8 Nonlinear Complex Dynamical Systems in Developmental Psychology

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Introduction

A good method for obtaining an idea of what a scientific discipline – developmental psychology in this particular case – entails is to browse through introductory student handbooks (Berger, 2003; Bukatko & Daehler, 2001; Cole & Cole, 1993; Kail, 2001; Newman & Newman, 2006; Sigelman & Rider, 2006; Seifert & Hoffnung, 1991; Vasta, Haith, & Miller, 1995). The consulted handbooks either focus on childhood to adolescence or on the human life span. The first chapters typically provide an overview of the "perspectives" on development and comprise a selection of theories ranging from psychodynamically (Freudean) inspired via learning theory to theories of Piaget and Vygotsky. Most handbooks address the nature–nurture problem, discussing the effect of genes and environment on development and present some sort of interactionist or transactionist approach. The main chapters are divided according to two dimensions. One is a content or domain dimension and comprises physical, cognitive, and social aspects of development. The other dimension refers to age and amounts to a distinction in phases or "ages." The standard children-and-youth division encompasses prenatal development and birth; infancy (0–2 years); preschool years (2–6), childhood (6–12) and adolescence (12–21). For each phase or stage, typical developments are described, such as the development of attachment in the first year of life, the development of theory of mind around 3 years, the emergence of logical thinking (including conservation and other Piagetian themes) around age 5, and so forth. Some handbooks pay attention to individual differences – for instance, individual differences in temperament from birth on – and eventually focus on clinical developmental problems such as autism of hyperactivity.

The main picture revealed through such handbooks is that development, and developmental psychology for that matter, is basically a collection of perspectives and approaches (theories), of influences on development (e.g., genes, environment), of aspects or dimensions (e.g., physical, cognitive), of phenomena

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(e.g., attachment, conservation), spread out across the life span or part of it, in phases or ages that are defined by tradition, as well as by biology and society. Developmental psychology is apparently not a first-principles-based science. There seems to be no fundamental developmental mechanism, the understanding of which forms the key to a thorough understanding of the emergence of developmental phenomena.

This lack of theoretical sophistication is relatively new. The field started with serious theoretical reflection on the basic mechanisms of development (Piaget's work is a good example of that). However, as it became more and more "empirical," it drifted away from its theoretical origins and became more and more of a descriptive science (van Geert, 1998a). Currently, the focus on theoretical explanation and on finding the nature of the basic developmental mechanisms comes mainly from system-oriented researchers. Examples are the theory of developmental systems, which has its roots in evolutionary biology (Ford & Lerner, 1992; Gottlieb, 2001; Lerner, 2006; Lickliter & Honeycutt, 2003; Oyama, Griffiths, & Gray, 2001; Sameroff, 2000), and the theory of nonlinear, complex dynamical systems, which is the focus of the current chapter.

Anyone who has witnessed a newborn baby grow up into a toddler and then a schoolchild, an adolescent, and an adult has an intuitive appreciation of the fact that developmental processes are prime examples of nonlinear dynamical systems (NDS). However, there is currently little thinking along the lines of complexity, nonlinearity, and dynamical systems among developmentalists (those who call themselves dynamical systems developmentalists form a small minority). In this chapter, I attempt to explain the foundations of a complexity-oriented, NDS approach to human development. Before doing so, however, I first explain what I understand by dynamical systems and how it relates to the assumptions that underlie most of the current developmental studies and theories.

Dynamical Systems and Explanatory Adequacy

Definition

Dynamical systems theory is an approach to the description and explanation of *change*. A simple definition is Weisstein's (1999): "a means of describing how one state develops into another state over the course of time," which can be expressed mathematically as

$$y_{t+1} = f(y_t), \tag{8.1}$$

expressing that the next state (at time $t + 1$), is a function, f, of the preceding state, at time t. In a slightly different notation:

$$\Delta y/\Delta t = f(y). \tag{8.2}$$

Stating that the change of a system, denoted by y, over some amount of time, denoted by Δt, is a function f of the state of y. The function f is also referred to

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as the evolution term or evolution "law." That is, it is important that f specifies some causal principle of change. An important property of the current equation is that it represents recursive relationships. Thus y_t leads to y_{t+1}, and according to the same principle, y_{t+1} generates y_{t+2} and so on.

A system can be described as a set of entities that are related to one another and influence one another, and a state of the system is the set of properties of its components at any particular moment in time. For quite a long time now, mainstream social science, including developmental psychology, has refrained from focusing on change per se. It has been building *static* models and has implicitly assumed that change – for instance, developmental change in an individual – could be approximated by stretching static relationships over the time axis (van Geert & Steenbeek, 2005). A characteristic expression of a static relationship takes the form

$$y_i = f(x_i), \tag{8.3}$$

with y a dependent variable and x an independent variable, which, for any possible value x_i generates a corresponding value for the dependent variable y.

For the sake of simplicity, take a system no more complex than a single property or variable (e.g., a child's growing lexicon, a child's ability to answer theory of mind problems). A dynamical system describes the current state of the system – that is, the variable's current value – as a function of its preceding state. It does so in a recursive way, taking the result of one step in the process (e.g., the lexicon today) as the starting value generating the next step, the lexicon tomorrow, and so on. The evolution term, f, must represent a theoretically justifiable principle of lexical change, for instance, the principle that the learning of new words at time *t* depends on the words already known and on the words actually spoken by the person with whom the child communicates at time *t*. The second principle, the dependence on the words spoken to the child, already illustrates the principle of embeddedness, which is characteristic of dynamical systems models of behavior and which are further elaborated in this chapter.

A static system, on the other hand, describes a particular value of the variable as a function of the value of another variable (or set of such variables). For instance, for any possible age, for any level of the mother's lexical knowledge, or for a combination of age and maternal lexicon, the static system or model will generate a predicted or expected size of the lexicon, without any reference to recursiveness.

Static and Dynamic Models

This distinction between static and dynamic type models has considerable consequences (Howe & Lewis, 2005; van Geert and Steenbeek, 2005). Whereas a dynamic model recursively generates a time series (a state and the next state and the next ...), a static model generates a sample or population of individuals that are in principle independent of one another (an individual with age *i* and

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lexicon *i*, an individual with age *j* and lexicon *j*, and so forth). Statements about populations do not necessarily apply to the individuals in the population. For instance, in a sample of drivers, a high level of conscious control of the driving behavior will in general be statistically associated with low driving quality. That is, high levels of conscious control are characteristic of novices, and they tend to have the worst driving behavior. Hence, we will tend to find a negative correlation between controlled driving behavior and driving quality. In an individual driver, however, the relationship might well be the inverse of the relationship in the sample. An experienced driver will tend to increase his or her conscious control on the driving behavior in more complex traffic situations, associated with driving behavior of high-quality driving, for instance, under difficult circumstances. In this example, the difference between the static-association interpretation and the dynamic interpretation (the mechanism behind the increase or decrease of controlled driving in a particular driver) is easy to see.

However, the behavioral sciences, including developmental psychology, often implicitly take a relationship between variables that holds across a sample as a representation of some dynamic rule or principle. For example, a recent study (Duncan et al., 2007) showed that early math skills in 5 to 6 year olds have the greatest predictive power for later school achievement, whereas socioemotional behaviors, on the other hand, had little or no predictive power, irrespective of gender and socioeconomic background. From such finding, it is easy to infer that increasing early math achievement (e.g., through preschool teaching programs) will thus lead to better school achievement at a later age, implying also that attempts to increase socioemotional skills should be reduced because they do not relate to academic achievement. However, there exists no logical or direct relationship between the static relationship (how is it associated across a population) and the dynamic relationship (how can something be increased or decreased in individuals). The dynamic relationship – how and to what extent the early growth in math skills contributes to the growth in academic achievement – depends on the mechanisms that govern math learning and academic achievement.

This homology error – taking a relationship holding on one level (e.g., the sample level) as a relationship that also holds on another level (e.g., the level of the life span of the subjects contained in that sample) is commonly made in the behavioral sciences (Hamaker, Dolan, & Molenaar, 2005; Molenaar, 2004; Musher-Eizenman, Nesselroade, & Schmitz, 2002). It is associated with a relative lack of interest for genuine process models and the assumption that associations between variables across a sample can be used as valid approximations of the dynamic relations that govern the process.

Complexity

A living organism is an ensemble of many closely interacting, interdependent components, the common activity of which is more than a sum of the actions of

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its components. That is, it is characterized by nonlinearity. It is self-organizing in that its structure and organization result from the interactions between its parts. Although constantly changing, it maintains its coherence over time. In short, it is a complex system (Bar-Yam, 1997; Holland, 1995). Understanding a system, including its growth and development, means to simplify it, but the simplification must conserve the system's characteristic features, one of which is its complexity. For instance, to understand the dynamics of lexical growth in a child, we must postulate a system of interactions at many levels – perceptual, motor, social, cognitive, and linguistic. To put it differently, the simplest possible explanation of lexical dynamics is a system that is complex enough to generate sound-meaning mappings through social interaction. Compare this with a static model of lexical growth that explains lexical knowledge across a sample as a function of variables such as linguistic input, intelligence, and so forth. The simplest possible explanation of lexical knowledge most likely consists of only a few of such variables. Any newly added variable will achieve only a minor gain in explained variance (i.e., in capturing the differences between the individuals, including those differences that covary with age). The notions of simplicity and complexity held by a dynamical model are of an entirely different kind than those held by a static model, and they cannot be traded for each other (not every beard can be shaved by the same razor, even if the razor comes from Occam). Trivial as this remark might seem to students of dynamical systems, it is far from trivial in mainstream (developmental) psychology, where a description of differences between persons is tacitly taken to represent a generalized but nevertheless valid description of differences within persons (i.e., change and development). To explain development as *change*, based on a plausible mechanism of change, we will have to follow a dynamical approach that accounts for a highly characteristic feature of development, namely complexity.

