joint product of the child and the cultural agenda of the society, and the total system has self-organizing and self-stabilizing characteristics.

Likewise, the issue of *change* motivates the *developmental system theory* of Ford and Lerner (1992). In reasoning that closely parallels our own, Ford and Lerner begin with a view of humans as “multilevel, contextual organizations of structures and functions” (p. 47) who exhibit varying kinds of stability and variability and who can change both in and between levels. Individual development, according to these theorists:

involves incremental and transformational processes that, through a flow of interactions among current characteristics of the personal and his or her current contexts, pro-

duces a succession of relatively enduring changes that elaborate or increase the diversity of the person's structural and functional characteristics and the patterns of their environmental interactions while maintaining coherent organization and structural-functional unity of the person as a whole. (p. 49, italics in original)

The definition, they maintain, implies a lifelong possibility of change, multiple (although not infinite) and nonlinear developmental pathways, discontinuities, and the emergence of new forms. Furthermore, the definition specifies that development is never a function of person or context alone, but indeed results as a function of their dynamic interaction. Figure 6.5 is Ford and Lerner's model of developmental change as a series of probabilistic states, where control systems interact in the person and the environment. States are thus the current configuration of the system, based both on current status and on the system's immediate and long-term history. We will repeat these themes throughout the remainder of this chapter.

Ford and Lerner's treatise is ambitious in scope; it ties biological and social development into a single developmental systems theory. Their intellectual debt is directly to the “organismic” and contextual school of developmental theory, and less so to physical and mathe-

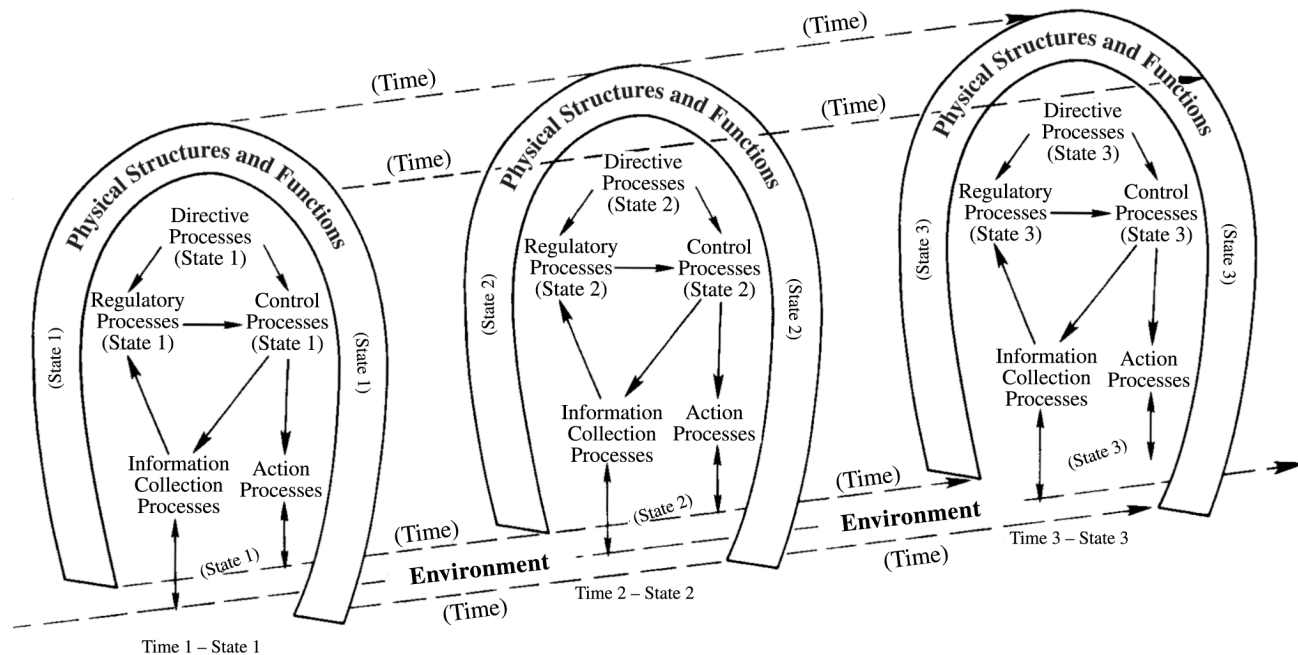


Figure 6.5 Ford and Lerner's model of developmental change as a series of probabilistic states.

mathematical dynamical systems. Likewise, they are not primarily concerned with operational verification of a systems approach, nor do they connect directly with the experimental and observational studies of individual child development.

This overview of the historical heritage shows systems approaches to have enduring appeal to developmentalists. This makes sense. As developmentalists, we are continually faced with the richness and complexity of the organisms we study and the elaborate causal web between active individuals and their continually changing environments. The recent contribution of the dynamic systems theories to this tradition is that such theories allows us to express, in words and in mathematical formalisms, complexity, wholeness, emergence of new forms, and self-organization. They provide a way to express the profound insight that pattern can arise without design: Developing organisms do not know ahead of time where they will end up. Form is a product of process.

An Introduction to Dynamics Systems Thinking

Despite a long tradition of systems thinking in development, from embryology to the study of culture and society, these formulations have remained more of an abstraction than a coherent guide to investigation or a means for synthesis of existing data. Developmentalists may acknowledge that systems matter, but it has been difficult to design and carry out empirical research based on a core of systems principles. In the remainder of this chapter, we summarize a set of dynamic principles applicable to human development and then show how research can be inspired, conducted, and interpreted from a dynamic perspective. We base our summary of dynamic systems heavily on the brand of dynamics set forth by Haken (1977) called *synergetics*. Note that other formal systems of dynamics have been applied to development, such as van Geert's "logistic growth model," van der Maas and Molenaar's "catastrophe theory" that we will discuss subsequently. Still other examples can be found in Smith and Thelen (1993).

Nature is inhabited by patterns in time. The seasons change in ordered measure, clouds assemble and disperse, trees grow to certain shape and size, snowflakes form and melt, minute plants and animals pass through elaborate life cycles that are invisible to us, and social groups come together and disband. Science has revealed many of nature's secrets, but the processes by which

these complex systems form patterns—an organized relationship among the parts—remain largely a mystery. In the past decade or so, however, physicists, mathematicians, chemists, biologists, and social and behavioral scientists have become increasingly interested in such complexity, or in how systems with many, often diverse, parts cooperate to produce ordered patterns. The scientific promise is that a common set of principles and mathematical formalisms may describe patterns that evolve over time, irrespective of their material substrates.

Order from Complexity

The key feature of such dynamic systems is that they are composed of very many individual, often heterogeneous parts: molecules, cells, individuals, or species, for example. The parts are theoretically free to combine in nearly infinite ways. The *degrees of freedom* of the system are thus very large. Yet, when these parts come together, they cohere to form patterns that live in time and space. Not all possible combinations are seen; the original degrees of freedom are compressed. But the patterns formed are not simple or static. The elaborate shapes or forms that emerge can undergo changes in time and space, including multiple stable patterns, discontinuities, rapid shifts of form, and seemingly random, but actually deterministic changes. The hallmark of such systems is that this sequence of *complexity to simplicity to complexity* emerges without prespecification; the patterns organize themselves. Our mountain stream shows shape and form and dynamic changes over time, but there is no program in the water molecules or in the stream bed or in the changes of climate over geological time that encodes the ripples and eddies.

Developing humans are likewise composed of a huge number of dissimilar parts and processes at different levels of organization, from the molecular components of the cells, to the diversity of tissue types and organ systems, to the functional defined subsystems used in respiration, digestion, movement, cognition, and so on. But behavior is supremely *coherent* and supremely *complex*, again showing complexity from simplicity from complexity. The self-organization of mountain streams is manifest; we argue here that the patterns seen in developing humans are also a product of the relations among multiple parts.

Both mountain streams and developing humans create order from dissimilar parts because they fall into a class called *open systems*, or systems that are *far from*

thermodynamic equilibrium. A system is at thermodynamic equilibrium when the energy and momentum of the system are uniformly distributed and there is no flow from one region to another. For instance, when we add alcohol to water or dissolve salt in water, the molecules or ions mix or react completely. Unless we heat the system or add an electric current, the system is stable. Nothing new can emerge; the system is *closed*. Systems such as moving stream beds or biological systems evolve and change because they are continually infused with or transfer energy, as the potential energy of water at the top of the mountain is converted to the kinetic energy of the moving water. Biological systems are maintained because plants and animals absorb or ingest energy, and this energy is used to maintain their organizational complexity. Although the second law of thermodynamics holds that systems should run down to equilibrium, this is only globally true. Locally, some systems draw on energy and increase their order.

Open systems, where many components are free to relate to each other in nonlinear ways, are capable of remarkable properties. When sufficient energy is pumped into these systems, new ordered structures may spontaneously appear that were not formerly apparent. What started out as an aggregation of molecules or individual parts with no particular or privileged relations may suddenly produce patterns in space and regularities in time. The system may behave in highly complex, although ordered ways, shifting from one pattern to another, clocking time, resisting perturbations, and generating elaborate structures. These emergent organizations are totally different from the elements that constitute the system, and the patterns cannot be predicted solely from the characteristics of the individual elements. The behavior of open systems gives truth to the old adage, “The whole is more than the sum of the parts.”

The condensation of the degrees of freedom of a complex system and the emergence of ordered pattern allows the system to be described with fewer variables than the number needed to describe the behavior of the original components. We call these macroscopic variables the *collective variables* (also called *order parameters*). Consider human walking, a multidetermined behavior. At the microscopic level of all the individual components—muscles, tendons, neural pathways, metabolic processes, and so on—the system behaves in a highly complex way. But when these parts cooperate, we can define a collective variable that describes this cooperation at a much

simpler level—for instance, the alternating cycles of swing and stance of the feet. This cyclic alternation is a collective variable, but it is not the only one. We might also look at patterns of muscle firing or forces generated at the joints. The choice of a collective variable is a critical step in characterizing a dynamic system, but it is not always easy to accomplish, and it may depend considerably on the level of analysis to be undertaken.

Attractors and Dynamic Stability

A critical property of self-organizing, open systems is that, although an enormous range of patterns is theoretically possible, the system actually displays only one or a very limited subset of them, indexed by the behavior of the collective variable. The system “settles into” or “prefers” only a few modes of behavior. In dynamic terminology, this behavioral mode is an *attractor* state, because the system—under certain conditions—has an affinity for that state. Again in dynamic terms, the system prefers a certain location in its *state*, or *phase space*, and when displaced from that place, it tends to return there.

The state space of a dynamic system is an abstract construct of a space of any number of dimensions whose coordinates define the possible states of the collective variable. For example, the behavior of a simple mechanical system such as a pendulum can be described completely in a two-dimensional state space where the coordinates are position and velocity as seen in Figure 6.6. As the pendulum swings back and forth, its motion can be plotted on this plane. The motion of

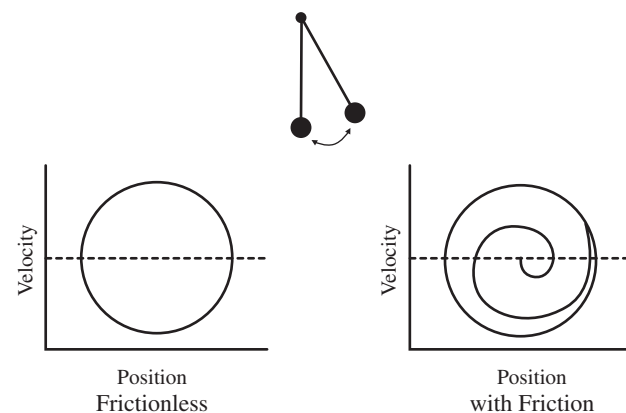


Figure 6.6 A simple pendulum as a dynamic system. Without friction, the pendulum will exhibit a *limit cycle attractor*. With friction, the pendulum will settle into a single, *point attractor*.

an ideal, frictionless pendulum prescribes an orbit or path through the state space that tracks its regular changes of position and velocity. If we add friction to the pendulum, it will eventually come to rest, and its orbit will look like a spiral.

The circular orbit of the frictionless pendulum and the resting point of the pendulum with friction are the attractors of this system. When friction is present, the attractor is a *point attractor* because all the trajectories in the space converge on that resting point, regardless of the system's starting point or initial conditions. Although the pendulum has only one fixed point, biological systems commonly have more than one point attractor; the system may reach one of the several possible equilibrium points, depending on the initial conditions. All the initial conditions leading to a particular fixed point attractor are called *basins of attraction*.

In the pendulum example, without friction, the attractor is of the *limit cycle* or *periodic* type; it will continually repeat its oscillations. When the pendulum is slightly perturbed, it returns, in time, to its periodic behavior. Once the pendulum is given its squirt of energy, these time and space patterns capture all other possible trajectories in the state space, and they represent stable collective variables for the pendulum system. In biological organisms, periodic behavior is often the collective result of the *coordination* of components each with its own preferred pattern (Kugler & Turvey, 1987; Schönner & Kelso, 1988). Consider human locomotion. The cyclic alternation of the legs during normal walking reflects the coupling of two legs 180 degrees out of phase. Such coordination dynamics can be represented on a phase space consisting of all the possible phase relationships between the two legs. In dynamic terms, there is a strong attractor at 180 degrees out-of-phase. Given ordinary conditions, people prefer to locomote by using their legs in alternation, however, there are also periodic attractors at 0 degrees (jumping) or 90 degrees (galloping), but they are far less stable under normal circumstances, and thus are rarely seen (at least in adults!).

Finally, a special type of attractor, the *chaotic* attractor, has received much attention in popular accounts of nonlinear dynamics. *Chaos* has a particular technical meaning in dynamics. Chaos describes systems whose behaviors look random at close glance but, when plotted over a long time on a state space, are not random and display extremely complex geometric structures. There is growing evidence that many biological systems are chaotic—for example, heart rate fluctuations (Gold-

berger & Rigney, 1988), electrical activity in the olfactory bulb (Freeman, 1987), and patterns of movements in human fetuses (Robertson, 1989).

For developmentalists, the most important dimension of a behavioral pattern preference or attractor is its *relative stability*. The concept of dynamic stability is best represented by a *potential landscape*. Imagine a landscape of hills and valleys, with a ball rolling among them depicting the state of the collective variable as shown in Figure 6.7. A ball on the top of a hill (a) has a lot of stored potential energy; with just a very small push, it will roll down the hill. Thus, the state of the system, represented by the ball, is very unstable. Any nudge will dislodge it. A ball in a deep valley (b), in contrast, has very little potential energy and needs a large external boost to change its position. The latter is a very stable attractor; the former is called a *repellor* because the system does not want to sit on the hill. A ball in a shallow well (c) is moderately stable, but will respond to a sufficient boost by moving into the neighboring well (while not dwelling very long on the hillock in between). Over a long enough time, all the balls in the landscape

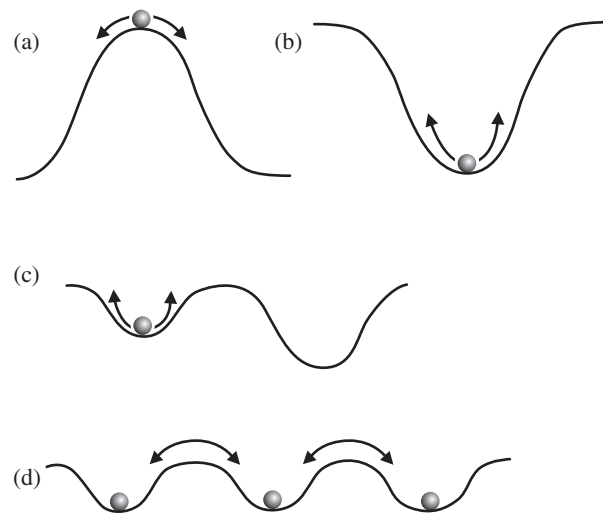


Figure 6.7 Stable and unstable attractors. The stability of the attractor depicted as potential wells. The ball on the top of the hill (a) has a lot of potential energy, and even a very small push will dislodge it; it is a repellor. The ball at the bottom of the step hill (b) requires a large energy boost to send it over the top. If perturbed, it will quickly return to the bottom. It is a stable attractor. The ball in the shallow well (c) is in a less stable situation. Relatively small perturbations will push the ball around, although, given enough time, it will probably end up in the deeper well because of its own stochastic noise. A behavioral system (d) may have multistability.

will end up in the deepest valley, although neighboring valleys may be deep enough that escape from them is very unlikely. Figure 6.7d also shows such a *multistable* attractor, with three point attractors and two repellers between them.

The stability of a system can be measured in several ways. First, stability is indexed by the statistical likelihood that the system will be in a particular state rather than other potential configurations. Second, stability responds to perturbation. If a small perturbation applied to the system drives it away from its stationary state, after some time the system will settle back to its original equilibrium position. As seen in Figure 6.7, when the potential valley is deep and the walls are steep, the ball will return quickly to the bottom. In contrast, the same perturbation applied to a ball in a shallow potential well will take longer to return to equilibrium because the restoring force is less. If the ball is pushed away from a hilltop, however, it will never return. Thus, one indication of system stability is this *local relaxation time* after a small perturbation.

Third, stability is related to the system's response to natural fluctuations within the system. Recall that complex systems exhibiting patterns are composed of many subsystems. Each of these subsystems has noise associated with it, and these intrinsic noises act as stochastic forces on the stability of the collective variable. This is another way of saying that complex systems, even apparently stable ones, are nonetheless dynamic. If the system resides in a steep and deep well, these random forces will have little effect and the ball will not fluctuate very much around the mean attractor pattern. In the shallow well, however, these small forces are more effective and the ball should roll around more. The size of the deviations from the attractor state can be measured, for example, by the variance or standard deviation of the collective variable around the attractor state. The more stable the attractor, the smaller the standard deviation around the attractor.

