

Self-organization in Developmental Processes: Can Systems Approaches Work?

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The induction of novel behavioral forms may be the single most important unresolved problem for all the developmental and cognitive sciences.

(Wolff, 1987, p. 240)

What does behavior come from? As modest observers of humans and other animals in their early times of life, we must ask this question every day. It is the most profound of questions. Nearly every field of human inquiry – philosophy, theology, cosmology, physics, geology, history, biology, anthropology – asks in some way about the origins of new forms. How can we start with a state that is somehow less and get more? What is the ultimate source of the “more”?

Traditionally, developmentalists have sought the source of the “more” either in the organism or in the environment. In one case, new structures and functions arise as a result of instructions stored beforehand, encoded in the genes or in the nervous system (and ultimately in the genes) and read out during ontogeny like the program on a computer tape. Alternatively, the organism gains in form by absorbing the structure and patterning of its physical or social environment through its interactions with that environment.

Of course, no contemporary developmentalist would advocate either pole in the nature–nurture dichotomy. Everyone now is an interactionist or a transactionalist or a systems theorist. We have example after example in both human and other animal research of the reciprocal effects of organism and environment in effecting developmental change. We would likely find no cases that would show anything else. Why then, can Wolff claim that the induction of new forms remains a great unsolved problem?

At one level, it seems clear that no current developmental models – whether they invoke interactional, transactional, or systems concepts, have been especially successful in accounting for a wide range of empirical data. That is, we lack general principles of development that apply across species or across domains in one species, and that can account for both the exquisite regularities and the often frustrating nonlinearities, regressions, and variabilities that characterize the emergence of new forms.

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Recently, several authors have criticized current developmental theorizing on perhaps an even deeper level. Oyama (1985), for example, cogently argued that by assigning the sources of ontogenetic change to either instructions from within the organism or information in the environment we have never come to grips with the ultimate origins of new forms. We seek to find the plans pre-existing somewhere that impose structure on the organism. Nativism and empiricism thus both share the assumption that “information can pre-exist the processes that give rise to it” (p. 13). This assumption of prior design located inside or “out there,” leads to an inevitable logical trap – who or what “turns on” the genes, who or what decides what information out there is “good.” However elaborate our story of regulator genes, feedback loops, comparators, and schema, Oyama claimed that we finally require a cause – and the old homunculus rears its head, although in more sophisticated guise. *Postulating an interaction of genes and environment in no way removes this logical impasse.* It merely assigns the pre-existing plans to two sources instead of one.

In a similar vein, Haroutunian (1983) criticized Piaget – surely our most thorough going interactionist – for failing to acknowledge the logical consequences of equilibration through accommodation and assimilation. Piaget’s logical nemesis is also infinite regress. How can equilibration produce new forms through accommodation and assimilation that are not properties of these functions themselves? How does the organism know to differentiate schema in the right direction? If the organism is testing hypotheses about the world, against what standards are those hypotheses tested? Piaget’s solution, Haroutunian claimed, was an implicit genetic nativism.

Are there, then, any candidates for general developmental principles that will avoid the logical pitfalls of dualistic theories and yet provide more than just rhetoric, principles that will provide structure to guide empirical research, formulate testable hypotheses, and integrate data within and across species and domains?

For many years, developmentalists have recognized that systems principles of biological organization offer a conceptually elegant solution to the problem of new forms. Systems principles are well-known: wholeness and order, adaptive self-stabilization, adaptive self-organization, hierarchical structuring (Laszlo, 1972). In addition to the classic statements of Von Bertalanffy (1968), Laszlo (1972), Waddington (1972), and Weiss (1969), a number of recent excellent essays and reviews detail the application of systems theory to development (e.g. Brent, 1978, 1984; Kitchener, 1982; Lerner, 1978; Overton, 1975; Sameroff, 1983; Wolff, 1987).

It is specifically the principle of *self-organization* that rescues developmentalists from the logical hole of infinite regress. That is, in biological systems, *pattern and order can emerge from the process of the interactions of the components of a complex system* without the need for explicit instructions. In Oyama’s (1985) terminology:

Form emerges in successive interactions. Far from being imposed on matter by some agent, it is a function of the reactivity of matter at many hierarchical levels, and of the responsiveness of those interactions to each other. . . . Organismic form . . . is constructed in developmental processes.

Systems formulations are intuitively attractive for many developmental issues, in addition to the question of the origins of novel forms. Despite this, systems remain more of an abstraction for most working developmentalists than a coherent guide to investigation or synthesis. I believe there are a number of reasons why systems have not “worked.”

Oyama suggested that the resistance to concepts like emergent order stems both from the prevailing reductionist and mechanistic approaches in biology and from a long tradition of belief in causation by design. Invoking emergent order seems like a retreat into vitalism. Equally important, I believe, is that we have had no accessible translation of systems principles to empirical design, methodology, and interpretation. By their very nature, systems are complex, multicausal, nonlinear, nonstationary, and contingent. The inherent nonlinearity and nonstationarity poses a real challenge to our needs for prescription and predictability. As a result, workers will often resort to a systems explanation only after their more direct main-effect or interactional models fail to explain a body of data. Systems views are often relegated to the discussion sections of papers: If everything affects everything else in a complicated way, then it must be a system (Woodson, 1988). Such *post hoc* incantation can dilute systems concepts to the point of vacuousness. Thus, although we need complexity and multicausality in our models because we have complexity and multicausality in our organisms, systems views seemingly lead to insurmountable obstacles for empirical analysis.

Certain contemporary work in physics, chemistry, biology, and psychology may now weaken the traditional resistance to the idea that organisms can produce pattern without prescription. The active fields of synergetics and nonlinear dynamics in physics, chemistry, and mathematics, for example, show in mathematically precise ways, how complex systems may produce emergent order, that is, without a prescription for the pattern existing beforehand (see, for example, Haken, 1983, 1985; Madore and Freedman, 1987; Prigogine, 1980; Prigogine and Stengers, 1984). Where is the "design" that allows aggregations of molecules to form laser lights, flow patterns in fluids, crystals, cloud formations, and other nonrandom collectives of simple subunits? In biology, field theories of morphogenesis in plants and animals allow for the highly complex differentiation of structural and functional elements from more simple, nongenetic factors such as gradients, nearest neighbor calculations, cell-packing patterns, and so on (e.g. French et al., 1976; Gierer, 1981; Meakin, 1986; Mittenthal, 1981). Developmental neurophysiologists are using terms such as *self-assembly* to describe the establishment and refinement of neural networks as a dynamic and contingent process (e.g. Barnes, 1986; Dammasch et al., 1986; Singer, 1986).

There is a growing trend toward viewing adult nervous system function also as a dynamic and self-organizing process; that is, modeling function as the emergent property of the assembly of elemental units, none of which contains the prescription or command center (Skarda and Freeman, 1987; Szentagothai, 1984). This work ranges from mathematical formulations of simple behaviors in relatively primitive organisms – locomotion in the lamprey eel, for example (Cohen et al., 1982), to computational models of the highest human brain functions such as memory and language (e.g. Hopfield and Tank, 1986; Rumelhart and McClelland, 1986; Shrager et al., 1987). I rely especially on the theoretical and empirical studies of human motor behavior of Kelso and his colleagues (Kelso et al., 1980; Kelso and Tuller, 1984; Kugler et al., 1980) based on dynamic principles, and in which the details of coordinated movement are seen to arise from the synergetic assembly of muscle collectives.

What these diverse formulations share – and what offers the empirical challenge to students of behavioral development – is the assumption that a higher order complexity can result from the cooperativity of simpler components. Vitalistic forces need not be invoked; it is the unique utilization of energy that can create "order out of chaos." Thus, the order and regularity observed in living organisms is a fundamental consequence of their thermodynamics; that they are open systems that use energy flow to organize and maintain

stability. This means that unlike machines, biological systems can actively evolve toward a state of higher organization (Von Bertalanffy, 1968).

But will systems work for developmentalists? In the remainder of this chapter, I outline a number of principles derived from the field of synergetics (the physics of complex systems) that have special relevance for the study of developing systems. I then suggest that these principles may be useful in two ways. First, on a metaphoric or heuristic level, I offer a characterization of developing systems that may serve as a guide for examining and understanding multicausal and nonlinear phenomena in ontogeny. I apply the systems metaphor to several domains of early sensorimotor development in humans and other animals, and I suggest how synergetic principles may lead to testable systems hypotheses about the origins of new forms. Finally, I present examples from an ongoing study of infant motor coordination designed to use synergetic principles. Please note that I invoke these concepts with great caution and in the spirit of exploration. When the principles of complex systems have been applied to biological systems (e.g. Kelso and Schöner, 1987), the phenomena modeled have been relatively simple and many variables could be rigorously controlled. We normally do not have that level of control over naturally developing organisms, nor can we be confident of the stationarity of our behavior over the measurement interval.

My introduction to synergetic principles came through my interest in early motor development. A fundamental question for understanding motor behavior is how a system composed of many, many “degrees of freedom” – muscle groups, joints, neuronal elements, and so on – “compressed” these degrees of freedom into coordinated movement with precise spatial and temporal patterning. The traditional theories invoking either “motor programs” or feedback-based machine models were beset with the same logical problem that faces developmental theories: the origins of new forms. Kelso and his colleagues have used synergetic principles to show how the neuromuscular system can be “self-organizing”; that is, how trajectories and coordinative modes can emerge without the need for prescriptive solutions (see Kelso and Tuller, 1984). A basic assumption is that synergetic principles of organization are so general that they may be applied across systems and time spans; that new forms arise in development by the same processes by which they arise in “real-time” action (see Fogel and Thelen, 1987; Kugler et al., 1982; Thelen, 1986b; Thelen and Fogel, 1989; Thelen et al., 1987).

Pattern Formation in Complex and Developing Systems

Compression of the degrees of freedom and self-organization

Complex systems are systems with many elements or subsystems. These elements can combine with each other in a potentially very large number of ways; the system has an enormous number of “degrees of freedom” (figure 18.1). Under certain thermodynamic conditions – thermodynamic non-equilibrium (a directed flow of energy) – these elements can self-organize to generate patterned behavior that has much fewer dimensions than the original elements. That is, when the participating elements or subsystems interact, the original degrees of freedom are compressed to produce spatial and temporal order. The multiple variables can then be expressed as one or a few *collective variables*.

At any point in time, the behavior of the complex system is dynamically assembled as a product of the interactions of the elements in a particular context. At the same time that

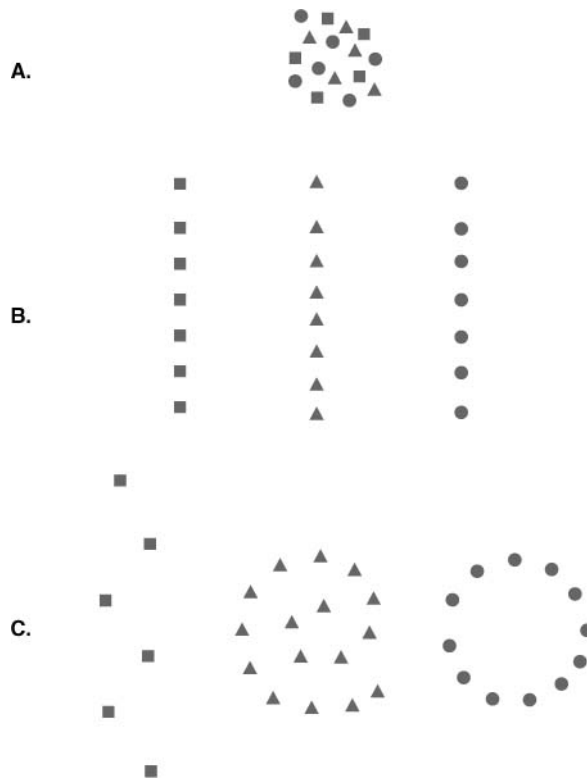


Figure 18.1 Schematic depiction of self-organization in a complex system. **A**, A complex system consists of a very large number of noisy elements or subsystems with very many degrees of freedom. **B**, Under certain thermodynamic conditions, such systems can self-organize to produce lower dimensional dynamics; the degrees of freedom are reduced. **C**, The dynamical system, in turn, exhibits behavioral complexity; it can have multiple patterns, multiple stable states, and adaptable configurations.

information is compressed, the resulting lower dimensional behavior can be highly complex and patterned. Behavioral complexity may be manifest in patterns evolving in space and time, in multiple patterns and stable states, and in remarkable adaptability to perturbations. Note that there is no prescription for this order existing prior to the dynamic assembly, either in the individual elements or in the context; the order grows out of the relations.