Explanatory Adequacy in Complex, Nonlinear Dynamical Models of Development

The preceding discussion of complexity is closely related to the fact that static models, common in mainstream developmental psychology, and dynamical models are of a different kind and aim at explaining different phenomena. The kind of criteria that make an explanation adequate in one approach is often different from the kind of criteria that make an explanation adequate in the other. Explanatory adequacy refers to the criteria that make an explanation useful – in the sense of testable, for instance – in a particular approach, be it static or dynamic. Let me explain this by means of an example that, again, refers to lexical growth. Students of early lexical development have claimed that the lexicon undergoes a spurt during the second year of life. Ganger and Brent (2004) challenged this idea by putting 38 longitudinal studies of lexical growth to a statistical test. They found out that a quadratic model of lexical growth with

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time as the only predictor (Eq. 8.4) is statistically superior to a "spurt" model, namely, a sigmoid function which also has time as predictor (Eq. 8.5).

$$L_{\mathrm{t}} = a + bt + \mathrm{c}t^2 \tag{8.4}$$

$$L_{\mathrm{t}} = K/(1 + (K/L_0 - 1)\mathrm{e}^{-rtK}) \tag{8.5}$$

They concluded the empirical evidence is against the spurt model. However, what the quadratic model – and the sigmoid model, for that matter – really represent is a static model. That is, they are both models describing time samples (levels of the lexicon at different ages) as a function of another variable, namely, the time at which the samples were taken. Indeed, as a sample model, the quadratic model was statistically superior to the sigmoid or spurt model. However, as developmentalists interested in the *mechanism* of lexical growth, sample models are of relatively little use. What we need is a model of lexical *change*. Fortunately, we can infer the models of change present in the statistical models proposed thus far by taking the first derivative of the model equations (the quadratic from Eq. 8.4 and sigmoid from Eq. 8.5, respectively):

$$\Delta L = b + 2ct \tag{8.6}$$

$$\Delta L/\Delta t = rL(K - L) \tag{8.7}$$

The first derivative of the quadratic model describes lexical change as the addition of a constant number of words per unit time plus a number of words per unit time that increases with time. On the other hand, the first derivative of the sigmoid model, which boils down to the logistic growth model that will be introduced later in this chapter, describes lexical change as a process of adding a number of words that depends on the number of words already present in the lexicon and on the number of words not yet known. More precisely, it describes lexical growth as a process of input- and state-based learning, whereas the quadratic model describes lexical growth as mere increase (or decrease for that matter) solely governed by time – more precisely, by the duration of the growth process.

What about the explanatory adequacy of these developmental models? In this context, explanatory adequacy means that the model relies on or refers to causal relationships with a demonstrable plausibility for the field at issue. For instance, the idea that how much you already know determines how you learn, or how much you profit from an experience, refers to a plausible causal mechanism of learning. The idea that learning depends on how much you do know yet relates to causal mechanisms such as filtering or interpreting one's experiences on the basis of what one knows to make use of what is new or unknown. This principle again relies on plausible causal mechanisms of learning. In short, from a developmental point of view, the sigmoid-based explanation of logistic growth, which encompasses these principles, is considerably more explanatorily adequate than the quadratic because it relates lexical growth to elementary developmental

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processes. The quadratic model, on the other hand, confines itself to observing that the lexicon increases with time, implicitly claiming that time itself is a causal factor (the claim could be relaxed by taking time as the substitute of a causal factor that linearly changes with time, such as – hypothetically – brain maturation, for instance).

However, the sigmoid model was rejected by Ganger and Brent (2004) on the grounds of unnecessary complexity (in terms of the number of parameters it needed) for explaining the *time sample* characteristics as a function of time. That is, the quadratic model fitt the data as well as the sigmoid model did, but it did so with fewer parameters. However, the statistical superiority with regard to time-sample characteristics has no direct bearing on the adequacy of the underlying explanation of change (i.e., of the dynamics of lexical growth). From a developmental point of view, the time-sample model must be rejected as a dynamic explanation of the lexical growth process. Its competitor, the sigmoid or in fact logistic model, is extremely simple but nevertheless comprises an elementary developmental model. In short, statistical simplicity criteria make little sense if they are posited without reference to an underlying plausible model of explanation. The problem relates to a point raised in a quote attributed to Albert Einstein: "Everything should be made as simple as possible, but not simpler."

Development and the Dynamics of Long-Term Change

The Meaning of *Development*

Etymologically, *development* means "unwrapping" or" unfolding", as in the unwrapping or unfolding of a book roll or the unwrapping or unfolding of a flower bud (Thomae, 1959; van Geert, 1986, 1995, 2003). In its basic meaning, development thus carries a notion of an inner logic in the sequence of the unfolding, a notion of potentiality (what is in there must come out) and a notion of finality (the unfolding comes to an end when the folded object is spread out). This historical meaning of development (the term became in use in the photographic sense in the mid-nineteenth century, for instance) can of course not determine how we see or define development in scientific discourse. However, if we apply the term to some observable phenomenon – and not use a word such as maturation, learning, and so forth instead – we do so because we wish to refer to a phenomenon that is characterized to a more than a trivial extent, by these notions of inner logic, potentiality, and finality. Development implies a directed process of change toward or unfolding of a mature state. It is a directed process, from an immature to a mature state, implying increasing complexity in terms of a system that differentiates (incorporates more and more elements, features, knowledge . . .) and at the same time integrates (constructs connections between the components).

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Readers familiar with dynamical systems will immediately recognize these notions as metaphorical representations of self-organizing dynamics. The inner logic corresponds with the evolution term or the change function that governs the dynamics, and the potentiality and finality refer to self-organization or the systems tendency to move toward a particular attractor state. The notion of increasing developmental complexity refers to theories of complexity and emergence (Casti, 1994; Holland, 1995, 1998; Waldrop, 1992). In short, given its core assumptions, developmental psychology seems like a natural domain of application for the approach of nonlinear, complex dynamical systems. Unfortunately, this is not the image that the majority of the scientific studies convey (see van Geert, 1998a, for a discussion). For instance, the majority of studies in development aim at simplifying our view on developmental processes by conceiving them as sums of independent factors (e.g., early math knowledge, socioemotional knowledge, socioeconomic background, and so forth) and by estimating direct effects of one variable on another by statistically controlling for the effect of other variables. Although these procedures work well for relationships across samples, they do not correspond with a model of the time evolution of the variables at issue, at the system level where they actually operate, which is the level of the individual person embedded in his or her environment. Complexity is replaced by the simplicity of adding factors, and nonlinearity is replaced by linear additions of effects of variables.

Aspects of Development Through the Human Life Span

In terms of change, the human life span encompasses more than just development. To begin with, change can take place in the form of learning and teaching (being taught by others). Let us, for simplicity, describe learning as the having of experiences that make a person change in a way that is consistent with those experiences. Teaching can then be described as giving a person experiences that are intended to make him or her change in a particular way. Learning and teaching are closely related to the process of appropriation, of mastering new skills, of assimilating and transmitting knowledge. However, there is also maturation and aging across the life span. They are biologically governed processes of change, with a connotation of rising and falling (deterioration). A somewhat overlooked form of life span change are processes we can call *niche-seeking* and niche construction (i.e. the organism moving toward and eventually actually creating and transforming environments that optimally fit its properties; Clark, 2006; Laland, Odling-Smee, & Feldman, 2000). This is the kind of mechanism that also features in distributed approaches to action and cognition (Clark, 1997; Clark & Chalmers, 1998; Fischer & Granott, 1995).

How does development relate to all this? In my view, development can be seen as the overarching term, covering the notion that these processes – and whatever others one wishes to distinguish – are coordinated in a dynamical way. The

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coordination entails that development is not just the sum of these processes but, as I stated in the definition of complexity and nonlinearity, that the ensemble of such processes cannot be derived from their summation and that it is nonlinear and self-organizing.