Soft Assemblies

As Figure 6.7 indicates, calling a pattern an attractor is a statistical statement about where the system prefers to reside, and how resistant it is to internal and external forces. Although some attractor states are so unstable as to almost never be observed, other attractor states are so stable that they look like they are inevitable. Because these behavioral states are so reliably seen under certain circumstances, it is easy to believe that they are gener-

ated by hardwired structures or programs within the system. Very stable attractors take very large pushes to move them from their preferred positions, but they are dynamic and changeable nonetheless. This is one way of saying that the system is “softly assembled” (Kugler & Turvey, 1987) rather than hardwired or programmed. The components can assemble in many ways, although only one or several of them are stable enough to be seen. We argue here that, in action and cognition, and in development, many configurations that act like programs, stages, or structures are stable attractors whose stability limits may indeed be shifted under appropriate circumstances. That is to say, many mental constructs and movement configurations—object permanence and walking, for example—are attractors of such strength and stability that only the most severe perturbations can disrupt them. They look as though they are wired in. Other abilities—transitive inference, visual illusions, and many sport skills, for example—have attractors whose stability is easily upset by contextual manipulations or lack of practice, or by not paying attention.

A good developmental example of a softly assembled system is the infant locomotor pattern of creeping on hands and knees. This pattern has traditionally been described as a “stage” in the ontogeny of human locomotion: Nearly all human infants crawl before they walk. It is tempting to think of crawling as a necessary precursor to upright locomotion; indeed, some physical therapists believe infants must go through this stage for successful sensorimotor integration. In dynamic terms, however, we can see creeping as a temporary attractor, a pattern that the system prefers, given the current status of the infant's neuromuscular system and the infant's desire to get something attractive across the room. When babies do not have the strength or balance to walk upright, creeping is a self-assembled solution to independent mobility—a statistical probability, but not an inevitable solution. In fact, some infants use anomalous patterns such as crawling on their bellies or scooting on their bottoms, and some infants never crawl at all. The typical crawling pattern then is a preferred attractor, but not a hardwired stage.

Soft assembly is the core assumption of a dynamic view of development. It banishes forever the vocabulary of programs, structures, modules, and schemas and supplants these constructs with concepts of complexity, stability, and change. Stability defines the collective states of the system, assessed by its resistance to change. Fluctuations around stable states are the inevitable accompa-

niment of complex systems. These fluctuations—the evidence that a system is dynamically active—are the source of new forms in behavior and development.

How Systems Change: Fluctuations and Transitions

We have defined behavioral patterns as variously stable, softly assembled attractor states. How do patterns change, as they do in development or in learning? Here we invoke the notion of nonlinearity, a hallmark of dynamic systems. A pattern in a dynamic system is coherent because of the cooperation of the components. This coherence is maintained despite the internal fluctuations of the system and despite small external pushes on it. Thus, because walking is a very stable attractor for human locomotion, we can walk across the room in high-heeled shoes, on varied surfaces, and even while we are talking or chewing gum. But as the system parameters or the external boundary conditions change, there comes a point where the old pattern is no longer coherent and stable, and the system finds a qualitatively new pattern. For example, we can walk up hills of various inclines, but when the steepness of the hill reaches some critical value, we must shift our locomotion to some type of quadrupedal gait—climbing on all fours. This is an example of a *nonlinear phase shift* or *phase transition*, highly characteristic of nonequilibrium systems.

In the case of our locomotor patterns, the parameter change was simply the steepness of the hill to climb. Gradual changes in this parameter engendered gradual changes in our walking until a small change in the slope causes a large change in our pattern. In dynamic terminology, the slope changes acted as a *control parameter* on our gait style. The control parameter does not really “control” the system in traditional terms. Rather, it is a parameter to which the collective behavior of the system is sensitive and that thus moves the system through collective states. In biological systems, any number of organismic variables or relevant boundary conditions can be relatively nonspecific, and often may be changes in temperature, light, speed of movement, and so on.

For example, Thelen and Fisher (1982) discovered that body weight and composition may act as a control parameter for the well-known “disappearance” of the newborn stepping response. Newborn infants commonly make stepping movements when they are held upright, but after a few months, the response can no longer be elicited. Although the traditional explanation has been inhibition of the reflex by higher brain centers, Thelen

and Fisher noticed that movements similar to steps did not disappear when infants were supine instead of upright. This made a central nervous system explanation unlikely. Rather, they noticed that infants gained weight, and especially body fat, at a rapid rate during the period when stepping was suppressed. They reasoned that as their legs got heavier without a concomitant increase in muscle mass, the infants had increasing difficulty lifting their legs in the biomechanically demanding upright posture. Body fat deposition is a growth change that is not specific to leg movements, yet it affected the system such that a qualitative shift in behavior resulted.

Change may thus be engendered by components of the system that are nonobvious, but, in other cases, the control parameter may be specific to the system in question. For example, practice or experience with a specific skill may be the critical factor. For instance, 8- to 10-month-old infants do not reach around a transparent barrier to retrieve a toy (Diamond, 1990b). Normally, infants have little experience with transparent barriers. However, when Titzer, Thelen, and Smith (2003) gave infants transparent boxes for several months, the babies learned to shift their usual response of reaching in the direct line of sight in favor of reaching into the opening of the box. In this case, infants’ learning the perceptual properties of transparent boxes through exploration was the control parameter engendering the new form of knowledge.

As we discussed earlier, not all changes in a system are phase shifts. At some values of a control parameter, the system may respond in a linear and continuous manner. Nonlinearity is a threshold effect; a small change in the control parameter at a critical value results in a qualitative shift. Control parameters (whether they are nonspecific, organic, or environmental parameters) or specific experiences lead to phase shifts by threatening the stability of the current attractor. Recall that all complex systems carry in them inherent fluctuations. When the system is coherent and patterns are stable, these fluctuations are damped down. However, at critical values of the control parameter, the system loses its coherence, and the noise perturbs the collective variable. At some point, this noise overcomes the stability of cooperative pattern, and the system may show no pattern or increased variability. However, sometimes as the control parameter passes the critical value, the system may settle into a new and different coordinative mode.

The most elegant demonstration of behavioral phase transitions comes from the work of Kelso and his

colleagues in a long series of studies and models of human bimanual coordination (see the extensive discussion in Kelso, 1995). The basic experiment is as follows: Participants are asked to move their index fingers either in-phase (both fingers flexed and extended together) or antiphase (one finger flexed while the other is extended). They are then told to increase the pace of the cyclic movements. Participants who begin in the antiphase condition usually switch to in-phase just by speeding up with no change in patterns. Thus, both patterns are stable at low frequencies, but only the in-phase is stable at higher frequencies. In dynamic terms, the collective variable of *relative phase* is sensitive to the control parameter, frequency.

Using this simple experiment, Kelso and his colleagues showed definitively that the phase shift from anti- to in-phase movements was accompanied by a loss of system stability. The standard deviations around a mean relative phase remained small until just before each participant's transition, when the deviations increased dramatically. Then, as the participant settled into the in-phase pattern after the shift, deviations were again small. Likewise, when Scholz, Kelso, and Schönner (1987) perturbed the movements with a small tug during the various frequencies, they observed that recovery to the desired frequency was more difficult as participants approach the anti- to in-phase transition. Disintegration of the system coherence was reflected in diminishing strength of the antiphase attractor to pull in the trajectories from various regions of the state space.

Development from a Dynamic Systems Perspective

In this section, we give an overview of dynamical systems using Waddington's epigenetic landscape as a means of illustrating the main concepts. We then use the developmental problem of learning to reach as an example of how these themes can be used to guide experiments and research. Finally, we turn to the development of the object concept, and, in particular, use the A-not-B error to show how these ideas may be incorporated into formal theories of behavior and development.

A Dynamic Epigenetic Landscape

We have thus far described self-organizing systems as patterns of behavior "softly assembled" from multiple, heterogeneous components exhibiting various degrees of stability and change. According to a dynamic systems

view, development can be envisioned as a series of patterns evolving and dissolving over time, and, at any point in time, possessing particular degrees of stability. Expanding on the potential landscape representation we introduced earlier, we can depict these changes, in an abstract way, in Figure 6.8 our depiction closely parallels Waddington's famous epigenetic landscape (Figure 6.2) in both its early (1957) and later (1977) incarnations.

The first dimension in Figure 6.8 is time (Muchisky, Gershkoff-Stowe, Cole, & Thelen, 1996). The landscape progresses irreversibly from past to present, from background to foreground. The second dimension—the surface—is that of the collective variable, or a measure of the cooperative state of the system. Each of the lines forming the landscape represents a particular moment in time. These lines depict the range of possibilities of the system at that point in time. The configuration of each line is a result of the history of the system up to that point, plus the factors acting to parameterize the system at the time—such as the social and physical context, the

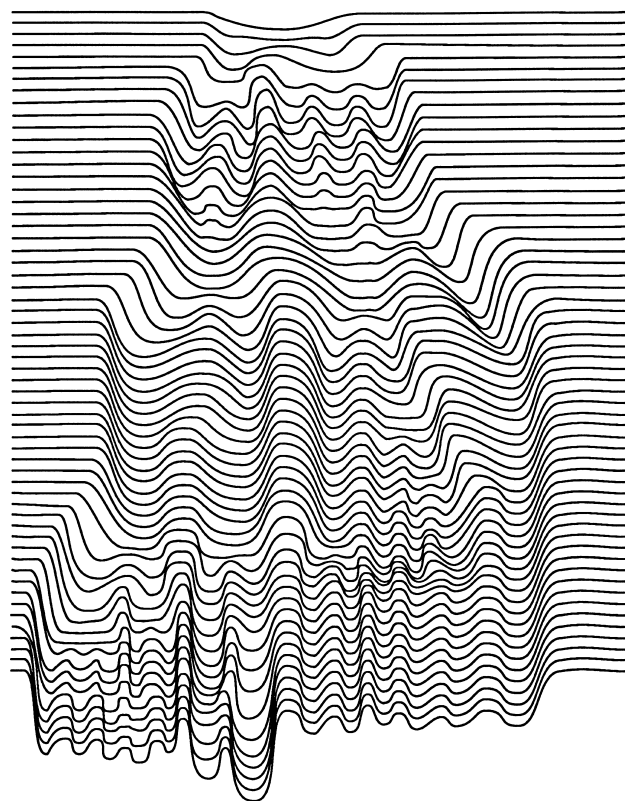


Figure 6.8 An adaptation of Waddington's epigenetic landscape (Figure 6.2). This version depicts behavioral development as a series of evolving and dissolving attractors of different stability.

motivational and attentional state of the child, and so on. The third dimension of the landscape is related to the depth of the variations of the collective variable lines, the various dips and valleys. The depth represents the stability of the system at that point in time, and in that particular combination of constraining factors, and thus captures the probabilistic rather than rigidly fixed nature of behavioral and cognitive states.

Nested Timescales

The landscape represents one critical property of developing dynamic systems: The nesting of changes on multiple timescales. The contexts and conditions that determine the stability of a system at any point in time (t) constitute the initial conditions for the state of the system at the next instant of time ($t + 1$). Likewise, the properties of the system at ($t + 1$) determine its state at ($t + 2$), and so on. The system is thus *reiterative*; each state is dependent on the previous state.

Most important, this reiterative process occurs at all timescales. Thus, a landscape of evolving and dissolving stabilities just as easily depicts the dynamics of a real-time process, such as reaching for an object, producing a sentence, or solving an addition problem as it represents changes in those abilities over minutes, hours, days, weeks, or months. In dynamic terms, the timescales may be *fractal* (Grebogi, Ott, & Yorke, 1987) or have a self-similarity at many levels of observation. For example, coastlines are typically fractal—the geometry of the coastline depends entirely on the scale by which it is measured. Represented on a scale of kilometers, the coast may be described as a simple curve, but that simplicity disappears when the measuring scale is meters or centimeters. Nonetheless, the simple curve *is* the collection of small coves and irregularities apparent to the person walking on the beach as well as to the small sand crab inhabiting a different geometric scale. Likewise, we argue, while perceiving, acting, and thinking occur in their own times of seconds and fractions of seconds, these accumulated actions constitute the larger coastline of developmental change (Samuelson & Smith, 2000).

In a dynamic view, each behavioral act occurs *over time*, showing a course of activation, peak, and decay, and with various levels of stability associated with each point in time, but every act changes the overall system and builds a history of acts over time. Thus, repeating the same behavior in seconds or minutes can lead to habituation or to learning, as the activity of one instant becomes the starting point for the activity of the next. We

can thus envision a small-scale landscape evolving in the domain of *real time* as in Figure 6.9. In our illustration, consider behavioral act A with a sharp rise time of activation and a very slow decay. With repetition, the threshold for activating A is diminished because the activity has been primed by previous activations. The behavior becomes more stable, more easily elicited, and less able to be disrupted—the person has learned something. An equally plausible account is that activating A might raise the threshold for a repetition of the same act, as happens in adaptation, habituation, or boredom.

Because the history of acting in real time counts, the real-time dynamics of actions may display this important property of *hysteresis* (e.g., Hock, Kelso, & Schönner, 1993), when the same conditions lead to different behavioral outcomes, depending on the immediate previous history of the system. Behavioral acts therefore carry with them not only the dynamics of their immediate performance, but a *momentum* (e.g., Freyd, 1983, 1992) so that the system is always impacted by every act of perceiving, moving, and thinking, albeit to various degrees. Just as minute-by-minute activities carry with them a history and build momentum, so also do these accumulated histories constitute the stuff of learning and development change. Each line in our landscape depicting the probability of the system's states contains its own fractal timescale. Thinking and acting are functions of the history of thinking and acting at the same time that development is also of that history. Habituation, memory, learning, adaptation, and development form one seamless web built on process over time—activities in the real world.

Such a view of nested timescales radically changes our views of what is “represented” in the brain. Typically, in

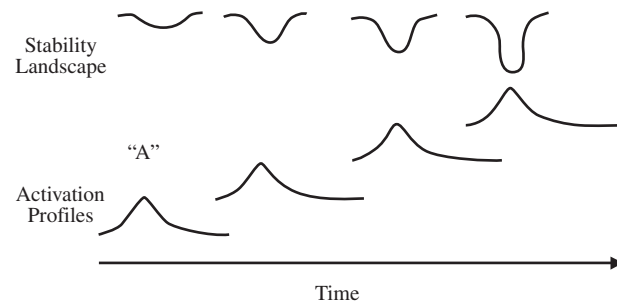


Figure 6.9 Effect of repeating behavior over time. Each activation may act to prime or to lower the threshold for the next repetition. A lowered threshold may make behavior more stable, acting as a local attractor.

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studies of cognitive development, researchers present infants and children with tasks designed to assess what the children really know. Thus, experiments that show infants possible versus impossible physical events purport to reveal whether infants know that objects are solid, cannot occupy the same space as another object, obey the laws of gravity and momentum, and so on (e.g., Baillargeon, Spelke, & Wasserman, 1985; see also Cohen & Oakes, 1993). Or, on the basis of their performance with a series of colored rods, children are assumed to “have” the ability to make transitive inferences—to infer a third relation from two others. (“If the blue rod is longer than the green rod and the green rod is longer than the yellow rod, is the blue rod longer than the yellow rod?”) If children fail on these tests, they do not have the knowledge of physical properties of objects or the ability to think about two things at the same time.

The core assumption here is that knowledge or abilities are stored “things” that are timeless and exist outside their here-and-now performance. An experimental task is good only as it reflects a “true” reading of the underlying mental structure. This common viewpoint has run into serious difficulties, however, both empirically and theoretically. First, literally thousands of studies have demonstrated that children’s knowledge or their ability to use certain procedures is extremely fluid and highly dependent on the entire context of the experimental situation, including the place of the experiment, the instructions and clues, their motivation and attention, and very subtle variations in the task (Thelen & Smith, 1994). For example, based on the colored rod task, Piaget concluded that preschoolers could not make transitive inferences. However, when Bryant and Trabasso (1971) drilled preschoolers in the premise information until they learned and remembered that “the blue rod is longer than the green one,” the preschoolers *could* make these inferences. Similarly, the failure of 6-month-old infants to search for hidden objects led Piaget to believe that infants cannot mentally represent objects when they are out of sight (Piaget, 1954). Yet, at the same age, infants act surprised when they *watch* objects disappear from expected locations.

To explain these strange results—how children can know things in one situation, but not another—developmentalists have proposed that the child has the “real” competence all along, but the failure lies in some performance ability. In the case of transitive inference, Bryant and Trabasso (1971) reasoned that the failure was not in lacking the mental structure, but in remembering the

premises. When they trained memory, the competence was revealed. Likewise, 6-month-old infants do know that objects persist, but they are deficient in searching—actually reaching out, removing a cover, and retrieving the object. Changing the task to remove the search component revealed the essential knowledge of object permanence. Very young children may thus possess considerable cognitive competence, but the competence is hidden because of immature memory, motor skills, language, or attention.

This distinction between competence and performance has been a major force in developmental thinking for the past 20 years (Gelman, 1969). In domain after domain, researchers have followed this train of logic: Define the *essence* of some knowledge structure, do a thorough task analysis, strip away the supporting process and performance variables, and see whether children possess the “essential” knowledge. By these procedures, researchers have unmasked cognitive competences at earlier and earlier ages, certainly beyond those proposed by Piaget and his followers. In addition, the competence/performance distinction seems to help explain Piagetian *decalage*: Why the same child may perform at one cognitive level in one task and at another level in tasks believed to tap into a similar structure. Again, the difficulty lies in the ability of the task to actually reveal the hidden structure.

Why does a dynamic account render the competence/performance distinction as theoretically insufficient? Because behavior is always assembled *in time*. There is no logical way of deconstructing what is the “essential,” timeless, and permanent core and what is only performance and of the moment. Because mental activity has developed in time from fundamentals in perception and action and is always tied in real time to an internal and external context, there is no logical way to draw a line between these continuous processes. The essence of knowledge is not different from the memory, attention, strategies, and motivation that constitute knowing. In addition, seeking a core competence often reduces to an exercise in task analysis. Does watching objects disappear constitute the true measure of object permanence? How many clues are allowed in the experiment, or how many familiarization trials are sufficient to peel away the superfluous performance impedances? Does not being able to retrieve a hidden object mean that the child really “knows,” or is knowing separate in this case from knowing in order to act? One danger of such accounts is that, in the quagmire of definitions and task

analysis, developmental process itself is lost. How does it happen that this child behaves as he or she does at this moment in this context? What in the child's history, or in the history of children in general, leads to these patterns in time?

