The central thesis of this paper is that grand theories of development are alive and well and should be paramount to those interested in behavioral intervention. Why? Because how we think about development affects how we approach treatment. Here I discuss the central concepts of a new theory of development—dynamic systems theory—to highlight the way in which a theory can dramatically alter views of what intervention is all about. Rather than focusing on one root of maladaptive behavior such as biological predispositions, environmental causes, or motivational states, dynamic systems theory presents a flexible, time-dependent, and emergent view of behavioral change. I illustrate this new view with a case study on how infants develop the motivation to reach for objects. This example highlights the complex day-by-day and week-by-week emergence of new skills. Although such complexity presents daunting challenges for intervention, it also offers hope by emphasizing that there are multiple pathways toward change.

The Role of Theory

In 1996, The Journal Psychological Science devoted a special issue to commemorate the centennial of Jean Piaget’s birth. Developmental psychologists have been sniping away at Piaget for many years,

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and some have declared his massive and eloquent theory as dead. In that issue, Alison Gopnik (1996, p. 221) wrote that the search for a grand developmental theory is, indeed, futile. We are better off, she advised, working out the details domain by domain: a theory of language, a theory of numerosity, a theory of mind, a theory of attachment, and so on. The traditional big issues of developmental theory—nature versus nurture, continuity and discontinuity, modularity versus distributed processes—should be cast aside in favor of the specifics of content.

I beg to disagree. We surely need the details of content, but we also need the big picture. We need to grapple with the hard issues at the core of human change. We must not scuttle the past masters—Freud, Piaget, Erikson, Bowlby—who were likely wrong in some of the details and perhaps in some of their assumptions. Rather, we must use as models their bold visions to probe deeply into the mystery and complexities of human development and to articulate general principles that give meaning to so many details.

Why does theory matter at all? Why do we still need to think of development on this grand scale? For those involved in intervention for change, there are two important reasons. First, and most obvious, is that assumptions about the nature of development profoundly affect how one treats children and how one interprets childhood. A good example is the radical change in views of the etiology of childhood autism. As is well known, children with this diagnosis have profound difficulties with normal social relationships. They are often unable to participate in the language and nonverbal aspects of normal social dialogue, seem obsessively self-absorbed or focused on inanimate objects, and display socially inappropriate behavior. Several decades ago, it was widely believed that mothers’ cold and rejecting behavior was the source of children’s autism (Bettelheim, 1972). Implicit in this view was the notion that the early emotional environment is so critical that it can produce permanent damage. Such an interpretation was consistent both with the then-dominant Freudian tenet of the central importance of the relationship to the mother and with the prevailing behaviorist assumptions about the preeminence of the environment in shaping change.

The theoretical landscape has changed. Today, one well-accepted theory about children with autism is that they are born lacking a particular module in their brains, the part responsible for developing
a “theory of mind” (Baron-Cohen, 1995). A theory of mind is an ability to understand how another person thinks, and a theory-of-mind module is a dedicated brain structure used for this purpose. The theoretical assumption here is that social behavior has a strong innate component and that the environment is not as critical. Children lacking this biological prerequisite are fated by nature.

These assumptions about development matter. When mothers were deemed responsible, therapists removed children from their homes. As a Freudian, Bettleheim sought to undo the damaging relationship with the mother by substituting a more emotionally supportive environment. Behaviorists also treat children by altering the environment, in this case, by changing the structure of rewards and punishments. Alternatively, if a therapist believes that the core problem is a missing brain module, he or she might choose an intervention focused only on that aspect of the child’s behavior or perhaps may decide that such a brain lesion means that no intervention is possible. Parents and friends may likewise decide that the person with autism is so deficient in social understanding that such a child cannot benefit from normal discourse. In short, how one views the etiology of a disorder—and one’s implicit or explicit theories of development—can profoundly alter how one treats a child.

Developmental theory also determines how a therapist invokes and uses childhood memories. Experimental psychologists have decades of studies showing that memory is fragile, elusive, and mutable. In particular, memories of events before the age of three or four years are seemingly lost completely, as explicit autobiographical narrative appears to require the consolidation of language (Fivush, 1998). Given the shaky and incomplete ability to recall one’s early childhood, whole systems of therapeutic intervention dispense with it altogether. Cognitive and behavioral therapists, with an implicit assumption of developmental discontinuity, deal with behavior in the here-and-now. Why try to raise implausible and perhaps faulty history? People can change by altering their current environments or the nature of their thinking.

Therapies in the tradition of Freud, of course, are grounded in strong continuity assumptions. Not only do such therapists believe that early events have lifelong consequences, they also assume that such events can be coaxed into consciousness and that the process of doing so will have beneficial consequences. In this tradition, Fogel (2003) has
written eloquently about the embodied and retrievable nature of early memories. Fogel argues that early memories are of a particular kind—participatory memories—that are the experience of reliving or reenacting the past. These memories are built from infants’ social relationships and contain the bodily memories of emotional reactions and self-action. Thus, they are largely inaccessible through language alone but may be tapped through reexperiencing their bodily content. In sum, the raging debate about the existence of early repressed memories and how they will be used is an issue of developmental assumptions.