These phenomena are best illustrated by a dramatic, nonbiological example: the now-famous Belousov–Zhabotinskii autocatalytic chemical reaction. When simple chemicals – bromate ions in highly acidic medium – are placed in a shallow glass dish, a remarkable series of events begins (see figure 18.2):

A dish, thinly spread with a lightly colored liquid, sits quietly for a moment after its preparation. The liquid is then suddenly swept by a spontaneous burst of colored centers of chemical activity. Each newly formed region creates expanding patterns of concentric, circular rings. These collide with neighboring waves but never penetrate. In some rare cases, rotating one-, two- or three-armed spirals may emerge. Each pattern grows, impinging on its

neighboring patterns, winning on some fronts and losing on others, organizing the entire surface into a unique pattern. Finally, the patterns decay and the system dies, as secondary reactions drain the flow of the primary reaction. (Madore and Freedman, 1987, p. 253)

It would, of course, be impossible to describe the Belousov-Zhabotinskii reaction in terms of the behavior of the individual ions. There are too many of them and a nearly infinite number of degrees of freedom. The dramatic patterns, however, represent a much more compressed description. Whereas the behavior of the individual atoms is random and chaotic, the patterns show order in both space and time. Although they compress the original degrees of freedom, these patterns are themselves complex.

Where do these beautiful patterns and elaborate designs come from? No pattern generator or schema can be found. The order is truly emergent from the initial conditions: the mix of the chemicals and the constraints of the container, the room temperature, and so on. Scientists can simulate these self-organizing properties by a computer program that sets up very simple initial conditions. When the program runs, the sequence of pattern emerges, but a program for the pattern itself was never written.

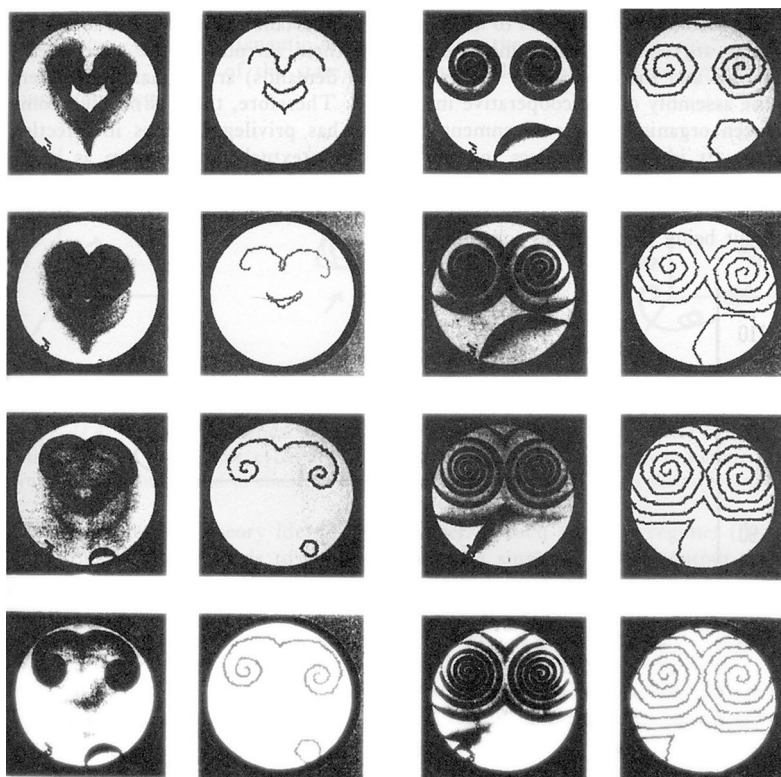


Figure 18.2 Evolving forms in the Belousov-Zhabotinskii reaction. The spontaneous development of structure can be seen in a sequence of photographs (left panels in each pair) that shows waves of chemical activity propagating through a receptive liquid medium. These complex forms can be remarkably well modeled by a simple computer simulation (right panels). (From Madore, B. F. and Freedman, W. L. (1987) Self-organizing structures. *American Scientist* 75, 561. Reprinted with permission of Sigma Xi, The Scientific Research Society.)

The parallel between the Belousov–Zhabotinskii reaction and the events of early biological morphogenesis is striking. From the fertilized egg, a seeming homogeneous bag of chemicals, the embryo divides, cleaves, invaginates, becomes polarized and lateralized, develops layers, and so on. Models of early morphogenesis have much in common with those used to simulate the Belousov–Zhabotinskii reaction as they call on gradient fields, states of excitation, nearest neighbor effects, and simple rules of interaction.

But unlike the chemical reaction, which decays as the elements reach thermodynamic equilibrium, the embryo is supplied with a continual supply of energy through metabolic processes. It remains in this thermodynamic nonequilibrium, and as it utilizes energy, its emergent forms not only remain, but become more elaborated, each pattern generating its own subpatterns and so on until a great number of functional structures have been generated. Of course the process is not random as species quite precisely reproduce themselves. In this case however, the genome may be thought to greatly underspecify the resultant product. Much evidence exists that genetic information sets the initial conditions, so to speak, but does not encode the topology that enfolds.

On a different level, behavior in developing organisms is likewise a result of the unique cooperativity of the subsystems in a context. Because of the thermodynamic status of living organisms, complexity in behavior may be an emergent property. No iconic representations of the behavior, either in the form of genetic codes, maturational timetables, reflexes, or cognitive schemes need exist *a priori*. As such, behavior is never hard-wired, but flexibly assembled within certain organismic constraints and the demands of the context or task. Order, therefore, is a product of *process*, not instruction. It is noteworthy that contemporary parallel models of neuronal and higher brain function are predicated on the processing of many individual subunits, none of which contains the icon or command of the resultant memory unit, perceptual trace, or word representation.

This formulation allows us to make another important claim. Because biological systems are openly exchanging energy with their surrounds, the state of the organism and the context for action (the task demands) are formally equivalent in the assembly of the cooperative interaction. Therefore, there is no dichotomy between organism and environment. Neither has privileged status in effecting change. It is as meaningless to talk of a decontextualized organism as of an environment without biological meaning to the animal. However, we may identify parameters either within or without the organism which act as agents of change, without being prescriptives for change.

Dynamic stability

Self-assembled behavior of complex systems is dynamically stable in any given context. Given a particular biological organization, and a particular context, we can say that the system prefers a certain range of behavioral outputs (characterized in dynamic terminology as an abstract *attractor* state; Abraham and Shaw, 1982). The system will “settle into” this dynamic stability from a number of initial states and will tend to return to its attractor regimes when perturbed. In figure 18.3, I have illustrated a hypothetical state space, the “fitness space” of an individual. The two axes of this state space are defined as the possible states of two measured variables of fitness, body temperature, and heart rate. Normal adult humans occupy a certain preferred part of this space. Illness or exercise may shift you temporarily to one portion of the space, but your system “wants” to return to the dark central spot and will do so after the perturbation of illness or exercise. This is a dynamic

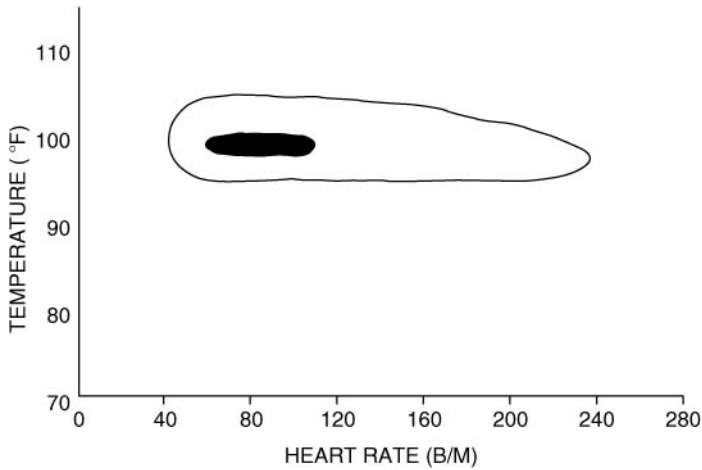


Figure 18.3 Hypothetical “fitness space” of a normal human individual showing dynamic range of heart rate and temperature. Individual “prefers” to spend time in the dark center portion, but is not limited to it. When perturbed, the system normally returns to the center oval.

stability because the system is not rigidly fixed to a confined region of the state space, but tends to stay in and return to a constrained region.

Dynamic systems theory identifies a number of such attractor regimes (figure 18.4). Behaviors that tends to converge around a single or several output states are called *point attractor* systems, whereas repetitive or cyclical behavior is characterized as a *limit cycle attractor*. A special attractor regime currently of great biological interest is the *chaotic* or *strange attractor*. Chaotic systems are globally deterministic, but locally nondeterministic. They look noisy by conventional statistical tests, but they are not. Their behavior can be captured by certain sets of equations, thus, they have fewer degrees of freedom than truly random noise (Skarda and Freeman 1987).

The attractor concept helps to understand how behavior can be both stable and variable. Developing organisms are neither stereotyped and “hard-wired” nor are they random. Behavior fluctuates, but within limits. That is, organisms tend to show a delimited number of behavioral patterns, which within certain boundary conditions, will act like dynamic

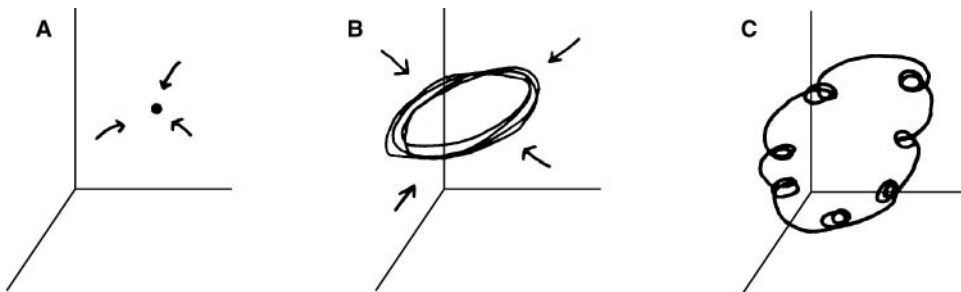


Figure 18.4 Three hypothetical attractors plotted in three-dimensional state space. A, Point attractor. B, Limit cycle attractor. C, Chaotic attractor. Arrows indicate that dynamic trajectories tend to converge on these behavior patterns of the collective variable.

attractors. These states will be the preferred configuration from a number of initial conditions, and they will be relatively resistant to perturbation. As a consequence of this dynamic assembly, developing organisms remain flexible in the face of tasks, but only within the constraints of their energetically stable possible states.

Attractors stabilize and destabilize during ontogeny

Because the components of developing systems are always in flux, the attractor states themselves have dynamic trajectories. Some behavior becomes more stable, more tightly constrained, more skilled, and less subject to perturbations. New walkers, like new drivers, must focus all their attention to the task and are easily distracted and dislodged. With experience, the skill becomes so stable that conversation, even chewing gum, is possible, and the walker can compensate for all manner of obstacles. Increasing skill can be conceptualized as an increasingly stable attractor.

Likewise, many ontogenetic phenomena require attractors to destabilize; behavior becomes less reliable, more disruptable, and more variable. For example, in infant mammals, sucking is a highly stable attractor state. All intact infant mammals must suckle in a skilled and reliable manner at birth. However, with weaning, suckling becomes more context dependent, less obligatory, more variable, and more likely to be interrupted. Eventually, the motor pattern itself disappears, as adults cannot reproduce the behavior.

I have characterized the continual and gradual changes during development as the stabilization and destabilization of preferred attractor states. What about the notorious discontinuities in development? As I discuss in the following sections, discontinuous changes also require the disruption of stable states.