Layered Levels of Analysis. Taking time seriously also means integrating over multiple timescales and levels of analysis. Neural excitation, for example, happens in milliseconds. Reaction times are of the order of hundreds of milliseconds. People learn skills after hours, days, and months of practice. Developmental change occurs over weeks, months, years. Traditionally, psychologists have considered action, learning, and development as distinct processes. But for the organism time is unified and coherent, as are the different levels in the system. Every step an infant takes, for example, is both a product and a producer of change—at the level of neurons, eyeballs and muscles, motivations, and ideas about space and surfaces. A complete theory of walking requires integrating mechanisms of change at all these levels. The study of development, then is necessarily concerned with how change at different times and at different levels of analysis interact.

An illustration of this is presented in the work of Neville and her colleagues (see Neville & Bavelier, 2002 for review) on the neural and behavioral development of deaf individuals. Growing up deaf leads to different outcomes in *visual processing* which are readily apparent in event-related potentials (ERPs) in response to peripheral visual events. She found that such ERPs from visual areas were 2 to 3 times larger for hearing than for deaf individuals. Neville explains these differences in terms of the competitive processes that operate in development between visual and auditory cortical regions. But think about what this means in terms of the dynamics of change. The moment-to-moment experiences of individual deaf children—internal neural activity on the order of milliseconds—is different for a visual system developing without audition than for one developing with audition. The accrued effects of these millisecond differences in neural activity *over the long term* create changes in neural connectivity that then determine the different patterns of neural activity evident in the ERPs of hearing and deaf adults. Events on the order of milliseconds, repeated over a longer timescale cause changes in both slower processes of growth (neuronal connectivity) and also faster processes of neural activation (ERPs).

We note here several other research programs that also explicitly seek an understanding of developmental change in nested levels of analyses (Gershkoff-Stowe, 2001, 2002) show how every word that a child utters changes the processes of lexical retrieval, changes that in turn enable the system to produce many different words in rapid succession. Likewise, Adolph, Vereijken, and Shrout (2003) show how every step taken down an incline plane changes the body dynamics and what an infant knows about slopes. Finally, Thomas and Karmiloff-Smith's (2003) recent work on developmental disorders, and particularly William's syndrome, cogently makes the point that understanding development—and intervening effectively—requires understanding how processes of change on multiple timescales interact with each other to create the developmental trajectory. Their general program of research is based on the idea that static models of brain functioning—where functions are mapped to circumscribed brain regions—are inappropriate for the study and understanding of developmental disorders, including genetically based ones such as William's syndrome. Rather, they argue that the brains of atypically developing children are not normal brains with parts intact and parts impaired (as is the case in normal adult brain injury) but brains that have developed differently throughout embryogenesis and postnatal development. Reminiscent of the conclusions from Neville's studies of brain development in the deaf, structure-function mappings in the brain are a product of a developmental cascade involving processes at many timescales. The simulation studies by Thomas and Karmiloff-Smith (2003) provide particularly useful insights into atypical developmental trajectories, which grow out of small differences in the timing and operation of general processes (see also Elman, Bates, Johnson, & Karmiloff-Smith, 1996).

Lewis has extended the idea of nested levels to the study of emotion and personality. He asks: How do we shift from being happy to sad when we are told of an unhappy event? How and why do moods settle in (e.g., depressions, contentment)? Why are some of us more prone to these moods than others? How do these happy and unhappy episodes and these moods create our personalities? How do our personalities create and play out in our emotional episodes, in our mood swings? Understanding emotion requires understanding how processes at different timescales influence each other. In a recent new theory of emotion and personality development,

Lewis (2000) likens the relationship between emotional episodes, moods, and personality to circular causality across different scales of analyses that characterize coastlines. The large-scale or macroscopic properties of a coastline—the bays, the ridges, the peninsulas—set the conditions for the small-scale or microscopic processes—waves, tidal forces, erosion. But these microscopic properties causally contribute to the long-standing macroscopic properties. This is an example of circular causality. Understanding emotion and personality development requires working out the same kind of circularly causal relationships—from the microscopic emotional states through the midscale of moods to the more stable personality. Table 6.1 summarizes Lewis's three scales of emotional development, showing parallels and distinctions across scales and the current understanding of the psychological and neurobiological mechanisms.

These developmental patterns fit the larger idea behind the landscape in Figure 6.8: The changing stability of patterns over many scales of time. Each line on the landscape represents the states of a behavioral pattern expressed as the collective variable; that is, the condensation of the multiple components into a simpler behavioral expression. Knowing the behavior of the collective variable is an essential first step in discovering the processes of change. But a more complete understanding also requires that we know about the behavior of the components that constitute the cooperative ensemble. This is especially important in developmental studies because the contributions and weights of these elements may themselves change over time and in different contexts. For example, leg mass and fat-to-muscle ratio may be potent contributors to behavioral expression of step-

ping at 2 months, but changes in these anatomical parameters may be far less important in the transition to independent walking at 12 months. At the later age, although infants need sufficient leg mass and strength to support their weight, the ability to maintain balance using vision and proprioception may be the critical component. Likewise, although focused attention may determine success in early stages of learning new skills, as skills become more automatic, the relative contribution of attention is diminished.

Because the components themselves have a developmental history and relationships among them are continually altered, a fuller representation of our dynamic landscape would look like Figure 6.10 That depiction shows three landscapes layered on top of one another, indicating that the components of the dynamic system themselves have a dynamic. The arrows connecting the layers show that the coupling between the components is complex and contingent, and may change over time. This means that the coupling is always multidirectional, and that effects of the subsystems on one another may cascade over time. To continue our infant stepping example, increasing leg muscle strength through activity in the first months of life facilitates standing, crawling, and walking. Independent locomotion induces change in spatial cognition, probably because as infants move around they pay more attention to their spatial landmarks (Acredolo, 1990; Bertenthal & Campos, 1990). But changes in cognition also feed back to locomotor behavior as more skilled infants explore and exploit more and different aspects of their spatial environment, change their motor planning, and are able to make rapid adjustments to unexpected events.

TABLE 6.1

	Emotional Episode	Mood	Personality
Timescale	Seconds to minutes	Hours, days	Years
Description	Rapid convergence of cognitive interpretation with emotional state	Lasting entrainment of interpretative bias	Lasting interpretative-emotional habits
Dynamic system formalism	Attractor	Temporary modification of state space	Permanent structure of interpretative state space
Possible neurobiological mechanism	Cortical coherence mediated by orbitofrontal organization entrained with limbic circuits	Orbitofrontal-corticolimbic entrainment, motor rehearsal, and prefference, sustained neurohormone	Selection and strengthening of some corticocortical and corticolimbic connections, pruning of others, loss of plasticity
Higher order form	Intention, goal	Intentional orientation	Sense of self

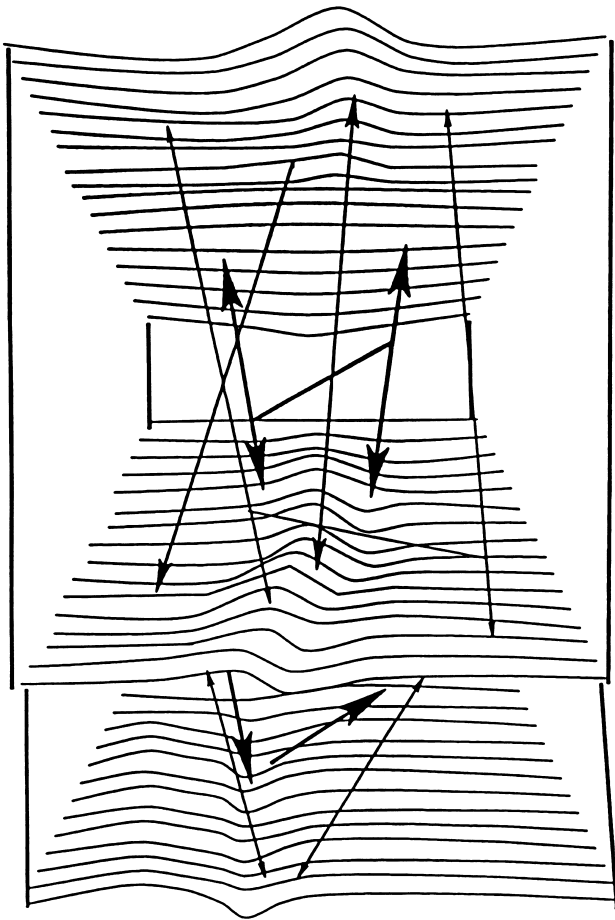


Figure 6.10 The epigenetic landscape as a multilayered system where the components mutually influence each other in changing ways.

Importantly, explanations at every level must be consistent and ultimately reconcilable. This is especially important when considering the neural basis of behavior. Since the time of Myrtle McGraw (1932), there has been a tradition in human developmental studies to seek explanation at the neural level, to look for some observed change in behavior *as caused* by a preceding and determining change in the brain. For example, Goldman-Rakic (1987) and others have suggested that massive reorganization of synaptic connections in the prefrontal cortex are the reason why 8- to 12-month-old infants show improvements in spatial cognition, inhibition of prepotent response tendencies, and even the onset of language. Thatcher and others seek to explain Piagetian stages as a result of stagelike changes in brain activity (Thatcher, 1991, 1992).

A successful search for the mechanisms of change during development may require *integration* of mecha-

nisms at very different levels of organization. For example, by discovering that the deposition of body fat acts as a control parameter in the disappearance of newborn stepping, we have supplied a mechanism of change. A physiologist might ask about the metabolic processes that accelerate the deposition of fat in the postnatal period, and that could also constitute a process-based explanation of change. But the metabolic explanation should not be construed as any more basic and more real than one at any other level. Indeed, because levels and processes are mutually interactive, it is impossible to assign one level as the ultimate causation. Descriptions of change of many components are needed so that multi-level processes and their mutual interactions can be fully integrated.

Multicausality. Developing organisms are complex systems composed of very many individual elements embedded within, and open to, a complex environment. These components continuously interact with each other and in so doing change each other and the system as a whole. This is the idea of *multicausality*. As in many other complex systems in nature, such systems can exhibit coherent behavior: the parts are coordinated without an agent or a program that produces the organized pattern. Rather, the coherence is generated solely in the relationships between the organic components *and the constraints and opportunities of the environment*. This is the idea of an open system, one in which the environment (the task) is a component, equal to all others, in generating coherence. This self-organization means that no single element—internal or external—has causal priority. When such complex systems self-organize, they are characterized by the relative stability or instability of their states. Development can be envisioned as a series of evolving and dissolving patterns of varying dynamic stability, rather than an inevitable march toward maturity. Thus, crawling is a coherent behavior that infants use to locomote when they have sufficient strength and coordination to assume a hands-and-knees posture, an environment to support it and to motivate self-movement, but a system not yet balanced and strong enough to walk upright. Crawling is a stable behavior for several months. But when infants learn to walk, the crawling pattern becomes destabilized by the patterns of standing and walking. There is no program for crawling assembled in the genes or wired in the nervous system. It self-organizes as a solution to a problem in a task context (move across the room), later to be replaced by a more efficient solution.

Heterogeneous Systems and Degeneracy. These ideas about multicausality, self-organization, and openness fit emerging ideas about neural development. The brain is made up of many different parts and processes, but each is in continuous interaction with the other parts and, through the sensory-motor system, with the world (e.g., Churchland & Sejnowski, 1992; Crick, 1994; Damasio, 1994; Edelman, 1987; Huttenlocher, 2002; Kelso, 1995; Koch & Davis, 1994). The brain also has a property that Edelman (1987) calls *degeneracy*, which in neural structure means that any single function can be carried out by more than one configuration of neural signals and that different neural clusters also participate in a number of different functions. Degeneracy creates redundancy such that the system functions even with the loss of one

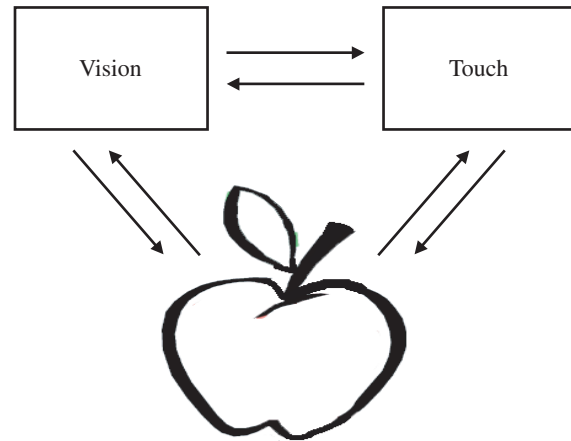


Figure 6.11 Illustration of the time-locked mappings of two sensory systems to the events in the world and to each other. Because visual and haptic systems actively collect information—by moving hands, by moving eyes, the arrows connecting these systems to each other also can serve as teaching signals for each other.

Brain plasticity has now been found not just in the somatosensory cortex, but also in somatic senses in sub-cortical areas and in the visual, auditory, and motor cortices in monkeys and other mammals (Kaas, 1991, see also Stein & Meredith, 1993). These demonstrations of adult plasticity are very important for understanding development because (a) they demonstrate that brain representations, even those that can be “geographically” located, are dynamic processes, and (b) they provide clues to the very processes by which development may take place.

The now classic experiments were performed by Merzenich and his colleagues on New World monkeys, which have relatively unfissured brains with a clear somatotopic representation of their sensitive hands. A painstaking mapping of the sensation on the finger and hand areas to electrophysiological responses on the cortical surface revealed detailed maps of adjacent areas that were similar, but not identical, in individual monkeys (Jenkins, Merzenich, & Recanzone, 1990). That these areas are plastic, not anatomically rigid, was demonstrated in several ways. First, when the experimenters amputated digits, the maps reorganized so that adjacent areas enlarged to fill in the finger spaces where input was eliminated. Second, when the Merzenich group fused two fingers of adult monkeys together, the monkeys’ brains eliminated the boundaries between the digits, and the receptive fields overlapped. When the skin-fusion was surgically corrected, distinctive digit areas returned. Enhanced function of a single finger through training enlarged its cortical representation, which again could be reversed when training ceased. Finally, even when no experimental manipulations were imposed, borders of digit representations changed somewhat over time, presumably reflecting the immediate use history of the finger. These and other experiments revealed, in the words of Merzenich, Allard, and Jenkins (1990) that “*the specific details of cortical ‘representations’—of the distributed, selective responses of cortical neurons—are established and are continually remodeled BY OUR EXPERIENCES throughout life*” (p. 195; emphasis and capitals in original).

We end this section with a point to an intriguing new idea: Synesthesia in adults is a remnant of the pervasive interconnectivity and exuberant multimodal nature of the developing brain. *Synesthesia* is defined as the regular involuntary experience of external, durable, and generic perceptions in senses not commonly associated

with a certain stimulus (Harrison, 2001). For example, the letter A might be associated with red or the smell of the flowers. Not all possible cross-modal correspondences show up as synesthetic experiences. Instead, they tend to consist of perceiving colored letters or musical notes or colored sounds and tastes. Synesthesia was long considered psychological exotica (see Harrison, 2001) and not systematically investigated—in part because synesthetic experiences are so constrained to a few odd kinds of correspondences, highly individualistic (while some individuals might perceive a high C as orange, others might perceive it as blue), and because very few adults report such cross-modal sensory experiences. However, recent behavioral studies with adults show the psychological reality in phenomena such as pop-out effects in search tasks and recent imaging studies show the neural reality. There are growing suggestions (see Mondloch & Maurer, 2004) that these idiosyncratic synesthetic connections in adults are vestiges of the exuberant interconnectivity in the developmentally immature, an interconnectivity that plays an important role in developmental process, and in the creation of the seemingly separate sensory systems in mature organisms (see also Turkewitz, 1994).

Multimodal Processes in Cognitive Development.

One demonstration of the developmental power of heterogeneous systems coupled to each other and time locked to the world comes from a study of how babies come to understand transparency. Transparency is a problematic concept; think of birds who harm themselves by trying to fly through windows. Transparency is a problem because correlations between visual cues and the haptic cues that characterize most of our encounters with the world do not work in this case. So babies, like birds, are confused by transparency. In one study, Diamond (1990b) presented infants with toys hidden under boxes such that there was an opening on one side—as illustrated in Figure 6.12. These boxes were either

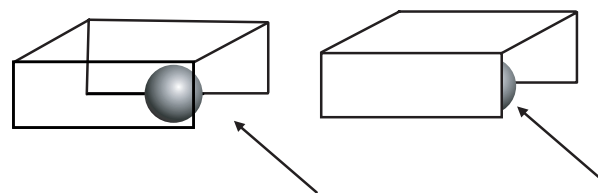


Figure 6.12 A toy (ball) hidden under a transparent box and an opaque box in the Diamond task. The opening is indicated by the arrow.

opaque—hiding the toy—or transparent so that the infants could see the toy under the box. The key result is that 9-month-old infants are better able to retrieve the toy from the opaque than from the transparent container. The problem with the transparent container is that infants attempt to reach for the toy directly, through the transparent surface, rather than searching for and finding the opening.

Infants readily solve this problem, however, if they are given experience with transparent containers. Titzer, Thelen, and Smith (2003) gave 8-month-old babies either a set of opaque or transparent buckets to play with at home. Parents were given no instructions other than to put these containers in the toy box, making them available to the infants during play. The infants were then tested in Diamond's task when they were 9 months old. The babies who had been given opaque containers failed to retrieve objects from transparent ones just as in the original Diamond study. However, infants who played with the transparent containers sought out and rapidly found the openings and retrieved the object from the transparent boxes.