The second reason why developmental theory is important for therapists is that therapeutic intervention itself is a developmental process. Development is change, and it happens at all ages and on every time scale. We seek general mechanisms of behavioral change. Why do humans, at some ages and under some circumstances, make rapid and easy adjustments to their environments but, at other times, seem “stuck”? Where do such novel behaviors originate, and how are they incorporated into the behavioral repertoire? How do complexity and integration emerge? How do social partners, or therapists, contribute to behavioral change? How can we identify the times of transition so that we may best intervene?

A Dynamic Systems Approach to Development

For many years, I have found the general principles of dynamic systems theory to be a useful and comprehensive way to conceptualize change at many levels and at different time scales. When we think about development, we usually imagine changes over months and years. But I am equally interested in changes that happen over shorter time scales, such as when someone produces a novel action, or when over the course of a day, a baby takes his or her first steps. Most important, I am concerned with how these different time scales of change interact. How do everyday second-by-second activities create and influence changes over a longer time span? This is an issue that impacts intervention directly. Any intervention is based on the premise that activities in the here-and-now will effect long-term change. Thus, a useful developmental theory must account not just for the final outcome of development, but also for the mechanisms that engender change.
Likewise, a good developmental theory must encompass all outcomes, individual and atypical as well as universal and typical. The basic principles of development apply in every case, although the initial conditions may be different and environments may vary greatly. In particular, I see nonoptimal outcomes as arising from the same system dynamics that produce more adaptive patterns. A dynamic systems theory addresses the issues of both mechanism and outcome.

A Metaphor

All theories are metaphoric; metaphors help us make the bridge from the theory to the phenomenon. A dominant metaphor in cognitive science is that the mind is like a computer, a characterization that evokes images of machines, programs, and interchangeable parts.

I suggest another metaphor for human behavior: a mountain stream. This is an apt comparison to keep in mind, because a stream is moving all the time in continuous flow and continuous change. Development is continuous—whatever has happened in the past influences what happens in the future. But the stream also has patterns. We can see whirlpools, eddies, and waterfalls, places where the water is moving rapidly and places where it is still. Like the stream, development also has recognizable patterns: milestones and plateaus and ages and stages at which behavior is quite predictable. In the mountain stream, there are no programs or instructions constructing those patterns. There is just water and the streambed under it. The patterns arise from the water and natural parts of the stream and the environment, such as the streambed, the rocks, the flow of the water, the current temperature and wind. The patterns reflect not just the immediate conditions of the stream, however; they also reflect the history of the whole system, including the snowfall on the mountain last winter, the conditions on the mountain last summer, and indeed the entire geological history of the region, which determined the incline of the stream and its path through the mountain. In addition, the stream also carves the rocks and the soil and creates its own environment, which then constrains and directs the water. It is not possible to say what directly causes what, because the whole system is so mutually embedded and interdependent.

Development also has these system properties. How a child behaves depends not only on the immediate current situation but also on his
or her continuous short- and longer-term history of acting, the social situation, and the biological constraints he or she was born with. Every action has within it the traces of previous behavior. The child’s behavior, in turn, sculpts his or her environment, creating new opportunities and constraints. The critical question to ask, therefore, is how dominant and strong are the old patterns and how do they interact with the new situation. How stable are they, how resistant to change? How open is the system to respond to new inputs?

There is another way in which development is like a mountain stream. Depending on the conditions of the stream, similar actions may have very different results. Thus, if I throw a rock into a deep pool, the pool may be disturbed by ripples for a short time, but it will remain largely unchanged. The same rock tossed into a shallow part may divert the stream completely, with consequences downstream.

Developmental patterns also show this kind of nonlinearity. It is difficult, maybe impossible, to predict the outcome of the process for any child in any particular situation. Sometimes chance events have large consequences; at other times, they have little impact. The same event in the family or the school may have vastly different effects. Some children are resilient in what seem to be very damaging environments, whereas others grow up with problems despite privileged backgrounds. A theory must be able to handle both the predictable aspects of development and those that surprise us.

Three Principles of Dynamic Systems Theory

A dynamic approach to development is based on more general theories governing pattern formation in complex physical and biological systems (Thelen and Ulrich, 1991; Smith and Thelen, 1993; Thelen and Smith, 1994; Kelso, 1995; Port and van Gelder, 1995; Gottman and Murray, 2003). The science of these complex systems has gained popularity under the name chaos theory. It is based on the notion that under certain thermodynamic conditions, collections of many (often heterogeneous) parts appear to self-organize to produce ordered patterns without any particular part having a code or recipe for the pattern. Common examples range from clouds (fluid flow systems) to communities of one-celled organisms through elaborate ecosystems and social systems. Nothing gives directions, yet the whole system has an order over time.
A commonplace example is heating a pot of water. When there is no added heat, the molecules move in random ways and the water seems still and homogeneous. As the heat increases under the pot, the water undergoes several transformations of pattern, from small bubbles, to large bubbles, to large rolling coils. How do the molecules cooperate? They act not from directions, but from constraints: the size and shape of the pot, the energy, the nature of the molecules themselves. Likewise, elaborate constructions of insects such as beehives and termite mounds have nowhere a blueprint of their design. Rather, they arise from cooperative effects of very simple behaviors from the individual insects (Kugler and Turvey, 1987).

New systems of mathematics have been developed to describe the behavior of such complex systems. (Gottman and Murray, 2003, give an excellent tutorial.) They are nonlinear in the sense that, depending on the conditions, large changes in the system may be generated by small differences, and they are dynamic in the sense that they are continuous in time.