The idea that development forms an encompassing term and, more precisely, an encompassing structure, for a variety of change processes during the life span is one that features prominently in the work of the classic developmentalists. They were the scholars who set the theoretical and empirical stage for the study of development and whose major works date, roughly, from the first half of the 20th century. I am referring to developmentalists such as Piaget, Vygotsky, Werner, Wallon, and others. Although their approaches to development were very different, they had one major thing in common, which is a common view – in abstracto – on the fundamental mechanism of development (for a thorough discussion and justification, see van Geert, 1998b, 2000). The hallmark of development in a complex system is that *all changes of the system occur through information that is moderated through the system. Changes* are both short-term and long-term changes (the related notion of time scales is discussed later). The *system* is a complex system and can refer to different levels of complexity: It can be an individual (an individual child), or a social network (a child–educator dyad for instance) or persons interacting in their characteristic environmental niches, including meaningful cultural artifacts. *Information* is used here as a generic term and denotes basically anything that the system can do or that can affect the system. The term *moderated* can take various meanings. It can mean that if the system is an individual, it is the system itself (the embodied brain), that encodes the information in terms of its abilities and then internally adapts its structure in function of this encoding. This is basically the mechanisms that Piaget hinted at with his terms *assimilation* and accommodation as the two forms of adaptation. Moderation can also mean that the caring and nurturing environment (educators, parents . . .) adapt the environment to the system's (e.g., the child's) current level and possibilities, the system changing in function of this adapted information. This is basically the model we find in Vygotsky's theory, for instance, in his notion of the zone of proximal development. Another possibility, discussed earlier, is that the system selects and creates its own niche – its own preferred environment.

Dynamics and Recursiveness of the Developmental Change Function

It is easy to see that the basic developmental function – *all changes of the system occur through information that is moderated through the system* – is a basically recursive or iterative function and is thus directly related to the definition of dynamical system as given earlier. Any theory that takes this function, in any of its many possible forms, as a starting point, must arrive at a dynamical systems theory of development. The problem with the classical theories was that although they used a recursive mechanism of change and also appreciated the

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nonlinearities of the developmental process (take Piaget's stages, for instance), they had no practically feasible means to deduce formally the nonlinear outcomes from the mechanism. In fact, we had to wait until computers became available as easily manageable simulation devices to see how such iterative principles naturally generated nonlinear and self-organizational phenomena. With only a few exceptions, unfortunately, developmental psychologists have so far hardly tried to do their "experimental theory building" (i.e., their simulations of the basic dynamics of development) and are thus still not yet in a position to see the possible links between mechanism and developmental outcome. One approach to simulation is relatively widespread in developmental psychology – namely, connectionist model building (see, for instance, Elman, 2005; Munakata & McClelland, 2003; Schlesinger & Parisi, 2004). However important such connectionist modeling, it does not in itself answer the question of whether recursive application of one or other formalized version of the basic developmental mechanism indeed generates the kind of dynamics that we see as characteristic of development (van Geert & Fischer, in press).

The Interactional Nature of the Developmental Change Function

In our description of how information that is capable of changing the system is in fact moderated through the system, we have implicitly specified that the dynamics is fundamentally interactional. That is, it involves an interaction between the system and another system, which, for simplicity, can be specified as the system's environment. *Environment* is used as a generic term. For instance, if we conceive of a child's lexicon as a simple one-dimensional system, the lexical system's environment is anything that to which the lexicon is dynamically related, such as the child's own cognitive system, but also the linguistic community and the actions of the child's caretakers. Even in the extremely simple dynamical model that I related earlier to the logistic growth model and that specifies the quantitative change in a single variable (for instance, the number of words known by a person), there is an explicit reference in the equation to what is not yet known or appropriated (e.g., the number of words not yet known by the child; this number implies a simple interaction between the child's lexicon and the linguistic environment from which this lexicon is drawn). A much richer notion of interaction emerges if we specify a developmental model as an interaction between components of an overarching system (e.g., motor, sensory, cognition, and language components in addition to "real" context aspects such as caretakers or cultural artifacts).

Intentional Action: An Implicit Component

The developmental change function, *all changes of the system occur through information that is moderated through the system,* aims at understanding long-term change, at the developmental time scale of the life span, in a complex system – for

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instance, a child in a physical, social, and cultural world. It does not specify where the generically defined "information" comes from, from which source it emerges. The classical developmentalists, Piaget and Vygotsky in particular, addressed this issue by emphasizing the importance of action for development. Action can take many forms, ranging from an individual child's curiosity-driven exploration of manipulable objects to a child's guided participation in an activity he or she cannot yet accomplish alone, or the actual teaching and learning that goes on in a classroom. This brings us to a different [illegible] of dynamics, which is the short-term dynamics of human action. I call it short term because it involves processes (actions) of considerably shorter duration than that of development.

Action and the Dynamics of Short-Term Change

The Dynamics of Action

Historically speaking, economics provides a good example of how macroscopic (i.e., economic) processes were based on a basic model of human action. The early theory of liberal economics of Adam Smith (1723–1790) conceived of individual human action as a utility-driven and utility-optimizing dynamics. That is, human action is driven by the intention to achieve maximal gain at minimal cost. Gain can be described in terms of actual goods but also in terms of an internal evaluation of the value of the context, of happiness and pleasure, satisfaction, and so on, with cost defined as effort. Human action encompasses the here-and-now events of trading, buying, and manufacturing. The acts of an individual make no sense without complementary acts of other individuals. The whole of such actions across space and time is economy, the dynamics of which emerge from the dynamics of individual actions. The notion that action boils down to motion to or away from certain "objects" – that it is dynamics in the most fundamental sense of the word – dates back (at least) to Hobbes's *Leviathan*:

> The real effect there is nothing but motion, or endeavour; which consisteth in appetite or aversion to or from the object moving. But the appearance or sense of that motion is that we either call delight or trouble of mind. (Hobbes, *Leviathan* I 6)

Let me give some examples of action in a developmental context. A 10-month old has been put on the lap of a strange person by his mother, and he does whatever he can to get back to her. A 4 year old spots a new toy in the play corner and wants to have it but meets another child who also seems to want it and gets into a fight with the other child. An 8 year old is given a math assignment by her teacher and tries to solve the sums from her workbook. A 15 year old gets into an emotional discussion with her mother about staying out late at night with her boyfriend. These examples illustrate the short-term dynamics of action as they are embedded in the long-term dynamics of development. A baby of 10 months

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old, for instance, has already formed the type of attachment that makes her try to escape from a stranger, something she would not have done at an earlier age. A 4 year old cannot solve the math problems because she does not yet have the skills to do so, and so forth. An important property of the action sequences is that they involve some sort of gradient that is strong enough to release energy for action (see Tschacher & Haken, 2007, who placed action in a thermodynamic perspective). The action of the 10 month old is aimed at solving the gradient between her position with the stranger and the position close to her mother. The 4 year old acts to solve the gradient between seeing the new toy and actually playing with it, and so forth. This theory of gradients is highly reminiscent of Lewin's field theory of action (Lewin, 1936, 1946; see also Beach & Wise, 1980; Koch, 1941). The gradients from the examples are associated with the value, or valence as Lewin called it, of objects, situations, or bodily conditions. Social psychologists tend to speak about evaluations in this regard (Cunningham & Zelazo, 2007), whereas theorists focusing on emotions often tend to speak about appraisals (Frijda, 1986, 1993; Scherer, 1999). Evaluations or appraisals can be specified over a great number of dimensions, involving bodily, physiological, and visceral aspects; social and self-related aspects (Leary, 2007); and cognitive aspects of different kinds. Together these dimensions can be conceived of as a dynamical state space, with a principal component that goes from low or negative hedonic tone (displeasure) to a high or positive hedonic tone (i.e., pleasure; see Cabanac, 2002; Johnston, 2003; Panksepp, 2000; Russell, 2003).

> Pleasure therefore, or delight, is the appearance or sense of good; and molestation or displeasure, the appearance or sense of evil. (Hobbes, *Leviathan* I 6)

The hedonic tone of a person's continuous evaluations has a distinct neurological underpinning (Cunningham & Zelazo, 2007; LeDoux, 1996; Sugrue, Corrado, & Newsome, 2004) and can take various qualities, experienced by the person in the form of emotions. The evaluative state space has specific attractor states, and the nature of these attractors depends on the totality of endogenous (person-specific) and exogenous (environment-specific) properties at any point in time. For instance, the example of the toy specifies an attractor of being close to the toy (in fact being able to play with it) and a gradient (being presently at some distance from the toy), which depends entirely on the current presence of the toy in the child's living space, or *Umwelt* as von Uexkull used to call it, and on the child's actual interest in the toy. As the child moves through his living space, the attractors of the evaluative state space change continuously, basically because they release actions resulting in resolving gradients and creating new ones in the forms of new opportunities. As noted earlier, this model is highly reminiscent of Lewin's field theory of action. The goals or intentions that guide a person's action are self-organizing attractor states, under the control of the entire dynamic system of organism–environment (Gibbs & Van Orden, 2003; Shaw, 2001; Van Orden & Holden, 2002; Van Orden, 2002).

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The dynamics of action are mutually coupled to the dynamics of evaluation (appraisal, hedonic tone). Action serves to optimize evaluation or hedonic tone in the multidimensional evaluation space. In our earlier example, the 4 year old moves toward the toy, thus decreasing the distance between him and the toy and increasing the hedonic tone along this particular dimension, but as he comes closer, he also comes closer to the other child, his competitor, who might frighten him, leading to a decreasing hedonic tone as he comes closer to that child, eventually resulting in a withdrawal and an exploratory sweep to find an alternative attractive toy without competitors. In a mentalistic perspective, the coupling between action and evaluation is covered by terms such as motivation, goal setting, effort allocation, and so forth.