Why? These babies in their play with the containers—in the inter-relation of seeing and touching—had learned to recognize the subtle visual cues that distinguish solid transparent surfaces from no surface whatsoever and had learned that surfaces with the visual properties of transparency are solid. The haptic cues from touching the transparent surfaces educated vision, and vision educated reaching and touch, enabling infants to find the openings in transparent containers. These results show how infants' multimodal experiences in the world create knowledge—about openings, object retrieval, and transparent surfaces.

Experimental studies of human cognition suggest that many concepts and processes may be inherently multimodal in ways that fit well with Edelman's idea of reentrance (e.g., Barsalou, 2005; Glenberg & Kaschak, 2002; Gogate, Walker-Andrew, & Bahrack, 2001; Lickliter, 1994; Richardson, Spivey, Barsalou, & McRae, 2003). One line of evidence for this conclusion is that even in tasks meant to be explicitly unimodal, multiple modalities contribute to performance. For example, *visual* object recognition appears to automatically activate the actions associated with the object. In one study, adults were shown a picture of a water pitcher such as that illustrated in Figure 6.13. The task was simple, to press a button indicating whether the object was a



Figure 6.13 Illustration of the Tucker and Ellis task. On each trial the task is the same, to answer as rapidly as possible the question: “Is this a pitcher.” Half the participants answer “yes” by pressing a button on the right and half by pressing a button on the left. Participants are faster when the handle is on the same side as the “yes” response.

pitcher (yes) or it was not (no). Response time was the dependent measure. This is a purely visual object recognition task. Yet, the participants were much faster at recognizing the object if the button pressed to indicate the yes response was on the same side as the pitcher's handle, as if seeing the handle primed (and readied) the motor response of reaching to that side. Similar results have been reported with a wide variety of objects and in tasks using several different methods. In general, people are faster in visual recognition tasks when the response to be made is compatible with a real action on the object. These results tell us that visual recognition is a piece of, in the same internal language as, action. This is how it must be under the idea of reentrant mappings, where visual recognition is built out of and educated by its time-locked connections with actions on objects.

Development as Selection. In an earlier section, we proposed very general principles of dynamic systems as a way of conceptualizing developmental change: Patterns assembled for task-specific purposes whose form and stability depended on both the immediate and more distant history of the system. We emphasized that a dynamic view meant that there must be continuity among the components of the system, both internal and external, and among the timescales over which the system lives. Contemporary discoveries of brain organization and function are highly consistent with these dynamic principles; indeed, they provide insights into the precise mechanisms of change.

Properties that point to development as a *selective* process indicate that the brain is a dynamic collective, with self-organizing and dynamic properties; it is designed to extract coherence from multiple, time-locked input; and its organization is maintained by function. In the following account, we rely heavily on Gerald Edelman's (1987) "theory of neuronal group selection" (TNGS) as the neural mechanism instantiating dynamic behavioral development.

Several additional assumptions are critical. First, it is assumed that genetic and epigenetic processes during neural embryology produce the global architecture of the brain (see Edelman, 1987, 1988). In that primary architecture, however, there is enormous variability in both the number of individual neurons and their connectivity. Second, connections between neurons and groups of neurons arise through use. Third, there is an overabundance of neurons and possible connections among them, and thus specificity arises through competition.

Imagine, then a newborn infant whose first experiences in the world include nursing at the breast. Associated with the perceptions of the baby's own movements of lips, jaws, tongue, and throat are the taste of the milk, the sight and smell of the mother's skin, the sound of her voice, and the whole body tactile experience of contact and warmth. Because of the degenerate and reentrant web of connections, these perceptions activate time-correlated groups of neurons meshed together, linking the patterns detected by the originally separate sensory systems. It is also highly likely that these perceptions are associated with neural nets from emotional and motivational centers that signal pleasurable feelings (Damasio, 1994; Edelman, 1987). With each suck and swallow, and repeated nursing episode, overlapping, but not identical, groups of neurons also become activated. Common assemblies become strengthened; less-used pathways become less stable. Because the structure is reentrant, common perceptual elements are extracted from these overlapping inputs that are marked by their correlations in real-world time. This mapping over heterogeneous input is the critical process; new relationships are excited and strengthened because they occur together.

With repetition, such a process of selection by function allows the newborn infant to recognize a constellation of features as a higher-order category: "Time to eat." But it is a dynamic category, invoked now by only partial and incomplete features—the nursing position, for example, or the sight and smell of mother, or the act

of sucking itself—and it is continually updated as experience accumulates. When feeding is supplemented by a bottle, for instance, the category "time to eat" may be enlarged to include the perceptual qualities of the bottle and an adjustment in the sucking movements to accommodate changes in the nipple. Higher-order knowledge about feeding, object properties, and the behavior of other humans is thus built by selection through everyday activities—looking, moving, hearing, and touching.

Edelman (1987) clearly follows Piaget (1952) in believing that these early perception-action categories are the cornerstone of development. In particular, the emergence of categories is a specific case of dynamic pattern formation. The task facing newborn infants is to reduce the degrees of freedom at many levels: In the external world—the potentially indeterminate nature of the stimuli—this is done by forming perceptual categories; and in the internal world—the equally indeterminate nature of the multiple joints and muscles—this is done by seeking patterns of motor coordination and control. At the same time, and most important, they must match their internal dynamics to those of the world around them; they must make their perceptual categories and their action categories congruent to function in flexible, adaptive ways. In our dynamic approach, perception, action, and cognition are not disjointed; they are part of a singular process.

Thus, we believe that whether we choose the term *pattern formation*, or *coordination*, or *category acquisition*, we are referring to the same dynamic processes whereby complex heterogeneous elements self-organize to produce coherence in time and space. Dynamic patterns can be fleeting or very stable, but, most important, they are time dependent and seamless. By *time dependent*, we mean that each event in the brain and body has a here-and-now, a history, and an effect on the future. By *seamless*, we mean that these time domains are themselves without interruption. The stuff of development is the dynamics of perception, action, and cognition in real time. What the infant sees, thinks, and does in the present provides the aliment for what the child is in the future, just as what the child did in the past is the substrate for how he or she sees, thinks, and acts right now. Thus, we can envision the neuronal processes postulated by TNGS as a specific form of dynamic pattern formation, with the patterns being the categories of perception and action that form the developmental core of higher mental functions and the patterns of thought that

become increasingly complex and generalized throughout infancy and childhood.

Exploration. How can a learner *who does not know what there is to learn* manage to learn anyway? This is a more difficult question than it might first appear. The issue is whether one needs to prespecify the learning tasks and the learning goals, whether the agent or its designer has to know what needs to be learned to learn. Evidence from human development gets us out of this quandary by showing that babies can discover both the tasks to be learned and the solution to those tasks through exploration, or nongoal-directed action. In babies, spontaneous movement creates both tasks and opportunities for learning. One demonstration concerns the study of reaching (Corbetta & Thelen, 1996). The week-by-week development of four babies was tracked over a 3-month period as they transitioned from not reaching to reaching. Four very different patterns of development were observed. Some babies in the nonreaching period hardly lifted their arms at all, but sat placidly watching the world. Other babies were more high-strung and active, flailing and flapping and always moving. These different babies had to learn to solve very different problems to learn to reach out and grasp an object. The flailer would have to learn to become less active, to lower his hands, to bring them into midline. The placid baby would have to learn to be more active, to raise her hands, to lift them up from their usual positions on her side. Each baby did learn, finding a solution that began with exploration of the movement space.

The course of learning for each baby appeared to be one of arousal, exploration, and the selection of solutions from that exploration space. In basic form, the developmental pattern is this: The presentation of an enticing toy is arousing and elicits all sorts of nonproductive actions, and very different individual actions in different babies. These actions are first, quite literally, all over the place with no clear coherence in form or direction. But by acting, by movements that explore the whole range of the movement space, each baby in his or her own unique fashion, sooner or later makes contact with the toy—banging into or brushing against it or swiping it. These moments of contact select some movements in this space, carving out patterns that are then repeated with increasing frequency. Over weeks, the cycle repeats—arousal by the sight of some toy, action, and occasional contact. Over cycles, increasingly stable, more efficient and more

effective forms of reaching emerge. What is remarkable in the developmental patterns of the children is that each found a solution—and eventually converged to highly similar solutions—by following individually different developmental pathways. As they explored different movements—in their uncontrolled actions initiated by the arousing sight of the toy—they each discovered initially different patterns, each had a different developmental task to solve. The lesson for building intelligent agents is clear: A multimodal system that builds reentrant maps from time-locked correlations only needs to be set in motion, to move about broadly, even randomly, to learn and through such exploration to discover both tasks and solutions.

The power of movement as a means for exploration is also illustrated by an experimental procedure known as “infant conjugate reinforcement” (Rovee-Collier & Hayne, 1987). Infants (as young as 3 months) are placed on their backs and their ankles are attached by a ribbon to a mobile which is suspended overhead. Infants, of course, *through their own* actions, discover this link. As the infants kick their feet, at first spontaneously, they activate the mobile. In *a few minutes*, they learn the contingency between their foot kicks and the jiggling of the mobile, which presents interesting sights and sounds. The mobile responds conjugately to the infants’ actions: The more infants kick and the more vigorously they move, the more motion and sound they produce in the mobile. In this situation, infants increase their kicking to above the baseline spontaneous levels apparent when babies simply look at a nonmoving mobile. Infants’ behavior as they discover their control is one of initial exploration of a wide variety of actions and the selection of the optimal pattern to make the interesting events—the movement of the mobile—occur.

Although this is an experimental task, and not an everyday real-world one, it is a very appropriate model for real-world learning. The mobile provides the infant with many time-locked patterns of correlations. More important, infants themselves discover the relations through their own exploratory movement patterns. The infants themselves are moving contingently with the mobile; the faster and harder they kick, the more vigorously the mobile jiggles and sways. This is for infants a highly engaging task; they smile and laugh and often become angry when the contingency is removed. Thus, the experimental procedure *like the world* provides complex, diverse, and never exactly repeating events yet all *per-*

fectly time locked with infants' own actions. And it is exploration, spontaneous nontask-related movement, that starts the process off. Without spontaneous movement, without exploration, there is nothing to learn from the mobile.

Young mammals—including children—spend a lot of time in behavior with no apparent goal. They move, they jiggle, they run around, they bounce things and throw them, and generally abuse them in ways that seem, to mature minds, to have no good use. However, this behavior, commonly called play, is essential to building inventive forms of intelligence that are open to new solutions.

Embodiment. Nervous system are in bodies—and it is through the body the nervous system is connected to (both affecting and being affected by) the world. There is increasing recognition and research on the ways in which cognition—and development—are deeply and completely the product of our continued interaction with the physical world through our bodies. This attention to the body's role in cognition is seen in the study of language (e.g., Glenberg & Kaschak, 2002; Lakoff & Johnson, 1999), in problem solving and memory (Richardson & Spivey, 2000), in joint attention and intention reading (Yu & Ballard, 2004), and in new approaches to a developmental artificial intelligence (Pfeiffer & Scheier, 2001). A key idea in this literature is that cognition does not just reside in organisms, but resides in their coupled interactions with the world (an idea that is also the heart of Gibsonian approaches to perception; see, Gibson, 1979).

One developmental implication is that the physical world serves as a crucial mechanism in developmental process itself. Not all knowledge needs to be put into the head, dedicated mechanisms, or representations. Some knowledge can be realized in the body, a fact dramatically illustrated by passive walkers. Knowledge of the alternating limb movement of bipedal locomotion—knowledge traditionally attributed to a central pattern generator—appears to reside in the dynamics of two coupled pendulums (McGeer, 1990). Some of our intelligence also appears to be in the interface between the body and the world. The phenomenon of change blindness is often conceptualized in this way. People do not remember the details of what is right before their eyes because they do not need to remember what they can merely look at and see (O'Regan & Noë, 2003). Similarly, Ballard and colleagues (Ballard, Hayhoe, Pook, &

Rao, 1997) have shown that in tasks in which people are asked to rearrange arrays of squares, they off-load their short-term memory to the world (when they can). This off-loading in the interface between body and world appears to be a pervasive aspect of human cognition and may be critical to the development of higher-level cognitive functions or in the binding of mental contents that are separated in time.

Smith (2005) has recently reported evidence on how the body—and the body's continuous coupling to events in the world—may play a key role in word learning. The experimental procedure derives from a task first used by Baldwin (1993) and illustrated in Figure 6.14. The participating subjects are very young children 1.5 to 2 years of age. The experimenter sits before a child at a table, and presents the child with one object to play with and then with a second. Out of sight of the child, the two objects are then put into containers and the two containers are placed on the table. The experimenter looks into one container and says, "I see a dax in here." The experimenter does not show the child the object in the container. Later the objects are retrieved from the containers and the child is asked which one is a dax. Notice that the name and the object were never jointly experienced. How then can the child join the object name to the right object? Baldwin showed that children as young as 24 months could do this, taking the name to refer to the *unseen* object that had been in the bucket at the same time the name was offered. How did children do this? How, if

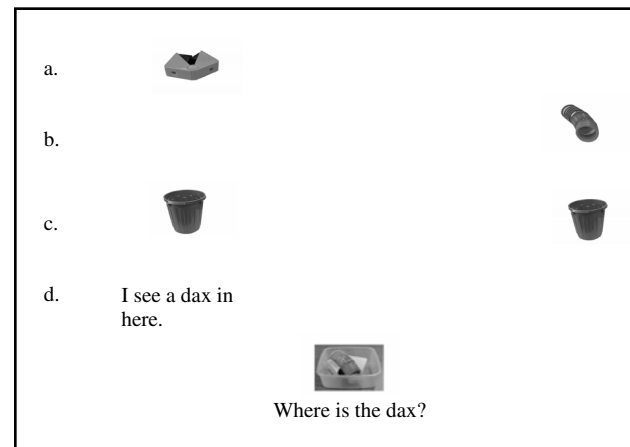


Figure 6.14 A schematic illustration of the course of events in the A-not-B task. After the delay, the hiding box is moved forward allowing the infant to reach and search for the hidden toy.

one were building an artificial device, would you construct a device that could do this, that could know the name applied to an object not physically present when the name was offered?

There are a number of solutions that one might try, including reasoning and remembering about which objects came out of which containers and about the likely intentions of speakers when they offer names. Smith showed, however, that young children solve this problem in a much simpler way, exploiting the link between objects and locations and space. What children do in this task is make use of a deep and foundationally important regularity in the world: a real object is perceptually distinguished from others based on its unique location; it must be a different place from any other object. The key factor in the Baldwin task is that in the first part of the experimental procedure, one object is presented on the right, the other on the left. The containers are also presented the same way and the name is presented with the experimenter looking into one bucket or at one location, for example, on the right. The child solves this task by linking the name to the object associated with that location. We know this is the case because we can modify the experiment in several crucial ways. For example, one does not need containers or hidden objects to get the result. One can merely present the target object on the right and have children attend to and play with it there, then present the distracter object on the left and have children attend to and play with it there. Then, with all objects removed, with only an empty and uniform table surface in view, one can direct children's attention to the right and offer the name (dax) or to the left and offer the name. Children consistently and reliably link the name to the object that had been at this location.

Young children's solution to this task is simple, a trick in a sense, that makes very young children look smarter than they perhaps really are. But it is a trick that will work in many tasks. Linking objects to locations and then directing attention to that location to link related events to that object provides an easy way to bind objects and predicates (Ballard et al., 1997). People routinely, and apparently unconsciously, gesture with one hand when speaking of the protagonist in a story, but with the other hand when speaking of the antagonist. By hand gestures and direction of attention, they link events in a story to the characters. American Sign Language formally uses space in this way in its system of pronouns. People also use space as a mnemonic, looking in the direction of a past event to help remember that

event. One experimental task that shows this is the "Hollywood Squares" experiments of Richardson and Spivey (2000). People were presented at different times with four different videos, each from a distinct spatial location. Later, with no videos present, the subjects were asked about the content of those videos. Eye tracking cameras recorded where people looked when answering these questions and the results showed that they systematically looked in the direction where the relevant information had been previously presented.

This is all related to the idea of *deictic pointers* (Ballard et al., 1997; Hurford, 2003) and is one strong example of how sensory-motor behaviors—where one looks, what one sees, where one acts—create coherence in our cognition system, binding together related cognitive contents and keeping them separate from other distinct contents. In sum, one does not necessarily need much content-relevant knowledge or inferential systems to connect one idea to another. Instead, there is an easier way; by using the world and the body's pointers *to that world*.

An emerging field pertinent to these ideas of embodiment is epigenetic robotics (Zlatev & Balkenius, 2001). This field results from the mutual rapprochement of developmental psychology and robotics, with a focus on the *prolonged epigenetic process through which increasingly more complex cognitive structures emerge in the system as a result of interactions with the physical and social environment* (Zlatev & Balkenius, 2001). Epigenetic robotics emphasizes three key ideas relevant to developmental processes in biological and artificial systems:

1. The *embodiment* of the system
2. Its *situatedness* in a physical and social environment
3. A prolonged *epigenetic developmental process* through which increasingly more complex cognitive structures emerge in the system as a result of interactions with the physical and social environment

This new interdisciplinary developmental research purposely borrows the term *epigenesis* from Piaget to development determined primarily by the *interaction* between the organism and the environment, rather than by genes. Current research within this field does not just emphasize sensorimotor interactions but also social processes with particular attention to the ideas of Vygotsky (1962). Current topics of study within epigenetic robotics that should be of interest to developmental psychologists are joint attention (Björne & Balkenius, 2004), imitation (Schaal, 1999), and observational

learning (Breazeal, Buchsbaum, Gray, Gatenby, & Blumberg, 2005).

From Theory to Practice: A Dynamic Systems Approach to Research

The strength of a dynamic approach is its great generality and thus its potential application across many domains and levels of analysis. For instance, a dynamic approach to development is more a way of thinking about development than a specific theory of, say, personality or the acquisition of formal reasoning. However, a dynamic approach does suggest a powerful research strategy for investigating particular domains. We first summarize the principle steps in a dynamic strategy, and then we illustrate an application of this approach to the development of a fundamental motor skill.

