Education and development as complex dynamic agent systems: how theory informs methodology

Henderien Steenbeek

Paul van Geert

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Corresponding author: Henderien Steenbeek PhD, University of Groningen, the Netherlands, h.w.steenbeek@rug.nl, 0031 50 363 7993

P.L.C. van Geert, University of Groningen, the Netherlands, p.l.c.van.geert@rug.nl

University of Groningen

Department of Developmental Psychology,

Grote Kruisstraat 2/1

9712 TS Groningen

The Netherlands

1 Introduction

In order to study education and development, researchers can choose among a plethora of methods. The Merriam-Webster dictionary tells us that “method” means: a procedure or process for attaining an object …such as …a systematic procedure, technique, or mode of inquiry employed by or proper to a particular discipline or art “ or “a way, technique, or process of or for doing something”, or “a body of skills or techniques”. Methods proper to the scientific study of education and development cover a very broad range of procedures, ranging from how to formulate and ask questions, how to design studies for answering such questions, how to perform such studies in real-world contexts, how to extract data and how to process them, how to relate processed data to answers on questions, how to communicate such questions and answers, and how to apply them to real world activities aimed at promoting education and development. This body of methods is customarily termed “methodology”, which is a concept that includes the methods themselves but also our understanding of their relationships and their rational and scientific justification. Let us call this body of methods and the justifications “Integrative methodology”. Researchers often tend to see this integrative methodology as a more or less autonomous set of good practice prescriptions. This view is consistent with practices of academic training in which methodology courses are offered separate from courses on disciplinarian contents, e.g. courses on development or educational science. As a consequence of this autonomy oriented view of methodology, scientific questions regarding development and education tend to be framed in terms of the available or habitual methods. For instance, we readily transform or translate concrete questions about the influence of some particular educational intervention in terms of a statistically significant difference between 2 representative samples that systematically differ in only one variable or feature of interest, which, in this case, is the intervention. Almost every word in this translation carries the heavy burden of methodological principles, concepts and presuppositions: “statistically”, “significant”, “difference”, “representative”, “sample”, “systematically”, “variable”, and “intervention”. And all these principles, concepts and presuppositions are taken from this autonomous body of integrative methodology, which forms our indisputable cookbook of good practices, outside of which no good — scientific — practices exist. The answers to questions that are shaped by this independent body of methodology will then contribute to existing theories of development and education. In this sense, it is the (allegedly) independent methodology that informs theory.

In this chapter, we will move against this current practice and make the — apparently deeply obvious — claim that it must be theory that informs the questions and the way we shall answer these questions. That is, it must be theory – that is, your body of justified knowledge about a particular phenomenon – that informs, influences and determines methodology, that is, the whole of methods, procedures and instruments that you use to study that phenomenon. . The sort of theory that should inform integrative methodology must be an *integrative* theory, that is to say a theory consisting of a consistent set of general principles and concepts shaping the domains of inquiry, which in this particular case are the related domains of development and education.

In this chapter, we suggest that the integrative theory that can serve as the basis of integrative methodology is the theory of complex dynamic agent systems. We shall explain this general theory by focusing on teaching-learning processes in the educational context, and on pedagogical actions and dynamic assessment in the classroom. We argue that the question of the assessment of educational and developmental systems is informed by addressing questions like: '*what is a complex educational/developmental dynamic system*?', "*What, in the context of such systems, is an agent and a community of agents?".* But it should also be informed by questions of practice and application, for instance 'given this particular integrative theory, *how does assessment look like in the work of practice assessors, such as teachers*?' '*how does this assessment influence teachers' instructional strategies'*?. We will draw upon examples using primary school teachers and students, and teachers and students in Teachers College, and will also focus on educational situations involving children exhibiting atypical patterns of development (AD). We invoke Fischer's (1980; Mascolo & Fischer, 2015) dynamic skill theory to understand processes that operate on the micro-developmental timescale (e.g., students' reasoning skills) and we will argue that microdevelopmental analyses help us to understand change on the macro-time scale.

We begin with a discussion on the nature of complex dynamic agent systems and their properties, and how educational/developmental processes can be understood as dynamic systems.

2. Complex Dynamic Agent Systems: What and How?

2.1 Self-Organization and Emergence

A complex dynamic system can be defined as a network of components that interact with each other. Examples are neurons in the brain, students and a teacher in a class, or classroom activities as they occur within the school itself. These examples illustrate that complex dynamic systems may be defined on various levels of organization, and that one level of organization may incorporate subordinate levels, each of which can be described as a complex dynamic system. These interactions lead to — and consequently originate from — *self-organization* and *emergence*.

Self-organization means that the network of components organizes itself (that is without external supervision) into a particular pattern of temporarily self-sustaining relationships among components. For example, in any given classroom, particular, self-sustaining patterns of interaction organize spontaneously between children and their teacher. Such self-organizing, temporarily self-sustaining patterns are customarily called *attractors* of the system because the system or some of its sub-systems tend to evolve toward it spontaneously, given certain starting conditions. 'Self-sustaining' means that systems resist external perturbations, at least to a certain extent. External perturbations, when they occur, may function for the better or for the worse. For instance, in a class characterized by a pattern of low-quality teaching and disorder, an intervention aimed at helping the teacher to reorganize the teaching would constitute a perturbation. As is commonly known from intervention research, the inadequate and disorderly pattern of interaction – the attractor — may resist the perturbation for a long time. Similarly, positive changes that occur during the intervention can rapidly disappear once the intervention has stopped, and the old inadequate class interaction pattern is restored (Wetzels, Steenbeek, & van Geert, 2016). Under various conditions, the self-sustaining nature of the attractor pattern can shift, if the external conditions change (e.g. as in the case of an intervention) or if the pattern has fulfilled a particular function. An example of the latter include episodes in which teachers provide explanations to students, which, once understood, are replaced by other, temporarily self-sustaining patterns, as might occur when students begin to work independently on an explained assignment (see Geveke et al., 2017). In short, a particular class — a teacher-student system — may be characterized by a number of such typical attractor states and shifts among them.

Geveke and co-authors made video recordings of authentic teacher-student interactions in the context of science lessons, which were then coded by means of a coding system specifically designed to capture the nature of the student-teacher interactions (Geveke, 2017). In order to demonstrate the existence of patterns of attractor states in the time series, i.e. temporal sequences of coded events, *of each individual* class, the authors employed techniques that are typically used in the context of data mining (signal smoothing, principal component analyses, Kohonen cluster analysis). The fundamental level of analysis in this study was the level of the individual class, because it is at this level that the student-teacher dynamics takes place. This approach is very different from the standard approach, in which individual cases are seen as error- or noise-laden observations of an underlying "real" pattern that can be revealed by averaging over many individual cases. Such procedure is based on the belief that such averaging cancels out the noise or measurement errors given in each individual case. In the study by Geveke et al. (2017), characteristic similarities and differences between cases were explored only after each individual class was analyzed as a separate case with its own, idiosyncratic properties.