Steenbeek and van Geert (2005, 2007a, 2008) constructed a dynamical model of dyadic action in children to explain the emergence of action patterns over time and the emergence of differences between children of different sociometric statuses. A central feature of the model is the child's concern or interest in playing with another child versus his concern to play alone with the available toys. It is based on the assumption that the preferred proportion of activities, with the optimal level of pleasure or hedonic tone, depends on the status (or valence) of the play partner versus the attractiveness of the toys. The model yields patterns in time that qualitatively resemble the empirically observed ones and generates distributions of behavioral and emotional variables that are similar to those found in the studied sample (which consisted of dyads composed of a child of average sociometric status with a play partner of either popular, average or rejected status).

Action and Social Interaction in a Developmental Context

The long-term process of development and the short-term process of action are intimately dynamically related. That is, action creates the conditions in which learning, teaching, maturation, niche-seeking, and so forth take place and thus alters the parameters and properties that constitute the long-term ensemble of development. For instance, if a child experiences that whining and nagging will result in getting the PlayStation he had wanted and that his parents found too expensive, the child will learn that whining and nagging are good means to pursue a goal, according to classical operant learning theory. Development, on the other hand, creates the conditions for actions, by changing environments, valences of environments, and the means for realizing one's goals. To really understand how development emerges as long-term dynamics out of the short-term dynamics of coordinated actions of children, adults, and cultural artifacts, one must understand the dynamics of action in the child and the adult in question, as well as how they relate to one another in terms of circular causality (Tschacher & Haken, 2007; Van Orden & Holden, 2002) and how they result in

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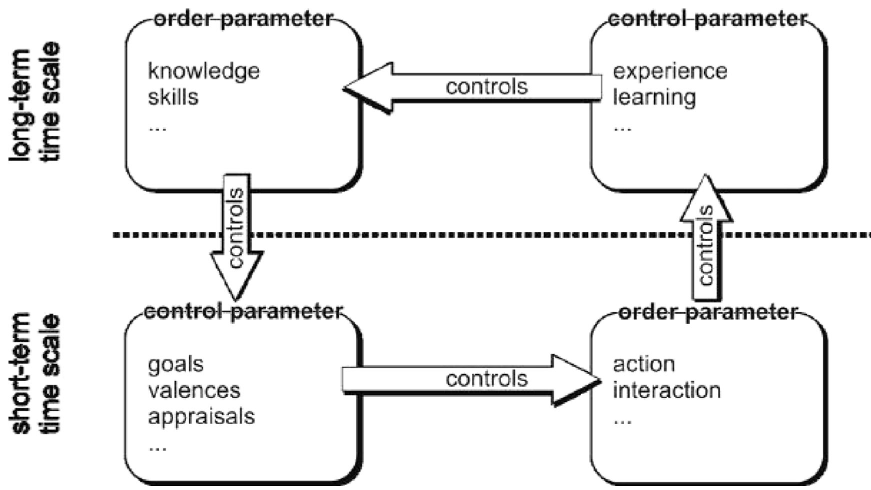

Figure 8.1. Cyclical relationships between order and control parameters on the short-term time scale of action and the long-term time scale of development.

the long-term change of development (Steenbeek & van Geert, 2008; Van Geert & Steenbeek, 2005).

Our current empirical understanding of these dynamics, however, is fragmented and scattered over many small pieces, referring to theories about motivation, teaching, operant learning, conceptual learning, social interaction, attachment, curriculum construction, and so forth, to name just a few possibilities in random order. From a viewpoint of complex dynamical systems, the major question to be solved refers to the fundamental principle(s), if any exist, of the coordination of the many levels implicitly distinguished so far. A major point concerns the coordination of short-term and long-term processes. Using the terminology of control and order parameters, Steenbeek and van Geert (2008) suggested a *circular causality* model of interactions between the short-term time scale of action and the long-term time scale of development. Order parameters on the short-term level of description (i.e., that of action) constitute control parameters at the level of development, giving rise to long-term order parameters (e.g., social status and social power of children in a group) that constitute the control parameters at the short-term level (see Fig. 8.1).

In the next section, I address a question that has occupied developmentalists since the founding of developmental psychology as a scientific discipline – namely, the question of stages. I try to show that the question is more than a descriptive and therefore relatively trivial matter. It touches on a number of issues regarding the fundamental mechanism(s) of development and how they shape the actual unfolding of development over time.

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Developmental Phenomena From the NDS Viewpoint

Developmental Stages and the Stage Debate

A typical feature of classical developmental theories (e.g., Piaget, Erikson) is that they view development as occurring in stages. Although the original scholars were less occupied with the stage issue than many current introductory handbooks suggest (see van Geert, 1998a, 1998b, for discussion), they nevertheless saw the course from the initial developmental state to some sort of end state as a stepwise path, or a path moving across various qualitatively distinct states. The current handbook version of Piaget's stages is probably the best-known example. It claims that children begin on a sensorimotor level of thought, that they proceed to a level called preoperational, then concrete operational, and stabilize at a level called formal operational, which is characteristic of adult thinking. What is important is that these stages represent characteristic features of thought, such as preoperational thinking, which is characterized by the fact that thinking is internalized (takes place in the form of internal representation and not as overt action as in the preceding state), but that it is still action-based (does not entail reversibility) and operates on concrete objects (van Geert, 1986, 1987a, 1987b). Reversibility is a property of a cognitive system, implying that every operation has an inverse operation attached to it that cancels out the effect of the first operation; for Piaget, a mature cognitive system is characterized by the formal properties of mathematical groups, notably identity and inverse.

The existence of stages has been heavily criticized, and some scholars saw them as mere bookkeeping categories, distinguished by completely arbitrary boundaries (Boom, 1993; Brainerd, 1978). Recent stage-oriented theorists, in particular, the neo-Piagetians, occupy a considerably more sophisticated standpoint (Fischer & Bidell, 2006). They make an analysis of the content structure of thought processes on the basis of general descriptive building blocks, such as representations, relations, systems defined as relations of relations, and so forth. Armed with this descriptive framework, they are able to distinguish "stages" as in fact qualitatively different forms of thought, or skill in general, that are developmentally ordered. The stages are context and domain specific (Case, 1992, 1993; Demetriou & Kyriakides, 2006; Fischer & Bidell, 2006). A child may function on Stage (or level) 1 in Domain A (e.g., simple mathematical operations) and on Level 2 in Domain B (e.g., social relationships). Within a domain, such stages – or one should say levels – can fluctuate with varying context, because context is a part of a person's skill (e.g., a child who faces a particular problem context may function on Level 2 with help and on Level 1 without help). The levels or stages may fluctuate strongly over the short-term time scale: while solving a problem, a child, or a collaborating dyad of two children, may go from mere sensorimotor experimenting to relatively deep conceptual understanding and back in a process that Fischer has called *scalloping* (Fischer & Bidell, 2006; Granott, 2002).

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However, irrespective of the domain and context specificity of the levels or stages and of the fact that they may fluctuate strongly over a short time span, there is also a fuzzy but nevertheless convincing ordering in the level or stages. Two year olds, for instance, will show a very different mixture and frequency of context- and domain-specific levels than adults and are thus characterized by a different major-stage category than adults are (Dawson-Tunik, Commons, Wilson, & Fischer, 2005). In sum, the current notion of stages reflects the complexity of the developmental system. It views stages or levels all the way down, in a complex, hierarchical, and dynamic organization. In the next section, I discuss to what extent the notion of stage or level really captures the fundamental aspects of the dynamical organization and mechanisms that shape development.

Dynamical Systems and the Notion of Stages

Stages as Attractor States of the Developing System

The notion of stage (e.g., level, phase) reflects an idea of internal coherence, a relatively stable structure of elements such as skills, habits, processes, and so forth that in some way or another support each other's existence. They can be replaced by other relatively stable structures, but they should not be seen as arbitrary collections of features. The notion of stage is thus highly reminiscent of a basic notion from dynamical systems – namely, the notion of attractor. In a multidimensional geometry (e.g., a space consisting of all the dimensions or features necessary to characterize the properties of human thought and action), an attractor can be a single point, a basin or a (quasi-)cyclical path, with a certain stability. Most points in this geometric space will be instable, and thus move toward more stable points, which are the system's characteristic modes of operation. We can now take as our starting point the theory of complex systems in general and follow the assumption that such systems tend to self-organize into islands of relative stability rather than remain unconnected collections of features in which any combination of such features is as likely and (un)stable as any other. From this, we can reach the conclusion that stages, defined in the dynamic and complex way explained earlier, should be the default option for a system as complex as human development. The difficult point is, of course, to describe and explain them properly and go beyond a naïve idea of age-dependent, easily specifiable, and uniform modes of thought and action.