Recall that the essential issues are the stability of the system, as indexed by the behavior of some collective measure of the multiple components, and the changes in stability over time. According to dynamic principles, transitions to new forms involve the loss of stability that enable the formation of new self-organized patterns. At transitions, systems may reveal which of their components is a control parameter or a critical element in change. Thelen and Smith (1994) outlined a series of explicit steps for research design, which are detailed in the following subsections.

Identify the Collective Variable of Interest. In a dynamic system, one or two variables can be identified that capture the degrees of freedom of a multidimensional system. In a development study, the goal is to describe the changes in this collective variable over time. It is not easy to find a collective variable over time or in a nonlinear, changing system. Performance measures at one age may not have the same meaning at a later age because the components of the system, and the relations between them, change. But this is a problem of any study over time, whatever the theoretical motivation.

One important criterion of a collective variable is that it should be a well-defined and observable variable, not a derived construct. Whereas “number of words in the lexicon” is operationally specific, “language processing capability” is not, because it cannot be defined outside of some other concrete behavioral measures. In some behavioral studies, the appropriate collective variable may be a *relationship*—the timing between a stimulus and a response, between movements of different parts of the body, or mutual turn taking during a social dialogue.

Characterize the Behavioral Attractor States.

Before beginning a study of change, it is important to understand the preferred states of the collective variable at different points in time and over different conditions. Here is where cross-sectional studies can be very useful. Sometimes, it is most helpful to know how skilled adults or children perform the tasks under varying conditions such as differing speed, accuracy, or spatial demands. It is also critical to sample the stability of the system at different ages, to pick appropriate timescales in a developmental study. If there are big differences between 8 and 12 months, for instance, and very little change after 12 months, intensive study would be directed toward the time of rapid transition.

As we mentioned earlier, the stability of a behavioral attractor is indexed by its variability around an average value: How easily it is perturbed and how quickly the system returns to a stable configuration after perturbation. Performance that varies greatly within the same individual and is easily thrown off course indicates that the attractor state is weak. Conversely, when performance converges on a stable value, especially from different initial conditions and in the presence of distractors and other perturbations, the attractor well is deep.

Describe the Dynamic Trajectory of the Collective Variable.

The heart of a dynamic analysis is a map of the stability of the collective variable. A crucial assumption in a dynamic strategy is that the individual (or the family unit) and any behavioral changes over time are the fundamental unit of study. It is common in developmental studies to compare groups of children at different ages and infer development from age-related differences in average group performance. Such cross-sectional studies are important for delimiting the boundaries of change, but they cannot inform about the processes that engender change. The essential nonlinear nature of dynamic systems means that attractors pull in trajectories from a variety of initial positions. This means that children may end up with similar behavior from very different starting points. At the same time, even very small differences in the initial conditions can lead to widely disparate outcomes (Figure 6.7). Group averages cannot disambiguate these pathways; the underlying developmental mechanisms may be profoundly different (or remarkably similar).

Thus, understanding developmental trajectories requires longitudinal study of individuals at appropriately dense sampling intervals to capture the timescale of

relevant change. In infancy, for instance, when new behaviors appear almost daily, even weekly observations may miss the critical transitions. Later in life, transitions may be relatively prolonged and much less frequent measures are needed.

Longitudinal studies are designed to probe the stability of systems over time; however, we are really testing systems over two related timescales. The obvious one is change over age or developmental time. Less explicit is the real time of the experimental task. By assessing performance over various trials and conditions within the single experimental session, we ask about the minute-to-minute dynamics. Thus, the history of the system *within the experimental session* may be very important. Effects of the number of trials and their order are also indexes of the system's stability. Does performance change after many repetitions, or is it stable whatever the preceding tasks?

Probing these two timescales is important because they must be inextricably interwoven in real life: When we observe infants and children at any point in time, their behavior reflects *both* their long-term developmental history *and* their immediate history within the task session. Likewise, developmental changes reflect children's repeated everyday experiences, which themselves modulate performance dynamics. It is useful therefore to consider the participants' *intrinsic dynamics*, or histories, as the background on which the experimental tasks are imposed: The intrinsic dynamics are the preferred stability landscapes, given previous history and organic conditions.

Identify Points of Transition. Transitions can be qualitative shifts to new forms, such as the first word spoken or the ability to do a transitive inference task, or they can be quantitative changes in the collective variable such as a shift in speed or the accuracy of a task. Transitions are critical because when a system is in transition its mechanisms of change can be identified and manipulated. Stable systems do not change; only when the coherence of the components is weakened are the components able to reorganize into a more stable form.

The branch of dynamics known as *catastrophe theory* is particularly concerned with sudden shifts from one form to another. These sudden jumps are associated with a number of *catastrophe flags* or indicators of shifts without intermediate forms. As discussed earlier, van der Maas and Molenaar (1992) have applied catastrophe theory to Piagetian conservation tasks to

ask whether the shift from nonconservation to conservation can be explained by a catastrophe model. Although they did not find strong evidence for a number of the flags, the flags are useful indexes of systems in transition. The flags are:

- *Bimodal score distribution*: Performance is either on or off, without intermediate forms.
- *Inaccessibility*: Related to bimodality; intermediate states are not accessible, they are unstable and rarely seen.
- *Sudden jumps*: People switch from one form to another rapidly without intermediate states.
- *Hysteresis*: The dependence of performance on the immediately past performance. For example, responses might be different when the task is speeded up through a range of speeds as compared to when it is slowed down through the same range.
- *Divergence*: The system may respond differently to changes in different control variables.
- *Divergence of linear response*: Nonlinearity suggests that a small change in a control variable or perturbation can lead to a large effect.
- *Delayed recovery of equilibrium*: From earlier terminology, a slow relaxation time after a perturbation.
- *Anomalous variance*: Increased and unusual variability.

Identify Potential Control Parameters

The purpose of mapping the dynamics of the collective variable is to discover when systems change. The next step is to find out how and why they change. What are the organic, behavioral, or environmental factors that engender developmental shifts?

Thoughtful experimental design is needed to identify potential control parameters. In some cases, the possible agents of change are fairly obvious; for example, practice facilitates learning to ride a bicycle or doing arithmetic. But, in many instances of developmental change, the critical processes and events are nonobvious and may indeed be in components that seem at first only incidental, or so commonplace as to be overlooked. West and King's (1996) study of songbird learning, described in an earlier section, is a good example: Female cowbirds' subtle wing flicks are critical determinants of male song development. Another example is Thelen and Ulrich's (1991) description of treadmill stepping in infants, where improvements in treadmill stepping were related to overall changes in dominant muscle tone.

One way to help discover relevant control variables—in addition to informed guesses—is to actually measure changes in a number of system variables along with the collective variable. Thus, if the behavior of interest is, say, object retrieval in infants, a collective variable might be correct retrievals of a hidden object. But because retrieval performance is a collective of many other processes that may contribute to change, independent, then concomitant measures of visual attention or of memory, for instance, may reveal correlated jumps and plateaus.

Instability in the collective variable reveals points of transition. Thus, Gershkoff-Stowe and Smith (1997) mapped children's word retrieval errors as a function of the rapid vocabulary growth characteristic of the period between 15 and 24 months. During this time, individual children's retrieval of known object names showed a brief (3- to 6-week) period of disruption. Children would point to a well-known object (say, *cat*) that they had named correctly many times in the past and misname it (e.g., *duck*). This transient disruption in lexical access was temporally related in individual children to an increased rate of new word productions, suggesting that the rate of new words being added to the lexicon is the control parameter for these word retrieval processes, and, thus, the driver of developmental change in lexical access processes.

Traditionally, variability in behavioral data is a researcher's nightmare. Too much within- or between-subject variability swamps any experimental effects. Thus, researchers deliberately choose tasks to make people look alike. But behavior in real children is not like that, it is notably fragile and context dependent. Abilities seemingly come and go, and even skilled adults might perform tasks differently each time (Yan & Fischer, 2002). Dynamic systems theory turns variability from a scourge into a blessing. In dynamic systems theory, the metric is not whether a child has some static ability or unchanging concept. Rather, as systems are always in flux, the important dimension is the relative stability of behavior in context over time (van Geert, 2000). New measures of variability allow researchers to see trajectories of change over the short timescales of problem solving or over a longer developmental span. For example, Yan and Fischer (2002) tracked adults learning a new computer program and found that the performance of each person varied, but that the patterns of variability differed between novices and experts. Also, De Weerth and van Geert (2002) col-

lected dense longitudinal samples of basal cortisol in infants and their mothers. Cortisol levels in infants decreased with age and did not show circadian rhythms, but each infant had great variability from measurement to measurement. Mothers, conversely, were individually very stable, but differed from each other more than infant to infant.

Manipulate Putative Control Parameters to Experimentally Generate Transitions. Mapping the dynamics of the collective variable and other components only provides suggestive and correlational evidence for possible control parameters. More convincing is to generate developmental transitions on a real or developmental timescale by manipulating the suggested control parameters. These simulations of developmental change work at points of transition because the system is not stable and thus is amenable to being affected by interventions.

It is of both theoretical and practical importance to know when interventions are effective in a developing system and when established behavior is so firmly entrenched that intervention is difficult. The Head Start program, for example, was targeted to the early preschool years because researchers discovered that enrichment was less potent with older children whose educational habits were already formed. Once a sensitive period is determined, developmental control parameters can be tested by providing specific interventions that may engender long-range behavioral change. For ethical reasons, these interventions are usually enrichments.

In the example discussed earlier, Titzer et al. (2003; see also Smith & Gasser, 2005) accelerated infants' abilities to retrieve objects from transparent containers by providing them with a variety of Plexiglas boxes to play with at home. Normally, 10-month-old infants have difficulty with the seemingly simple task of retrieving a toy from a Plexiglas box when the opening of the box is on the side. Although the toy is in full view, infants reach in their direct line of sight—smack into the Plexiglas—and not into the box opening. Titzer et al. reasoned that, because infants lacked experience with the properties of transparency, they relied on their usual pattern of reaching straight to what they see. The control parameter for developmental change was the repeated handling of transparent containers and learning about objects that could be seen through but not reached through. The experimenters provided 8-month-old infants with varied transparent containers and told the

parents to allow their children to play with the containers for 10 minutes twice a day, with no other specific instructions. By 9 months of age, infants in the experimental group were more facile in retrieving toys than a control group of 10 months of age who did not have enriched experience. Enriched experience pushed the system into new forms.

In a similar vein, Gershkoff-Stowe and Smith (1996) used training to investigate the disruption observed in word retrieval errors, which we described earlier. These authors reasoned that the disruption in word retrieval with accelerated vocabulary growth was the product of a lexicon crowded with many new and unstable additions. If the retrieval of words in a newly crowded lexicon is easily disrupted because word retrieval is relatively unpracticed, then naming errors during this period should decrease with practice at word retrieval. Here, the control parameter for developmental change was the repeated seeing and naming of objects by the child. These experimenters provided 17-month-olds with extra practice in producing one set of object names. When these children's rate of productive vocabulary began to accelerate, the researchers observed increased word retrieval errors for many known words but not for the words that had received extra training. This training study demonstrates how seeing and naming objects may be the cause of more stable and less perturbable lexical retrieval, and how the activity of the system itself may be the cause of developmental change.

Equally as informative as long-term interventions for testing control parameters are what Vygotsky (1962) called *microgenesis* experiments (e.g., Kuhn & Phelps, 1982; Siegler & Jenkins, 1989). The experimenters try to push children into more mature performance by manipulating possible control parameters over a shorter time period, sometimes within an experimental session. For example, Thelen, Fisher, and Ridley-Johnson (1984) tested their hypothesis that the control parameter for the "disappearance" of the well-known newborn stepping response was the rapid deposition of subcutaneous fat, making the baby's legs relatively heavy. If, they reasoned, the weight of the legs was critical for whether babies stepped or not, changing leg weights should mimic developmental changes, and indeed it did. Decreasing the mechanical load on the legs by submerging the legs in water increased stepping, and adding weights decreased the response.

We emphasize again that many developmental studies manipulate potential control parameters. Those that pro-

vide training, enrichment, or increased parental support hope to show more advanced performance; those that increase attentional or processing demands or offer ambiguous stimuli or distractions will demonstrate less skilled actions. What is different about a dynamic systems approach is the situating of these experiments in the larger context of the overall collective dynamics so that principled decisions can be made on when and what to manipulate in experimental sessions. In the previous examples, the interventions worked because the experimenters knew from other data that the children were in periods of rapid change.

In the following section, we report on a developmental study designed and conducted using these explicit dynamic systems principles. We demonstrate that a dynamic perspective revealed change processes that were not discovered from conventional approaches.

A Dynamic Systems Approach to Learning to Reach

Reaching for and grasping objects is a foundational perceptual-motor skill that is critical for normal human functioning. Normal infants first reach out and grab things they see when they are 3- to 4-months-old. At first, their coordination and control are poor; they often miss their targets, and their movements are jerky and indirect. Within a few months, they become much more skilled, and by the end of the first year, they can grab things off the supermarket shelves as they are wheeled by in shopping carts.

The pioneering work of Halverson (1931, 1933) and especially of von Hofsten (1991) has documented that, within those first months of reaching onset, infants' reaches become more accurate, straighter, and smoother. But the developmental processes involved in the emergence of the skill and its improvement have remained little understood. Reaching is a function of many component structures and processes, including the physiological, metabolic, and biomechanical properties of the muscles and joints, the state of the central nervous system, vision and visual attention, motivation, and so on. All of these elements are changing during the first year of life—some, at a rather rapid rate. What are the control parameters that move the system into new states?

To begin to understand these processes, Thelen and her colleagues designed a study of the emergence of reaching using explicit dynamic systems principles. The focus was on reaching as an emergent perceptual-motor pattern acquired throughout the soft assembly of mutually interacting with multiple components within a con-

text. All of the components are essential for the skill to emerge and improve, but one or more components may act as control parameters at different points during development. The overall design was to measure behavior repeatedly and intensively in a small number of children at multiple levels (from behavioral to patterns of muscle activation) and at multiple timescales (real time and developmental time).

The study involved four infants, Nathan, Gabriel, Justin, and Hannah, whose reaching and nonreaching arm movements were observed weekly from 3 weeks until 30 weeks, and in alternating weeks thereafter. The study tracked *multiple components* in looking at reaching performance: The kinematics (time-space parameters) of the movement trajectories, the coordination between the arms, and underlying torque or force patterns moving the joints, the patterns of muscle activation that generate the forces, and the everyday postural and motor states of the baby. In addition, the study addressed *multiple timescales*. Each week, the experimenters presented the infants with attractive objects in such a way that the reach was embedded within a larger session, and motor variables were recorded so that the transition from nonreaching movements to reaching could be captured. Thus, they recorded transitions on two timescales: (1) the real time of the trial where the toy was presented, and (2) the developmental timescale, where patterns of stability may evolve and dissolve.

Collective Variable Dynamics. The first step in a dynamic systems approach is to define a reasonable collective variable or variables—measures that capture the state of the system and its developmental changes. Previous descriptions (e.g., Fetters & Todd, 1987; Mathew & Cook, 1990; von Hofsten, 1991) suggested that improvement in reaching could be described by two measures of the path of the hand to the offered toy: Its straightness and its smoothness. A straight-hand path takes the shortest distance from the start of the movement to the target: Adults' hands move in a very nearly straight path for direct reaches. Smoothness is a measure of how often the movement starts and stops or slows down and speeds up. Infants' jerky movements have many "speed bumps" characterized by accelerations and decelerations. In contrast, adults' movements toward a direct target show only one acceleration and one deceleration.

The developmental dynamics of these two collective variables for the four infants are depicted in Figure 6.15

(Thelen, Corbetta, & Spencer, 1996). Overall, the infants became better reachers; they converged on relatively straight and smooth hand paths by the end of the first year. These performance results are consistent with previous reports showing improvement with age (von Hofsten, 1991). But the picture revealed by this dense longitudinal study is much richer, and more surprising, than that painted by previous work.

Most notably, the dynamics of reaching performance over the first year were highly nonlinear (in contrast to the seemingly linear improvement revealed by less dense and group data). First, infants differed dramatically in the age of the first transition (from no reaching to reaching). Whereas Nathan reached first at 12 weeks, Hannah and Justin did not attain this milestone until 20 weeks of age. Second, the infants showed periods of rapid change, plateaus, and even regressions in performance. All infants were poor reachers at first. But three of the four infants—Nathan, Hannah, and Gabriel—also showed an epoch where straightness and smoothness appeared to get worse after some improvement (labeled as A in Figure 6.16). Finally, there was in Nathan, Justin, and Hannah a rather discontinuous shift to better, less variable performance (indicated by T in Figure 6.16 on p. 295). Gabriel's transition to stability was more gradual, but clearly nonlinear overall. These phase shifts to different states were confirmed statistically.

The developmental course of reaching looks very different when the individual trajectories of change are plotted using dense sampling. Although all four infants converged on remarkably similar values by 1 year, they did not get there by identical means. Can these collective variables dynamics provide insight to the processes underlying the onset and improvement of reaching? Are there control variables that are common to all four infants? What accounts for their individual differences?

The First Transition: The Onset of Reaching.

The longitudinal design allowed Thelen and colleagues to pinpoint with some accuracy the first phase shift, the appearance of successful reaching for and contacting the offered toy. (Note that these weeks of onset were confirmed by the more naturalist observations of these babies.) Having identified a developmental transition, the next step in a dynamic approach was to look for potential control parameters. Recall that we make strong assumptions of continuity across levels and timescales; discontinuities must arise from, and be part of, these continuous dynamics.