**Complexity**

The first useful principle from the science of complex systems is the notion of complexity itself. Human behavior, whether mental activity or overt movement, is the product of many interacting parts that work together to produce a coherent pattern under particular task, social, and environmental constraints. Every behavior is the condensation of these heterogeneous components. For instance, when I walk across the room, you could describe my behavior rather well with only a few variables, perhaps the relationships of phasing of my legs and arms. Yet those relatively few variables contain highly complex physiological, mental, and metabolic processes interacting with the surface of the floor, the ambient light, and so on. All of the components are co-equal in producing the behavior. Just as my gait may change if I develop arthritis in my knee, so also it must change if the floor is highly polished and slippery.

This idea that everything counts in producing behavior has profound implications for our conceptualization of developmental causality. In particular, we must reconsider any single-cause explanation, be it organic or environmental, and instead focus on interactions and entertain the possibility that the interactions are nonlinear. This means that it may not be easy to find a clear causal chain from previous
conditions to later outcome and that the contributions to that outcome may be unexpected.

I am particularly interested in the contributions of embodied processes: perception, movement, and their emotional accompaniments in the production and development of behavior. Humans perceive and move continually during every waking minute, and much of this has an emotional valence. Yet, in many purely cognitive accounts, the roles of perception, emotion, and especially movement are considered secondary to mental activities. But according to the principles of dynamics, mental activities not only are founded in emotion, perception, and action but also are part of the causal web of behavior throughout life. Moreover, I suggest that even small difficulties with these processes early in life can have lifelong consequences.

**Continuity in Time**
Second, patterns that self-organize from multiple components can be complex, but they are always continuous in time. In the language of complexity theory, *dynamic* means that the state of the system at any time depends on its previous states and is the starting point for future states. Continuity of process applies to components at many different levels of organization, ranging from ion channels in cell membranes, through network properties of populations of neurons, through time scales of synaptic change and consolidation, and into longer-term development. The critical point is that processes occurring on these different time scales are completely nested in one another as well as being coupled to one another. The critical issue for development, as I mentioned earlier, is to understand how activity on short time scales, say on the order of milliseconds, cascades into the behavioral changes in which we are interested. It may be, for example, that we cannot draw a line and call one process learning, another development, and still another a therapeutic intervention; it is all change over time.

**Dynamic Stability**
The third principle of dynamic systems that is important for development is the concept of *dynamic stability*. When complex systems organize into patterns, the patterns may have different degrees of stability and flexibility. Some human behavior is so stable and reliable
that we are tempted to say that it is programmed. For example, all
human children who are not seriously damaged learn to walk and to
speak a language. Some have argued that, because of their universality,
both walking and language are genetically or developmentally
programmed. From a dynamic systems point of view, the issue is not
whether a behavior is hardwired or learned so much as understanding
its stability. Walking and speaking are so constrained by human
structure and social systems as to be highly stable behavior patterns.

But stability does not mean immutability. Even in highly practiced
actions, stability is dynamic. Patterns are assembled and maintained
“softly,” on line and in response to the context (Kugler and Turvey,
1987). Because they are the confluence of many components, they
also can be flexible, to shift and rearrange as befits the situation. For
example, I can walk across the room wearing high-heeled shoes, with
a brace on my leg, and while carrying on a conversation. Walking is
resistant to many perturbations in me or in my environment. On the
other hand, I could tap-dance across the room, but it would not be a
very stable behavior. I would have to concentrate, and I certainly could
not do it with a brace or while talking. I would need to practice every
day to maintain the steps, and if I were to hear the fire alarm while
tapping I would quickly revert to my more stable form of locomotion.
The old, practiced behavior would be rapidly assembled, and walking
would dominate the novel pattern.

I see development as this process of assembling patterns of behavior
to meet demands of the task in the biological possibilities of the child
at that time. Sometimes the behaviors are stable for a time—they are
easily elicited and frequently performed. Then other behaviors emerge,
and the old ones become less available or less preferred. In this sense,
children are always problem solving, using what they have to perform
actions that are intrinsically rewarding or pleasurable for them.
Development is thus the product of the child’s everyday and continual
efforts to make things happen in the world.

Consider the behavior of crawling on hands and knees. In the classic
views of motor development, crawling is seen as an important
developmental stage in the progression to upright locomotion, a stage
that reflects the maturation of the voluntary centers of the brain over

1 “Softly assembled” is a term from nonlinear dynamic systems theory designed to
describe the fluid, contingent process of structure building.
the spinal and subcortical areas (McGraw, 1945); some theorists have even imagined crawling as an ontogenetic throwback to our quadrupedal ancestors. In a dynamic view, crawling is an online solution that babies discover when they lack the balance control and strength needed for upright walking but want to get to something that they cannot reach. It is an opportunistic assembly of the components that results in a temporarily stable and useful pattern. For many months, it becomes infants’ preferred mode of self-transport. Infants often begin crawling by using a variety of patterns of limb coordination, but each soon settles on his or her own mode, which is usually an alternating pattern among the four limbs. Some infants, however, find and implement a combat crawl, using hands, feet, and the belly, or they scoot on their bottoms, whereas others maintain an idiosyncratic asymmetric gait. Each infant, through trial and error, discovers his or her own pattern, depending on the environment (carpet? smooth floor?), body size, and to some degree by chance solutions. Often, an infant settles on a good-enough pattern and sticks with it, even though it doesn’t look like the textbook way of moving.