(Dis-)Continuous Transitions

Developmental psychologists who took seriously the idea of patterns of stability and coherence and thus adhered, in some way or another, to the notion of stage in the general sense of the word (meaning "relatively stable state, in the sense of attractor") have turned to the issue of discontinuity and continuity in development. The (dis)continuity problem asks whether there is anything between two qualitatively distinct stages or states, A and B. Let me give an

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example from the field of theory of mind research, which is currently one of the most prolific fields of research in social–cognitive development, with considerable implications for clinical practice. Let B be the typical "other-minds" stance of a child who thinks according to the principles of theory of mind, and A be the "own-mind" stance of a child who has not yet developed a theory of mind (Blijd-Hoogewys, van Geert, Serra, & Minderaa, 2007). For instance, we show a child a candy box and ask him what it contains; the child says "candy," and then we show the child that instead of candy, there are marbles in the box. We then ask the child what his father, who will come in later, will say when asked what the box contains. The B child will say "candy," reasoning from an other-minds stance, lacking the information the child himself has. An A child will say "marbles," reasoning from an own-mind stance, identifying his own knowledge with that of somebody else. With this example, I am in no way making the claim that such answers are caused by some internal mechanism called the child's theory of mind. So far our insight into the direct mechanisms in what makes children generate this sort of answer is not deep. Recent studies suggest that executive functioning, notably the ability to inhibit rapid associations, explains part of children's answer tendencies; other studies have pointed at language understanding, the presence of child-aged siblings, and the automatic simulation of an other person's perspective (Gallese & Goldman, 1998; Hughes & Ensor, 2007; McAlister & Peterson, 2007; Pellicano, 2007).

According to the discontinuity view, there is nothing in between the A and B state. A child's problem solving, for instance, when faced with a false-belief experiment, is either A or B, not something in between, as continuity theory would assume. Such discontinuities are the topic of catastrophe or bifurcation theory. In the field of organizational psychology, empirical applications have been pioneered by Guastello (Guastello, 1981, 1987, 1988, 1995). Also developmental researchers have used the framework of catastrophe theory to answer their questions about developmental (dis)continuity (van der Maas & Molenaar, 1992; van Geert, Savelsbergh, & van der Maas, 1999). By testing for empirical indicators of the so-called catastrophe flags (structural properties of discontinuities in general), they have tried to show that developmental transitions are instances of the so-called cusp catastrophe and thus entail a clear form of discontinuity. Examples of phenomena studied are the transition between nonconservation and conservation understanding in young children (Hartelman, van der Maas, & Molenaar, 1998; van der Maas, 1993; van der Maas & Molenaar, 1992), reasoning (Hosenfeld, van der Maas, & van den Boom, 1997a, 1997b; Jansen & van der Maas, 1997, 2001a, 2002a; van der Maas, 1993; van der Maas, Jansen, & Raijmakers, 2004), reaching and grasping in infants (Wimmers, Savelsbergh, van der Kamp, & Hartelman, 1998; Wimmers, Savelsbergh, Beek, & Hopkins, 1998), and syntactic development (Ruhland & van Geert, 1998; Van Dijk & van Geert, 2007). The results show that rapid, jumpwise development takes place in a variety of domains. However, it remains unclear whether these

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changes are real discontinuities in the bifurcation sense. In addition, they seem to occur in some children, but not all. A problem with discontinuities is that the empirical detection depends on the definition given by the researcher (Van Dijk & van Geert, 2007).

(Dis-)Continuities in Embedded–embodied Agents?

The question is whether this particular branch of bifurcation dynamics is appropriate for dealing with developmental (dis)continuities. The discontinuity approach employed in the developmental studies referred to earlier employed the cusp catastrophe model, which implicitly focuses on simple dynamical systems – namely, those that can be described by means of two control parameters. Control parameters can be estimated as regression functions of any set of parameters, however (Guastello, 1987, 1988; Hartelman et al., 1998). Children are instances of a considerably more complex kind of dynamics. An example of a complex dynamic is Thelen and Smith's model of the dynamics of embedded and embodied action and thought (Smith, 2005; Thelen & Smith, 1994), or Fischer's dynamic skill theory (Fischer & Bidell, 2006). The model of embedded–embodied dynamics claims that thought is a process driven by the continuous dynamic coupling of an organism to an environment. Intelligence is not in the head but in the interface of person and environment. Examples of developmental studies along these lines are those on object permanence in infants and on word learning (Clearfield, Diedrich, Smith, & Thelen, 2006; Jones & Smith, 2002; Kersten & Smith, 2002; Ryalls & Smith, 2000; Samuelson & Smith, 2000; Sandhofer, Smith, & Luo, 2000; Spencer, Smith, & Thelen, 2001a; Thelen, Schöner, Scheier, & Smith, 2001; Smith, Thelen, Titzer, & McLin, 1999; Yoshida & Smith, 2001). In this embodied–embeddedness view, what I earlier called a developmental state is in fact a temporary construction of relationships between the organism's overt and covert actions and components and aspects of the context, related to a descriptive developmental framework. A child's acting and reaching in a so-called A-not-B error problem situation, in which objects are hidden in front of the infant, involves a variety of real-time events, such as visually focusing on the object display, reaching and grasping, refocusing as a result of that, and so forth. Nowhere in this process is an entity called "object concept," which causes the child to act in a particular way (for a similar point, see the discussion on theory of mind earlier in this chapter).

However, the absence of such entity does not mean that one cannot assign a developmental state or level to this series of actions. The particular properties of this process definitely map onto a descriptive framework of developmental levels and states, but the mapping is not unequivocal. That is, the relationship between an actual process of thought and action and a particular developmental level can be ambiguous or fuzzy. Actual, ongoing processes of thought and action are complex sequences that can involve elements and properties of various developmental levels or states simultaneously. If they do, they are likely to

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change, more or less rapidly across developmental time, into processes that are more coherent in terms of their functional or formal properties. That is, such processes are likely to move toward more stable and coherent attractor states, the developmental specification of which is relatively unequivocal. Where does this leave us with regard to the (dis)continuity issue? The answer is that a complex developmental system – a child acting in and with the world – maps onto a developmental geometry (a system specifying developmental levels or states) in a complex way. It can create processes that have properties of developmental states that are in themselves mutually incompatible, given their formal properties. Although I realize the dangers of the comparison, actual thought-and-action processes, as conceived by dynamic skill theory or the theory of embodied action and thought, are like quantum physical states in that a kind of superposition principle applies. They can be in different states at the same time (van Geert & Steenbeek, 2005). A more down-to-earth description of the phenomenon involves fuzzy logic, describing a phenomenon by means of continuous membership functions, instead of discrete membership functions that apply to mutually exclusive categories (van Geert, 2002). This sort of mixture of properties, which is fairly characteristic of complex dynamical systems, is different from the notion of simple continuity (or discontinuity) that applies to low-dimensional phenomena (phenomena that can be described relatively exhaustively by means of only a few linear dimensions).

This overview suggests that there exist so many kinds of transitional and stagelike phenomena in development that the question "Are there stages in development?" should be considered as unanswerable – or better, should be considered not the right kind of question. The basic issue should be this: Is there any general dynamic principle underlying the process of human development, and, if so, what is the pattern of change that results from it? Is it smooth, coarse, continuous, discontinuous, stagelike, or maybe a bit of everything?

The Pattern of Developmental Change

Imagine the following thought experiment. Suppose you have a direct, unlimited, and durable access to all of a child's actions, including his covert thoughts and the components of the context with which the child interacts. Suppose also that you are able to map any point of this long-term time series onto a developmental geometry. Remember that a developmental geometry is a state space consisting of all dimensions, properties, or variables that you need to describe sufficiently the child's actions and capabilities from a developmental viewpoint. Dimensions are quantitative (e.g., the sheer number of words in the lexicon) or of a more structural, qualitative kind. Examples of the latter are descriptions of actions in terms of cognitive structures (e.g., a cognition concerns a relation between representations, versus a relation between relations; see Dawson, Fischer, & Stein, 2006; Dawson-Tunik, Commons, Wilson, & Fischer, 2005a; Fischer & Dawson, 2002; Rose & Fischer, 1998). Other examples

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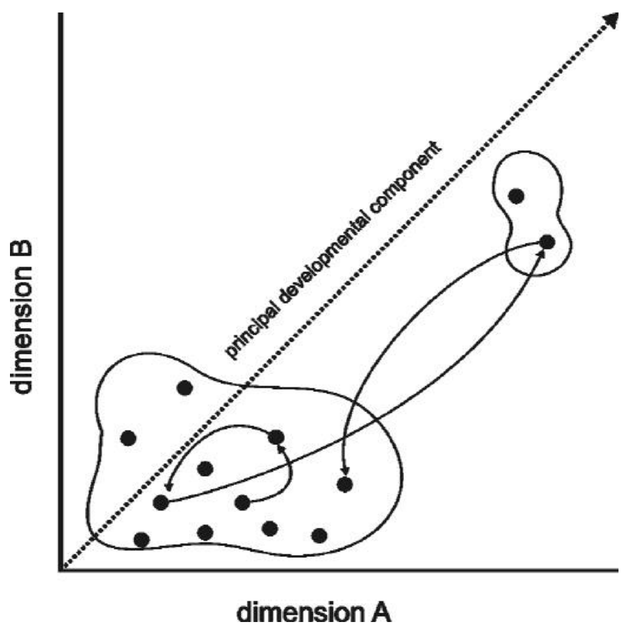

Figure 8.2. An imaginary developmental state space, with two descriptive dimensions, A and B, and a principal developmental component. Dots represent positions in the space corresponding with a concrete action or experience in real time, arrows represent successions between actions or experiences. The distribution is bimodal, with a dominant mode on the low end of the developmental component.

concern cognitive strategies in various degrees of developmental complexity, as in Siegler's often-studied balance scale task (Boom & ter Laak, 2007; Jansen & van der Maas, 2001b, 2002b; Quinlan, van der Maas, Jansen, Booij, & Rendell, 2007; Siegler, 2005; Turner & Thomas, 2002; van der Maas & Jansen, 2003; van Rijn, van Someren, & van der Maas, 2003). An example from language development concerns developmentally ordered syntactic patterns – for instance, patterns of word-order use in learners of German as a foreign language (Pienemann, 2007). What distinguishes learners (or moments in the learning process, for that matter) is the relative frequency with which any of the patterns is used in spontaneous language. Whatever the nature of these dimensions, I consider them primarily as descriptive reference points, comparable to using dimensions of longitude and latitude to describe a particular place on the globe.