Discontinuous phase shifts

Complex systems may exhibit multiple behavioral patterns. An important characteristic of such complex systems is that they switch between patterns *in a discontinuous manner*, by exhibiting discrete phase transitions. That is, the shift from one stable behavioral mode (attractor regime) to another behavioral regime occurs without stable intermediate states (Haken, 1983). *Bifurcations* are phase shifts where the collective variable jumps into two or more discrete, stable modes. Complex systems may undergo multiple bifurcations (figure 18.5), resulting in increasing behavioral complexity. Phase shifts and bifurcations give rise, therefore, to new forms and multiple states.

Developing organisms are well known to display qualitatively discrete phases during ontogeny. Sometimes, the animal seems even to lose behavioral forms or regress to less mature performance. The premier developmental question is, of course, the nature of the transition from one developmental stage to another – the emergence of new forms. How does a system retain continuity and yet produce discontinuous manifestations?

Control parameters

Developmental theorists may well look to synergetic principles for help with the perennial puzzle of continuity-within-discontinuity. In complex systems, behavior that is ordered

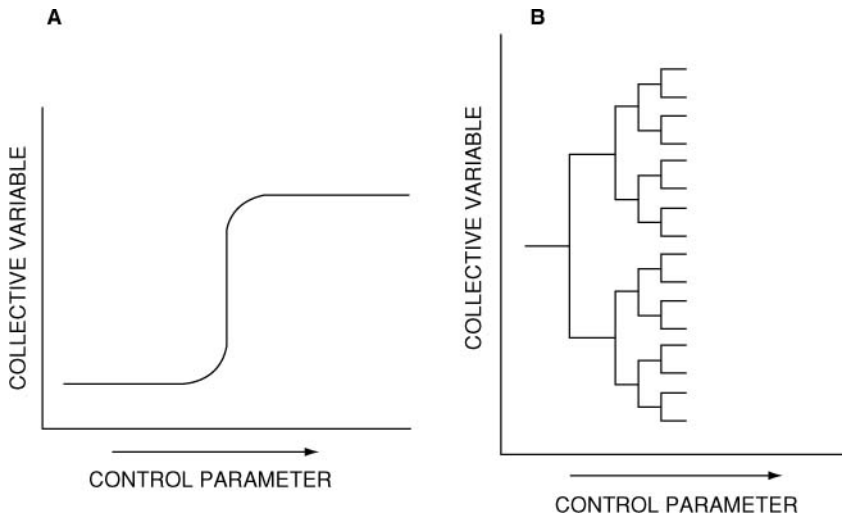


Figure 18.5 The appearance of new forms through discontinuous phase shift. **A**, Scaling on a control parameter shifts the system into a new state without a stable intermediate. **B**, Scaling on a control parameter induces multiple stable behavioral states.

results from the cooperativity of the subsystems. But at points of change – phase shifts – not all of the elements drive the system into a new phase. An important synergetic principle is that at a phase transition, scaling on only one or a few *control parameters* shifts the entire system. Because of the holistic nature of cooperative systems, this change in a crucial variable beyond a critical point reverberates to a system-wide reorganization (Kelso and Schönner, 1987). Again, because organismic and contextual variables are equally important in the dynamic assembly of behavior, there is no formal difference between exogenous and endogenous sources of change. The control parameter must in no way be envisioned as a prescription for change. Control parameters do not themselves encode or represent change. They may be rather unspecific, like physical parameters of pressure, temperature, or energy to the system, but they act to reorganize the system in specific ways. Continuity is maintained because most of the components of the system have not materially changed; discontinuity is manifest because the components relate to one another in a different fashion, and their low-dimensional, collective behavior has undergone a qualitative shift.

Here I would like to illustrate such a nonequilibrium phase shift and the role of the control parameter with a compelling real-time example from the human motor system, which has been elegantly modeled by Kelso and his colleagues using synergetic principles (Haken et al., 1985; Kelso et al., 1986; Schönner et al., 1986). Kelso asked human subjects to flex and extend their index fingers in time to a metronome, beginning at a slow pace and with the fingers moving out-of-phase, that is, with one finger flexing while the other was extending. As the experimenter increased the metronome pacing, subjects spontaneously and instantaneously shifted their coordination pattern from out-of-phase to in-phase at repeatable critical points in the speed scalar. (No such shift occurs if subjects begin with in-phase movements.) The degrees of freedom contributing to finger-flexing movements were compressed by the motor system such that the behavior could be described by much fewer variables – in this case the relative phasing between fingers. Although out-of-phase

movements were stable at lower speeds, at a critical point the system assumed a new, and presumably more stable regime. No prescription for this phase shift is assumed; the new coordinative pattern arose from the task demands and the thermodynamics of the combined elements that produced it. In this case, a single control parameter – the energy delivered to the system to increase the speed, appeared to drive the phase shift. The anatomical and physiological elements participating in the ensemble were reorganized to produce a different output while themselves remaining stable.

Control parameters in developing systems

We have proposed that at developmental transitions, one or several components of the complex system may act as control parameters, including variables in the context or in the environment (Fogel and Thelen, 1987; Thelen, 1988). Although all of the elements or subsystems are essential for the systems output, only one or a few of the subsystems will trigger transitions, which, in turn, will lead to system-wide reorganization.

This principle helps explain the heterochronic, asynchronous, and often nonlinear character of behavioral ontogeny. We commonly observe “pieces” of a functional behavior long before the performance of the mature behavior. These pieces seem to be used out of sequence, in inappropriate or different functional contexts, only under certain experimental conditions, or otherwise not properly “connected” with the other elements needed for goal-directed activity.

Theories that assume that developmental change is driven by a unified timetable in the form of maturational plans, neurological reorganizations, or cognitive structures have had difficulty accounting for both the anticipations of function and regressions. In this systems approach, we strongly emphasize that contributing components may mature at different rates. The component processes are thus developing in parallel, but not synchronously or symmetrically. Figure 18.6 depicts a developing system composed of many component profiles in a heterarchical, rather than a hierarchical assembly. At any point in time, behavior is a compression of these components within a specific task context. This means that some elements of functional actions may be in place long before the performance but may not be manifest until the slowest component allows the system to dynamically assemble in a new form (the *rate-limiting* component).

Because it is the task, not instructions that exist prior to the task, which assembles the components, these subsystems may be opportunistically appropriated for different actions for different ontogenetic goals. The component is continuously available, but as it is only manifest in a task, its expression is task specific. For example, leg kicks may be used by young infants as expressive or exploratory behaviors, although these coordinated activities may be later recruited for locomotor systems. Fogel and Thelen (1987) and Thelen (1981) give other examples of coordinative patterns transiently recruited for tasks quite unrelated to their mature forms.

How control parameters drive developmental change

Scalar changes in a single control parameter. In particular, we have proposed that control parameters can act to trigger developmental transitions in two ways. First, there may be scalar changes in one or more existing components that reach the critical values that initiate

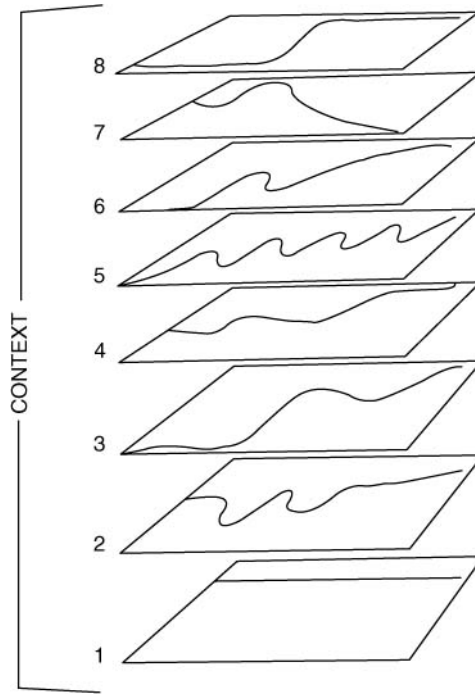


Figure 18.6 Developing systems pictured as a layered ensemble of subsystems, each with its own developmental trajectory. The low-dimensional behavior (collective variable) is assembled only within a contextual frame. No subsystem has hierarchical priority.

a phase shift. These may be identified at many levels of analysis: incremental growth in anatomical systems, increase (or decrease) of neural elements or concentrations of neurotransmitters, changing perceptual, cognitive or motor abilities or memory capacity, or change of attentional mechanisms.

Contextual factors may, however, be equally potent in effecting the appearance of new forms. We have especially stressed the role of the social partners of young animals in promoting developmental change (Fogel and Thelen, 1987). Social conspecifics often create contexts that support or facilitate the organization of systems by substituting for organismic elements that are later developing. Human parents, for example, continually provide access to objects, appropriate “frames” for social dialogue, correctly scaled language opportunities, and so on, which provide a task context within which the child’s organismic capabilities may coalesce. Without these supportive contexts, the infant performs at a less mature level.

I offer the phenomenon of the newborn stepping response as an illustration of how, in a systems approach, a scalar change in a crucial control parameter can lead to the emergence (or in this case, the disappearance!) of ontogenetic forms. The regression of the coordinated stepping seen in normal newborns has conventionally been interpreted as the result of maturing cortical inhibitory centers. Donna Fisher and I (Thelen and Fisher, 1982) found, however, that a simple contextual manipulation – placing the infant supine – “restored” the patterned behavior even in infants who performed no steps when held upright. We proposed that the developmental transition from stepping to no-stepping was triggered

by a simple, nonneural scaling of a body composition parameter, the increase of nonmuscular or fat tissue, which made the legs comparatively heavy and weak and prevented the infant from lifting the leg upright, but only when the infant was in the biomechanically demanding upright posture (Thelen and Fisher, 1982). My colleagues and I have shown that stepping in young infants can be elicited or suppressed by a number of contextual manipulations that systematically change the biomechanical demands on the legs, including postural changes, submerging in water, adding weights, and placing infants on motorized treadmills (Thelen, 1986a; Thelen et al., 1984; Thelen et al., 1982).

In dynamic systems terminology, then, the low-dimensional behavior of stepping, characterized by a definable relation between the excursions of the joints of each limb and between the two legs, is not a product of some abstract “program” for stepping that exists before the performance. Rather, it is the interaction of the contributing components, including the biomechanical elements in relation to a specific task context, which determines whether the infant steps or does not step. The body composition control parameter effects a developmental shift in one context, but perhaps not in other contexts. In other words, under certain conditions, the stepping topography represents a preferred and stable output of the system. Changing the internal or external conditions causes the system to reassemble in another attractor state. We therefore cannot define the system removed from the context.

The control parameters themselves change during ontogeny. Conventional single-causal models of developmental change assume that the control parameter in any one domain remains stationary over long periods of developmental time (i.e. that cognitive reorganizations or cortical growth organize diverse aspects of behavior over a long time span). Our systems view, however, proposes that the control parameters themselves shift as the contributing components grow and differentiate and as the physical and social contexts of the organism change as a result of its development. This is the second source of transitions. The process of development itself is nonlinear, and as the systems regroup and coalesce, these nonlinearities serve as a continuing wellspring for new forms. In figure 18.7, I represent these changing control parameters as the migration of a surface in three-dimensional state space.

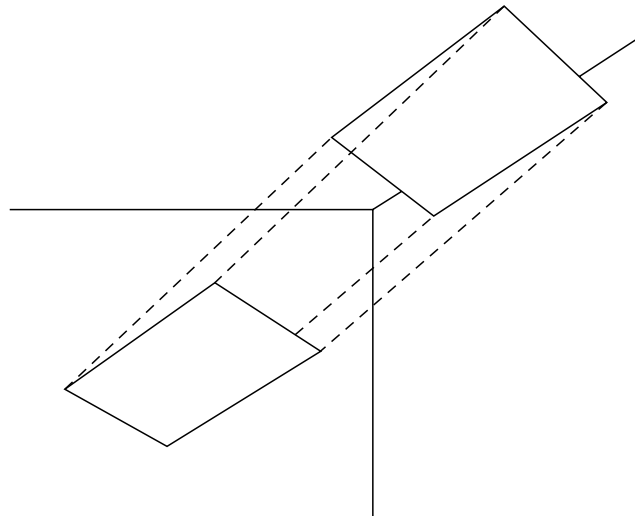


Figure 18.7 Developing system depicted as a surface in three-dimensional state space. With time, the surface itself migrates in the space, resulting in changing control parameters.