Emergence means that the interactions between the components of a system lead to the origination of properties that are new, in the sense that they transcend the properties of the components taken separately. For instance, an individual student's learning process functions as a complex dynamic system. The components of this system can include various forms of memory and knowledge, aspects of emotion, the student's language and communicative skills, as they operate within a student's characteristic niche, (e.g., the student's familiar environment). For a particular problem context (e.g. a math context at school), the particular pattern of thinking and acting produced by a particular student emerges as a product of the relations among the components of the student-teacher-context system. For example, imagine that a student, when asked by her teacher, is able to multiple 10 x 10 to achieve the product of 100. Imagine further that, upon completing the task, on request, the student is able to successfully divide 100 by 10. In addition, when asked about the relation between these two operations, the student is able to identify *division* as the *inverse* of *multiplication*. This insight is an example of what Fischer (1980) would call abstract mappings. In this particular situation, the student — with our without some help of the teacher — constructs a relationship of complementarity between 2 sets of subordinates relationships, namely the relationships between numbers involved in the principle of multiplication, and the relationships between numbers involved in the principle of division. In this particular situation, the constructed abstract mapping is an *emergent* property of the way the relevant components in the student's system (including the contribution of the teacher) interact in the *here-and-now*. The idea underlying this abstract mapping, namely that that division is the inverse of multiplication is not present in either of the component operations separately. Further, the mapping operates as an overarching pattern that might be relatively self-sustaining in the sense that if the current problem conditions reoccur in the future, a form of abstract mapping could again emerge in that new context. In that sense, the abstract mapping should not be seen as some sort of internally stored cognitive rule that is ready to be "taken out" of some sort of internal cognitive toolbox, as a carpenter might take a particular screwdriver out of a toolbox (Fischer & Van Geert, 2009; Van Geert & Fischer, 2014). Nevertheless, such patterns may be relatively self-sustaining; that is, they may become consolidated into typical attractor patterns in the sense described above.

This view on educational interaction patterns as emergent, temporarily self-sustaining phenomena provides an interesting conceptual and methodological background for the analysis of the processes by which teaching and learning organize over time in educational settings (). For instance, in a study of individual math instruction in special education, Steenbeek, Jansen & Van Geert (2012) followed the sequence of math instruction events in 5 children over the course of 2 years. The researchers were interested in processes of self organization and emergence, which, they hoped, would manifest themselves in the form of relatively stable patterns of instruction in math performance events and in the form of spontaneous transitions to new patterns. The researchers focused on variables such as response matches (i.e., to what extent does the response of the student match a teacher's remark, question, etc. or vice a versa) and self-iterations (e.g. teacher's asking a question and giving the answer oneself). In order to find such patterns and transitions, the authors used nonstandard statistical techniques particularly suited for the relatively small number of observations in their time series, namely Monte Carlo analysis (computer simulation of the null hypothesis), change point analysis (a technique a statistical technique to determine sudden changes in averages and/or standard deviation of variables in a time series; Bai & Perron, 2003) and decision trees (which is a form of machine learning). As in the Geveke et al. (2017) study, the choice of these statistical methods was explicitly informed by the underlying theory and the associated hypotheses of emergence of new stable patterns of interaction.

2.2. Layers of Organization and Time Scales

2.2.1. Layers of organization

Self-organization pertains to the organization of the system in different layers, including, layer-specific components and their interactions. For example, in education and development, the system of interest can be defined in terms of the within-individual layer of organization, and the researcher's attention would focus on the dynamics of within-individual processes such as emotion, memory, action, etc. The dynamics of the within individual layer arise from interactions between the *within-individual* properties and components of the contextual niche in which the individual operates. An example of this level of organization is the emergence of a student's understanding of the relation between division and multiplication discussed above. Focus on the within-individual system is often the preferred level of description of developmental theories. For instance, a developmental theories such as that of Piaget (Piaget & Inhelder, 1969/2000) or of Fischer (1980; Van Geert & Fischer, 2009; Fischer & Van Geert, 2014) describe how individuals develop, that is, how within-individual properties such as cognitive structures, change across developmental time. Although such changes occur as a result of an individual's interactions with other people within cultural contexts, the theory's focus remains at the individual level and on within-individual changes.

Another level of organization that provides an important — or we should say the major — perspective on processes of education and development is the *between-individual* layer (see also Mascolo, 2016; 2017; about the intersubjective level of psychological knowledge). On this level, the system consists of individual persons (with different within-individual properties) in relation to each other. Social interactions (i.e., communication, joint action etc.) proceed using material objects and cultural artifacts. To understand the dynamics on this level, the components of the between-individual dynamics should be conceived of as *agents* (e.g Steenbeek & Van Geert, 2007; 2008; 2013). We shall discuss the notion of agency as well (next section), as it features in a complex dynamic systems approach to development and education, in a separate section.

A third level of organization that is of interest in the study of education and development occurs on the *supra-individual* level in which the components are defined as ‘above-individual’ groups or organizations, such as classes, schools, school districts, and governments.. Decisions that are taken on this level of organization have a direct impact on the other levels of organization. Various political, bureaucratic and school level decisions have an effect on the other levels, i.e., influence teachers’ functioning, such as their adaptation to new working methods in schools, and in that sense influence both the first and the second level (Adelman & Taylor, 2003; Goldspink, 2007; Wetzels et al., 2016). However, this third level is also influenced by what happens in the first and second level; e.g. school regulations about appropriate social relations between student and teachers are influenced by what occurs on the between-individual level (e.g. in real-time interactions in the classroom between a teacher and her students), and in the within-individual level (e.g. in the interplay between a teacher’s acts, thoughts, and feelings in her functioning as a teacher).

These layers of organization serve as perspective for understanding what are in fact multiply-nested and interpenetrating systems. The within-individual layer, for instance, cannot be properly understood independent of the between-individual and supra-individual layers of organization. Conversely, a between-individual perspective — for instance on teaching-learning interactions in a class —must occur in conjunction with both within- individual (e.g. a description individuals as agents) and supra-individual (the organizational structures in which the interactions between persons take place) perspectives. Note that there are some similarities here with the levels of contexts that Bronfenbrenner (1995) distinguishes in the bioecological system model that stresses the interactive, reciprocal effects of the characteristics of the individual and the multiple contexts in which development occurs, together forming the system in which children function and develop (Bronfenbrenner & Morris, 2007).

2.2.2. Timescales

In addition to being organized on different levels, complex dynamic systems operate on a variety of connected timescales. Irrespective of the actual level of organization chosen (e.g. either the within-or the between-individual level), the system will show behavior, i.e., changes in time, on a short term timescale (sometimes called ‘real-time’, or the timescale ´of human conscious actions´), or on a long term timescale. The latter is also being defined as *developmental* time; the time over which development takes place. What exactly constitutes short-term or long-term (and anything in between) timescales depends on the level of organization one as chosen as one's perspective, on a particular complex system. For instance, on the between-individual level, changes in interaction between the participants in an activity on a second-to-second or minute to minute scale, are typically short-term. Changes in the "nature" of a particular relationship — for instance between parents and their children —typically arise and become consolidated over longer-terms, such as months and years. Similarly, effects of teaching, such as teaching children to read and write, are typically defined on a long-term timescale of months or years. Events on diverse timescales are causally connected. To say that timescales are "connected" means that what happens on the short-term timescale of actual interactions has an effect on long-term changes, and vice-versa. Thus, at the start of an individual instruction of a teacher to a student, the student has a certain level of understanding of the topic at hand. This level of understanding determines what the student will bring into the interaction during individual instruction. The teacher will respond to and act upon the level of understanding that the student shows.

What happens during the short-term (the actual conversation, as can be measured using micro-measures) determines what the student will learn over the long-term time scale; i.e. her understanding of arithmetic..

Each timescale is characterized by its own dynamics. Short-term dynamics are co-dependent on the context and on external influences and perturbations, as well as on the properties that have emerged as a consequence of the long-term dynamics of learning and development. That is to say, in a complex dynamic system, the dynamics not only depend on the nature of the connections among the components of the system, but also on the nature of the connections between and among the various levels of organization and the various timescales.