As infants gain experience in the balance of standing alone and shifting their weight, they venture to step forward, and the preferred mode of transport shifts to walking. When babies are new walkers, however, it is common to see them revert to crawling when the surface is unfamiliar or when they want to move quickly to get a desired toy. The crawling pattern does not disappear—indeed, adults may choose to crawl under certain circumstances—but it is supplanted by the more efficient upright mode.

It is a tenet of dynamic systems that they must lose stability to shift from one stable mode to another (attractor states). When patterns are very stable, there are no opportunities to explore and reassemble new solutions. Indeed, maladaptive behavior is usually the result of excessive stability. People may move, or reason, or base their social interactions on rigid patterns—patterns that may have worked in the past but are now not appropriate for new situations. Problem solving is limited by the lack of new softly assembled possibilities. One critical issue, then, is what both engenders the stabilities of the system and leads to instability. Just as systems are composed of many elements, both internal and external, they may be destabilized by a variety of means. Sometimes the coherence of a pattern is threatened by a new input, as when a crawling infant discovers that coffee tables facilitate...
pulling to stand. But instability may also come from organic changes in the person: changes of chemical balance or growth or aging. The goal of both developmental research and therapeutic intervention, then, is to describe patterns, characterize their stability, and ask what parts of the person or the environment can or do engender the loss of old patterns and the discovery and maintenance of new ones. Such a formulation suggests that there may be many routes to such change. In development, and in therapy, multiple pathways may lead to adaptive outcomes.

A Developmental Cascade

Taken together, these dynamic principles highlight the deeply epigenetic nature of change. By epigenetic, I mean "one thing follows another": development happens not because of either a genetic program or imperatives from the environment, but by a seamless interweaving of events in time, both internal and external. As development moves forward, the system (like a mountain stream) is never in the same place twice. Its state at the present is inseparable from all the states it has occupied in the past, yet it is also different from them. Time’s arrow never goes backward, so it is impossible to truly re-create an earlier state. Memories of childhood are reconstituted through the current state of the adult, and reversions to childlike behavior in the aged are only convergent solutions. Elderly people walk like toddlers—with a shuffling gait, taking small steps—not because they have disinhibited an earlier ontogenetic stage, but because both very young and very old have discovered a common solution to threats to balance and stability. Again, because the system is multidetermined, surface similarities may be emergent from different underlying processes.

Initial Conditions and Nonlinear Change

As I said earlier, dynamic systems can produce novelty and complexity from interactions of components without having the outcome specified ahead of time in a programmed fashion. Once the developmental cascade begins at conception, each state in time is the initial condition for the next instant of time. Nonetheless, it is of great importance to know what the initial conditions are at birth, and thus what constitutes the starting points of development. Some developmental psychologists
assign elaborate mental structures as part of the genetic blueprint: modules dedicated to knowledge of objects and events, numerosity, faces, and language (Spelke and Newport, 1998). Psychoanalytic theory builds in drives, instincts, needs, and motivations that compel individuals toward their satisfaction. Ethological theory likewise starts with specific instinctual patterns for social and nonsocial behavior. Even behaviorists—the ultimate environmentalists—believe animals are born with learning rules that structure their interactions with the world.

We know that, for patterns to form in a self-organizing manner, there must be at least minimal organization in the initial state, some small node or perturbation in the homogeneous field around which the cascade can organize. For example, there is considerable structure in the fertilized egg, not just in the DNA, but also as gradients in the cell itself. These gradients are essential for the large morphogenetic changes that occur in the first days of life. The genetic program itself is not sufficient; it is only in the interactions between nucleus and cell structure that development proceeds (Edelman, 1988).

I have found it useful to think about the initial conditions at birth as an exercise in parsimony: how little needs to be specifically built in to start the developmental cascade? How much complexity can arise from the developmental process itself, as one event follows another? Oyama, Griffiths, and Gray (2001) call these the “cycles of contingency,” because the ensemble literally creates itself through reiterative activity.

**Learning to Reach**

As an illustration, I offer a story about an important developmental transition: infants’ learning to reach and grab objects. Reaching is an emergent behavior in the sense that it appears from precursors that are not reaching. Reaching allows infants to actively acquire objects and to contact people and pets, opens up new possibilities for exploration and manipulation, and initiates the enormously variable and skilled uses of the hands in human activity. Babies reach and grab things at about four months of age, although there is considerable variation. How do they assemble the components of this behavior? How much of the skill is somehow prefigured, and how much is actively
constructed from much more simple beginnings? The task here is to make the minimum assumptions and let development do the work. The stakes are to show how complex developmental outcome can arise in such a cascade.

I focus specifically on one component of this transition, the motivation to reach and grab an object. The question is important but is seldom addressed in developmental psychology. What impels an infant or child to gain new skills? Are newborns endowed with modules and programs (for reaching, crawling, and talking) that are waiting for the maturational signal to unfold? Or does each newly emergent skill prepare the motivational field for the next, one step at a time? If so, can we understand the mechanisms that produce these changes?