Control parameters for developmental shifts at different ages and in different domains cannot be identified *a priori*. Identifying the sources of change remains an empirical exercise at every level of analysis. This is important because sometimes it is the nonobvious contributions to the system that drive the shift, as I illustrated with the newborn stepping system. Although, for example, the onset of verbal language appears to reflect a major cognitive reorganization, it is at least an open possibility that what in fact delimits the appearance of words is articulatory control over the vocal apparatus. Thus, although brain development may be a necessary condition for the appearance of new behavioral modes, it may not be sufficient, because we can never assume a one-to-one mapping of the structural basis of behavior and its performance in any individual or at any time. We can find many other instances of developing systems where only careful experimental analysis can dissect the interacting systems to reveal the driving subsystems.

For example, coordinated stepping behavior while upright reappears in the repertoire of normal infants at about ten months. I have proposed elsewhere that the control parameter driving this developmental shift (from no-stepping to stepping) is different from the one responsible for the earlier transition (Thelen, 1984). In particular, voluntary walking emerges when elements of both balance and extensor muscle strength reach values critical for allowing infants to support their weight on one leg in a stable manner while the other is lifted for the step. When we support newly stepping infants by holding their hands, or by providing them with walkers, we augment these control parameters and allow the system to display its more mature patterns (i.e. infants can successfully step).

Adaptive behavior emerges from successive bifurcations

Ontogenetic systems thus increase in complexity by a cascade of successive bifurcations or phase shifts. As the system reorganizes through the scalar change in a component, the newly emergent forms themselves act as control parameters. Changes in any one domain therefore may become amplified and have system-wide reverberations. What may appear to be a small change or acquisition may trigger a succession of major developmental landmarks – I provide examples here. I emphasize, however, that the track of successive bifurcations is a stochastic rather than a deterministic process. Ontogenetic outcomes are similar in the members of a species because certain attractor regimes are dynamically stable and certain configurations are more likely than others. Individual differences are possible because the fluctuations of the internal and external milieu provide elements of uncertainty and because the collective variable is exquisitely sensitive to the task. That is, the system may find alternative configurations to meet task constraints. For example, the task of moving toward a goal may be accomplished by young infants by a variety of locomotor modes – rolling, crawling, creeping, scooting, propelling in a wheeled device, and so on. The precise configuration is a function of the maturational and motivational state of the infant and the constraints of the support surface, provision of the wheeled device and so on.

Phase transitions result from the amplification of fluctuations

By what processes do control parameters induce changes of form? In complex systems, change results from the amplification of naturally occurring fluctuations or instabilities as the control parameter is scaled past a critical value (Kelso et al., 1986).

As a result of their complexity and multiple degrees of freedom, biological systems are *dynamically* stable. This means that they exist within a range of possible states and fluctuate among those states. As one component is gradually changed, there exists a point where the coalition of elements is no longer stable. Normal fluctuations become amplified until this noise disrupts the dynamic stability and the system autonomously reorganizes into a new stable state. Note again that fluctuations may become amplified from such control parameters acting outside as well as within the organism (figure 18.8).

Stability can be measured in complex systems in two ways. First, if the system is driven by a small perturbation away from its stationary state, it will tend to return to that stationary state. The time it takes to return to stationarity is a function of the stability of the system, and surprisingly, independent of the size of the perturbation, if it is small. Second, the inherent noise in any system acts as perturbations on the behavior. If the system is stable, the noise produces few variations from the stable state. At points of instability, however, the noise drives the collective behavior into more variable manifestations (figure 18.8).

From these considerations, we can make two powerful predictions about nonequilibrium systems at the point of phase transitions. First, that we should be able to detect the essential enhanced fluctuations at phase transitions in the form of increased variability in our behavioral measure. (This assumes we have chosen the correct collective variable to describe the behavior of interest, a nontrivial problem and one I discuss further later.) Second, because the system is inherently less stable at these transitions, it should be more sensitive to perturbations and thus restore itself to its stable attractor more slowly when perturbed.

These predictions were rigorously confirmed in the bilateral rhythmical finger movement experiments by Kelso and colleagues previously mentioned. These investigators found clear evidence of enhanced fluctuations in the relative phase measure just before and during the spontaneous phase shift from out-of-phase to in-phase coordination (Kelso et al., 1986). In addition, when they mechanically perturbed the movements, they observed a slower return to an equilibrium state at or near the phase transition (Scholz et al., 1987).

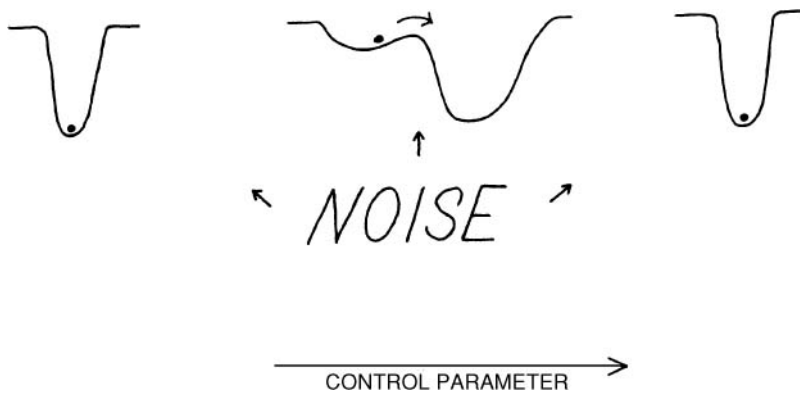


Figure 18.8 Phase shifts result from the amplification of normally occurring fluctuations or noise. The stability of a complex system is depicted in the steepness of a potential well; stable systems have steep wells. It is difficult to dislodge the ball from the steep well. At certain values of a control parameter, the internal fluctuations overwhelm the system stability and the system seeks new stable modes.

What does this mean for developing organisms? That ontogenic change results from a dialectic process of equilibrium arising from disequilibrium has long been a feature of developmental theories, including those of Piaget, Vygotsky, Lerner, Langer, Riegel, Overton, and Werner. However, the empirical instantiation of equilibration has been of little concern. Certainly, contemporary Piagetian research has centered more on the validity of a structural approach and the validation of invariant sequences than on Piaget's actual process of change.

If phase shifts through amplification of fluctuations are characteristic of systems in general, we should, by using the appropriate empirical strategy, be able to detect these phenomena. Indeed, such a demonstration would offer strong support to the autonomous or self-organizing abilities of developing systems.

Using Dynamical Systems Principles to Understand Development: Some Examples

Thelen et al. (1987) and Fogel and Thelen (1987) show how dynamic principles can help explain persistent puzzling aspects of early motor and expressive-communicative development. Here I present some additional examples.

Behavioral states in the newborn period: Self-organization and phase shifts

Thelen et al. (1987) suggested that the clustering of discrete variables seen in newborn state behavior was an important illustration of phase shifts or discontinuities in behavioral organization. Wolff (1987) has recently written an eloquent analysis of state behavior from a dynamic systems perspective.

In this treatment, Wolff emphasized the nonlinearity of state as a behavioral organizer in the newborn period. This nonlinearity means that there is no one-to-one correspondence between the input to the system and its response. Newborns are indeed very nonlinear: Their motor patterns form discrete clusters, and a stimulus presented in one cluster (such as sleep) may lead to a very different response than when the identical stimulus is presented during another cluster (such as alert wakefulness). Transitions from one behavioral state to another usually occur relatively abruptly, with unstable intermediate conditions.

Wolff explicitly rejected the traditional conceptualization of infant state as points along a continuum of behavioral arousal or activation. The traditional view assumes that one central agency such as the brainstem drives the discrete motor patterns, but is extrinsic to them. Rather, the cluster of behaviors we identify as state, Wolff argued, represent self-organizing aggregates of movement patterns, which are stable and resist perturbation. No outside executive assembles these clusters; states "fall out" because the system can exist only in one of several stable attractor regimes. These attractor regimes may themselves be different as development progresses; that is, the ensemble of interactive motor patterns may change with age.

Presumably, a number of control parameters can disrupt the dynamic stability of one state and lead to a qualitative shift to a new state. If a sleeping infant is tickled very gently, he or she may remain asleep, however, if we increase the tactile stimulation, there will likely be a point where the stability of the sleep state is disrupted, and the infant awakens. If he or she immediately falls asleep again, we would judge the infant's sleep state to be very deep;

that is, the attractor regime is very stable. If the infant stays awake, we could assume that she was close to the transition point to wakefulness and the tickling acted as a control parameter driving the phase shift. Likewise, nonnutritive sucking may be the control parameter to shift the fussy infant into a more quiet state (see also Fogel and Thelen, 1987).

Evidence from the early development of sleep states supports this self-assembly view. In premature infants, differentiation of active and quiet sleep states occurs progressively with age from a more indeterminate sleep type. Curzi-Dascalova et al. (1988) showed that this differentiation could be characterized by the association of increasing numbers of state criteria behaviors from 31 to 41 weeks of gestational age. They recorded EEG, eye movements, tonic chin EMG, gross limb movements, and respiration. In the youngest premature infants, only the EEG and eye movement patterns “hung together” to distinguish active and quiet states from indeterminate sleep. By 41 weeks, states were reliably characterized by larger constellations of variables. As sleep states entrap more components, they also become more stable, in terms of well-defined and regular cycles. State development looks not so much like the maturation of a single controlling structure as the progressive strengthening of stable attractor states that serve, in turn, as major organizers of behavior.

Variability and instability at phase shifts: Three examples

The three examples I offer – two recent human studies and the well-studied weaning period in rat pups – fulfill dynamic predictions: that increased variability and more sensitivity to perturbation will accompany ontogenetic transitions.

Postural Stability. Shumway-Cook and Woollacott (1985) studied the development of postural stability in three groups of children aged 15–31 months, 4–6 years, and 7–10 years. The children stood on a moveable platform that provided a rapid forward or backward displacement of a few centimeters to which subjects respond by an appropriate postural compensation. The experimenters measured the onset latency of the contraction of the stabilizing muscle groups in the lower leg and the delay between the onset of the activation of the lower leg and thigh muscles over a number of trials. The oldest group of children and adults showed consistent responses that rapidly adapted over succeeding trials; that is, the subjects damped their responses to minimize overcompensation to the perturbation. The youngest children also showed consistent, rather longer latency responses, but they did not habituate to the destabilizing trials – a less mature strategy. In the transition group of four- to six-year-olds, the response latencies were not only significantly longer than in the younger and older groups, but also the variability was greatly increased, both within and between subjects (figure 18.9). Postural compensation, like stepping, is a dynamic product of the neurological mechanisms detecting the perturbation and producing the corrective response and biomechanical considerations, in this case, the natural sway frequency of the body. (Children have a faster sway rate than adults, Forssberg and Nashner, 1982.) These authors speculated that the rapid change of body proportion seen in the 4–6 age range may have disrupted the stable, but less adaptable, earlier stage. In dynamic terminology, the body proportion may have acted as one (although likely not the only) control parameter. In addition, the four to six-year-old group performed more poorly when they were given discrepant information about their postural stability from two sensory modalities, vision and ankle and foot proprioception. Younger infants apparently rely largely on visual input, whereas older subjects are able to rapidly integrate the two sources. In the transition group, however, the perturbation proved to be much more disruptive.