The study by Steenbeek, Jansen & Van Geert (2012) on emergent patterns and individual math instruction (see the section on self-organization and emergence) also explicitly addresses the notion of timescales. In addition to studying long-term changes in the nature of the instruction dynamics over the course of 2 years, the authors also studied the typical short-term changes in the variables of interest (such as response match and self-iteration) over the course of a single lesson. The short-term dynamics was described in the form of so-called transition graphs, which are graphical representations of the sequences of events that take place during a lesson. This graphical format allows the reader to immediately see the qualitative difference between short-term dynamics before and after a transition to a new, emergent pattern.

- *Insert figure 1 here –*

The results of the short term dynamics of scaffolding indicated that the change points (indicating transitions) found on the long term were clearly reflected in the dynamics on the short term time scale. As can be seen in figure 1, both before and after the transition, there was a clear pattern of consistent asymmetry with regard to the ratio teacher- and student self-iterations, whereas a dramatic change could be observed in the ratio matches and mismatches. This latter finding seems to underpin the indeed difficult interaction dynamics between this teacher and the student with emotional behavioral problems, which deteriorated over time. In addition to using transition graphs, researchers focusing on the dynamics of interaction and or learning are now using a variety of techniques. A typical technique, specifically designed to visually show the nature of developmental and educational processes taking place on a variety of timescales, is the state space grid (Hollenstein, 2013; for applications in education see Van Vondel et al., 2017). The grid consists of every possible combination of events or behaviors taking place in the participants of an interaction (or in the components of a process of learning or development). Arrows are used to show the sequence of events over time, and the thickness of the arrows can be used to represent the frequency with which such sequences occur in a particular individual process. The sequences represented in the grid can be subjected to calculations and statistical tests that are typically developed for the purpose of understanding the dynamics of developmental and educational processes.

- *Insert figure 2 –*

Figure 2 gives an example of using SSG to show the quality of the interaction dynamics between students and teacher in two different primary school classes, during science education. The student utterances are depicted on the y-as using an ordinal scale of scientific understanding (non-complex; sensorimotor; representation; abstraction). The teacher utterances are shown on the x-axis using an ordinal scale of extent of stimulation (instruction; information; closed question; encouragement; follow up). Q1 represents non-optimal interaction patterns: no co-construction; non-complex student and non-stimulating teacher utterances (match). Q2 represents suboptimal interaction patterns: complex student utterances and non-stimulating teacher utterances (mismatch). Q3 represents suboptimal interaction patterns: non-complex student utterances and stimulating teacher utterances (mismatch). Finally, Q4 represents optimal co-construction: complex student utterances and stimulating teacher utterances (match).

2.3. Agency and inter-agency/ action and inter-action

The agent perspective is in the first place a practical and intuitive perspective about agents operating in concrete situations that guides their actions and interactions. That is to say, it is a perspective that guides inter-agency, i.e., interaction. The practical importance of this perspective is illustrated, among others, by the fact that this understanding of agency emerges already very early in development (Blijd & Van Geert, 2016). However, researchers in the educational and learning sciences often work with an ability perspective of agents instead. But learning incorporates both a cognitive and a social component which are intertwining elements, forming a dynamic whole. That is, they cannot be separated as distinct factors, i.e., the person who learns (a cognitive activity) often does so in the context of help by another person (social activity), the help being determined by the ongoing learning (Cobb & Yackel, 1998; Lerman, 1998). All this occurs in the form of actions, carried out by agents. Therefore, taking an agent perspective is important for getting a grip on teaching-learning processes.

What do the notions of agent and agency entail? Agents have interests, desires, goals and concerns they wish to realize or accomplish (Frijda, 2001; Deci & Ryan, 2000). They have a behavioral repertoire to accomplish their concerns, organized in the form of a wide variety of skills. They perceive, explore and evaluate their immediate environments — including other agents — in function of their interests, goals and concerns. Agents have tools to act upon the environment such as to realize their goals, desires, concerns and so forth. These tools can be physical organs (the Greek word *organon* means tool or instrument) or (potential) patterns of activity in the form of skills. Agents evaluate events in the form of emotions, which correspond with specific forms of action readiness. They have knowledge of their environment that they infer from their own perception, memories of past events and communication with other agents. Their knowledge takes the form of beliefs about what is the case in the environment they act upon. Agents have expectations; they anticipate what will happen, and organize their actions around their expectations and anticipations. They act with a certain drive or energy and make choices that depend on the perceived or evaluated relationship between their interests, goals and concerns on the one hand, and the actual context. In social agents, such as human beings, the major part of the environment or the contexts of action are other agents, and action takes the form of inter-action with other agents, that is to say, of joint activity patterns. These activity patterns emerge out of the participating agents' interests, concerns, goals, knowledge, perceptions, emotions, in short of all components that are characteristic of an agent. Agents may differ in all these components, including the skills they have for initiating and participating in interaction patterns, that is to say, in patterns that transcend the properties of the agents' individual actions or individual contributions to the interaction pattern.

In order to serve as a theoretical framework for our analyses of developmental and educational interaction patterns, we believe that the agent perspective should be an integrated component of a complex dynamic systems theory of education and development. Since development and education are systems of interacting agents, we can ask ourselves what the theoretical and methodological consequences are of incorporating agency into a complex dynamic systems approach.

The first consequence of combining agency with complex dynamic systems is an altered view on the nature of complex dynamic systems themselves. In a typical, let's say physical, complex system, the next state of the system is determined by the current state, i.e. by its immediate past, or immediate precedent state. However, in systems of agents the current state of the system contains information[1] about the long-term past. They are systems that are shaped by their history: agents adapt to the possibilities and challenges of their environments, which means that the past has shaped the agents' memory, and that learning has taken place. Another typical property of agent systems is that their behavior (what they do) is not only determined by immediate and the more remote past, but that it is also determined by the agent's representations of the future. The future in this particular case takes the form of expectations of events to come, of anticipations, of goals that the agent wishes to achieve, of intentions that the agent wishes to realize, of the

[1] Note that *information* is a term with a very broad meaning. Particularly in this context it should not be identified with a record of past events, or internal mental representations of one's past. This type of record is only one form of information an organism can have about its past. Changes in the organism's action readiness on the basis of past experiences, i.e. on the basis of learning, should also be considered as information about the organisms' past.

specific action readiness, and so forth. The fact that agents are capable of projecting their current states into a potential future state, that they wish to achieve by means of action, is a direct consequence of the fact that agents themselves are extremely complex systems, equipped with organs, perceptual systems, brains and so forth, and in the case of humans, that they create cultural artifacts that extend their organismic possibilities (such as books or computers that are in a sense material extensions of their memory and cognitive functions). The fact that actions and interactions are not only determined by the system's past — which is not the real past, but the past as it is represented in or reflected by the systems' current physical and contextual properties — but also by the systems' future — which is a future in the form of present intentions, desires, anticipations, expectations, and readiness — has considerable consequences for our view on the particular form of agent interaction that we catch under the terms of education, development, teaching and learning, as we shall see in some of the themes discussed further in this chapter.