Some developmental psychologists lean toward the prefigured account. For instance, Trevarthen (1984) described visually elicited smooth arm-extension movements in newborn infants, using the term prereaching. At about the same time, von Hofsten's (1982) careful and pioneering studies demonstrated similar movements—infrequent and unsuccessful but apparently well-aimed reachinglike movements in newborn and very young infants. Both authors report that these early movements decline in frequency, to be replaced some months later by the familiar, clumsy first attempts at reaching. As Trevarthen put it, “Infants are born with a considerable part of the neural structures that will coordinate these functional patterns . . . in adults” (p. 247). Development, in this view, consists of refining and remodeling patterns that are already there. Both Trevarthen and von Hofsten propose a major neural reorganization at about four months whereby cortical centers become functional and coordination between the more cortical control of grasping and the subcortical innate connections is established.

What then is the status of these early prereaching movements that are subsequently lost? Are they truly continuous with later behavior? If so, what makes them disappear and then reappear? Does the infant want to reach right from the start but simply lack the motor control to do so? How is the behavior actually linked to the motivation? “Neural remodeling” is a vacuous phrase, with no content and no mechanism proposed. A more parsimonious explanation of these rare, early arm extensions is that the infant is simply aroused by the sight of an interesting object and stiffens the limbs. If the head is directed to the object, by chance, so will the arm be. In any developmental story, simply attaching names to behavior does not necessarily explain it.
Loosely defined constructs abound in psychological explanation, but they do little real work in telling us about mechanism.

I propose an empirically plausible mechanism for a motivational cascade: starting simply and letting one thing follow another. My version is close to that of Piaget (1952), who spends a considerable portion of his Origins of Intelligence providing rich descriptions of the construction of reaching skill in his own children. Piaget’s account is dynamic and epigenetic, and it should be required reading for every student of development. According to Piaget, visually elicited reaching and grasping evolve gradually from the progressive modification and melding of several more elementary schema, especially the schema for visually interesting objects, vision (and feel) of the hand, and the reflexes of grasping and sucking. As is well known, Piaget believed that with each repetition, a schema changes by assimilating the environment, and that this progressing activity leads to change in the schemata, the process of accommodation. The critical, rate-limiting step is the integration of the sight of the object and the sight of the grasping hand. In Piaget’s account, this coordination is acquired as infants first link these two visual components of reaching by chance encounter of hand and object in the visual field. Then, by repetition, infants succeed in getting the hand and eye schemata together. Thus, Piaget's position is essentially constructionist; that is, he views the process as one of putting a skill together from initially independent parts.

**The Task of Learning to Reach**

Although I am addressing in detail only one aspect of learning to reach—the motivation to do so—it is important to note that motivation is just one part of an ensemble of components that must coalesce for the behavior to appear. I argue that the motivational cascade is nourished by infants’ successful encounters with the world, so that as infants gain strength and solve issues of motor control, their movements fulfill their intentions more often, and their motivation to move again increases. Thus, desire to move in this instant of time depends on all of the factors that have contributed to success in the previous instances of time. For reaching, the list of requirements is long and formidable:

(1) Infants must have some motivation to obtain an object in the world around them. We know that this is normally provided by
vision; babies universally visually fixate on objects before reaching for them. Blind infants with normal motor functions are severely delayed in this milestone because they are denied the usual visual motivation (Fraiberg, 1977). The issue of motivation is primary.

(2) Infants must thus have the **visual capacity** to detect and localize a graspable object in reachable space. If the baby cannot accurately see the target, he or she cannot control movements toward it (see review in Kellman and Arterberry, 1998).

(3) Infants must have, or must soon learn, what objects afford reaching and grasping and what constitutes a reachable space, that is, what they can successfully obtain by extending their arms or by moving arms and torso (Bruner and Koslowski, 1972; Field, 1977). This requirement is related to the previous two.

(4) Infants must have some means by which to transduce the coordinates of the object in external, Cartesian space into a frame of reference suitable to moving the arm on the shoulder, which must be internally referenced (e.g., Flanders, Tillery, and Soechting, 1992).

(5) Infants must have some (even rudimentary) ability to **plan** their movements before executing them. This requires recognizing what muscle activations and what forces move the limbs into what positions in space, before moving them. Otherwise, movements will be badly misdirected right from the start and will require large corrections (von Hofsten, 1993).

(6) Infants must have some—perhaps also rather crude—ability to **correct movements on the basis of sensory feedback once they are executed.** No movement is ever planned in an entirely feed-forward manner. We know that adults, children, and even older infants have a good ability to rapidly correct reach trajectories on line, on the basis of visual or proprioceptive feedback (see, for example, Desmurget et al., 1995).

(7) Infants must have enough **control of their muscles** to actually lift an arm against gravity and keep it sufficiently stable while the hand moves forward and the object is grasped. This is a biomechanically extremely complex task and indeed an engineering nightmare. Muscles and tendons are highly nonlinear—that is, they have very different properties depending on how much they are currently stretched and how
fast they are stretching. Moreover, because the arm is a linked segment, forces delivered to one segment are transmitted to the other segments (Hollerbach and Flash, 1982). Thus, the arm must be stabilized to avoid the problem of the marionette—pulling only one string activates the whole puppet, and not always in desired ways.

(8) Infants must also stabilize their heads and trunks so that when an arm is lifted, the reactive forces generated do not cause slumping over because of the linked segments, as just noted. These processes are sometimes called anticipatory postural reactions because such adjustments are often done before the focal movement begins. In reality, they may be planned and executed as part of a single movement synergy (Savelsbergh and van der Kamp, 1993).