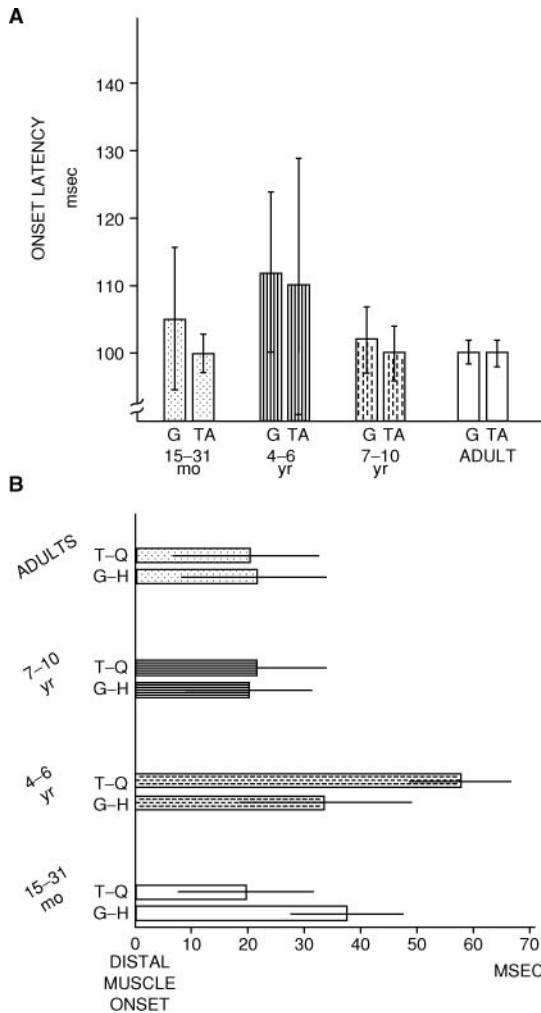


Figure 18.9 A, Average onset latency (+ SD) in the appropriate distal muscle in response to a forward sway translation (G) or backward sway translation (TA) as a function of age. Response latencies are slower and more variable in children 4-6. B, Temporal delay between distal and proximal muscle activation as a function of age. Children ages 4-6 demonstrate greatest temporal delay in activation of proximal muscles suggesting diminished synergic coupling between distal and proximal muscles. (From Shumway-Cook, A. and Woolacott, M. H. (1985) The growth of stability: Postural control from a developmental perspective. *Journal of Motor Behavior* 17, 137. Reprinted with permission of the Helen Dwight Reid Educational Foundation. Published by Heldref Publications, 1319 Eighteenth St., NW, Washington, DC, 20036-1802. Copyright © 1985.)

Piagetian conservation. Church and Goldin-Meadow (1986) presented a compelling measure of instability in transitions in a classic Piagetian conservation task. When these authors asked five- to eight-year-old children to explain their conservation judgments nearly all children gestured spontaneously as they spoke. Some children,

however, conveyed information in their gestures about the task that did not match the information of their spoken explanation. These “discordant” children were far less consistent in the nature of their explanations of the various conservation tasks and in matching the actual judgment of conservation with their explanation. These authors suggested that the discordant children “appeared to have pieces of information that they had not yet consolidated into a coherent explanatory system” (p. 59). In dynamic terms, the tasks did not elicit a stable attractor state – either conservation or nonconservation. If we consider verbal production as one compression of the degrees of freedom and gestural production as yet another way that the system can reduce the dimensionality for a lower dimensional output, we have a dramatic example of the fluid assembly of the components, especially at a time when system has not settled in to a more stable regime.

Indeed, the children in the discordant group proved to be much more sensitive to environmental perturbations. When the experimenters explicitly trained these children on conservation principles or even just allowed them practice with the materials, the children improved both on their judgments and on their explanations. Concordant children did not benefit from training. This intervention, therefore, acted as the crucial control parameter that pushed the unstable system into new forms. The stable systems of the concordant children could not be disrupted. It is consistent with a Piagetian interpretation to conclude that naturally occurring experience with conservation-like tasks would eventually shift the system into the conserving mode.

Weaning in rat pups. In the rat pup, the shift from suckling to independent ingestion of food is a well-defined behavioral transition. In the first two weeks of life, rats meet their nutritional needs exclusively by suckling and after 28 days they only eat and drink independently. The shift in feeding modes is most pronounced between days 21 and 24 (Hall and Williams, 1983).

Although under natural conditions the transition is relatively discrete, experimental manipulations have revealed that the process is a complex one, reflecting the synergetic and symbiotic relationship between the behavior and physiology of both the mother and the pup. Noteworthy from the present systems view is the mobility of the component subsystems and their ability to coalesce in particular task-specific configurations that can be relatively independent of age.

For example, although the rat pups do not normally eat and drink independently for several weeks after birth, Hall and Bryan (1980) have shown that even newborn rat pups will ingest liquid or semisolid food from the floor of a test chamber. In young pups, this oral activity was activated only when the ambient temperature was high. The presence of food and external warmth served as control parameters to shift the rat pups into an ontogenetically more mature performance, independent ingestion.

Equally intriguing is the demonstration by Pfister et al. (1986) of a context-determined prolongation of suckling. These experimenters provided weaning-aged rat pups with a succession of nursing dams and their 16- to 21-day-old litters. Under these conditions, rats continued to nurse until as much as 70 days of age, long beyond the time they were eating independently, but they attached to the nipple and withdrew milk only when the younger littermates had attached. A combination of the social facilitation of nursing littermates, a dam who allowed continued nursing, and the continuation of the suckling experience here coalesced to maintain the animal in a stable state characteristic of an earlier ontogenetic stage.

It is noteworthy that during the natural weaning transition, ingestive behavior in a choice situation was highly variable and subject to disruption. The youngest rat pups in Stoloff and Blass's (1983) forced choice experiment consistently chose to suckle and the over 28-day group never chose suckling over eating. However, the 21–24 day transition group exhibited highly unstable and variable responses, and their choice behavior was described as “markedly affected by each manipulation undertaken in this experiment” (p. 451).

These results make it unlikely that there is a “weaning clock” somewhere in the rat pup, ticking off time or metering out some “weaning substance.” Rather, weaning may be a phenomenon emergent from this confluence of ongoing systems, each with constraints and demands. In recently completed work, Thiels (1987) has shown that at the weaning transition, rat pups show increases not only in independent eating and drinking, *but also in many other actions as well* (see figure 18.10). The increased locomotor ability of the pup, its increased size and energy demands, its abilities to move away from the mother to seek food, and so on, are all contributions to the weaning transition and potential control parameters. No specific weaning instructions need be invoked. Weaning falls out, so to speak, from an ensemble of dynamic processes.

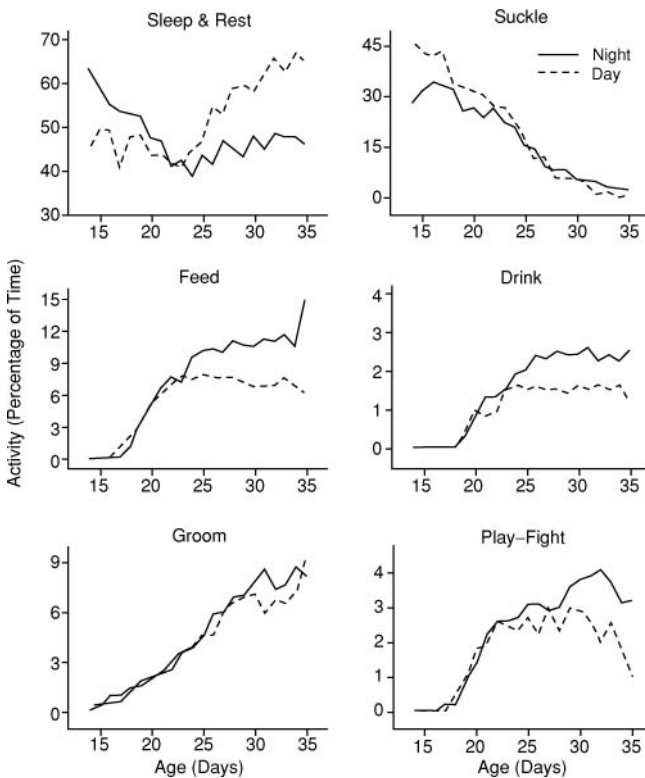


Figure 18.10 Percentage of time rat pups spend in various activities as a function of age. Note increase of many independent functions between ages 20–25 days. (From Thiels, 1987, reprinted with permission.)

The development of early lateral preferences: phase shifts and attractors

By the age of two, human children show lateral preferences for hand use almost as consistently as adults. Developmentalists have long been intrigued with the developmental origins of laterality, especially because hemispheric specialization for manual behavior may be related to specialization for speech. Nonetheless, it is not easy to determine when and how this preference is manifested in infancy. Lateral preferences often appear to wax and wane, making prediction from infant hand use to adult handedness very difficult.

The strong, predominantly rightward, asymmetrical head posture seen in the newborn period makes it likely that the central nervous system is laterally biased from birth. Indeed, neonatal head preference is a good predictor of hand-use preference in the second year (Michel and Harkins, 1986). There is considerable debate over whether the asymmetries of head posture are manifestations of the same lateralities that are later expressed in handedness, or whether these head postures induce handedness through biasing hand-eye contact and arm movements (see Young et al. (1983) for further elaboration of this debate and several models of laterality development).

In a recent review, Michel (1987) offered a plausible scenario by which the initial head biasing has cascading effects leading to eventual laterality in handedness. Head orientation leads to an asymmetry of visual regard of the hand and arm movement, which in turn, may induce asymmetrical reaching, and later manipulation. Thus, the infant's own experiences generate laterality in progressively developing skills.

If, however, the system is inherently biased, why is infant handedness so shifting and unstable? Michel suggested that the actual manifestation of the preferred hand is a function of both the infant's level of manual skill and the particular task. For example, Michel et al. (1986) tested 6- to 13-month-old infants for lateral preference in three manual skills: reaching for objects, manipulating objects, and coordinating complementary bimanual actions. Infants generally showed consistent hand-use preferences among the tasks (and about 75 percent were right handed). However, there were some surprising shifts. Although all of the 12-month-old infants preferred the same hand for reaching and bimanual manipulation, 56 percent of the 13-month-olds chose the opposite hand for bimanual manipulations from the hand they used for reaching. It is important to note that bimanual manipulation becomes a common skill for infants only in about the twelfth month. Michel speculated that many of the reaches of the 13-month-old infants were with the nonpreferred hand so that the preferred hand could be left free to begin bimanual manipulation. When bimanual manipulation becomes practiced, presumably infants could both reach and manipulate with the preferred hand. Lateral preference is a useful metric only when combined with a task analysis.

This account of lateral preference is consistent with a dynamic systems view. Let us depict strong, adult-like lateral preferences for hand use as two point attractors whose stability is represented by the steepness of the well seen at the bottom left of figure 18.11. The attractor for the right hand is very strong; the ball "prefers" to roll to the bottom of the well and will return there very quickly when perturbed. Right-handed people may be able to use the left hand for some tasks, but they prefer not to under ordinary circumstances. However, if their right arms were in a cast and sling, they would recruit the left hand to do tasks not ordinarily undertaken. That is, given a strong perturbation (broken arm), the ball can be shaken out of the deep well into another attractor state (left hand use), as a qualitative phase shift.

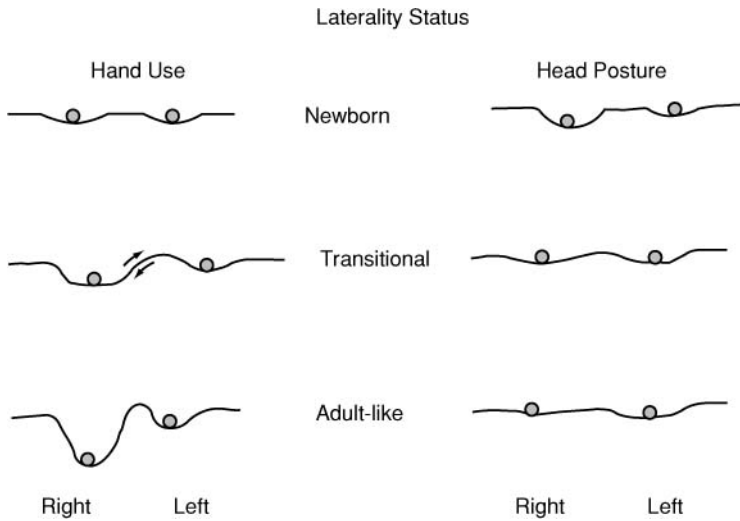


Figure 18.11 Lateral preference depicted as a series of point attractor states. Hand use attractors are the left-hand panel, head posture attractors on the right-hand panel. Transitional states are bistable and are especially sensitive to task context.