3. How theory structures methodology in studying education studying

3.1 Agency in teacher-student interaction

3.1.1 Components of (inter-)action as emergent phenomena

The perspective of complex dynamic systems suggests that agent properties such as intentions, goals, and concerns, but also skills and emotions should be seen as emergent phenomena, i.e., emerging out of the action and interaction itself (Steenbeek & Van Geert, 2007, 2008). For instance, in an interaction, a person might have the intention, intention to achieve something with the other person, make him do something such as solving an addition problem, or make him believe something, such as persuading the other person that he or she can solve that problem without help. This intention may emerge as a consequence of perceiving particular opportunities, or particular impediments. For instance, an educator might see a particular educational opportunity in the here-and-now activity of the child with whom he is interacting. Consequently and immediately, an educational intention to achieve a particular short-term educational goal may emerge as a consequence of this perception of an opportunity. Put in somewhat different terms, one could say that an educator perceives certain activities of the student in terms of educational affordances, i.e. educational action potentialities. Hence, an educator's ability to look at a child from an educational perspective, and by doing so open the possibility of seeing specific educational opportunities, is an important part of the educator’s educational skill. Of course, seeing opportunities and emergent educational intentions are always based on or embedded in the educator’s past, i.e. his or her experiences and professional training. The skills used to achieve certain goals — in this case emergent educational goals — should also be seen as emergent phenomena themselves, namely patterns of actions inter-activity that self-organize in the current context (Thelen and Smith, 1996, spoke about *soft assembly* in this regard, see also Fischer & Van Geert, 2009). Again, such soft assembly or self-organization always takes place against the context of the educator’s and the child’s past, in the form of their experiences and what they have learned from earlier interactions. In order to empirically study such processes of soft assembly and self-organization, researchers must analyze the short-term processes of action and communication that take place between an educator and a child, for instance in the context of solving a particular kind of problem. In our studies, we have focused on very young children’s understanding in the form of explanations and predictions of scientific phenomena, in the form of simple mechanical interactions, air pressure or floating and sinking. Thus, instead of administering a validated test that is supposed to measure the child’s “true” knowledge of a phenomenon such as air pressure for instance, we have meticulously analyzed the sequence of steps in the construction of such understanding during a real-time activity of problem-solving (Van der Steen, Steenbeek, Van Dijk, Van Geert, 2014; Meindertsma, Van Dijk, Steenbeek, & van Geert, 2014: Guevara, Van Dijk, van Geert, 2016. For instance, in a science education lesson the teacher works with a group of 9 -10 year old students (upper grade/ regular education). She places two piles with books of equal height next to each other (in between: 15 centimeter; 5.9 inch), on top of both piles lies a paper sheet. She then asks the students what will happen when one blows underneath the paper sheet. One of the students replies: ‘I have no idea’. The teacher then asks the same question again: ‘what do you think will happen with the paper sheet?’. All these (and the subsequent) utterances are coded and analyzed.

Whether one chooses for the method of validated tests or for the method of analyzing the sequence of events in a real-time problem-solving activity of a child and an educator (or a class and the teacher) is entirely determined by one’s underlying theory. A researcher who has a theory that knowledge is an enduring internal representation that can be retrieved by means of a test (theory A), will choose for the method of the validated test. A researcher who has a theory that knowledge emerges in a process of construction that is embedded in a particular real-time context (theory B) will use the method of observation, coding and analysis of concrete problem-solving processes. It is important to note that the validity of theory A versus theory B will not be determined by the empirical outcomes of the type of studies based on either of the theories. For a theory A person, the real-time construction process is a set aside as an unstandardized and uncontrolled event that is unable to measure the real underlying knowledge of the child. For a theory B person, the validated test is nothing but a very particular, limited and a typical construction process resulting in a score that tells nothing about the embedded and enacting knowledge construction process. The validity of theory A and theory B must be determined on the basis of much more general criteria, namely how plausible theories A or B are in light of what we know about complex phenomena such as biological human beings growing up in complex cultural and material contexts. Given the hinterland of knowledge about such phenomena, our bet is that the odds are very much in favor of the B theory — complex dynamic agent systems — and does very much in favor of methods that are in line with such theory.

3.1.2 The role of reflection in the emergence of educational interaction patterns

In the preceding sections, we have seen that an educational interaction pattern should be viewed as a pattern emerging out of the actions of the teacher as well as of the learner, with the actions themselves depending on how one participant perceives the opportunities or affordances of the actions of the other. In addition, educational interaction patterns may differ in the extent to which they actually serve the goals and concerns of the participants (for instance in cases where the goals and concerns of student and teacher contradict each other, Steenbeek & Van Geert, 2013).

- Insert figure 3 about here -

Figure 3 shows how interactions emerge on the basis of actions that take the form of iterative loops. “Iterative” means that the next state (e.g. the next action) is the consequence of the preceding action, i.e., that the preceding loop or action forms the occasion and condition for the origination of the next action. Inter-actions are formed out of two types of action, namely between-person actions and within-person actions. The between-person actions take the form of perception-action loops. For instance, in an educational interaction a student perceives or observes what he or she himself is doing in addition to what the teacher is doing (e.g. the student perceives that the teacher is demonstrating a solution procedure for a calculation the student is making), and acts upon that perception (e.g. by carefully listening and imitating the steps explained by the teacher, or by expressing signs of distraction and frustration). These actions of the students are perceived by the teacher, who then acts upon that perception with a certain type of response. The within-person actions take the form of emotional appraisals of what happens, of evaluations in terms of the current goals or concerns, of reflections and thoughts about what happens in the situation and so forth.

Very often, reflections and speculations of one of the participants about what happens in a particular situation (and why) require an amount of time that is not always in accordance with the time scale of the evolving action itself. For instance, if the teacher needs reflection time each time a student does something in the context of the current activity, such as writing down a number at the start of a particular calculation, the interaction would probably slow down and come to a standstill. Hence, reflective activities typically occur if the smoothness of the interaction has been disturbed anyway, for instance, if something has happened that the teacher cannot immediately interpret, such as an unexpected error or unexpected solution given by a student, or by some form of disturbance that does not match the current flow of teaching events.

It is important to note that these components of interactions, such as perceptions, actions, emotional appraisals and reflections depend on the person's knowledge and expectations, that is to say on the person's (teacher and student) "mental models" of the situation in which the person is currently involved. Mental models are traditionally seen as internal representations, i.e. internal schemes or models that are retrieved if they are needed and compared with the information given. However, in a complex dynamic agent systems framework, mental models are themselves emergent phenomena, patterns that emerge on the interactions between the person and the context in a particular situation (for instance, that of a student making an unexpected mistake on a particular math assignment). That is to say, they are patterns of perception, understanding, explanation or interpretation that are constructed on the spot, based on the constructors' knowledge and past experiences and on the current perceived context. Being emergent patterns, they tend to converge on certain stable pattern characteristics. They tend to converge on person-specific attractors (see our discussion of typical attractor patterns studied by Geveke et al., 2017). These attractors, i.e. these patterns of perception and interpretation typical of a particular person, form an expression of that person's "mental model" of the situation in question (in this section we focus on the teacher, but the general principles discussed here apply just as well to the students). For instance, while reflecting on a particular educational situation, or while observing the activity of a particular student, teachers currently often converge on an interpretation heavily inspired by psychological deficit models. This deficit or disorder interpretation occurs if teachers are trying to interpret all signals they pick up from a student's actions in terms of – often overly simplistic and biased – knowledge about psychopathological conditions such as ADHD, dyslexia, ASD, and so forth (see te Meerman, Batstra, Grietens & Frances, 2017).

But what if the teacher has been introduced to another kind of thinking and perceiving, namely one that is inspired by the theory of complex dynamic systems? A teacher (female, age 32, teaching experience 5 years who learned about principles and properties of a CDS perspective on development and learning, such as agency and the role of interaction) filled in a questionnaire, containing four open questions, focusing on 1. her prior knowledge, 2. what she had learned in the course, 3. in what way her knowledge and skills was changed, and finally, 4. how she applies this newly learned knowledge in her actions in the classroom. Her answers show that learning about CDS approach to educational processes changed both her knowledge and her actions in the classroom, in that she was much more aware of the dynamic character of interaction processes. For instance, she reports to consciously use differentiation while interacting with students in order to examine what their individual potentialities are, in order for her to guide her further actions.