(9) Infants must have some ability to remember an action just performed in relation to success in obtaining the goal. This is critical for any improvement to take place. The networks underlying more successful and less effortful movements should be competitively strengthened in comparison with others that are less efficient (Sporns and Edelman, 1993).

Thus, the emergence of even that first awkward and inaccurate reach requires the cooperative interactions of every part of the infant’s body and nervous system.

A Dynamic Account

A common theme among previous accounts of reach emergence is that infants come into the world with some existing organization that facilitates the developmental cascade. The nature of the preorganization is debated—Piaget believed in “reflexes,” and others talk of “amodal matching of hand and eye.” But all agree that something is there beforehand, whether or not it actually looks like reaching. It is useful to recast these classic issues in the terms of dynamic systems. What patterns of behavior are stable and easily elicited at birth? What destabilizes these patterns? What new patterns emerge? This way, we need not look for continuity of form—the elements that coalesce to produce reaching need not look like reaching to begin with. Nor do we need to propose any sort of
hardwiring. Rather, we look for patterns that may assemble under some circumstances and dissolve under others. In particular, I suggest that the stable perinatal patterns work to establish a motivational matrix that allows reaching to truly self-organize from other nonreaching components.

Motivation: A Dynamic Cascade
The main question I address in this article is why reach at all? Learning to reach is hard work. What keeps infants trying, despite many unsuccessful efforts? Do they need a reach icon or a drive to reach genetically stamped in their brains to motivate this behavior? The question is important because in most, if not all, psychodynamic theories, humans behave as they do because they are fulfilling basic, genetically organized drives. The drives are filled with content: sex, aggression, attachment, safety (Ghent, 2002). They are assumptions about the initial state and about continuity. Yet all are conspicuously lacking in mechanism. What does the module or disposition for aggression look like in a newborn infant? How does it play out in the everyday experience of the child and his or her social and physical world? Are these emotional drives different in kind from the drive to perform ordinary skills? In short, do we need one developmental theory or many?

This is a critical issue in the study of mind and behavior. In drive theory as well as in conventional views of cognition, the content of mental states is envisioned as existing separately from the real-time mechanisms that produce behavior. In this view, persons have knowledge, beliefs, drives, concepts, and ideas that exist in disembodied, pure, and Platonic form. And like little operators in the head, the ideas or drives are seen as causing behavior. But there is a profound problem with linking presumptive mental states to the messy, often irrational, inconsistent, context-bound, and embodied realities of everyday behavior.

The point of the dynamic view is to show how knowledge and motivation arise in a dynamic cascade from the start as infants begin problem-solving to gain the ordinary skills of life. In other words, knowledge and motivation are emergent with perceiving and acting in the world and stay tied to them throughout life. Every act in every moment is the emergent product of context and history, and no component has causal priority. I use the example of reaching to show how this might happen.
Following Piaget, we can now construct a story in which reaching emerges from very simple, nonreaching precursors. Following Edelman (1987) and others, I suggest that what is necessary are rather general, biologically plausible, and quite nonspecific biases in the system, or to use Edelman’s term, “value.” Value means that certain neural connections, when activated, are intrinsically favored and their activation strengths are increased. We know from many neural net simulations that systems need such biases to reach a stable solution—biases either present in the initial connections or acquired through differential input. For example, the autonomous robot built by Almássy, Edelman, and Sporns (1998) learned to visually discriminate between real-world objects with different patterns (blobs and stripes). Initially, these objects differed to the robot only in their value—some “tasted” good and others were aversive. By repeated and varied movements, however, the robot came to recognize the favored objects by vision alone. It appeared to develop the motivation to seek objects with a particular pattern. Thus, we endow the system with a strong hedonic content attached to some plausible biology, plausible in the sense that these values have unarguable adaptive use for the individual.

In the same way, motivation to reach can emerge dynamically from a system with a few simple biases, values, and linkages. Here are my candidates for what starts this cascade in human infants.

Looking
First, infants come with a bias to look at visually complex parts of the environment. Using Piaget’s term, interesting sights act as “aliments” to the vision schema, and they are actively sought by babies. Since the groundbreaking work of Fanz (1958, 1963), it is well established that an infant’s attention is captured by high-contrast patterns and moderately complex stimuli, including faces and bull’s-eyes, and that this bias can be detected, however painstakingly, in newborns. Preference for complexity increases with age, although there is likely an optimal range that maximizes attentiveness. Babies like to look at interesting visual displays. This can be realized by a visual system that seeks contrast and pattern and prefers it over a less structured input. Moreover, we know that after looking for a while, infants habituate to visual stimuli, disengage, and seek new visual input. This process can be accomplished with relatively simple activation-inhibition dynamics (Schöner and Thelen, in press). Even when stimuli are very simple and devoid of real-world meaning, basic processes of interest and
habituation (Thompson and Spencer, 1966) ensure that infants fill their visual world with changing scenes.