We can characterize newborn head posture as a relatively strong attractor, which entrains the arm and hand system to become progressively more laterally differentiated. However, in the transitional period, the attractor basins are shallow. Even rather small perturbations will drive the ball out of the well, up over the wall, and into the opposite hand attractor. The system is especially sensitive to the task and skill-level interaction because each new demand acts as a perturbation. Thus, the onset of bimanual manipulation acts as a control parameter and disrupts the stability of the reaching laterality, leading to a phase shift.

How does this account differ from a model of development as simply increasing hemispheric laterality? Here I emphasize the systems nature of lateral preference, which is always assembled “softly” in relation to the task and action patterns available to the infant. The system prefers certain places in the state space, but it is not restricted to them. Accomplishing the task is always a higher priority than the particular means by which the infant executes the action, so that the attractors are shallow enough to allow for flexibility in the face of obstacles. Likewise, the system becomes lateralized only as it supports adaptive actions. At the same time as the hand use attractors are becoming lateralized and stable, the head posture attractors are becoming progressively weaker. It is not adaptive for action to have an obligatory, or even strongly preferred head posture. Similarly, spontaneous leg movements develop from an initial strong asymmetry to symmetrical activity, reflecting the demands of locomotion and postural support for bilateral symmetry (Thelen et al., 1983).

Although hand use preference may indeed reflect an increasing hemispheric specialization, this explanation alone misses the richness and complexity of the process of change over time. We sometimes view the nonlinearity and nonstationarity of behavior over time as noise in the smooth trajectory toward maturity. The lesson from nonlinear dynamical systems is that these aberrations are the very stuff of ontogenetic change. It is at these transitions that the system reveals what holds it together and what drives it to new forms. A

synergetic strategy of development will exploit these nonlinearities for a deeper understanding of process.

An Empirical Strategy Based on Systems Principles

We know that self-organizing phenomena in physics, chemistry, and some biological systems may be modeled with precision and elegance. This goal may not be attainable with behaving and developing organisms. Can principles of complex systems help developmentalists in our everyday unraveling of real life behavior? Do we have just another set of agreeable postulates which are neither objectionable nor useful?

I believe the lessons from complex systems analysis can serve developmentalists well, not only as a conceptual framework, but as an empirical strategy that is independent of level and content domain. Nothing I propose here for operationalizing systems is, in itself, new. Developmentalists have been using these methods – observational, longitudinal, experimental – since the adoption of scientific methods for studying ontogeny. What may be new, however, is the systematic linking of these strategies to synergetic principles:

- 1 The focus is on process not just outcome measures.
- 2 No component or subsystem has ontological priority.
- 3 Task and context, not instructions, assemble behavior.
- 4 Control parameters are not stationary. (The state space itself evolves through time.)

The first requirement for a systems approach is to identify the essential collective variables and their behavior. What is the best way to describe, for any particular organism and set of developmental questions, how the system compresses the degrees of freedom? Note that this description of the collective states can be done in many domains and at many levels of analysis. For infant animals, this may be a measure of perceptual performance or motor output, a psycho-physiological measure, or variables indexing social interaction. The dynamical description is level-independent. However, the choice of an appropriate collective variable is neither a trivial nor a simple matter because ontogeny is so often nonlinear. Because we are interested in the processes of developmental change, it is likely that our first approach would be longitudinal. For animals like humans, where significant individual variability often renders group means meaningless, the analysis may require a case-study design.

Because we assume in this perspective that the task or context, not pre-existing instructions, assembles the system into a measurable collective variable, it is essential that our developmental descriptions also contain a task analysis. This also may be difficult, especially in long-term longitudinal studies, because the meaning of the task or context itself changes with the development of the infant. For example, grasping a 1-inch cube is not the same task for a three-month-old as for a 12-month-old simply because of the body scale changes in the dimensions of the hand relative to the object (Newell, 1986). Nonetheless, it is a mistake to assume that sources of developmental shifts are organismic when they may indeed be in the match between the organism and the task.

The second step in this analysis is to identify the developmental transitions or where the organism shifts from one stable mode of performance to a new mode. Again, if there is variability in the age-dependent onset of new behaviors, or if complex contextual eliciting factors are involved, such shifts may be best discovered in the course of individual

developmental profiles. Synergetic theory predicts that at such transitions, the system will show enhanced fluctuations and loss of stability. In developmental data we would expect an increase in the variability of our collective variable – that is, an increase in the deviations from the mean performance when compared to either the earlier stable performance or the new behavioral mode.

Experimentally induced perturbations or facilitations at the point of transitions can test the stability of the system. Developmentalists may probe a transition by experimentally perturbing the infant with an appropriate contextual manipulation (or, in nonhuman species, a surgical or pharmacological intervention). Systems near phase transitions are predicted to recover more slowly than those in more stable states.

The third, and crucial, step is to try to identify the control parameters: the one or few variables in the complex system that drives the shift. How can this be done? First, we would expect that a component or subsystem acting as a control parameter would itself show scalar changes in the time period of the phase transition. One clue to identifying control parameters is to look for variables that themselves change rapidly prior to or during the phase shift. This is not foolproof, however! In dynamic systems even small changes in crucial scalars can amplify fluctuations and lead to new equilibrium states.

If we understand our developing organism fairly well, we can make reasonable guesses about which components may drive developmental systems. Nonetheless, it may be a mistake to assume a control parameter *a priori*. A more fruitful strategy would be to map several likely control parameters so that they may be tested individually.

Once candidates for control parameters are identified, we can perform experimental manipulations or exploit the natural variability among individuals to confirm whether changes in the single parameter drive the system reorganization. The former tactic is more easily employed if we can discover a contextual manipulation that will serve as a substitute for a natural control parameter. In humans, neural or organismic variables may need correlational methods or observation of nonnormal populations.

The final step in a synergetic strategy would be the integration of the different levels of description. In the abstract, the dynamics at the neural level should be coupled to the dynamics at the behavioral level, and so on, regardless of the level used. For example, Kelso and Scholz (1985) have related amplifications in fluctuations at phase transitions seen in the kinematics of finger movements to similar phenomena measured at the level of muscle contractions. Such elegant mappings may be quite difficult over developmental time.

A Synergetic Approach to Locomotor Development

The onset of independent, upright locomotion – learning to walk – can be viewed as a dramatic phase shift in motor development. One day, the infant cannot walk alone, and the next day he or she toddles by herself. Traditional explanations attribute this milestone to maturational changes in an executive function such as increasing cortical or cognitive control of movement. My colleagues and I have suggested that walking alone is not so much commanded as emergent. No “walking” schema *per se* need exist; the behavior is rather the stable compression of many variables in an organism with a particular neural, anatomical, and biomechanical configuration, with certain motivations and goals, and supported on a permissive substrate. The benefit of viewing walking as a multicomponent emergent phenomenon is to open a window on how the skill is actually constructed during development.

For a synergetic strategy we must first ask: By what collective variable can we capture the compression of the degrees of freedom involved when people walk? A number of kinematic and kinetic variables might suffice. We focus on one essential characteristic of human bipedal walking: the regular, 180 degrees out-of-phase alternation of the legs needed to maintain both upright stability and forward progress. (Humans could use other symmetrical gait patterns such as hopping or galloping, but presumably they are less efficient.) When infants begin to locomote in the upright position, they use an alternating gait, although they are more variable in their phasing than in older toddlers and children (Clark et al., 1988). How do they acquire this ability? Is this a pattern that emerges with independent locomotion? What component skills do infants need to step? How does the environment support this skill?

Infants are capable of regularly alternating movements of their legs long before the onset of upright locomotion. Even in the newborn period, supine leg kicks may alternate, but the limbs appear loosely coupled. Throughout the first year, leg kicks seem to be like a weak, cyclic attractor. Alternation is a preferred, but not very stable state (Thelen, 1985).

This stability greatly increased, however, with a simple contextual manipulation. When I supported seven-month-old infants, who normally do not step, over a motorized treadmill, I saw dramatic increases not only in their step rate, but in the strictly alternating excursions of their limbs (Thelen, 1986). These treadmill steps were not simple reflexes, but dynamic and adaptive motor coordinations. Infants not only adjusted their step rate in accord with the speed of the treadmill in a manner identical to independent walkers, but also were able to compensate for extreme perturbations – one leg driven at twice the speed of the opposite leg – to maintain the right–left alternation (Thelen et al., 1987). It is unlikely that, at seven months, either the onset of stepping or the continual compensations were mediated by conscious or voluntary processes.

Figure 18.12 illustrates such leg alternation in a single eight-month-old infant girl (CH). CH's leg excursions were tracked by means of an optico-electronic motion detection system through a series of trials beginning with the treadmill belts turned off and continuing through seven more trials where the speed of the belts was gradually scaled up. The speed adjustment was made after 5 seconds in each trial except the first moving belt trial. It is easy to see where the 5-second perturbation occurred and CH's subsequent adjustment to maintain alternation. After the eighth trial, the belt was again turned off. In this second no-movement trial, CH performed some leg movements, but they were poorly coordinated. Finally, we perturbed coordination by moving one belt twice as fast as the other, but the infant still kept on walking!

Thus, the collective variable of interest is a measure of interlimb phasing – the relative coordination of one limb to another. These patterned movements represent the low-dimensional output of a system composed of many components – neurological networks, bones, joints, muscles with characteristic strength and tone, and motivational and attentional elements, including the infant's state, physiological parameters, and so on.

We may ask about the developmental course of this coordinative ability, and especially about two transitions. First, at what point in ontogeny does this neuromotor ability develop? Second, what allows coordinated upright stepping to become manifest during the last few months of the first year? Our ultimate question is, which of the essential elements in the system will serve as control parameters in effecting the development shifts?

Beverly Ulrich, my collaborator in this work, and I began our synergetic strategy with an effort to understand the dynamics of our collective variable over developmental time. We used a multiple case-study, longitudinal design by observing nine infants each month from

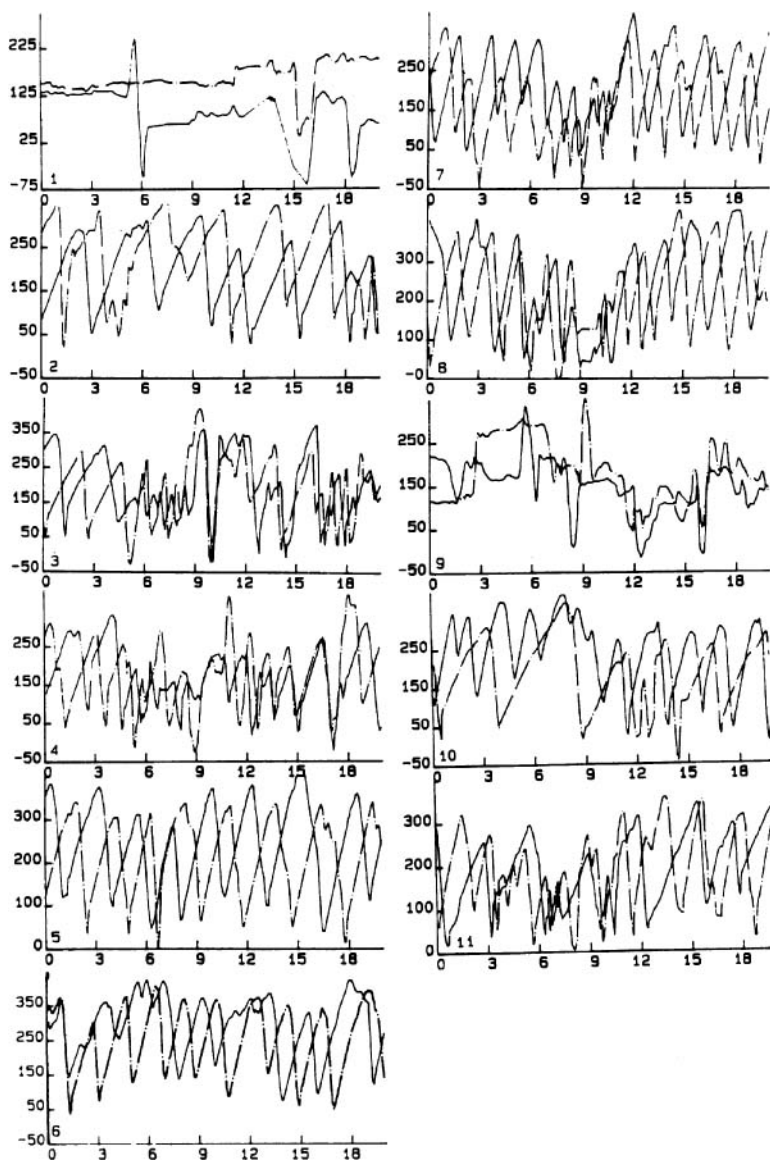


Figure 18.12 Excursions of the right and left foot of an eight-month-old girl (CH) as a function of treadmill speed condition. Trials 1 and 9 are with the belt turned off. In trials 2–8 the speed is gradually increased; the increase occurs after 5 seconds of the trial. Note CH's adjustment. Trials 10 and 11 are "split-belt" trials, where one belt is moving at twice the speed of the opposite belt. Note the continuation of alternation.

age one month until they walked independently or refused the treadmill (usually between seven and nine months). Each infant participated in two identical experimental sessions each month to assess within-age variability and to elicit optimal performance. The treadmill task is identical to the series of trials just described for infant CH, one of the subjects in the

study. In addition, we obtained Bayley scales of motor development, behavioral state assessments, and anthropometric measurements because previous research suggested that these variables affected stepping performance.