3.1.3. Educational (inter-)action on a variety of timescales

The theory of complex dynamic systems suggests that agent properties such as intentions, goals, concerns skills, and emotions occur on a variety of timescales and on a variety of levels of organization. The events on each time scale or level of organization have their own dynamics, but the timescales and organization levels are coupled in such a way that they influence each other. In section 2.2.2 we have already discussed the study by Steenbeek, Janssen & Van Geert (2012) which sought to unravel among others, the links between, on the one hand, the dynamics of a real-time instructional interaction between a teacher and a student in special education, and, the dynamics of long-term stability and sudden transitions to a different pattern of real-time instruction dynamics. Studying the combination of short and long-term timescales requires a deliberate methodological choice, based on a theory that explains how and why these timescales are intertwined. One should not expect that a study such as this one will result in a causal explanation of why the described interaction patterns emerge and why they relatively suddenly change. Such a type of causal explanation might be beyond the possibilities of research of complex human phenomena, which change and stabilize as a consequence of the myriad of interactions on all levels of organization and timescales involved. However, studies as this one might begin to provide hints about the nature of the underlying processes and hints about how such processes may be guided and transformed. Hence, the methodological question is not whether a study such as that of Steenbeek et al. (2012) delivers knowledge that is generalizable to the population. The methodological question should be about the potential contribution of this and comparable studies to the lengthy *process* of generalization to which each of these studies can contribute. A single-case (or small-n study fort that matter) provides a model of the time course of a learning-teaching process that provides a framework of interpretation and expectation for a following up study. The results of that new study may lead to a verification, alteration or revision of the time course model. Our understanding of the learning-teaching processes that these studies focus on, increases as more and more of such individual studies are done and connected with one another. This type of replication and model revision is not different from what happens with large-n studies that claim direct generalization to the population level. The current discussion on reproducibility has shown that the allegedly generalizable results of many such studies cannot be replicated (e.g. Zwaan, Lucas & Donella, 2017). That is, also in studies with large samples, claiming direct generalizability to the population level, generalization must be accomplished by a series of replication studies.

An important component of action and interaction are the goals or intentions of the participating agents. In an educational interaction, an agent's intentions exist on the level of immediate, real-time action, and are likely to take the form of attention to particular kinds of information and particular kinds of actions consistent with that information. For instance, a child driven by a willingness to learn a particular skill might be sensitive to those actions and communications from an adult that will help her to learn this skill. The intentionality of this situation is immediate, context specific, emergent on the actual conditions of the situation, and most likely intuitive and non-discursive (meaning that it does not occur in the form of some sort of explicit, conscious representation corresponding with a statement such as "I now want to learn this or that"). One could also say that the educational intentions are *enacted*, rather than explicitly represented, that they are *embodied*, in the sense that they take the form of direct bodily activity, and that they are *embedded* (or *situated*) in the sense that they exist by virtue of the current, ongoing interactional context. In the same vein, an educator's current, situation-bound intentions to help a child learn or achieve something may equally be emergent on the actual situation, and may equally be intuitive, immediate and non-discursive. But in addition to this immediate and intuitive nature, the perceptions and actions of a competent educator may reflect a high level of educational skill. In a different situation or in another educator, those perceptions, interpretations and actions might eventually reflect a low level of educational skill and the inability to provide adequate educational support, which we think is a source of teacher stress (Jennings et al., 2017).

Intentions to learn or to teach may also take the form of long-term patterns, for instance explicit long-term educational goals that an educator can reflect on, that emerge on the basis of his experiences and professional learning, that are recorded in the form of written documents of educational policies, and so forth (see Van Geert & Steenbeek, 2014, for a discussion in the context of a complexity approach). The short term and long term educational intentions are causally intertwined. Long-term educational intentions may have a direct influence on short-term, intuitive intentional educational activities. On the other hand, short-term intentions and the resulting educational activities, which might be successful or not, may have a direct influence on the educator's long-term educational goals or intentions, for instance in the form of a personal interpretation of these long-term goals, and their achievability by means of concrete educational activities. Note however that the coupling may vary between very weak to very strong. This type of mutual causal influences between educational phenomena on different time scales produces particular trajectories of learning and teaching, which might be successful or unsuccessful, and which might be modelled by means of dynamic systems simulations (see for instance Steenbeek & Van Geert, 2013).

- Insert figure 4A about here -

In summary, long and short-term aspects of educational agency — which involve actions on the level of teacher and student, parent and child, policymaker and educational practitioner — have their own dynamics in addition to being causally intertwined (Van Geert and Steenbeek, 2014).

In the next section, we shall focus on the role of the teacher, and on the teacher's educational goals (defined broadly as the complex of educational intentions, concerns, desires, specific goals and so forth) and the educational skills that are needed to achieve those goals..

3.2. Studying Pedagogical Action

3.2.1 Pedagogical actions, educational goals and educational skills

Students' educational goals

Skills and goals are distributed across the participants in the educational activity. For instance, schoolchildren have *educational goals* in the sense of representations of what they must learn, of ideas on what sort of professional they want to become, what sort of competences they wish to achieve and so forth. These goals may be typically short-term ("what is it that the teacher wants me to accomplish with this particular learning activity or assignment", or "what is it that I want to accomplish with making this particular math assignment"), but they are also typically long-term ("what sort of person do I want to become", "what are the competences I want to achieve through learning and education", etc.). These goals may be highly variable or not, dependent to greater or lesser extent on the actual context, they may be fuzzy, intuitive or they may be quite explicit, and so forth. All these variations and variability are typical of the dynamics of educational goals in the educated persons (but in the educators as well). In a study on the effect of an aggression reduction intervention in special education, we explicitly addressed the children's ideas about the goals they wished to accomplish by behaving aggressively towards others, and the goals they inferred from the intervention to which they were subjected (Visser, Singer, Van Geert & Kunnen, 2009). By explicitly incorporating the children's complex intentions and goals, it was possible to arrive at a better understanding of the contradictory outcomes of the intervention. In fact, we did not treat the intervention as a separate causal factor, endowed with an intrinsic effectiveness, which could be freely transported to other intervention conditions. On the contrary, the intervention was seen as a highly context-specific unfolding of a particular process of interaction, embedded in the broader range of interaction processes and agent intentions of the children at this particular school (Visser, Kunnen & Van Geert, 2010; see also Wetzels, Steenbeek & Van Geert, 2016, for a broader methodological discussion).

Educational goals and skills of teachers

The unfolding of educational interaction processes depends on the intertwining of goals and intentions of all participants involved. Educators, for instance teachers, have long-term educational goals which are based on policy documents, stating what the government wants them to achieve with students, goals which are based on their daily experience in the class with the educational activities they engage in, goals based on their professional training, communication with their colleagues, and goals based on any combination thereof. They have short-term educational goals in the form of direct and immediate intuitions of what they want a particular student to understand or do in a particular educational activity or assignment and which are emergent on the actual educational activity context that evolves in real-time.

Educational skills are present in the teachers or educators, and in the persons who are taught or educated. For instance, schoolchildren have particular educational skills, namely skills that allow them — to various extents — to actively and productively participate in educational and teaching activities, for instance variable levels of ability to learn from particular forms of teaching, variable levels of ability to focus on learning assignments, variable levels of ability to trigger adequate educational support from their educators of teachers, and so forth.