If you determine a developing child's position in the descriptive state, you will obtain a point (or cloud, collection of patches, or whatever else is an appropriate description) that moves through the state space and in fact specifies the child's developmental trajectory. The geometry of the state space allows one to specify the distance between any pair of points on the trajectory and thus to specify the rate of change at any point in time (see Fig. 8.2).

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What would the graph of the rate of change over time look like? In the preceding section, potential answers to this question have already been suggested. The classical developmental theories predict a stepwise pattern, whereas modern stage theorists would predict a somewhat fuzzy stepwise form, rounded off by the various moments at which context- and domain-specific transitions take place. The majority of developmentalists would probably be inclined to see the many small transitions and likely continuous changes as a summative process averaging out to something that looks relatively linear, leveling off toward adulthood. Another possibility I discuss in this section is that the developmental distance curve will consist of many steps of different magnitudes, statistically distributed according to a power law. The distribution across time would probably also follow a kind of power law, with the distances in time between the major shifts exponentially increasing. Why would this be so?

Are Developmental Transitions Phase Transitions?

One possibility is that what has traditionally been called stages are states that form the natural attractors of the developing system. They are comparable, in that sense, to the phases of physical matter (gaseous, liquid, solid) and depend, in essence, on a single parameter or a confluence of parameters. In the language of synergetics, the developmental stages (if any exist) are the states defined by the developmental system's major order parameter, and they are determined by the system's major control parameters, which are, in all likelihood, the cumulative amount of experience on the one hand, and maturation – in particular, brain maturation – on the other hand (it goes without saying that this is an extremely simplified representation of reality, but what matters here is the principle, not the details). Developmental stages form attractor states in that they are represented by habitual, coherent patterns of performance, skill, or action that self-organize spontaneously in the person's habitual contexts, niches, or living spaces. These patterns consist of mutually supportive and sustaining features. To give a simple example, Piaget's sensorimotor stage defines thought in the form of external action on objects. For instance, reaching to and grasping an object requires the coordination in real time of myriad components or aspects, including the coordination of the muscles in the arm and hand, the coordination of vision and movement, the coordination of vision of the object and vision of the own arm and hand, and so forth. These patterns are not innately given but self-organize through processes that eventually amount to discontinuous changes; a particularly nice example is given in Wimmer's studies of early prehension development (Wimmers, Beek, & Savelsbergh, 1998; Wimmers, Savelsbergh, van der Kamp, & Hartelman, 1998b; Wimmers, Beek, & van Wieringen, 1992). The characteristic feature of these sensorimotor patterns is that their contextual self-organization (e.g., in the form of reaching to and grasping a particular object) emerges on the basis of dominant driving forces or control parameters that are of a sensory and motor nature. See, for instance, dynamic field theory (Erlhagen & Schöner, 2002; Schutte, Spencer, & Schöner, 2003) and in particular its application to infant problem solving (Schutte & Spencer, 2002; Spencer, Smith, & Thelen, 2001b). In addition, the sensory and motor control parameters of infant action are likely to be biologically preadapted to important features of the environment, such as object–person distinctions, numerosity, and so on (Spelke & Kinzler, 2007; Wimmers, Beek et al., 1998; Wimmers, Savelsbergh et al., 1998; Wimmers et al., 1992). A characteristic feature of these sensorimotor patterns is that there is likely to be little influence of control parameters from language or long-term memories in symbolic representational form. The latter type of control parameters emerge later in development, helping the skill and action patterns self-organize in different ways, characteristic of later and higher-developed stages.

The question is whether there is any empirical evidence suggesting that major developmental stages, if any occur, amount to phase transitions. Indirect evidence comes from calculating the relative durations of these stages over the life span. Irrespective of the stage theory under consideration, the durations tend to increase in a logarithmic manner (van Geert, 1994).

Are Developmental Transitions Caused by Self-Organized Criticality?

One might ask if the distribution of stage durations relates to the power law distribution characteristic of self-organizing phenomena (Van Orden, Holden, & Turvey, 2005; Pincus & Guastello, 2005) and, more particularly, to self-organized criticality (Bak, 1996). The phenomenon of self-organized criticality emerges in complex systems, consisting of many components that entertain local relationships. The embodied–embedded brain (or its semantic transformation, the mind) is such a system, consisting of many components (perceptions, thoughts, actions, memories, tools, environments) that are temporally and functionally connected. This complex system is under a certain external "tension": The person has an ongoing stream of experiences. There are problems to solve, goals to achieve. The person does so by means of the complex system of skills, knowledge, and sensory and motor systems. Not every action is successful, and the person adapts, learning from his or her experiences and from being taught by other people. This complex, interconnected system exchanging information with the world is a likely example of a system that shows self-organized criticality. Its attractor states are critical states, that is, states for which any external influence can cause patterns of change with a wide variety of magnitude and duration, dissipating the stress that has been build up in the system. Note the major difference from a phase transition model, in which the attractor states are the phases, whereas in a critical transition model, the attractor states are those where a transition might occur.

The magnitudes and durations of changes are statistically distributed according to a power law distribution, with few large-scale changes and increasing

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numbers of smaller scale changes. It is tempting to see development as an example of such a self-organized criticality: a succession of metastable states punctuated by changes of various magnitude (e.g., a relatively small change in a relatively context-specific problem-solving strategy versus an avalanche of changes in many aspects and domains of cognitive performance, the latter characteristic of which would count as a stage transition).

Is there any reason development should show self-organized criticality? To begin with, it has a number of features that are characteristic of such systems. It consists of a great many components (e.g., perceptual, motor, linguistic, cognitive, emotional skills and combinations thereof; knowledge; memories) with local connectivity. For instance, two perceptual skills share more components than a perceptual and a linguistic skill; some skills are mutually supportive through the effect of their performance, whereas others can be mutually competitive (van Geert, 1991, 1996, 2003). Thus if for some reason something changes in one skill (or knowledge, ability, action pattern, habit), it is likely to affect other skills (habits, etc.) to the extent that these two developmental components are interrelated. However, the second component, affected by the first, can eventually affect a third one to which it is connected, and so forth. In principle, such changes can remain quite limited, but they can also grow into an avalanche of changes that affects the whole developmental system. If we assume that in a developing system the "weakest," that is, the least adapted or effective skills (habits, knowledge), are eliminated (or altered) more easily than better-adapted or more effective skills, we wind up with a system that closely resembles the Bak–Sneppen model of biological evolution through punctuated equilibria (Bak & Sneppen, 1993; Boettcher & Paczuski, 1996). This model of evolution changes through many events of extinction and speciation, interspersed with periods of stasis.

Although most of the evolutionary changes are small, the evolutionary record counts a few major extinction–speciation events, corresponding with rapid shifts in the structure of the global ecosystem. The pattern of change is clearly reminiscent of the course of human development, with many small and a few major changes. The principle of eliminating or altering the weakest component is also applied in a routine for solving hard optimization problems, called extremal optimization (Boettcher & Percus, 2000). The solution patterns are characterized by shifts following the power law distribution. In a certain sense, (cognitive) development is like solving a hard optimization problem, an adaptation of knowledge and skills to the complexities of reality. It would thus not be surprising that the general dynamic structure of cognitive development follows a pattern very close to that of the extremal optimization process, including the power law distribution of the changes.

Transitions in a Complex System with Developmental Dynamics

Although the similarity between the Bak–Sneppen model of evolution and development is tempting, there is a major difference that might jeopardize the

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applicability of the self-organized criticality model. In essence, the species ecology of the evolutionary model is a closed system of interacting species; physical environmental circumstances are treated as implicit constants. The environment of a species consists of other species that it feeds on or that feed on it; for an example in biological ecosystems, related to catastrophic changes, see Scheffer and Carpenter (2003). The ecology of a developing system, such a young child has more of a dual nature, in that it is in essence an interacting system of an organism in an environment. The developing system consists of the abilities or effectivities of an individual, substantiated in the individual's brain and body, and the affordances and properties of a physical, social and cultural environment in which the individual lives and acts. This environment is also specifically adapted and adapting to the individual, in the form of protection, education, teaching and so forth. Let us call these subsystems, for convenience, the endo-system and exo-system, respectively. Although development takes place through the dynamic interface between these two coupled systems (action, as described in the section on short-term dynamics), the coacting systems should be treated separately to understand the dynamics of development. Adaptations (changes, alterations, eliminations) of components in the endo-system (the individual) or in the exo-system (the environment as it is accessed by the individual) occur through local and temporal coordinations of components in the two subsystems (i.e., actions). Adaptation does not occur through continuous elimination of weakest elements, all acting simultaneously, as is the case in the species ecology. Thus the first principle of a developmental dynamics is that it occurs through short-term events consisting of couplings or coordination, in time, between the endo- and exo-system.