**Mouthing**
The second *inborn bias* is to stimulate the tactile receptors in the mouth; having something in the mouth feels good. Oral sensitivity and pleasure are the most basic survival mechanisms of mammalian young. The drive to suck and to suck on objects placed in the mouth is, of course, extremely strong at birth. Sucking movements are established early in fetal development, appear as the first patterned movements after birth, and remain powerfully reinforcing throughout infancy. Spontaneous mouthing movements are also extremely common (Wolff, 1987). The oral muscles are particularly well innervated at birth, and the seventh facial nerve is selectively matured. Infants can quite sensitively adjust their sucking rate, coordinate sucking and swallowing, and even entrain to an external stimulus (Finan and Barlow, 1998). Infants constantly seek oral stimulation, even in the absence of milk delivery and when they are not hungry. Although associations with the breast and the mother are rapidly acquired, these need not be built in. The baby only needs to make the more simple association of stimulation of the oral receptors as pleasurable. The baby also needs to have the ability to repeat something that feels good. The primacy of oral reinforcement is, of course, at the heart of Freud’s theorizing and plays a prominent role in Piaget as well.

**Grasping**
Third is the bias to grasp when the tactile receptors in the hand are stimulated. The grasp response to tactile stimulation is also elicited easily at birth (Prechtl and Beintema, 1964). Again, nerve endings in the palms of the hands are densely packed. Some have speculated that this reflex is a remnant of an arboreal primate ancestor, or as a mechanism for grasping mothers’ long hair, fur, or breasts. Or it may simply reflect the overall flexor bias in muscle tone and action in the first months of life.

**Repeating**
None of these biases would move the system very far without the ability to *repeat an action that produces pleasurable outcomes*. This is Piaget's (1952) "secondary circular reaction" which he describes in his own infant daughter: "Observation 94... Lucienne shakes her bassinet by
moving her legs violently (bending and unbending them, etc.), which makes the cloth dolls swing from the hood. Lucienne looks at them, smiling, and recommences at once” (p. 157).

This form of simple instrumental conditioning—associating a pleasurable response with an action on the environment—is present very early in life as long as a response modality is available. Thus, experimenters have conditioned sucking and head-turning in newborns (Papousek and Bernstein, 1969). Conditioned foot-kicking is widely used to study infant perception and memory in three-month-old infants (Rovee-Collier and Gekoski, 1979). In these studies, experimenters attach a ribbon from an overhead mobile to infants’ ankles. When babies kick, the mobile jiggles. Babies learn not only the association between their movements and the movements of the mobile, they also learn the perceptual features of the mobiles and the contexts in which this learning takes place. Using such a procedure, I facilitated such learning in my five-week-old infant grandson; five weeks of age is probably as soon as the visual system can focus on the overhead mobile. What is so striking about the mobile foot-kicking paradigm is the enjoyment infants show when they discover that their movements are causing the mobile to move. They watch intensely, smile, laugh, and vocalize, as did Piaget’s daughter, Lucienne. When the contingency is extinguished (the experimenter removes the ribbon from the baby’s ankle so that movement is no longer effective), the infant grows somber and often fusses and cries.

The ability to derive pleasurable sensations from one’s actions on the world appears to be one of the basic tendencies of human infants. It is the critical step in establishing the developmental cascade for all subsequent skills: How can I be effective in the world? How can I configure my abilities to produce these effects? Thus, reaching need not be specifically prefigured because these initial biases set up the motivational substrate for reaching to emerge in the context of other general changes in the system.

But there is also strong evidence for coupling among these systems (Rochat, 1993). Several modalities are linked to movements of the mouth. For instance, stimulation of the hand, as well as fluid in the mouth, leads to mouthing movements (Korner and Beason, 1972; Rochat, Blass, and Hoffmeyer, 1988; Blass et al., 1989; Rochat, 1993). Rochat (1993) provides evidence that this hand-mouth linkage is established early in prenatal development. Very young infants also
respond with oral activity to interesting visual sights. Jones (1996) showed increases in mouthing and tongue protrusion movements in six-week-old infants when they were shown flashing lights.

There is a strong tendency to put the hand in the mouth as well. Spontaneous hand-to-mouth contacts are seen at birth (Butterworth and Hopkins, 1988) and throughout the early months (Lew and Butterworth, 1997). Moreover, Korner and Beason (1972) reported a concurrence between hand-to-mouth contact and visual alerting in newborn infants. When experimenters put objects into infants’ hands, the infants’ contacts with the mouth increased in infants of about two months of age or older (Rochat, 1989; Lew and Butterworth, 1997). Overall, there appears to be a tight coupling between vision, tactile input to the hands and mouth, and movements of the hands and mouth.

Thus, in the first months of life, the mouth is activated by both visual and tactile stimuli and is the target for the hands and for objects placed in the hands (whatever is available). Early hand-to-mouth movements look as though infants are reaching for the mouth with their hands (Bower, Broughton, and Moore, 1970), although the presumed target is felt, not seen (Butterworth and Hopkins, 1988). My own data further illustrate these patterns: Figure 1 shows the frequency of different types of hand-to-face and hand-to-mouth contacts in the first half of the year in four infants. The infants were seated, and each was offered an object at midline and shoulder height. Consider first the time before reach onset, which is indicated by the vertical line in the graph. At first, hand-to-face contacts were the most common. As infants’ arm control improved, more of their movements actually hit the mouth target. The near-misses decreased as successful hand-to-mouth movements increased. The first step in reaching is to reach for one’s own mouth, because stimulating oral receptors is intrinsically pleasurable.