Teachers´ educational skills take a typical long-term form as more or less stable educational and pedagogical skills, in the form of a particular potential to provide more or less adequate educational support and guidance in the variety of educational situations that is typical of their particular profession (e.g. a teacher in special education might have a different sort of educational skills than a teacher in regular education). The short-term educational skill amounts to the actual processes of educational interactions that "self-assemble" in concrete educational events, with concrete students. As we noted before, these educational activities are emergent patterns in the sense that they emerge out of the activities of the participants, and transcend the sum of the component actions. These real-time activities are characterized by a certain flow or smoothness, which is high if competent teachers and competent students are interacting, and which is a low, intermittent, shaky or coming to an early standstill where such educational competence is lacking. In this sense, Kurt Fischer's notion of a dynamic skill, as a variable pattern incorporating the support or resistances of the context, can also be applied to the concept of educational skills, in educating as well as in educated persons.

- Insert figure 4B about here -

The dynamics driving these processes on the distinct timescales are clearly different. Take for instance the process of educational skill in the teacher that evolves over the short-term timescale versus the long-term timescale. On the short-term timescale, the educational skill is typically driven by the logic of immediate perception-action loops, with the actual perceptions and actions dependent on the evolving contexts as well as on the educational skill as a long-term property of the educator in question (see figure 4A). The perceptions, for instance, involve perceptions of a particular student's skill as it is expressed in the student's here-and-now performance, or perceptions of educational opportunities in this particular context. The actions involve actual questions asked to the student, actual support given, when and where to give the student the opportunity to solve the problem on his own and so forth. These actions are dependent on the current action context (i.e., on which immediately precedes in this action context) and on the educational, pedagogical and didactic skills as long-term, more or less stable properties of the teacher (note that a comparable story could be told for the student, with educational perceptions and educational actions from the perspective of the student as an active agent in this educational activity).

3.2.2 Pedagogical Action and Educational Assessment

Traditionally, assessment takes the form of 'measuring', 'evaluating', 'valuating', or 'taxing' and is defined as collecting relevant information that may be relied on for making decisions. An important question concerns the status of the information that is collected, i.e., what information is considered to be *relevant*? The relevance always gets its meaning in the light of the specific aim of the assessment. These aims can differ broadly. No matter what the aim is, in all these cases it is important that the child's skills are viewed in relation to the context the child functions in, i.e. 'in order of merit' at this particular point in time: The child's skills that are assessed are 'dynamic' skills (Steenbeek & van Geert, 2017).

Instead of following the traditional methodological path, we will discuss aspects of pedagogical actions and dynamic assessment of a child's skills in the light of the CDS principles and properties as discussed in the previous section, such as agency, layers of organization and layers of time-scales. Our starting point is the above described notion of actions in the classroom that take the form of iterative perception-action loops, on the within-person layer of organization. We will argue that dynamic assessment ideally takes place in these iterative perception-action loops during interaction, on the short-term -time scale, e.g. during instruction sessions. These short-term iterative perception action loops are considered to be the basis of getting a grip on describing and explaining students' learning processes over diverse layers of time scales, such as developmental time, and on possible (un)wanted attractor states that emerge, i.e., whether students' learning progress takes the form of 'successful' or 'unsuccessful' trajectories over time (Steenbeek, Jansen, & van Geert, 2013). A 'successful' learning trajectory can then be defined as a learning trajectory in which the learner shows the progress in acquiring new knowledge and skills that is expected on the basis of the learner's personal capabilities and the quality of the education provided, based on task-oriented engagement and activity in the learner himself (see also Clements & Sarama, 2004; Crosnoe et al., 2010; Sarama & Clements, 2009). This is typically what we would call a successful trajectory (see section 4.1). In contrast, a learner with an unsuccessful learning trajectory lags behind the progress in acquiring new knowledge and skills that the learner is supposed to make given the learner's capabilities and the educator's pedagogical skills (Steenbeek & van Geert, 2013).

3.2.3 The (in-) ability to provide adequate educational support and teacher stress

Unsuccessful learning-teaching trajectories are characterized by a perceived chronicle gap between the intended and the actual learning-teaching trajectory. The intentions might be those of the teacher, or those of educational policymakers who have a particular goal in mind for a particular population of learners (e.g. students in special education). If such a – perceived – chronicle gap occurs, teachers often experience an *in*ability to provide adequate educational support, which easily results in teacher stress (Jennings et al., 2017). The literature tends to attribute teachers' experience of stress to intrinsic problems in the students with whom they work, such as behavioral problems, low SEL(Greene, Beszterczey, Katzenstein, Park, & Goring, 2002), or emotional behavioral problems (Hofstetter, Steenbeek, & Bijstra, 2014). However, just as the interaction patterns with those students are emergent phenomena — in which intentions and skills of all participants involved definitely play a role — stress is an emergent phenomenon. Stress might enter into a self-amplifying loop, because teachers who experience high levels of stress and frustration may transmit these feelings and their impacts directly to students via 'stress-contagion' (Wethington, 2000, p. 234). How does this 'stress-contagion' take place, , i.e., as related to the iterative perception-action loop? Goei and Kleijnen (2009) define teacher's inability to provide educational support asthe issues that teachers mention or experience– such as doubt, stress, deficits in knowledge or skills, deficits in competences, - in not being able to act in a goal-oriented way within the action space that they have. Thus, the teacher experiences a shortage of possibilities to being able to act in an adequate manner, i.e. a lack of possibilities to enable the student to have a ´succesful´ learning progress. Teachers experience feelings of failure, stress and incompetence, which in too many cases contribute to teachers' burnout complaints or even attrition (Costa, 2011, Jennings, 2017).

Teacher stress is the result of the complex interplay between characteristics of the teacher herself, the student she works with, and contextual factors. Certain student behaviors can lead to teacher stress in a particular school situation, while in another – for instance, a more supporting school context— these student behaviors don't cause teacher stress (or if they do, teacher stress occurs on a manageable level). An important process component is the ongoing 'fit' (or lack thereof) between teacher and student (Van der Wolf & Van Beukering, 2009), i.e., the match between the teacher's educational goals and skills, and those of the student(-s), leading to more or less (in-)adequately iterative perception action loops. The level of teacher stress that a teacher experiences can be conceived of as a direct consequence of a number of preceding here-and-now interaction moments. These experiences contribute to building the overall quality of the teacher-student relationship over time. Over time, possible unwanted – emotionally negative – 'attractor states' (Thelen, 1994; Van Geert, 2003) may emerge, that may become more stable over time, which – among others — lead to increasing levels of teacher stress and demotivation in the teacher and /or the student.

Two sorts of inability can be distinguished, departing from the central notion of *iterative perception-action loops* that take place. A first form implies that a teacher' is unable to *perceive* the educational opportunity (or problem). This means that the iterative perception action loops (see figure 1) do not have a sub-optimal form. Sub-optimality means that the teacher's perception of an educational opportunity in the preceding action of a student is not adequate, which results in a relatively ineffective action of educational support. In a special education setting, for instance, the teacher might act in an over-supportive way, e.g. by solving a particular math problem while the student as nothing else to do but to watch the teacher the work the student is supposed to do.