Whereas the evolutionary (and optimization) dynamics occurred through elimination (or alteration) of the weakest components and correlated changes in the associated components, developmental dynamics occurs through a different mechanism. I found the inspiration for the basic mechanism in the work of Piaget and Vygotsky. They see development as the result of what I have freely termed *conservative* and *progressive* forces. The abstract dynamics of development based on these notions can be explained as follows. Let us begin with the geometric notion of development as specified earlier, that is, the developing system defined as a manifold of dimensions or variables, describing all of its relevant developmental properties. Because all those dimensions can be ordered along a scale of developmental progress (a developmental "ruler"), the developmental state space is thus characterized by a principal component that can be used to specify any kind of developmental progress or succession. At any point in time, a developing system occupies a particular region of the developmental space. This region can be relatively condensed, but it can also be scattered across the state space in diverse ways. For instance, if a child alternates between solving a problem in either a less or more developmentally advanced way (see for instance the examples of the balance scale rules), it occupies two regions in the developmental space between which it shifts randomly. Any point or region

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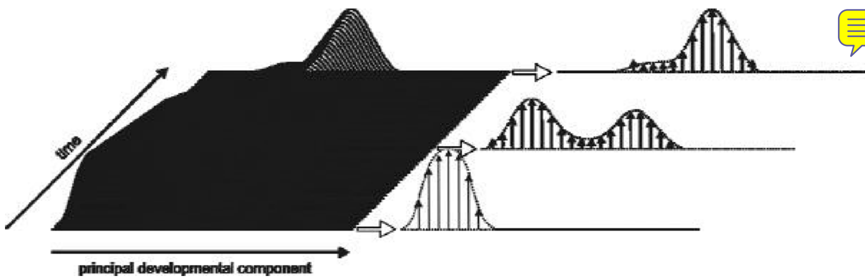

Figure 8.3. Probability functions of developmental levels assigned to potential actions or experiences of a child across time. The probability wave moves from a dominant mode on the left to a bimodal mode in the middle to a dominant mode on the right (see the three probability functions with vectors at the right).

in the developmental state space can be mapped onto the principal component of the space, that is, the general developmental distance introduced above. Any point or region in the space has a certain probability of being "visited" by the developing system. These probabilities can be represented as a vector field, with an activation vector for each point in the developmental principal component or distance dimension. The vector field can specify a single peak, in which case the developmental state of the individual is crisp and unimodal (the classical ideal), or a landscape of peaks, in which case the developmental state of the individual is multimodal, fluctuating, and fuzzy (which is more like reality; see Fig. 8.3).

Development can then be represented as the change of the vector field over time, beginning with a dominant mode in the lower and ending with a dominant mode in the upper regions. The short-term dynamics of development consists of the individual's actions, experiences, and interactions in real time. The idea is that during any such event the individual functions on a particular level of the developmental distance dimension, that is, his or her actions or experiences are characteristic of this level and invoke knowledge and strategies, contextual support, among others, that are characteristic of this level, and so forth. The level at which an individual operates is a stochastic function of the vector field, with the individual's main modus operandi corresponding with the major peak (or peaks) in the vector field.

The aforementioned conservative and progressive forces, inspired by Piaget and Vygotsky, operate as follows (see van Geert, 1998a, 2000, for an explanation of the model). It is assumed that any activation of components of the developing system in the form of a particular action, experience, or event have a consolidating effect on those components and hence on the developmental level(s) that they represent. The consolidation depends on the functional success of the action or experience in question, that is, on its short-term dynamics in terms of the gradient processes discussed earlier. The consolidation takes place in the form of increasing the vector values at the levels corresponding with the action

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or experience in question. The consolidation function spreads out to nearby regions and becomes negative (reducing vector values) for regions farther away on the developmental distance dimension. It is actually some sort of familiarity effect, which decreases with increasing distance from the actual, or familiar, level.

The developing system is also driven by a second force – namely, novelty – which is a general term for novelty (new things) per se, inspiring curiosity, interest, goal-related activity, and so forth. Novelty is a function that increases with increasing distance from the familiar. Assuming that familiarity and novelty are governed by their own characteristic parameters, there is a point on the developmental distance dimension where the combination of both has a maximal value or optimum (see Fig. 8.3). The vector values corresponding with this point are also upgraded, with an upgrade function that is in principle similar to the conservative upgrade function. A new short-term action or experience will then be a stochastic function of this updated vector field, will cause the vector field to update again, and so forth.

Simulations based on this model of development show that, depending on the values of the main parameters (familiarity and novelty parameters, rate of vector field upgrading, nature of information activating vector loadings, and so forth), a rich landscape of developmental phenomena can be achieved, ranging from stepwise growth as described in the Piagetian and neo-Piagetian theories, to models of overlapping waves of strategies (Siegler), microgenetic fluctuations in performance, and so forth.

A study by Bassano and van Geert (2007) illustrates the process of the emergence of three successive syntactic generators: the holophrastic, combinatorial, and syntactic generators. The holophrastic generator is basically a "one-word grammar," that is, the set of early grammatical principles that generate utterances with a characteristic word length of one. The combinatorial generator is the developmentally more advanced set of principles that generate combinations of words, typically two per utterance. The syntactic generator is the set of principles that use the syntactic rules of sentence formation typical of mature language. Although the frequency of spontaneously produced sentence types most likely associated with either of these types (one-word, two- to three-word, and four-plus-word sentences) comes and goes in a pattern of continuous waves, there are two periods of increased variability that mark the transitions from a dominant holophrastic to a combinatorial, and from a dominant combinatorial to a syntactic generator. A continuous growth model can explain the pattern of frequencies but not the peaks of variability, which require the conservative–progressive forces model explained earlier (see Fig. 8.4).

Fuzziness, Ambiguity, and the Developmental Construction of Novelty

As developmental psychologists primarily interested in real-life manifestations of development, doing research in naturalistic settings, my collaborators and

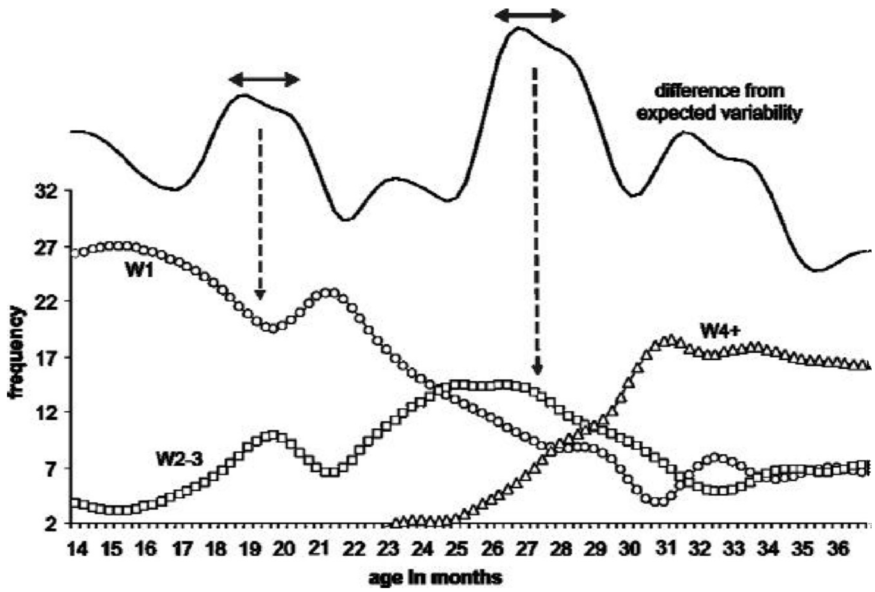

Figure 8.4. Waves of one-word, two- to three-word, and four-plus-word sentences in Pauline, between the age of 14 to 37 months (based on data from Bassano & Van Geert, 2007). Two peaks of increased variability correspond with assumed transitions between dominant modes of sentence production (holophrastic, combinatorial, and syntactic, respectively).

I are frequently confronted with issues of interpretation of what we see, and also with the fact that what we see today is not necessarily the same thing as what we will see tomorrow. The standard interpretation of these observations is that they reflect measurement problems – more precisely, problems of reliability caused by superposition of noise on the data. The interpretation issue – for instance, deciding whether an observed phenomenon is in reality an instance of a category A or of a category B – is seen as a problem of signal detection. The noisy signal is either an A or a B, and given the observed properties, we estimate a certain probability that it is an A, for instance. In terms of class membership, the observed phenomenon has either a class membership of 1 with regard to the class A (and by implication a class membership of 0 to B) or vice versa. In fuzzy logic, however, class memberships can have any value between A and B, and the phenomenon can be a bit of A and a bit of B. It is likely that such fuzziness, leading to disagreements among observers who take the possibility of unanimity for granted (among others), is a typical footprint of complex nonlinear dynamical systems.