Here, then, is how a few of these simple biases might initiate a motivational cascade that culminates in goal-directed reaching for objects: stimulation of oral receptors by nipples, objects, and their own hands is presumably pleasurable for infants, and they repeat the actions that get things into the mouth. This bias is perfectly plausible as a selective advantage in a feeding system. This leads to considerable practice in bringing hands and objects held in their hands to their mouths. When infants are given toys to hold, they explore them
Figure 1. Hand-and-object to mouth behavior in four infants followed longitudinally. Figure shows the proportion of specific contacts with mouth and face as a proportion of all the hand/face contacts. Note the shift from face contacts to mouth contacts to putting objects in mouth.
Figure 2. The mouth as motivation to reach: Nathan at 12 weeks, the first week of successful reaching. In this example, Nathan has reached bilaterally for a toy presented to him at midline (top photo). He missed the toy but grabbed his other hand and brought both hands to his mouth (bottom photo). The wires are for the LEDs for the computer-assisted motion analysis.
visually, haptically, and orally. What is left for infants to discover is how to actually grab the objects by extending their arms. Reaching is a natural solution for obtaining a distal object to place in the mouth (Bruner, 1969; Rochat, 1993). Object reaching and grasping need not be acquired directly through evolutionary design but may be achieved indirectly as a consequence of biases for feeding, which probably do have a strong selective advantage.

Several other lines of evidence support the view that reaching is an emergent online solution for oral exploration. First, when infants could reach out and grasp toys, they substituted these toys for their hands in their mouths. As seen in Figure 1, infants switched from hands in the mouth to objects in the mouth at the time of reach onset. Oral activity continued with what was available. This primacy of the oral goal is illustrated also in Figure 2. Nathan, in his first week of successful reaching, has reached out with both hands to grab the toy offered on a device in front of him. He has missed the toy but has grasped the other hand instead, and both hands have been immediately transported to his mouth. Second, the “empty” (in the sense of action absent an actual object) oral exploration movements of tongue protrusions in the presence of visually interesting sights dramatically declined just at the time of reach onset (Jones, 1996). Mouth openings remained relatively stable. After reach onset, infants still opened their mouths in anticipation of the grasped object, but the tonguing movements were now presumably used in service of oral exploration and could no longer be seen. Finally, there is the intriguing phenomenon of “oral capture” described by Rochat (1993). Here, infants unable to reach nonetheless attempted to grab the offered toy directly with their mouths. This is an excellent example of motor equivalence, or using whatever motor solution is available to attain the object in the mouth. Infants are flexible and problem solving: when objects are unavailable for oral exploration, hands will do. When hands are not fully skilled in reaching, mouths will do.

**Conclusion: Taking Development Seriously**

The extended period of human infancy and childhood allows us to view the day-by-day and week-by-week activities that constitute developmental change. I chose the example of learning how to reach
to emphasize how complex skills and motivation can emerge from very simple, biologically plausible biases in the system and from the child’s active problem solving. I have drawn a general picture of the developmental pathway leading to the first reaches. But our detailed longitudinal studies (see Thelen, Corbetta, and Spencer, 1996) also showed how much individual variability is subsumed in these general tendencies. Each infant solved these problems in his or her own time and via many different way stations. The infant Gabriel, for instance, was large and very active, with forceful, windmill-like limb movements right from the first weeks. Hannah, in contrast, was small, quiet, and reflective, spending most of her time with her hands already flexed near her face. Because these babies had different initial conditions of body size and energy level, they faced different postural and biomechanical issues. Gabriel had to learn to control his flailing arms to get the toy into his mouth, whereas Hannah had to learn to extend and stiffen her arms sufficiently to reach the toy. They had different problems to solve, and they solved them. As infants gain experience in moving, that experience provides the initial condition for the next experience. So it must be with the motivational cascade: as the child accomplishes one social or physical task, he or she sets up the motivational matrix for the next challenge.

I believe that a dynamic systems approach offers both good and bad news for intervention and therapy. First, here is the bad news, in the words of Stephen Jay Gould (1994): “Webs and chains of historical events are so intricate, so imbued with random and chaotic elements, so unrepeatable in encompassing such a multitude of unique (and uniquely interacting) objects, that standard models of simple prediction and replication do not apply” (p. 85).

Gould’s words about evolution are exactly applicable to development. Because every child has a unique body, a unique and extraordinarily complex nervous system, and unique day-by-day experiences filled with chance events, the course of development is nearly impossible to predict. The developing system is so highly nonlinear that even small events may cascade to have large consequences, although the system may buffer even rather traumatic experiences. Because the future course is largely unknown, the web of past causality can hardly ever be really untangled. Stories told about the past are always also about the present, because we cannot reverse the processes that brought us here.
And now the good news: The very same time-dependent complexity that gives us this circular causality also provides multiple ways to change. As I discussed earlier, complex systems such as developing humans can be characterized by the stability of their states. For stable patterns (say, in relationships or self-concept) to change, some internal or external factor must disrupt the habitual way of thinking or moving. As a person’s stable patterns are the product of many interrelated organic and experiential factors, any number of those factors may also be an entry to disrupt those patterns. The job of a skilled therapist is to detect where the system is open to change, to provide the appropriate new input to destabilize the old pattern, and to facilitate the person’s seeking of new solutions (a process much like a baby’s learning to reach). The entry may be through self-reflection or narrative, through establishing new relationships, through learning new behavior, through movement, or through art. Because of my long-standing research program in movement, for instance, I have become interested in the role of movement in mental change and have thus trained as a Feldenkrais Method practitioner. Just as many systems cooperate to produce stable patterns, so many systems may be available to disrupt those that have become too rigid and maladaptive.

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