I present here some preliminary results in the single infant, CH, to illustrate the paradigm. In figure 18.13, we plot the cycle durations of alternating steps taken by infant CH as a function of age and treadmill speed trial. (Remember that trials 1 and 9 are on

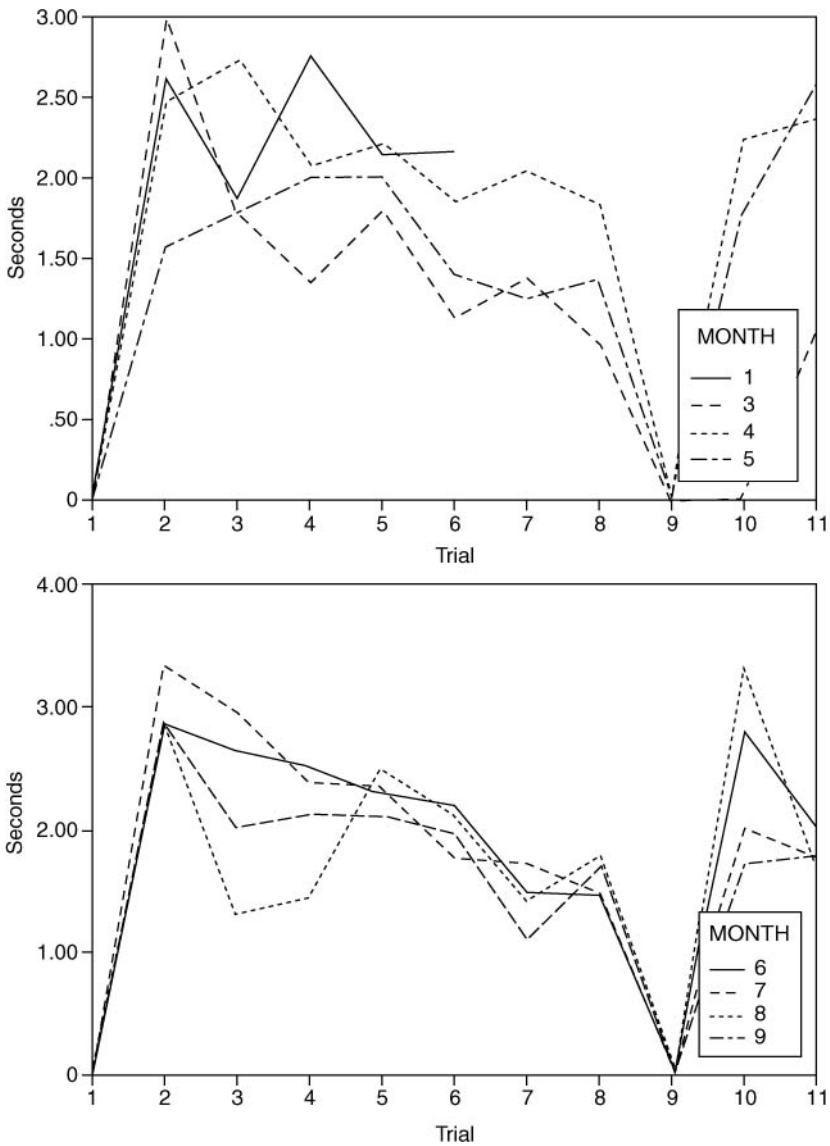


Figure 18.13 Cycle durations of alternating steps performed by CH as a function of treadmill speed. Each trace represents the “better” day of each month’s testing. Trials as in figure 18.12. Note decrease in cycle durations as belt speed increases and increased sensitivity to treadmill speed, especially in months 5–8. CH did not step at all in month 2.

stationary belts and that the belt speed was gradually increased in trials 2–8). In general, cycle duration was inversely related to belt speed, but in months 1–3, CH's performance was erratic. By month 4, however, she adjusted her steps to the belt speed, and she continued to do so, although the very fastest belt speeds sometimes appeared to inhibit performance. (We do not know whether this reflected an inability of the legs to cycle at such a high frequency or a fatigue effect, but other infants also showed this decrement at the highest speeds.)

We can also look at a more precise index of bilateral coordination, the relative phasing between the movements of each leg. In mature stepping, the step cycle of one leg is initiated at 50 percent of the cycle duration of the opposite leg (the limbs are precisely 180 degrees out-of-phase). In figure 18.14, we can see that in the early months, CH's interlimb phasing is very variable, but that it approaches the adult-like 50 percent value more consistently in the second half of the year. The coupling between the limbs becomes tighter. The other infants in our sample showed remarkably similar developmental trends.

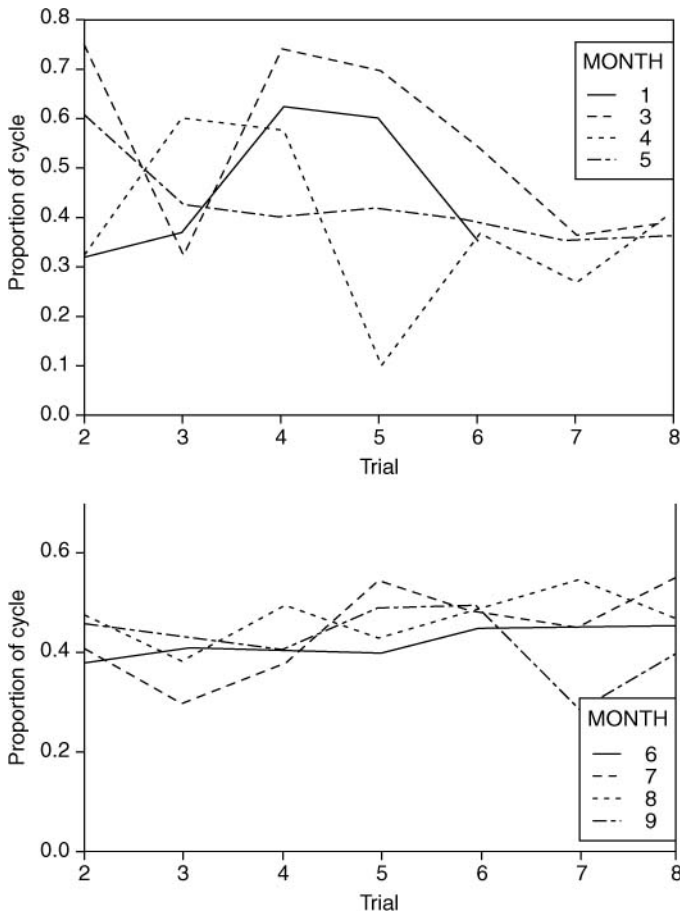


Figure 18.14 Relative phase lags between left and right foot steps in infant CH as a function of age and treadmill speed. Lags are expressed as the proportion of the step cycle of one leg when step in the opposite leg was initiated.

These descriptive data give us a picture of the dynamics of change of the ability to coordinate the two legs. Some ability, albeit rather primitive, is manifest at the first month. In CH, we saw no abrupt transitions from no stepping to fully articulated stepping on the treadmill, but rather a gradual increase in steps with age. This suggested that the basic mechanism whereby limbs respond to a backward stretch by alternating swings is in place at a very early age, but that the system is not very stable. The attractor becomes progressively stronger with age.

These results are only the first step in a synergetic strategy; an understanding of the dynamics of our collective variable over developmental time. It is an essential (but often laborious) step to identify the points of transition when the system is unstable and when the control parameter dynamics can be explored. In the case of treadmill-elicited stepping, this analysis points to the first three to four months as the period of most rapid change, reflected in instability and variability. We have some indication of a relative decrement in treadmill performance at months 1 and 2 and then a more rapid improvement. What, then, are the control parameters shifting the system at these transition times?

One source of clues is to look at the other elements of the system indexed by the anthropometric, state, and motor maturity measures. In figure 18.15, for example, we show CH's stepping performance plotted with several other anthropometric indices. The first few months are a time of especially rapid changes in the rate of weight gain, and in

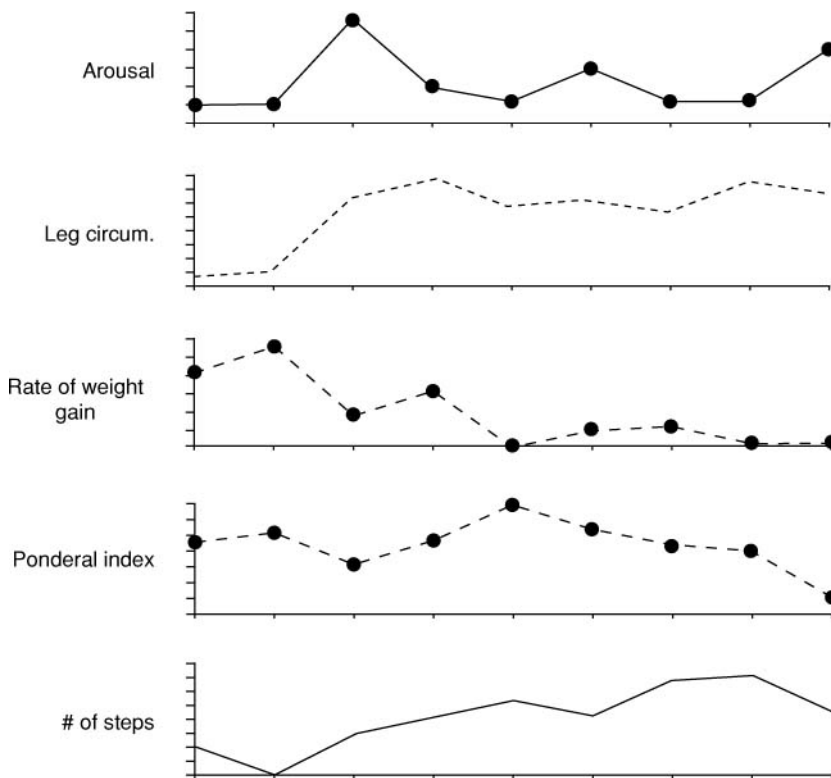


Figure 18.15 Anthropometric measures, "arousal" scale, and number of treadmill steps of infant CH from months 1 through 10. Anthropometric indices include rate of weight gain, summed circumferences of the thigh and calf, and Ponderal Index, $\text{weight}/\text{length}^3$. Note that there are rapid changes in the first four months on all variables.

measures of chubbiness and leg volume. Do these other system variables act as control parameters for treadmill stepping? Clearly, we cannot answer this question on the basis of correlational and case-study data. Many other things change very rapidly in the first few months of life that may affect this behavior. Nonetheless, this method does allow us to dissect our system to see what components are in place and what components are rapidly changing and may be candidates for control parameters. This then suggests possible experimental manipulations to test causal hypotheses.