This event has an effect on the student's perception of the action as being either helpful or not, given the student's goals and intentions, which might be to spend as little effort in the math problem as possible. The student's action, following the action of the teacher, are likely to further consolidate this cycle of passivity and lack of learning progress in the student, which on its turn is a source of increasing frustration in the teacher. This pattern of events has consequences not only for the *between-person* loops, but also for the *within- person* loops that contribute to the dynamics of the interaction, the student's and teacher's emotional appraisals, drives and motivation, and cognitive reflections about the nature of the interaction of the possibilities for action.

A second form of teacher' inability occurs when the teacher perceives a certain problem or possibility adequately , e.g. with regard to classroom management, but *fails to couple an adequate action* to this observation. This causes the iterative perception-action loops again to not run smoothly or optimally. This also has an effect on the student' s perception of the teacher's action, on the subsequent action of the student, and on the consequences for both the between-person loops and the within person loops. Note that one could consider the first form of teacher' inability basically a problem of assessment, and the second form a problem of intervention.

Can this inability be restructured into ability? An example from recent research about the quality of day care centers (Slot, Leseman, Verhagen & Mulder, 2015; Egert, 2015) shows that continuous professionalization on the 'spot', i.e., at the actual work floor, is a good predictor of quality. The same applies to teachers in primary education (See van Vondel et al, 2017: Menninga et al. , 2017). But what should professionalization look like, especially when students with atypical development are in play? We think it should center around iterative perception-action loops as the basis for all pedagogical actions, of cycles in which perception, evaluating, and acting-upon-that-evaluation subsequently follow (Steenbeek & van Geert, 2014). A particularly good method of accomplishing this is the video feedback coaching approach, because it allows teachers and coaches to focus on the ongoing process of student-teacher interaction (Wetzels et al. 2016). While observing student's behavior, the teacher can make use of examining verbal and nonverbal behavior, e.g. by examining what kind of initiatives the student has taken with regard to task behavior. She can reflect on the possible cause of the difficulties by making use of existing dimension scales that help observing the level of problematic behavior that students show in daily classroom situations (Lutz, Fantuzzo & McDermott, 2002: McDermott, Watkins, Rovine & Rikoon, 2013). This helps her to formulate micro-hypotheses about the reason why the student behaves as she does at this particular moment during the lesson. Subsequently, she can test this micro-hypothesis by action and observing at the same time what the student says/ does in reaction to her action. These hypothesis-driven teacher actions are not wrong or right, but can be falsified or verified; the verified hypotheses can be repeated. These continuous perception-action cycles with intermittent cycles of reflection, help the teacher in building up her intuitive expertise with regard to working with this student. This expertise is also of great value in building an educational network around the student with atypical development, together with parents and other educational professionals, which is especially valuable when the student must be placed in other specialized educational settings. Finally, in line with the usefulness of video feedback coaching for teacher professionalization, video recordings of authentic educational interactions are also great sources of learning for teachers in training, because they reflect the ongoing process in its authentic context and with its inherent complexity (Geerts, Steenbeek & Van Geert, 2017).

3.3 Methods for understanding educational complexity

Complex dynamic agent systems are what they say they are, namely *complex*. How can we learn to understand complexity as it features in the context of educational processes? In this section we focus on two different didactical means for promoting understanding of educational complexity. One is the use of simulation models, which enable the user to experiment with the concepts and principles of complex systems "in sillico" as opposed to "in vivo", which is often impossible. The 2nd is the use of a "ruler" for measuring learning-teaching processes in a way that does justice to their inherent dynamic and complex nature, namely Fischer's dynamic skill theory.

3.3.1. The use of simulation models

Simulation models as ways to understand complex realities

The use of simulation models is a method for demonstrating and investigating how a particular dynamic theory actually works. In a linear model where a phenomenon is explained on the basis of an aggregation of contributing factors — for instance one that explains how learning affects are dependent on a wide variety of factors ranging from SES to student motivation — there is no actual need for simulation. A model of additive factors is easy to understand. However, this ease of understanding is no longer warranted in the case of dynamic theories and the models that are inferred from it, for instance dynamic models of teaching and learning. A simulation model shows how dynamic networks of interacting components or factors generates sequences of events over time that capture the main qualitative properties of a particular process of interest (see den Hartigh et al, 2016.), The general idea is that higher-order properties (e.g. a child's level of performance in a particular academic subject) are phenomena that emerge on the basis of the dynamic interactions between lower-level components (Barabási, 2009). The relations between lower-level components, such as concrete behaviors, emotional expressions, perceptions, goals and intentions etc., are expressed in their coupling strengths, and can take the form of supportive or competitive relations, and can be symmetrical as well as asymmetrical (van Geert, 1994, 2003, 2014). In summary, the variables constitute a network of mutual relationships that are not necessarily symmetrical and not necessarily direct (e.g. variable A may affect C via B). Such network models make intuitive sense, but it is very hard to imagine what sort of dynamics — for instance learning trajectories — they produce if one can only rely on graphical representations or an intuition. It is here that simulation models can play an important role, helping a practitioner form an idea of the properties and a variety of dynamic interactions of the type the practitioner tries to manipulate in his own practice.

Note that the primary aim of dynamic simulation models is to understand the basic qualitative properties of a particular dynamics, i.e., of a particular processes as they occur to particular individuals (or dyads). They are not models of statistical associations among variables that occur across samples of individuals. Dynamic simulation models generate descriptions of specific or particular processes, for instance the process that occurs with a particular teacher-student dyads during a sequence of individual instructions. For this reason, dynamic simulation models are in line with the methodology of empirically studying individual cases, and of interpreting a sample or population as a collection of individual cases. A dynamic simulation model typically describes the most general or essential features of a particular dynamics, features that are supposed to be characteristic of a class of phenomena, for instance the phenomenon of educational teacher-student interaction. However, the actual functioning of the dynamics might be highly idiosyncratic, i.e. typical of each particular case. For instance, , a component that exerts a negative influence on a particular ability in one person might have a zero effect or even a positive effect in another , person. In earlier work, we described a dynamic agent model of goal-orientation (Steenbeek, van Geert, 2008, 2013), building on the concerns for autonomy, relatedness, and competence (derived from self-determination theory; Deci & Ryan, 2000) as driving forces for both teacher's and student's emotions and behavior in the classroom. The core of the model consisted of the dynamic interplay between teacher's and student's actions and emotions, in which the former moment influenced the next moment in the interaction process. We concluded that goal orientations and their underlying concerns and content-related interests form dynamic network structures: each concern has a specific but changeable strength, and it is highly likely that the strength changes as a consequence of classroom experiences that emerge out of the relationships between these concerns and interests. This short-term model was used to show how teaching-learning processes get their form in the interaction between student and teacher as autonomous, intentional agents.

In addition, we described a network model of long term development (Steenbeek & Van Geert, 2013) in which a great number of short-term interactions during lessons could be combined into a long sequence of short-term interaction dynamics. Each variable was assumed to have a particular but changeable level. The change in each variable was determined by the dynamic relationship it had with other variables, and these relationships were justified by the short-term dynamics of action. The patterns of dynamic relationships among the variables described particular individual cases, and formed the parameters of the long term model. The question was how these parameters change, stabilize, or sustain each other.

The aim of such modeling is threefold, namely, first, to build *process* theory about relations between variables that build up higher-order properties of all kinds of phenomena, (such as student's learning progress); second, to discover whether the network of dynamically connected variables is able to generate time series that are qualitatively similar to temporal trajectories observed in empirical data, and, third, to find out which patterns of parameter values and connections between the variables are responsible for which types of developmental or educational trajectories. In addition, these models can be used as working model for understanding the underlying dynamic properties of human actions in general. They can also be used as didactic means in teacher training or in academic courses on educational science, to help students build an intuitive but substantiated understanding of dynamics and complexity in their field of training.