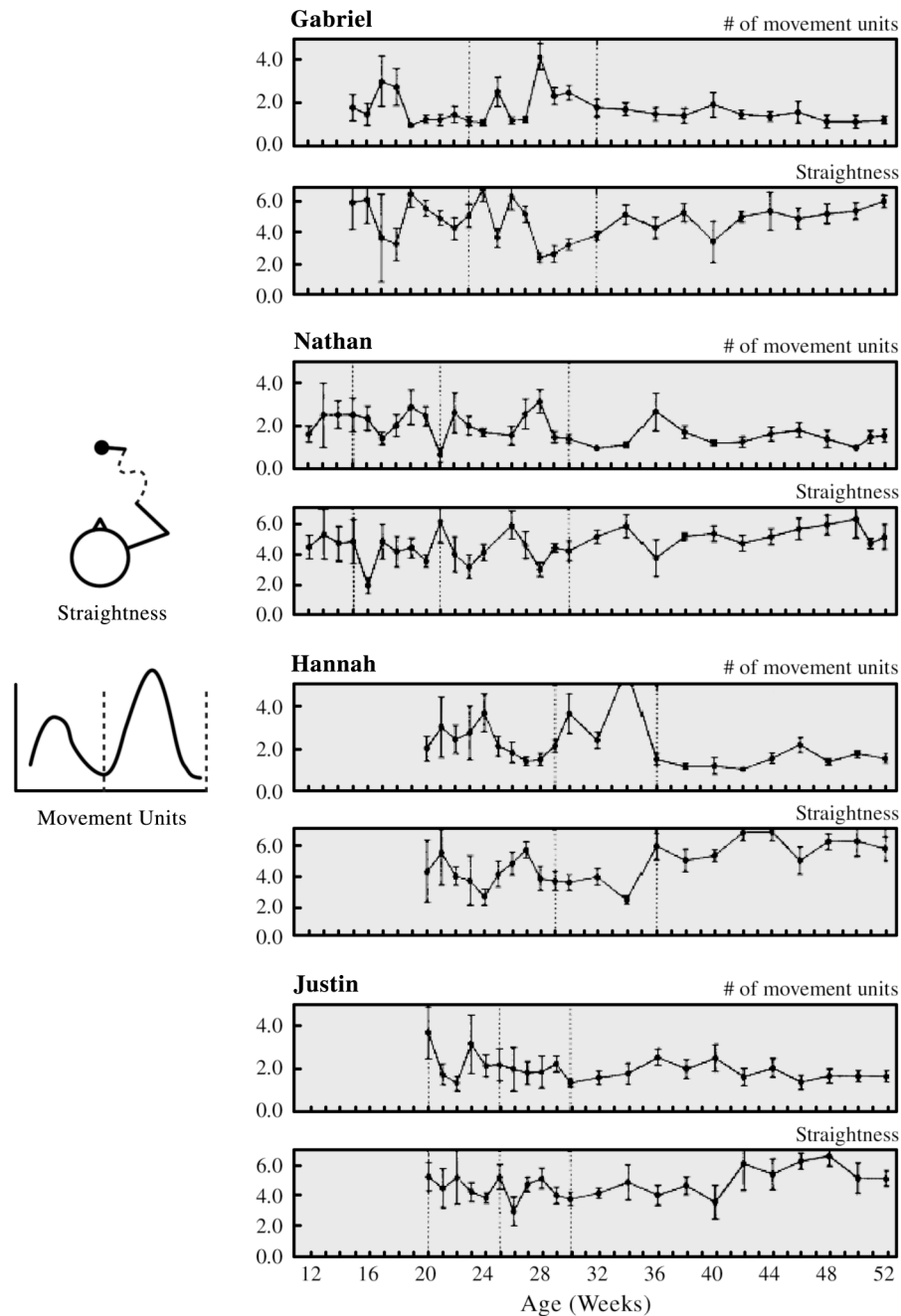


Figure 6.15 Changes in the straightness and smoothness of reach trajectories of four infants followed longitudinally over the first year. The collective variables are number of movement units (fewer = a smoother reach) and straightness index, where a value of 1 = perfectly straight from start to target. *Source:* From “The Development of Reaching during the First Year: The Role of Movement Speed,” by E. Thelen, D. Corbetta, and J. Spencer, 1996, *Journal of Experimental Psychology: Human Perception and Performance*, 22, pp. 1059–1076. Copyright 1996 by the American Psychological Association. Reprinted with permissions.

What is continuous for young infants is that they are always moving their limbs, from birth and even before. Reaching, the new form, must emerge from the continuous processes of moving and perceiving that occur before infants perform the first goal-directed reach—and

that continue as nonreaching arm movements even after this new behavior appears. Thelen et al. (1993) looked at the transition to first reaching as a process of infants’ “discovering” a reach from among many and varied nonreaching movements.

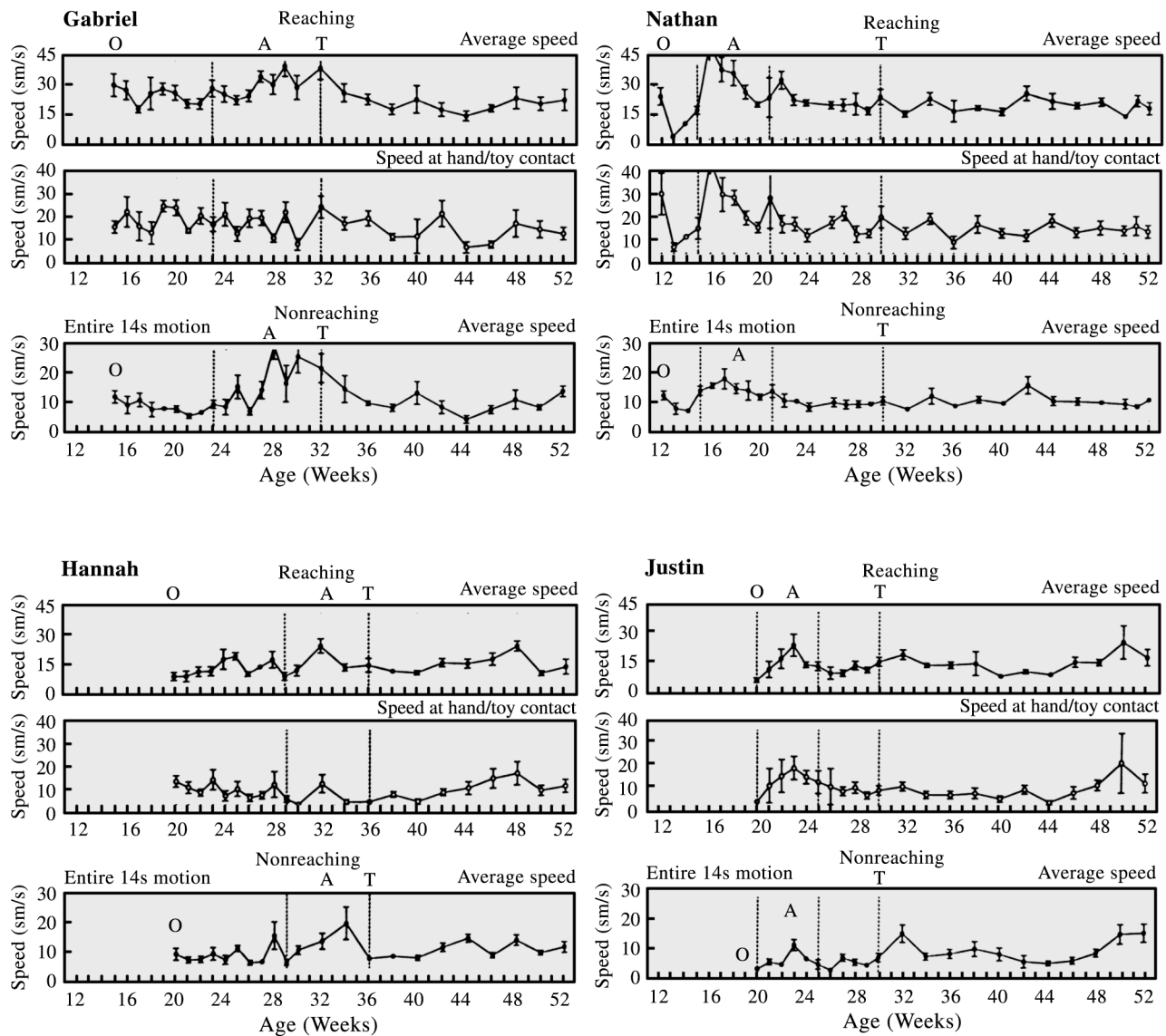


Figure 6.16 Average speed of reaching, speed at toy contact, and speed of nonreaching movements for the four infants in Figure 6.15. *Source:* From “The Development of Reaching during the First Year: The Role of Movement Speed,” by E. Thelen, D. Corbetta, and J. Spencer, 1996, *Journal of Experimental Psychology: Human Perception and Performance*, 22, pp. 1059–1076. Copyright 1996 by the American Psychological Association. Reprinted with permissions.

These authors found that the preferred states of infants’ motor systems in nonreaching movements—their individual intrinsic dynamics—profoundly influenced the nature of the transition to reaching. In particular, the four infants differed in the amplitude, and especially in the vigor, of their spontaneous arm movements in the months previous to reach onset. Two infants, Gabriel and Nathan, had large and vigorous movements; the other two were quieter and generated fewer

and slower, less forceful movements. The task for all the babies was the same: To get their hands in the vicinities of the desired objects. But they had different problems to solve to do this: Gabriel and Nathan had to damp down their forceful movements to gain control; Hannah and Justin had to produce more muscle force to extend their arms forward in space and hold them stiffly against gravity. Examination of the actual torques used to move the arm segments showed

that Gabriel and Nathan were using their muscles primarily to counteract the passive inertial forces generated by the rapid movements of their arms, while Hannah and Justin were using their muscles to counteract gravity.

Many components are necessary for infants to begin to reach. They must be able to see the toy (or other target) and locate it in space. And they must want to get it. The visual and motivational aspects of reaching are probably not the control parameters because other evidence suggests that infants can locate objects in three-dimensional space rather well, if not perfectly, by age 3 months, and that they grasp and mouth objects and show interest in them. More likely, selecting the correct muscle patterns and scaling the activation appropriately allow infants to fashion their first reaches from their undirected movements.

Indeed, analysis of infants' muscle synergies from electromyographic (EMG) recordings reveal that reaching onset was associated with changes in functional muscle use. Spencer and Thelen (1995), comparing EMG patterns in reaching and nonreaching movements before and after reach onset, discovered that when reaching infants frequently recruited their anterior deltoid muscle, alone and in combination with other muscles. (This shoulder muscle raises the upper arm.) Before reaching, infants sometimes also raised their arms, but they used other combinations of muscles to do this. The ability to selectively activate and control this muscle group was associated with goal-directed movements.

Thelen and colleagues speculated that infants learn specific functional muscle patterns through experience in moving during the weeks and months before reaching actually emerges. Infants' real-time activities of moving—sensing the “feel” of their limb dynamics and perceiving the consequences of their movements—are time-locked input to the degenerate and reentrant neural nets we described in an earlier section. As a consequence, categories of limb parameters emerge from all the possible combinations that are appropriate to the spatial location of the toy.

Changes in other system components may facilitate this discovery. For example, Thelen and colleagues found that infants did not reach until they could also stabilize their heads in a midline position. Possibly, strength and control of neck and head muscles are necessary before the arm can be lifted independently. Stable head and eyes also facilitates accurate localization of the to-be-reached object in space.

Shifts in Control during the First Year. Recall that in three infants, the collective variable dynamics had a striking nonlinear course over the first year (Figure 6.15), with a distinct period of seeming instability followed by a period of stability. Recall also that the individual infants had very different intrinsic movement dynamics, especially in relation to characteristic speeds. Studies of adult reaching have repeatedly shown that the speed of movements—reflecting the amount of energy delivered to the limbs—is a critical parameter in many aspects of motor control. Faster movements are generally less accurate, probably because there is less time to make fine adjustments (Fitts, 1954). Reach trajectories may require different strategies of control and different patterns of muscle activation, depending on whether they are performed slowly or rapidly (Flanders & Herrmann, 1992; Gottlieb, Corcos, & Agarwal, 1989). Similarly, very fast movements produce much greater motion-related passive forces than slow ones do, and thus pose different problems for neural control (Latash & Gottlieb, 1991; Schneider, Zernicke, Schmidt, & Hart, 1989). Could movement speed be acting as a control parameter in these developmental shifts?

Figure 6.16 illustrates the four infants' characteristic speed of movements over their first year. Plots show average and peak speed of the reach itself, as well as speed at the start and termination of the movement. In addition, Thelen et al. (1996) reported infants' speed of *nonreaching* movements, that is, all the movements infants produced during the 14-second sampling trials when they were not reaching. This analysis revealed several remarkable results. First, infants converged on more or less similar *good* movement and contact speed; it was not functional to grab the toy either too slowly or too rapidly. Second, within this common speed solution, individual speed *personalities* or intrinsic dynamics remained, on average. For example, Gabriel was a faster mover than Hannah. Third, there was close correspondence between characteristic movement speed in reaching and in nonreaching movements. The reaches were not isolated from the ongoing preferences and habits of the babies, but were molded from those dynamics. Finally, periods of faster movements were associated with instability in the collective variables, indicating poor control.

Although the factors that led the infants to move more quickly or more slowly are as yet unknown, this overall speed variable clearly acts as a control parameter on the straightness and smoothness of the reach trajectory. Again, individual acts of reaching are fashioned

at the moment and carry with them the state of the system at that moment, which, in turn, is determined by the system's history.

Bimanual Coordination

This interplay between task and intrinsic dynamics is equally well illustrated by another aspect of infants' reaching: Whether they reach with one or two hands. Gesell (1939; Gesell & Ames, 1947) first noted that the bilateral symmetry and preference of infants was very unstable and frequently shifted from unimanual limb use to bimanual, and from strongly lateralized preference to symmetry. The four infants in the Thelen et al. (1996) study amply demonstrated these shifts. Figure 6.17 (Corbetta & Thelen, 1996) shows individual frequencies of one- or two-handed reaching. Note that, in this situation, toys could always be grasped by one hand, so two-handed reaching was not obligatory for function. Not only did individual infants have mixed preferences, but no two infants were alike in their developmental course.

As in the single-arm trajectory, Corbetta and Thelen (1996) discovered that bimanual coordination was also influenced by infants' intrinsic dynamics—in this case, whether their limbs moved in a coupled fashion in non-reaching movements as well. When infants reached with two hands, the two arms tended to speed up and slow down together in all movements; limbs were symmetrically coupled. In contrast, no such coupling was noted at times when infants preferred to use only one hand to grab the toy. Furthermore, epochs of bimanual symmetry in reaching and nonreaching were associated with *periods of higher speed movements*. Gabriel, for instance, used two hands and had coupled movements almost throughout the year, and he was the most energetic baby. Hannah, in contrast, was largely unimanual and uncoupled (and moved slowly), except for the period in the middle of the year when her movement speed increased and her movement symmetry did as well. Movement speed was a control parameter for both the efficiency of the movement and the strength of bilateral coupling.

Although the infants had an obvious task goal in reaching out to grab a toy, this dynamic act emerged from a background of ongoing movement. The state of the infants' systems was emergent from their body architecture, metabolism, and motivation, and from how they had been moving in the months before. In such a view, no one part of the system is privileged—there is no dedicated reaching code in the brain. Reaching is a pat-

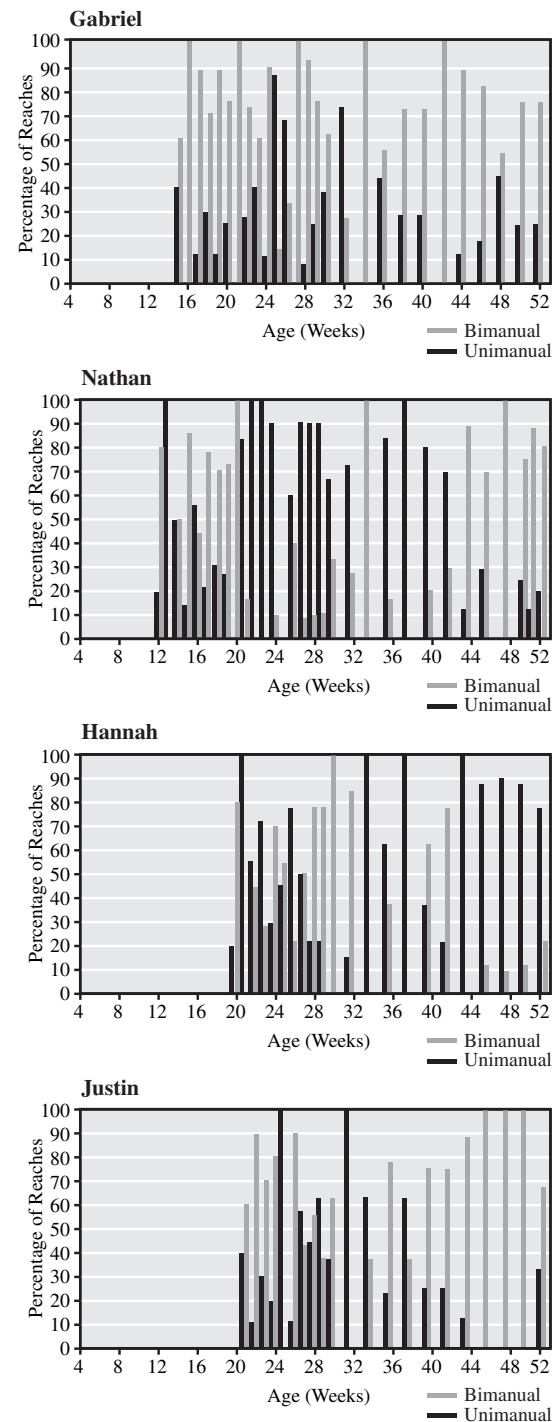


Figure 6.17 Percentages of uni- and bimanual reaches for the four infants in Figure 6.15.

tern that self-organizes from multiple components over several timescales: The here-and-now dynamics of the task and goal, and the longer-term dynamics of the infants' history of moving and reaching.

A Model of Levels of Control

A dynamic view of the development of reaching revealed stagelike changes in the collective variables at the same time that reaching was embedded in the infants' continuous and ongoing intrinsic dynamics. In this section, we present a dynamic model of emergent control that reconciles these multiple levels and multiple timescales by proposing that they are dynamically *coupled*.