Conclusion

In this view, ontogenetic change is the reorganization of components to meet adaptive tasks. It assigns the sources of new forms to the self-organizing properties of systems that use energy in a particular configuration. Pattern and complexity can emerge from the cooperativity of more simple elements. It says that developing systems are stable and predictable where their adaptive demands have constrained, through phylogenetic mechanisms, their range of solutions. (All mammals must suckle; at birth, the architecture of the suckling system leads to a very stable periodic attractor.) But this view also accounts for the variability and flexibility of these same systems when the task demands are not strict, or when experimental manipulations challenge the developing organisms with unique circumstances. (Suckling can also be curtailed, or prolonged, or the action patterns used for other goals, such as exploration.) Because prescriptions for action do not exist outside of the context that elicits action, components are free to assemble and reassemble within the constraints of the organism and the task. The physical and social context of the developing animal is more than just a supportive frame; it is an essential component of the assembled system. In such systems, new forms arise when the stability of the system is disrupted when random fluctuations are amplified by the scaling of a critical component. The process of developmental change is thus normally accompanied by a period of instability, where the system is exploring, so to speak, another level of stability.

A dynamic systems perspective may require new empirical strategies in which variability is the substance rather than the noise. By identifying developmental transitions, where the system may be “fooled” into progressions and regressions, we can then test the limits of the organism and the context in eliciting new forms. In reality, many developmentalists have implicitly adopted such an empirical strategy; this perspective provides a rationale consistent with pattern-formation processes in other physical and biological systems.

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Chapter Update

Systems Approaches Can Work!

This 1989 paper was the result of nearly a decade of my grappling with issues of development in light of the new theories of human movement that emerged in the early 1980s. The key moment for me was reading two chapters that appeared in a 1980 volume of otherwise conventional papers in motor behavior (Stelmach and Requin, 1980). The main authors of the papers, Peter Kugler, Scott Kelso, and Michael Turvey, were colleagues at Haskins Institute in New Haven. In these chapters, they presented an amalgam of ideas – from physiologists Bernstein and von Holst, physicists Haken, Iberall, and Prigogine, systems theorists von Bertalanffy, Pattee, and Yates, and were inspired by Turvey's work on perception from a Gibsonian perspective (Kugler, Kelso, and Turvey, 1980; Kelso, Holt, Kugler and Turvey, 1980). Despite the dense writing and the eyestrain print, I saw that these ideas of self-organization were not only a brilliant solution to the issues of motor control, but that they could also be applied to any systems that change.

Systems ideas have been around in biology and psychology for many years. What distinguished the new formulation, however, was its solid grounding in both formal theory and experimental results. Could the tenets of system theory be useful for understanding development as well, especially for bringing together theoretical ideas and rigorous empirical work? Thus, the goal of my chapter was to pose this question and to suggest some strategies to make that happen.

In the decade since the 1989 chapter, I, and others, have conducted programs of research grounded in the belief that developing organisms can be best understood as dynamic systems. The intervening time has seen a number of major books on these new ideas (Elman, Bates, Johnson, Karmiloff-Smith, Parisi, and Plunkett, 1996; Fogel, Lyra and Valsiner, 1997; Newell and Molenaar, 1998; Smith and Thelen, 1993; Thelen and Smith, 1994; Van Geert, 1994) and dynamic systems has been accepted as a major theoretical approach (e.g. Lewis, 2000, Goldhaber, 2000; Thelen and Smith, 1998). In some ways, the promise of the new theory has been fulfilled, but in other ways, more work still needs to be done.

For the purposes of this update, it is useful first to review the major principles of dynamic systems that have continued to be important in thinking about development. Then we can discuss how these principles have been implemented in empirical research and modeling.

1. *Multiple causation and self-organization.* The idea that complex living systems, with many, heterogeneous parts, produce coherent behavior in a self-organized manner, has inspired many studies and simulations. The critical point here is that in such systems, all components are important. No agents are privileged and causality is circular. What allows self-organization to happen is that such systems are “open” to the environment and thus the physical and social worlds are as important in producing behavior as the organism. In such systems, new forms can arise as a function of the relationship of the parts.

For example, in my own studies of infant motor development, I was inspired by dynamic systems ideas to measure multiple, interacting components to begin to understand system change. For instance, in a longitudinal study of the development of infant reaching, my colleagues and I recorded multiple measures from the same small sample of infants at very dense intervals. Thus, we could relate the onset of reaching and improvements in that skill to control of muscle forces (Thelen, Corbetta, Kamm, Spencer, Schneider and Zernicke, 1993; Zaal, Daigle, Gottlieb, and Thelen, 1999), the underlying patterns of muscle activation (Spencer and Thelen, 2000), and to system-wide postural reorganizations (Spencer, Vereijken, Diedrich, and Thelen, in press). Likewise, in our re-interpretation of Piaget's "A-not-B" error from a dynamic perspective, we showed that there were multiple influences on the task, including the task design, visual cue, movement and posture, and memory of previous actions (Diedrich, Thelen, Corbetta and Smith, 2000; Smith, Thelen, Titzer and McLin, 1999; Thelen, Schöner, Scheier and Smith, 2001). We have recently simulated this dynamic interplay of causality in a formal field model, generated novel predictions from the model, and then tested them empirically (Thelen, et al., 2001). To me, this work is an especially gratifying demonstration that systems approaches can work, and in particular, are able to produce a mutually informative collaboration between theory, model, and experiment.

The notions of self-organization are also predominant in another important breakthrough of the last decade, the use of connectionist models. Ellman et al. (1996) give the most comprehensive overview and rationale for these modeling techniques. In brief, connectionist models demonstrate that patterns can emerge from initially non-patterned networks through simple rules and their own repeated activity. Rumelhart and McClelland's (1986) simulation of the ontogeny of the past tense in language learning is the classic example, but recent efforts to use these networks to simulate the development of object representation are also noteworthy (Mareschal, Plunkett and Harris, 1999; Munakata, 1998; Munakata, McClelland, Johnson, and Siegler, 1997).

Finally, mention must be made of the use of dynamic principles to understand the emergent principles of social interactions. In these cases, it is not the organism and the physical environment that constitute the system, but two or more individuals communicating with one another, either adults, or adults and children. In his important work, Fogel (1993; Fogel, Lyra and Valsiner, 1997) shows by minute analysis of dyadic interactions, that such interchanges are mutually co-regulated so that the meaning of the interaction is literally constructed through the relationship.

2. *Continuity in time.* The second useful insight from the dynamic perspective is that behavior always occurs continuously in time, such that current actions are a function of events and experiences in the past, and, in turn, set the stage for actions in the future. Although this is, of course, the hallmark of development, process approaches have not always been the standard of the field. In the last decade, there has been renewed interest in time, and especially in the relationship between short (or real-time) processes (action and learning) and changes over a developmental time scale.

One consequence is more attention to longitudinal studies, often using small sample sizes, but with a dense sampling schedule that enables the researcher to determine the pathways of change. I feel no small satisfaction, for example, to have two of our longitudinal studies of infant reaching, based on only four participants, published in one of the premier journals of experimental psychology, *Journal of Experimental Psychology: Human Perception and Performance!* What such designs relinquish in generalizability, they gain in detailed insight of process.

A second new focus on process consistent with a dynamic approach is termed *microgenesis* (Granott and Parziale, in press; Siegler and Jenkins, 1989). Microgenetic studies focus on transitions, and especially in identifying and manipulating experimentally variables that may be critical for developmental change. Many microgenetic studies involve training children in particular tasks to accelerate skills in a certain domain. For instance, Siegler and Jenkins (1989) showed that practice in particular, more efficient strategies for learning arithmetic helped children whose strategies were less mature.

3. *Nonlinearity.* There has been a remarkable attention in the last decade to the presence of nonlinearity in development. In dynamic systems, small changes in one or more components can have large, and cascading effects. This means that processes that are continuous can show what appear to be startling discontinuities. Indeed the differences in the initial differences may be so small, that the direction of these changes may not be knowable, resulting in a natural indeterminacy in developing systems (Fogel, Lyra, and Valsiner, 1997).

The most important theoretical work in this area has been by Paul van Geert (1994), who uses a particular kind of mathematical dynamic system (logistic equations) to model non-linear growth. Again, using only simple growth rules as initial conditions, van Geert's models produce complex, stage-like developmental profiles, fluctuations, and periods of exuberant growth and plateaus, much like real developmental data. Van Geert's efforts have been mainly directed to simulating patterns of language development (largely because of the rich corpus of dense longitudinal data in this domain), but others have used similar dynamic equations to model brain growth (Fischer and Rose, 1994; Thatcher, 1998), and interpersonal dynamics (Newton, 1998).

4. *Transitions and variability.* Related to both the issues of nonlinearity and microgenesis, dynamic systems approaches have also highlighted the importance of transitions and variability as a window for understanding change. For example, in longitudinal studies of treadmill stepping (Thelen and Ulrich, 1991) and reaching (Thelen, Corbetta, and Spencer, 1996) we have identified times when behavior undergoes transitions and when it is stable by looking at the variability. Dynamic systems predicts that behavior that is relatively less variable will be less likely to be perturbed or changed by an intervention, indicating that the system has found a relatively stable attractor state. Thus, Vereijken and Thelen (1997) found that infants were more likely to benefit from training in treadmill stepping when their movement patterns were highly variable than when the patterns were stable.

In dynamic systems thinking, variability is the key to change because when system components are too tightly coupled, the intrinsic noise inherent in any biological system is damped down. Conversely, when the components are more loosely coupled, the system is more flexibly able to adapt to changes in the organism or in the environment. Lampl and Johnson (1998) provide a beautiful demonstration of the dynamics of developing complex biological systems in their models of human growth. By extremely careful measurements, they show that growth of fetuses, infants, and children is not linear, but occurs in spurts and plateaus. In infants, for instance, growth occurs in pulses of between 0.5 and 1.6 cm in 24 hours and then 2 to 63 days with no detectable growth. They claim that these growth dynamics are the natural result of "the output of complex, interrelated underlying processes that combine both endogenous signals and the physiological effects of the organism's interaction with environmental input" (p. 30). Indeed they see this dynamic pattern as a measure of a "robust and flexible" system "in which network and external forces substantially influence component behavior." "Variability in the amplitude

and frequency of discrete events a mechanism providing pathway divergence for the attainment of reproductive adulthood amidst highly variable environmental circumstances” (p. 31).

Have they worked? I think the answer to the question I posed in 1989 is a loud “Yes.” We have seen the ideas of dynamic systems more widely accepted over the last decade and making an entry to nearly all domains of developmental study. But there is still much work to be done before we have shown conclusively that a dynamic approach is the most powerful way to conceptualize development. First, I believe that the qualitative appeal of the theory and the abstract models from it have themselves progressed faster than the empirical applications. In other words, many developmentalists like the ideas of dynamic systems but do not know what to do with them in their research. This has not changed much since 1989. Collecting appropriate time-based and intensive sets of data is very difficult, especially when compared to cross-sectional experiments. We are still developing appropriate statistical tools to deal with time-series data and to look at intensive single-subject design. On the modeling side, theorists are creating increasingly sophisticated mathematical models (e.g. Newell and Molenaar, 1998), but there are fewer examples where the models do more than fit curves of existing data. Dynamic models are very powerful. What is needed is more work where models make unique predictions that can be tested against new experiments.

One strength of a dynamic approach is to unite dynamics across time scales and across levels. This also should be on our future agenda. How do brain and behavior dynamics intersect in real or developmental time (c.f. Fischer and Rose, 1994; Thatcher, 1998)? What about the coupled interactions of perception, action, and cognition (cf. Thelen et al., 2001)? I believe studies asking such questions will prove the key to future progress using a dynamic approach.

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