In language development, for instance, a child is constructing a linguistic system and linguistic categories. There is a time at which no sign exists in

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the child's language of categories, such as verbs or prepositions (the words the child uses may sound like the words that are verbs or prepositions in the adult's language, but in the child's language, they do not yet have the syntactic properties that such categories need to have). The trajectory toward verbs and prepositions is paved with linguistic forms that are highly fuzzy or ambiguous (some linguists call them "proto"-prepositions or verbs, for instance, or fillers; see Peters, 2001). The problem is not that a particular word of a child spoken in a conversation is "really" a preposition and that the information needed for the observer to make a correct decision is not yet present in the child's performance. The problem is rather that the word is truly ambiguous, truly undecidable from the point of view of the descriptive syntactic system, and that this ambiguity is characteristic for a system at a certain level of syntactic development. It is possible to quantify degrees of ambiguity, among others, by taking observer disagreement as information and to use the changes in ambiguity over time as a time-serial indicator of underlying developmental processes (van Dijk & van Geert, 2005; van Geert & van Dijk, 2002, 2003).

The issue of fluctuation that I discussed in the context of developmental transitions is yet another example of fuzziness and ambiguity in development. If a child fluctuates between various developmental levels over a short period of time, its developmental level is ambiguous or, more precisely, bimodal or multimodal, which is a phenomenon that I discussed earlier. It is even possible for a child to display a particular developmental level in his or her verbal behavior that is different from the level expressed in its motor actions (Garber & Goldin-Meadow, 2002; Goldin-Meadow, 1997, 2000; Goldin-Meadow & Singer, 2003; Özçaliskan & Goldin-Meadow, 2005). This form of superposition of developmental-levels is characteristic of the way complex systems relate to descriptive frameworks, such as developmental level frameworks, that make crisp categorical distinctions to describe a world that is in essence ambiguous, fuzzy, and seemingly contradictory.

Another form of fluctuation concerns the occurrence of relatively isolated spikes or surges in the use of developmentally more advanced forms, superposed onto developmental trajectories that are continuous and even linear. See, for example, our study on the development of spatial prepositions (van Dijk & van Geert, 2007).

A typical developmental form of fluctuation is what one might call initial state fluctuation. Adaptive functions in babies, such as crying and other vocalizations of unease, touching, and smiling, but also physiological reactions to stress, seem to show a broad range of fluctuation in the beginning, zooming in onto a narrower band of fluctuation that seems best adapted to the infant's current environment (de Weerth & van Geert, 1998, 2000; 2002a; de Weerth, van Geert, & Hoijtink, 1999; for reactions to stress, see de Weerth & van Geert, 2002b). The phenomenon has a clear evolutionary and developmental functionality: A

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newborn does not "know" the environment in which it will be placed and thus profits from a broad range of possibilities at the beginning.

And Where's the Brain?

In this era of brain research and neuroscience, an overwhelming and rapidly growing literature emerges showing how the activity of the brain relates to behavior and performance. The suggestion is that an understanding of how the brain develops is the key to our understanding of development on the level of observable actions. Sometimes the implicit message is that development is driven by brain development and that brain development is like an autonomous trajectory; see, for instance, the discussion on brain-based education in Fischer et al. (2007) and Bruer (2002). The brain is part of the complex system of the individual acting and developing in his or her habitat or environment. The development of the brain has its own self-organizing properties and constraints (Lewis, 2005a, 2005b), but this is not to say that development is unidirectionally driven by the brain any more than the development of the brain is unidirectionally driven by the properties of the environment.

Any attempt to understand how the brain and the environment interact in development must reckon with two things. The first is that there is no direct brain–environment interaction (one needs a science fiction movie for that); the interaction is a theoretical abstraction of what in reality amounts to a conscious, embodied agent trying to accomplish his intentions and goals in a concrete, cultural and social environment. The second is that the constituents of the game (e.g., the brain, the body, actions evolving in time, context, environments, cultural artifacts, etc.) are not inert components modeled by causal influences from elsewhere but that they have their own dynamic constraints and possibilities, their own self-organizing tendencies given the overall system in which they function and develop.

An interesting illustration of these principles is the phenomenon of brain plasticity, which is the brain's ability to be shaped by experience, resulting in the brain's facilitation of new experiences, which result in further brain adaptation, and so on (Nelson, 1999). The phenomenon of brain plasticity typically invokes a recursive or iterative mechanism characteristic of the mutualistic dynamics of development in general. Brain plasticity is not another word for brain development: Experience can alter brain structure long after brain development is complete (Kolb & Whishaw, 1998).

Brain plasticity is not a constant property of the brain but a typical dynamic property that is nonlinearly dependent on the brain's developmental history. The change in plasticity is not simply linear or curvilinear, as suggested by the notion of a gradual decline in plasticity as the person grows older. Rather, there are nonlinear peaks of plasticity, known as critical periods or sensitive periods. These critical or sensitive periods in which the brain is particularly sensitive to

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particular experiences are in themselves also self-organizing and dynamical phenomena (Bruer, 2001). They emerge epigenetically from the brain's development and are thus codependent on biological brain growth and the unfolding of experiences, including teaching and learning over developmental time (Knudsen, 2004; Thomas & Johnson, 2006).

A dramatic illustration of how brain plasticity – and development as a whole, for that matter – always passes through the short-term dynamics of action is the development of children after hemispherectomy. Hemispherectomy is the surgical removal of a brain hemisphere, mostly as a last possibility for curing major and highly frequent epileptic insults that cannot be treated pharmacologically (Battro, 2001; Immordino-Yang, 2005; Vargha-Khadem, Carr, Isaacs, & Brett, 1997).

In a recent study, Immordino-Yang (2005, 2007) described the developmental trajectory of Nico and Brooke. Nico lost his right hemisphere at age three, Brooke his left hemisphere at age eleven. Both showed remarkable recovery in that they learned to function extraordinarily well, given the seriousness of the neurological impairment. According to Immordino-Yang (2007), the boys' developmental trajectories show the active role of the learner as well as the organizing role of emotion, which brings us back to the issue of the relationship between the long-term dynamics of development and the short-term dynamics of action and emotional appraisal. Above all, the boys demonstrate the incredible plasticity of the developmental system as well as the fact that self-organizing development occurs through the investment of all the available personal, social, and cultural resources.

Conclusion: The Complex Dynamics of Development

The course of human development over the life span is a prime example of a complex nonlinear dynamical system. The process of development is recursive and self-organizing. It occurs simultaneously at many levels of organization – for example, the individual person and the person in interaction with others, institutions, and cultures to which the person relates. These levels of organization encompass processes on various time scales.

Unfortunately, the current field of developmental psychology tends to simplify the complexity by taking out most of the features that are fundamental to development as a complex nonlinear dynamical system. It attempts to linearize the developmental process by focusing on differences among persons in samples as a source of information about underlying processes, and by doing so largely fails in uncovering the mechanisms of developmental change and the properties of the individual developmental trajectories.

In this chapter, I have focused on the interdependence of processes of long-term change in the form of developmental, life-span processes on one hand and short-term processes of action on the other. However, more time scales can

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be distinguished and should be incorporated into a comprehensive theory of development.

Understanding the long-term developmental changes requires that we take into account that development occurs to a system of an individual embedded in a network of environmental niches and thus that development is a process distributed over the person and the contexts in which that person acts, on the basis of his or her changing concerns and the changing means and tools used to realize them.

To obtain a better understanding of the underlying processes of development, I have discussed three issues that refer to characteristic features of the developmental system as a complex, NDS. The first issue relates to the classical problem of stages and modern views on stages as relatively stable organizations that emerge as soft assemblies in supportive environments and with time can become less dependent on the exact properties or fine-tuning of the supportive environments (e.g., Fischer's approach to stages). The gist of the stage question is not whether there "are" stages, how many there are, and what the ages are at which they occur. The importance of the stage question is that it relates to the possibility of attractor states forming in complex and to the issue of phase transitions and criticality. In this chapter, I have discussed yet another perspective on such developmental attractors states, namely, that of the developmental system as a probability wave over the principal components of the system, including continuous as well as discontinuous changes. The form of change and (dis)continuity provides further information about the nature of the underlying mechanisms that govern developmental change.

The second issue discusses the relationship between the scientific observer of the complex NDS and the system itself and focuses on fuzziness, ambiguity, and multimodality. Instead of discarding such properties as primarily relating to measurement error and lack of information, we should see them as actual fingerprints of complexity, giving us more insight into the processes that we attempt to understand. A final question concerned the relation to brain development and the embodied brain as part of the larger self-organizing system, the development of which is codependent on the behaviors, actions, and contexts it makes possible.

To conclude, the structure of the developmental process far outreaches the triviality of explained variances and associations between variables and will continue to surprise us as long as we keep an open eye to the paradoxical relationship between the magnificent simplicity of its fundamental principles and the complexity of its forms, trajectories, and outcomes.

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