What Is Skill?

It is useful here to digress briefly and ask: What is involved in controlling the arm (or any body part) for successful and adaptive movement?

According to Bernstein (Bernstein, 1996), one of the hallmarks of skilled activity is the ability to flexibly adapt movements to current and future conditions. What constitutes skilled performance is not just a repeatable and stable pattern, but the ability to accomplish some high-level goal with rapid and graceful, but flexible solutions that can be recruited online or in anticipation of future circumstances. Consider, for example, a skilled equestrian whose goal is to stay on the horse and maintain a graceful posture, while leading the horse through an intended course. Skill in this case means making minute, online adjustments in response to the horse's movements while anticipating changes in the terrain.

Indeed, in movement, as well as in cognitive or social activities, we can define skill as being able to rapidly recruit appropriate strategies that meet the changing demands of the social, task, or physical environment. For reaching, good control means being able to efficiently reach in all directions, for moving or stationary objects, when the light is bright or dim, from any posture, while our attention is focused or distracted, and so on. On further analysis, we can identify the sources of potential disruption as affecting one of three levels of control of the reach. As depicted in Figure 6.18, reaching must be stabilized first against transient mechanical perturbations—various forms of external forces acting on the moving limb in a way that would tend to push the intended trajectory off course. (We know that adults are very good at maintaining their movement trajectory in the face of little bumps against the limb; e.g., Hogan, Bizzi, Mussa-Ivaldi, & Flash, 1987.) Second, reaching must be stabilized in the face of different task demands of the timing of the

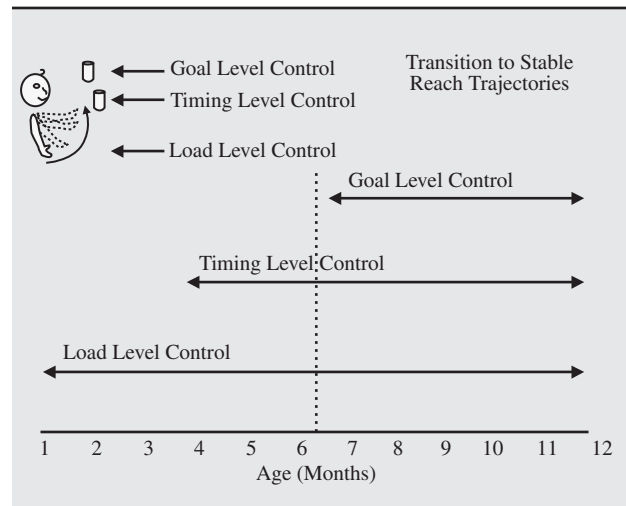


Figure 6.18 A simple model of increasing control over reaching. After Schöner (1994), we have defined control as protecting that level from perturbations from the other levels. The load level involves the internal and external forces acting on the limbs and the associated stretch reflexes. The timing level involves the generation of a trajectory and the timing of the joints and muscles to execute the trajectory. The goal level is the spatial target. Infants only gradually gain control of these levels.

movement, such as setting the coordination pattern of the various joints and muscles, and producing the time-space trajectory of the arm. Finally, reaches must be stabilized even when the global goal parameters change—when the target is unexpectedly displaced (adults make these kinds of adjustments quickly and smoothly; Jeannerod, 1988). Using Gregor Schöner's (1994) terminology, we can define these levels of control as the *load*, *timing*, and *goal* levels.

In ordinary adult skilled actions, these levels are not separable; that is, people perceive, think, and act as one unit in the physical world. Levels of control are revealed only through extraordinary experimental manipulations, for example, when experimenters tell participants to hold a limb position constant when they apply an external load, or to reach to a target that is suddenly displaced. Adults are able, intentionally, to isolate, protect, or control their activities at several behavioral levels. This means that, in skilled adults, the levels of control are not tightly coupled; the goal level is not a slave of the arm's biomechanics although the load level contributes to the movement. We must emphasize that these levels are strictly a function of the imposed task demands.

They do not exist anatomically or functionally in the absence of the tasks.

Development of Levels of Control

Infants, in contrast, do not start out with this ability to protect one aspect of the task against perturbations—that is, to control their actions against unanticipated (and even anticipated) bumps from the environment. Indeed, what we want to argue here is that the initial state is highly syncretic; infants' movements are initially tightly coupled to lower-level dynamics, and only through experience and organic changes does a fully protected higher-level goal dynamic emerge.

We can see very clear examples of this in early spontaneous movements of the arms and legs. As we have argued previously, when young infants inject sufficient energy into their limbs, the resulting patterns suggest the dynamics of coupled oscillators with a periodic forcing function. Such dynamics must be the collective result of simple neural patterns in combination with the springlike properties of the joints and muscles and the effects of gravity—the load-level dynamics.

In the first months of life, infants are largely the captives of these dynamics. They cannot control well, or at all, the positions of their limbs in space or the timing of the segments during movement. Thus, the first problem that infants have to solve is control of these load-level dynamics; they must begin to weaken the obligatory coupling between the load level and the higher levels of control.

By the time infants first reach and grasp, at age 3 or 4 months, they must have begun, through their repeated movements, to generate a trajectory in time and space to attain something they see. But their reaches are still not fully controllable independent of the load level dynamics. Infants often reach too fast or too slowly; they overshoot, or inject energy bursts in stops and starts, leading to the patterns of acceleration and deceleration so characteristic of early reaching. This model predicts that without good control of the arm, the reach trajectory would degrade when movements are fast. This happens because fast movements create inertial forces between the segments of the arm, which require precise control—something skilled movers have continually. And, indeed, this is what happened in the four infant reachers described earlier: When movement speed increased, reach trajectories became more jerky and less straight (Figure 6.16).

The dramatic transition to smoother and straighter reaching that we saw at around age 7 months is, we sug-

gest, the system's discovery of a stable trajectory solution—that is, the isolation and protection of the time-space parameters of getting the felt hand to the seen toy. Thus, by this age, reaches were no longer buffeted by load-level dynamics. Infants could reach smoothly and in a relatively straight manner, and they could control the segments against their own inertial forces.

Although 8- to 12-month-old infants, under ordinary and everyday conditions, look like pretty good reachers, we can create conditions that reveal that they have not yet mastered the highest level of skill—the ability to protect the goal from the lower-level dynamics. In the following section, we report on studies where the goal level—the location and the nature of the object to be reached—was perturbed. These experiments revealed that, in this unstable period, infants were not flexible; they were held captive, so to speak, by the arm pathways they had previously produced. Their trajectory formation was good but not flexible; they were stuck in the habits of previous reaches. We focus on classic object retrieval experiments—Piaget's "A-not-B" error. A dynamic systems account challenges the traditional explanations that object retrieval tasks tap into enduring knowledge about objects. Rather, we suggest that infants show traces of obligatory coupling between the goal and timing levels of trajectory control.

The Task Dynamics of the A-Not-B Error

One of the primary tasks of infancy is to learn about the properties of objects to act on them, think about them, and, eventually, talk about them. Literally thousands of papers have been written about the nature of object representation: When and how babies come to understand the spatial and temporal permanence of objects. One signature task that has been used to measure infants' understanding of objects asks infants to retrieve a hidden object. Odd patterns of search errors and dramatic developmental changes characterize performance between the ages of 6 and 12 months. We briefly review here our dynamic systems account of one of these search errors, the classic Piagetian A-not-B error (Smith, Thelen, Titzer, & McLin, 1999; Spencer, Smith, & Thelen, 2001; Thelen, Schöner, Scheier, & Smith, 2001; Thelen & Smith, 1994).

The A-Not-B Error. We present an example of how we have used the dynamic concepts of multicausality and nested time to revisit a classic issue in developmental psychology. The question originally posed by Piaget

300 Dynamic Systems Theories

(1962) was “when do infants acquire the concept of object permanence?” He devised a simple object-hiding task, which has been adopted by several generations of researchers. The experimenter hides a tantalizing toy under a lid at location A and the infant reaches for the toy. This A-location trial is repeated several times. Then, there is the crucial switch trial: the experimenter hides the object at new location, B. At this point, 8- to 10-month-old infants make a curious error. If there is a short delay between hiding and reaching, they reach not to where they saw the object disappear, but back to A, where they found the object previously. This A-not-B error is especially interesting because it is tightly linked to a highly circumscribed developmental period: Infants older than 12 months of age search correctly on the crucial B trials. Why this dramatic shift?

Do 12-month-old infants know something that 10-month-old infants do not? Piaget suggested that only at 12 months of age do infants know that objects can exist independently of their own actions. Others have suggested that during that 2-month period, infants shift their representations of space, change the functioning of their prefrontal cortices, learn to inhibit responses, change their understanding of the task, or increase the strength of their representations (Acredolo, 1979, Bremner, 1985).

There is merit to all of these ideas, but none can explain the full pattern of experimental results (Smith, Thelen, Titzer, & McLin, 1999). This might be because these accounts seek an explanation in terms of a single cause when there is no single cause. We offer a formal theory, the dynamic field model (Thelen et al., 2001) to explain how the A-not-B error is the emergent product of multiple causes interacting over nested timescales. The account begins with an analysis of the looking, reaching, and memory events that comprise the task, as illustrated in Figure 6.19.

Task Dynamics. The dynamic field simulates the decisions of infants to reach to location A or B by integrating, over time, the various influences on that decision. The field model is neurally inspired, of the type described and characterized analytically by Amari (1977), but it is abstract and not anatomically specific. The model has a one-dimensional activation field, defining a parameter space of potential activation states (in this case the locations of targets A and B). Inputs are represented by their location and their influence on the field. Most important, points in the field provide

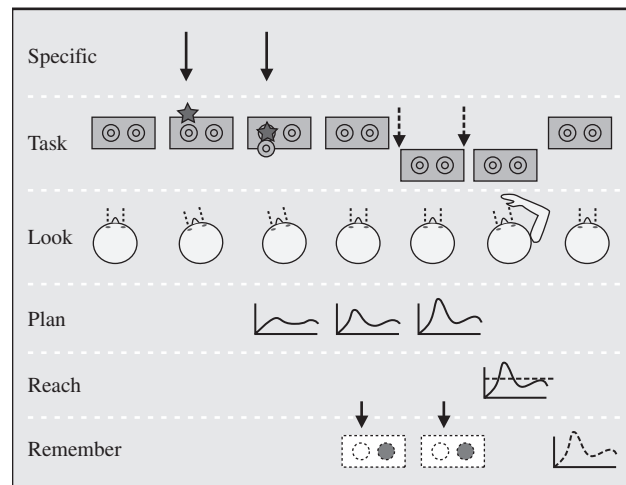


Figure 6.19 A task analysis of the A-not-B error, depicting a typical A-side hiding event. The box and hiding wells constitute the continually present visual input. The specific or transient input consists of the hiding of the toy in the A well. A delay is imposed between hiding and allowing the infant to search. During these events, the infant looks at the objects in view, remembers the cued location, and undertakes a planning process leading to the activation of reach parameters, followed by reaching itself. Finally, the infant remembers the parameters of the current reach.

input to one another, which allows the field to become self-organizing. A highly activated point will exert a strong inhibitory influence over the points around it, allowing an activation to be maintained in the absence of external input.

Figure 6.20a illustrates the evolution of activation on the very first A trial. Before the infant has seen any object hidden, there is activation in the field at both the A and B locations from the two covers. As the experimenter directs attention to the A location by hiding the toy, it produces a high, transient activation at A. Then the field evolves a decision over time. When the activation peak crosses a threshold, the infant reaches to that location.

Most crucial for this account is that once infants reach, a memory of that reach becomes another input to the next trial. Thus, at the second A trial, there is some increased activation at site A because of the previous activity there. This combines with the hiding cue to produce a second reach to A. Over many trials to A, a strong memory of previous actions builds up. Each trial embeds the history of previous trials. Now, consider the crucial B trial in Figure 6.20b. The experimenter provides a strong cue to B. But as that cue

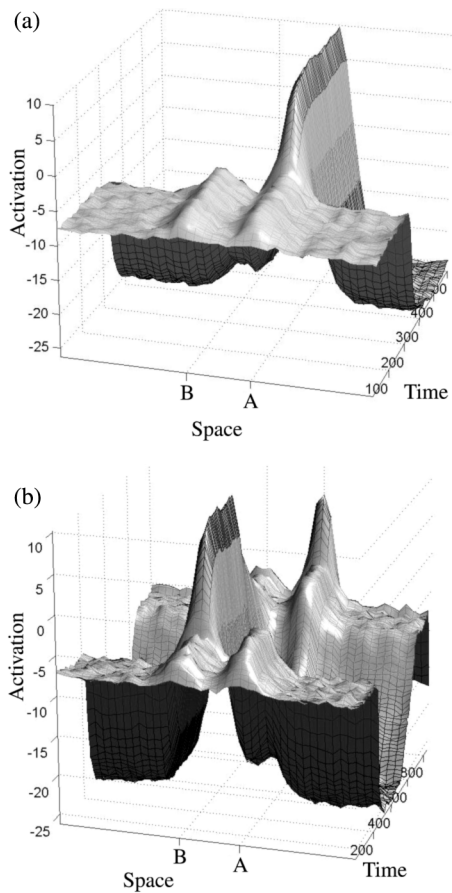


Figure 6.20 (a) The time evolution of activation in the planning field on the first A trial. The activation rises as the object is hidden and due to self-organizing properties in the field is sustained during the delay. (b) The time evolution of activation in the planning field on the first B trial. There is heightened activation at A prior to the hiding event due to memory for prior reaches. As the object is hidden at B, activation rises at B, but as this transient event ends, due to the memory properties of the field, this activation is pulled in the direction of the longer-term memories, toward A.

decays, the lingering memory of the actions at A begin to dominate the field, and, over time, to shift the decision back to the habitual A side. The model clearly predicts that the error is time dependent: There is a brief period immediately after the hiding event when infants should search correctly, and indeed they do (Wellman et al., 1987).

Using this model as a guide, experimenters can make the error come and go. This is achieved by changing the delay, by heightening the attention-grabbing properties of the covers or the hiding event, and by increasing and decreasing the number of prior reaches to A (Diedrich,

Thelen, & Smith, 2001; Smith et al., 1999). The error can occur (and not occur) even when there is no toy to be hidden (Smith et al., 1999). Directing attention to an in-view object A heightens activation at the location, and infants reach to that continually in-view object. Subsequently, when the experimenter directs attention to a different nearby in-view object B, infants watch, but then reach back to the original object A. Experimenters have also made the error vanish by making the reaches on the B trials different in some way from the A trial reaches. In the model, these differences decrease the influence of the A trial memories on the activations in the field.

One experiment achieved this by shifting the posture of the infant (Smith et al., 1999). An infant who sat during the A trials would then be stood up, as shown in Figure 6.21, to watch the hiding event at B, during the delay and during the search. This posture shift causes even 8- and 10-month-old infants to search correctly, just like 12-month-olds. In another experiment, the similarity of reaches on A and B trials was changed by putting on and taking off wrist weights (Diedrich, Smith, & Thelen, 2004). Infants who reached with “heavy” arms on A trials but “light” ones on B trials (and vice versa) did not make the error, again performing as if they were 2 to 3 months older. These results suggest that the relevant memories are in the language of the body and close to the sensory surface. In addition, they underscore the highly decentralized nature of error: The relevant causes include the covers on the table, the hiding event, the delay, the past activity of the infant, and the feel of the body of the infant.

This multicausality demands a rethinking of what is meant by knowledge and development. Do 10-month-old infants know something different when they make the error compared with when they do not? The answer is yes if we conceptualize knowledge and knowing as emergent or made at a precise moment from multiple components in relation to the task and to the immediately preceding activity of the system. What do 12-month-olds know that 10-month-olds do not? There can be no single cause, no single mechanism, and no one knowledge structure that distinguishes 10-month-olds from 12-month-olds because there are many causes that make the error appear and disappear. Instead, both 10- and 12-month-olds can be regarded as complex systems that self-organize during the task. However, just as trial dynamics are nested in task dynamics, so are task dynamics nested in developmental dynamics.



Figure 6.21 An infant sitting for an A trial and standing for a B trial.

Developmental Dynamics. The A-not-B error has been important to developmental theory because it is tightly linked to a few months in infancy. However, the neural field model suggests that the dynamics that create the error in infants are basic processes involved in goal-directed actions at all ages. Indeed, by changing the task, researchers can make preservative errors come and go in older children and adults, just as in infants.

Recently, Spencer and colleagues (2001) invented an A-not-B task that was suitable for 2-year-olds by hiding toys in a sandbox. The surface of the sand presents a uniform field, so there are no markers to indicate the two possible hiding locations. Experimenters gave toddlers many trials at location A, and then hid the toy at location B. With a delay of 10 s, the toddlers, having watched the toy being hidden at location B, still returned to location A to dig in the sand for the toy. Indeed, there are many other situations in which both children and adults fall back on a habit despite new information (Butler, Berthier, & Clifton, 2002; Hood, Carey, & Prasada, 2000). Nonetheless, in the standard A-not-B task, infants change their behavior over 2 months. In the field model, this is simulated by increasing the resting activation of the field. This makes it easier for the input from the hiding cue to form a self-sustaining peak at B to compete with the A memory. Similarly, in her model of the error (also a dynam-

ics systems model), Munakata (1998) simulates development by stronger self-sustaining memories for the hiding event.

If self-sustaining memories drive the successes of older children, then we must ask where they come from. What are infants doing every day that improves their location memory? One possibility is their self-locomotion. Crawling appears to improve the spatial memories of infants (Bertenthal & Campos, 1990). But there are also other possibilities. Their fine motor control improves markedly during the last part of an infant's first year. Perhaps more experience perceiving objects and manipulating them improves the flexibility of infants to notice differences in the targets or to be less tied to their previous actions. Simply practicing the A-not-B task repeatedly improves performance (Diamond, 1990a). In this way, real-time activity in the task is unified with developmental time. Developmental change evolves from the real-time activities of the infant.

Implications of a Dynamic Approach. A dynamic systems theory of development helps to resolve an apparent theoretical contradiction. At a very global level, the constraints imposed by our biological heritage and by the similarities in human environments seem to result in similar developmental outcomes. All intact human infants learn to walk, progress from making the A-not-B

error to not making it, speak their native language, and form intense social relationships. But when one looks at the details of development, the picture seems far less deterministic. Children from the same family grow up to be amazingly different from one another. Children with social and economic advantages sometimes fail in life, whereas those from impoverished backgrounds succeed. Such nonlinearities might be reflected in development as stagelike shifts and might underlie the dramatic differences between 10- and 12-month-olds in the standard A-not-B task. But if development is made from real-time events, then these nonlinearities might also create individual differences. Even very small differences in beginning states and in developmental histories can amplify and lead to large individual differences. If this is so, then at the microlevel, development will be messier and very much tied to the idiosyncratic real-time activities of the infant. From a dynamic perspective, it is important to understand the processes by which the everyday activities of children create developmental change—both the universal attainments and the individual pathways.

What Is Knowing? What does all this mean for Piaget's original conclusions from watching his own children search for objects in the "wrong places"? What does all this mean for the results of Baillargeon and Graber (1988) and others who have found that infants seem to know that objects stay where they are put, in tasks in which they only watch but do not act? How does this dynamic systems account fit with Munakata, McClelland, Johnson, and Siegler (1997) and their connectionist account, in which internal representations of objects reside in one set of layers that deliver input to a separate system that acts?

One possible answer to these questions is that the A-not-B error is simply about reaching—not about the object and not about *knowing*. According to this answer, infants in the A-not-B task represent objects *independently from their actions* right from the beginning, although those representations may not, as Munakata et al. (1997) suggest, be strong enough to support goal-directed manual action. This answer divorces knowing from acting; the infant knows where the object is when it is hidden in B, but just cannot control the reach.

We believe this answer is wrong. Knowing is the process of dynamic assembly across multileveled systems in the service of a task. We do not need to invoke represented constructs such as "object" or "extended in space

and time" outside the moment of knowing. Knowing, just like action, is the momentary *product* of a dynamic system, not a dissociable cause of action. Churchland (1986) put it this way:

[B]rains are not in the business of pattern recognition for its own sake, and the nature of pattern recognition, as accomplished by brains, must be understood in the context of its role in how brains achieve motor control. Evolution being what it is, pattern recognition is there to subserve motor coordination. . . . [I]f we ignore motor control as the context within which we understand pattern recognition, we run the risk of generating biologically irrelevant solutions. (pp. 473–474)

We think to act. Thus, knowing may begin as and always be an inherently sensorimotor act. Our dynamic systems account thus stands on common ground with Piaget in the origins of thought in sensorimotor activity but also on common ground with Johnson (1987); Varela, Thompson, and Rosch (1991); Churchland (1986); and Edelman (1987) in the newer ideas of Barsalou (2005) and Glenberg and Kaschak (2002) that cognition emerges in the recurrent sensorimotor patterns that enable action to be perceptually guided.

Dynamic Systems and Other Theories of Development. How different is dynamical systems as a theory of development from other approaches? Thelen and Bates (2003) recently considered this question and their conclusions are summarized in Table 6.2. They specifically considered the following theoretical frameworks:

1. Chomsky's (1968, 1975, 1988) nativist theory of language development (which has inspired nativist theories in other domains as well—for a discussion, see Fodor, 1983)
2. E. J. Gibson's (1969) theory of perception and perceptual development (which is empiricist in emphasis)
3. Vygotsky's (1978) theory of cognitive development in a social framework (a theory that is strongly empiricist in flavor, though it is certainly a complex and interesting example of an empiricist approach)
4. Piaget's (1952, 1970) constructivist theory of cognitive development (a direct predecessor to today's emergentist approach)
5. Connectionism as laid out in Elman et al. (1996)
6. Dynamic systems as laid out in Thelen and Smith (1994)

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TABLE 6.2 A Taxonomy of Developmental Theories

Theory	Chomsky	Gibson	Vygotsky	Piaget	Thelen/Smith	Elman/Bates
Emphasized mechanism of change	Maturation	Perceptual learning	Internalization	Construction	Self-organization	Emergence/learned connections
Experience	No	Yes	Yes	Yes	Yes	Yes
External information	No	Yes	Yes	Yes	Yes	Yes
Social	No	No	Yes	No	No	No
Biological constraints	Yes	Yes	No	Yes	Yes	Yes
Brain development	No	No	No	No	Yes	Yes
Embodiment	No	Yes	No	Yes	Yes	No
Mental representations	Yes	No	Yes	Yes	No (not in traditional sense)	Yes
Dynamical systems	No	No (yes)	No	No	Yes	Yes
Formal models/simulations	Yes	No	No	No	Yes	Yes

Adapted from "Connectionism and Dynamic Systems: Are They Really Different?" by E. Thelen and E. Bates, 2003, *Developmental Science*, 6, pp. 378–391.

These six theories were compared with regard to (1) the primary mechanism of change, (2) the structuring role of external information, (3) the importance of social interaction, (4) the role of biological constraints, (5) the use of information about brain development as a theoretical constraint, (6) emphasis on sensorimotor processes, (7) emphasis on and elaboration of mental representations, (8) invocation of dynamic systems as a source of causation/explanation of structure and change, (9) use of mathematical formalisms, and (10) use of computer simulations as a tool for the study of development.

Mechanisms of Change. Chomsky invoked two related mechanisms to account for developmental change and the role of the environment: parameter setting and triggering. *Triggering* refers to the release of a preexisting behavioral option by an environmental event (not unlike the triggering of the processes that lead to male genitalia in the embryo by the genetically timed release of testosterone). *Parameter setting* is an enriched form of triggering, a process whereby children use environmental signals to select the correct parameters for their native language from an array of innate grammatical options. In elaborating these ideas over the years, Chomsky has consistently stressed that learning is highly overrated as a source of change, at least for those domains of behavior that are especially important for the species. For Gibson, the primary mechanisms of change are children's exploration of their environment and the discovery of matches between their current abilities and the affordances for

action inherent in a richly structured environment. This is primarily a process of *perceptual learning*, or an increasing ability to discern relevant features in the perceptual array and thus to tune actions appropriately to them. Vygotsky built his theory on *internalization*. For Vygotsky, many of the cognitive and linguistic structures that make us human are first played out in the realm of behavioral interaction with a competent adult. By participating in social interaction, the young organism moves from incompetence to competence, internalizing the relevant structures until he or she can finally produce them on his or her own. Although this is a richer and more sophisticated form of environmental determination than one finds in many writings by many of Vygotsky's behaviorist contemporaries (American, European, and Russian), internalization is certainly a mechanism that is "pushed" from the outside. Piaget's seminal contribution was his consistent emphasis on the bidirectional nature of cognitive development, whereby children act on the world (assimilation) and then adjust their action schemata in accordance with their degree of success or failure (accommodation). The mechanism of change in connectionist accounts of development are principally changes in connection weights among sub-symbolic neuron-like nodes such that the regularities in the world are incorporated *into* the internal processes that connect nodes to each other, and input to output. Some models begin with few constraining assumptions about architecture, whereas others base their architecture on current understanding of neural pathways or as a

consequence of experience (see O'Reilly & Munakata, 2000, for a comprehensive review and tutorial). In all, however, the principal mechanism of change is incorporation of statistical regularities in the learning environment.

How does dynamic systems differ with regard to the principle causes of change? The concepts of self-organization and emergence proposed in dynamic systems theory bear a strong historical relationship to Piaget's constructivism, the emphasis on sensorimotor processes is shared with Gibsonian approaches, and a structuring role for the environment with connectionism. Contemporary dynamic systems approaches have not considered social interactions, but could in principle (see Yu & Ballard, 2004). Chomsky (and nativism) seems to be left out, but is he really? There are explicit formal theories of change in dynamic systems consistent with a triggering mechanism of change. Specifically, Yamauchi and Beer (1994) showed how the dynamics of continuous time recurrent networks can generate highly distinct patterns of sequential behavior, shifting between different attractor states, in response to an external trigger. That is, Chomsky's general idea of triggers and parameter settings could well be realized in a dynamic systems framework as a mechanism of change.

The Structuring Role of External Information.

This dimension is strongly correlated with the mechanisms of change just described, although it is not quite the same thing. Nativist theories tend to downplay the structuring role of external information, while empiricist theories tend (by definition) to view the environment as a primary source of structure. Thus for Chomsky, the environment plays a limited role and acts primarily through triggering. Indeed, Chomsky has continually emphasized the paucity of the environment. For Vygotsky, in contrast, the social environment is a critical source of structure, internalized by the child through social interaction. Likewise, for Gibson, the child does not need to build complex mental structures to represent the environment because the environment is already rich in information, waiting only to be discovered. In this regard, Piaget continually emphasized the structured nature of the world in which the child exercises his or her minimal innate sensorimotor schemata, using information about a mismatch between his or her intentions and realization (disequilibrium) to motivate change. However, the endpoint of cognitive development (formal operations) reflects a long series of transformations and

reorganizations, resulting in structures that cannot be detected directly in the outside world. External information is critical to connectionism because the incorporation of statistical regularities in the world is the principal mechanisms of change in those theories. External structure is critical to dynamic systems theories because the world, the specific task at hand, and a history of interaction in that world, is one of many causes organizing the system. However, in dynamic systems, a change in external structure may result in a completely different endpoint, but the endpoint itself is not contained in the environment. This then is a shared point with nativism: However, whereas nativism sees the main cause as the constraining properties of the system itself; dynamic systems sees the history of a complex system of many interacting internal and external components.

Importance of Social Interaction. Of the six theories summarized in Table 6.2, Vygotsky's theory is the only one that has taken social interaction seriously as a source of structure in cognitive development. Chomsky denies that social factors play any important structural role in language development, and Gibson does not assign any privileged status to social factors. Piaget acknowledged the importance of social factors in the construction of the mind (particularly in his works on language and culture—see Piaget's remarks on Vygotsky's views in Piaget, 1986), but did not study social processes. Thelen and Bates acknowledge that, to date, dynamic systems have failed to recognize social factors as a source of structure in developmental process.

The Role of Biological Constraints. Of the six theories compared in Table 6.2, Vygotsky's is the only one that had little or nothing to say about the role of biological constraints on development. Thelen and Bates suggest that this may be more a result of the issues of main interest to Vygotsky than a principled denial of the role of biology. All contemporary serious developmental theories acknowledged the role of biology. Theories differ from stronger (nativist) to weaker (most connectionist) in the role of biology in determining specific outcomes. Dynamic systems in its multicausal, multilayered, *historical* approach sees biology and environment as continually meshed and inseparable. It makes no sense to ask which is most important or most determining.

Brain Development as a Source of Constraints. Thelen and Bates note that none of the four classic

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theorists—Piaget, Gibson, Vygotsky, Chomsky—made much use of information from developmental neurobiology. But to be fair, there was far less useful information available in the first 50 to 60 years of the twentieth century. In the last 20 to 30 years, there has been an explosion of information about plasticity, activity-dependent factors in brain development, and the bidirectional roles of both genes and environment in brain development (see especially Chapter 5 of Elman et al., 1996; Chapter 5 of Thelen & Smith, 1994). Much of this information is incompatible with strong nativist theories (which emphasize a rigid form of biological determinism), and highly compatible with the kind of dynamic approach to development that we espouse. Still, the serious incorporation of advancing knowledge about neural development into general developmental theories has not yet happened. This is an important limitation on dynamical systems as yet developed.

Sensorimotor Bases of Higher Cognition. Piaget's emphasis on the sensorimotor bases of higher cognition is the linchpin of his theory, and may be viewed as his most creative and important contribution. The same point is explicitly disavowed by Chomsky (who is committed to a grammar that is autonomous from the rest of mind, much less the body itself). It is implicit in Gibson's theory, but for Thelen and Bates, not because of Gibson's strong critique of mentalism (see following), the idea was never fully developed. Vygotsky also gave these factors little role once language learning and socialization came into play. Current connectionist theories like most cognitivist theories give little attention to the role of the sensory-motor system. Dynamic systems theory, with its emphasis on perceptual-motor development, stands strongly in the tradition of Piaget in espousing the fully embodied mind.

Mental Representations. In their discussion, Thelen and Bates give representation to all theoretical perspectives but Gibson, noting that while some dynamic systems theorists eschew representation (Smith et al., 1999; Thelen & Smith, 1994), others embrace it (Spencer & Schoner, 2003). However, what one concludes depends on what one takes representation to mean. In the strong traditional sense, representation means Newell, Shaw, and Simon's (1957) physical symbol system: internally represented propositions that operate as symbols (with a syntax and a semantics) *within* a computational system. This is represen-

tation in the sense of Chomsky, Piaget, and Vygotsky among others. Then, there is representation-like: Any internal event in the system with some stability (or recurrence) that the *theorist* can point to as corresponding to some regularity in behavior. This is "representation" in the sense of connectionism and Thelen and Bates. Under this definition, it is hard to imagine a theory that does not have representations (because any internal regularity that corresponds to a behavioral regularity counts).

Dynamics as a Source of Structure and Change.

Developmental theory should be about time: how real time events literally make (create) change. Dynamic systems, as a theory of development, represents an effort to implement insights from dynamic systems theory in physics, mathematics, and biology to a theory about change over time. This is the very core of the enterprise. Because dynamic systems is itself a late twentieth century movement, it is not surprising that these ideas had little influence on the four classic developmental theories. However, modern-day Gibsonians like Turvey, Kelso, and Shaw (Kelso, 1995; Turvey, 1977; Turvey, Shaw, Reed, & Mace, 1981) have been pioneers in using dynamic systems to explain aspects of perceptual and motor functioning in adult humans. Similarly, connectionist models as nonlinear neural networks are nonlinear dynamical systems (see especially Elman et al., 1996, Chapter 4); they embody the principles and phenomena that define dynamic systems theory. Although not all practitioners of connectionism are aware of the extent to which this is the case, and not all connectionist models have much to say about the interplay of real-time activity and the slower dynamics of learning and developmental change, Thelen and Bates conclude that connectionism and dynamic systems share, at base, the very same ideas about the nonlinear dynamics of change, sensitivity to initial conditions, and the sudden catastrophic transformations (including U-shaped behaviors) that can take place after gradual increments along some quantitative parameter. However, the mathematics of dynamic systems provides a way of studying, describing, and explaining change in general, including as we noted earlier, trigger-like and parameter-setting processes such as those proposed by Chomsky.

Mathematical Formalisms and Simulations. Formally specified theories have played an important role in Chomsky's and J. J. Gibson's theories, parts of Pi-

aget's theory, connectionism, and dynamical systems. Formal mathematical theories will become increasingly important in developmental psychology. Theories, which are merely strings of words (often ill-defined ones at that), can lead to debates about "what is really meant" and to confusions about the predictions that do or do not follow from some claim. Mathematical specification of theoretical claims and predictions derived from simulations are clearly the future for developmental theories of all persuasions.

SUMMARY

The point of Thelen and Bates's exercise was to situate dynamic systems in the larger landscape of developmental theories. As should be evident, dynamic systems is a powerful framework in which many different ideas—from triggers to associative learning to embodiment to socialization—may be realized. Dynamic systems is not so much in opposition to these other perspectives but a new way of unifying the many threads that comprise developmental change. What dynamic systems *adds* to this current landscape is both an emphasis on understanding development as a complex system of nested dynamics, and a complex system of self-organizing interactions at many levels of analysis, including those between the brain and the body, and between the body and world.

CONCLUSION: WHY DYNAMICS?

The major contribution of a dynamic approach to development is the potential to bring theoretical coherence to a field that has been beset by dialectics: Nature versus nurture, learning versus maturation, continuity versus discontinuity, structure versus process, perceptual versus conceptual, symbolic versus presymbolic, and so on. The danger of such either-or thinking is not that good studies have not been done, or cannot be done, but that the point of the enterprise, understanding change, can be forgotten. Only the framework and language of dynamics can erase these dualities and shift the focus to *how* the developing system works.

The promise of dynamics is realized through the assumptions of coupling and continuity. Coupling means that all components of the developing system are contin-

ually linked and mutually interactive in the individual and between the individual and the environment. Continuity means that processes are seamless in time and cumulative; mental and physical activity are assembled in the moment and always as a function of the system's history. Actions done in this moment, in turn, set the stage for behavior in the next second, minute, week, and year. With this formulation, it makes no sense to ask what part of behavior comes from stages, mental structures, symbol systems, knowledge modules, or genes because these constructs do not exist in timeless, disconnected form. There is no time and no level when the system ceases to be dynamic.

Dynamics is the language of stability and change, and a dynamic approach frames developmental questions about when systems are stable or change, and what makes them change. The power of dynamics is that these issues can be posed at many levels and timescales. The system is dynamic all the way down and all the way up! We can ask meaningful developmental questions at the neural, physiological level, or individual or social behavior level. Because dynamics seeks to be construct free, there is a real potential for integrating levels of analysis. Likewise, we can probe the system as it changes over the time of a single event, an experimental session, more extended training, or what we consider the *developmental* timescale of weeks or months. That dynamics is a framework and a language rather than a specific theory of the development of *something*—language, peer relations, visual perception, adolescent adjustment, and so on—is both a strength and a weakness. The strength is the potential for viewing many traditionally separate domains as subsumed under the same dynamic processes. The weakness is equally apparent. A dynamic approach does little of the real work. It suggests a way of thinking, a strategy for collecting developmental data, and hopefully, some analysis and modeling techniques that have broad generality. (That's not too bad!) The approach is not a substitute for the hardest part of understanding development: Collecting good data and using both descriptive and experimental methods. There are grave pitfalls in collecting data without clear theoretical assumptions, but it is equally dangerous to spin theories, verbal or mathematical, without a constant dialogue with data. For example, thinking dynamically allowed us to reinterpret the A-not-B error and generate new predictions, but only trudging back to the laboratory gave substance to the theorizing. These experiments hold promise for new theoretical insights, and so forth.

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