An example of a simulation model: a model of scaffolding

Granott and co-authors (Granott, Fischer, & Parziale, 2002) define scaffolding by comparing it with the building of a roman arch. Applied to learning, scaffolding is the use of some “external” support for the student in order to make a particular learning process possible and that can be discarded after the learning has taken place. Scaffolding is an intrinsically dynamic notion in that it describes how a particular level of knowledge or skill in a student changes as a result of the scaffolding process. That is, it describes learning as a result of the help given at a level close to the student's current level of unaided or unassisted performance. The notion of scaffolding implies intertwined perception-action loops in a teacher and in a student or students, and as such it is a typical example of a dynamic system with a potentially complex dynamics. Studying a dynamic simulation model provides an excellent way of getting to understand the complexity of scaffolding, which is a major pedagogical principal in teaching-learning processes.

In our model of scaffolding (2005), we used a *´ruler´* that described both the student's skill level and the teacher’s level of support (Fischer & Dawson, 2002; Fischer & Rose, 1994; Rose & Fischer, 1998), and specified the difference between those levels. The student's *learning rate* is inferred on the basis of the time the pupil needs to achieve the skill that will allow him to do these more difficult tasks without help. The student is expected to interiorize the help given to him (based on Vygotsky's notion of the zone of proximal development; Vygotsky, 1978). This implies that, over time, the student’s skill will advance towards the level incorporated in the teacher's past scaffolding. Running the simulation model, it becomes visible that the teacher's scaffold, more precisely, the competence level embodied in that scaffold, is an attractor for the pupil's current level (the pupil's level moves towards that of the teacher). If the principle of scaffolding is applied successfully, the teacher's scaffolding level will tend to stay ahead of the pupil's competence level, i.e. the student's competence level is a repellor for the teacher's help level (the teacher's level moves away from that of the pupil).

It also becomes clear that three parameters are important in the model. As to the pupil, two parameters govern movement towards the attractor, first, the ´learning rate´ and second the ´optimal scaffolding distance´. The´ learning rate´ parameter determines the speed with which the attractor level is reached, and is related to psychological variables such as general intelligence, domain-specific intelligence or knowledge, and motivation. The ´optimal scaffolding distance´ parameter depicts the distance between the pupil's level and the level of help or scaffolding, for which the learning effect is maximal. By means of varying these parameters, one can study the effect of typical student properties on learning, in the context of the additional properties of the particular scaffolding situation. The change in the teacher's help level is governed by a third parameter, the ´demand-adaptation rate´, which reflects the height of the 'stair-case' of difficulty of subsequent assignments. By varying this parameter — which typically reflects the teacher's pedagogical skills and ability to make adequate assessments of a student's current performance — one can study the effect of different forms of such teacher's skills on the process of learning and teaching in the context of particular student parameter values.

For more information with regard to these parameters and the scaffolding model, we refer to Steenbeek & van Geert, 2005. For now, the most important point is that this model can be used to explore what happens when a teacher's assessment in the iterative perception-action loop is incorrect, or what will happen when teacher's actions are not consistent with her perceptions. This exploration is carried out in an artificial world, namely a mathematical model in a computer program, which follows the rules and principles that we think are operational in the real world. In a split second, the mathematical model provides an image of what would happen if a particular condition of scaffolding would apply. In addition, the model can give direction towards what is worthwhile to empirically examine. Thus, the model can give directions for both teachers´ and researchers´ actions. For instance, practitioners can experiment with the simulation model to visualize the nonlinearity of the various student and teacher parameters, or to visualize the principle of optimal fit between teacher and student properties, and how this relates to learning outcomes.

3.3.2 Using dynamic skill theory on the short term time scale

The hierarchical complexity framework (Fischer, 1980) comprises ten hierarchical, empirically validated, complexity levels of cognitive skills, which describe long-term development from birth to adulthood. Skills refer to structures that are the result of a self-organizing process in the here and now, i.e., an action or cognitive structure that is expressed at that moment. In order to get insight into what happens in short-term interactional processes, and into how change over time is built up, by subsequent series of these short-term interactional processes, we constructed a microgenetic Skill Theory measure, based on Fischer's hierarchical complexity framework (1980), aiming to get insight into students´ reasoning skills in the classroom. This measure (Meindertsma et al, 2013; van der Steen et al, 2014) allowed us to quantify students' behavior on the short term time scale, for assessing change on the long term time scale. In our studies we concentrated on young student's science and technology understanding, and used the Skill Theory measure to describe change in students' scientific reasoning skills, both in lower and upper grade levels of primary school students and their teachers (van der Steen et al, 2014, van Vondel, 2017a, 2017b, Menninga, 2016, 2017). For instance, van Vondel et al (2017) used this measure to code task-related utterances of the upper grade students, by first dividing them in complex or non-complex utterances. Non-complex utterances were utterances related to the task at hand but in which the student did not display any understanding. For instance, the student reads out loud what he needs to do. Complex utterances were observations, predictions and explanations related to the task. Next, students' complex utterances were quantified based on a scale based on dynamic skill theory, using three tiers (see Table 1; Fischer, 1980; Fischer & Bidell, 2006). Van der Steen et al. (2014) used the dynamic skill theory measures to study the emergence of understanding of principles of air pressure in a 4 year old, under the guidance of an adult. The study showed that that the pattern of understanding follows a typical up and down path, consistent with Fischer's notion of scalloping (Fischer, 2008). In addition, the study also showed that this up-and-down pattern was based on initiations by the adult during the first scaffolding session, and that the initiative gradually shifted towards the child to become a typically child driven pattern in the 3rd session.

These and comparable studies lead to the conclusion that the growth of cognitive complexity in children is the result of an underlying dynamics producing typical scalloping patterns on the short-term timescale of real-time interaction, and gradual as well as discontinuous changes in the underlying parameters of the dynamics — such as the probability that a high level of complexity is relatively easily arrived at in a problem-solving situation — on the long-term timescale of learning and development. These patterns of change cannot only be represented quantitatively in the form of numbers and tables, but, maybe more importantly, also in the form of visualization methods that are particularly suited for showing the structure of thought processes over time, such as smoothed the time series (Van der Steen et al., 2014) or state space grids (van Vondel et al., 2017). Such visualizations are made possible by the use of a versatile "ruler" (i.e. dynamic skill theory) in combination with a simple "clock" (i.e. the temporal sequence of events in a single lesson and across a sequence of such lessons).

- Insert table 1 here –

Future applications of this short term Skill Theory Measure can be used to code teacher's pedagogical actions as well. For instance, this measure can also being used to get a grip on complexity levels in teacher's functioning, as they are learners in being teachers (Rodriquez et al, 2013; Geveke, Steenbeek, Doornenbal, & van Geert, 2017). Promising applications seem to be to code complexity levels of teachers' social emotional cognition, and what role it plays in micro-developmental processes that contribute to promoting students with atypical development or disabilities to develop healthy pathways and successful learning trajectories.

4. Conclusion

In conclusion, this chapter discussed the use of a complex dynamic agent systems approach to education and development by focusing on teaching-learning processes in an educational context. and on teachers´ pedagogical actions and students´ dynamic assessment in the classroom. We began with an explanation of complex dynamic agent systems and their properties in the context of education processes. We then explained how such a theory informs the questions we ask, and the ways we try to answer these questions, on issues such as student-teacher interaction, pedagogical assessment and skills, and various methods for arriving at an understanding of the intrinsic process nature of educational phenomena, including their characteristic complexity and nonlinearity.

In this chapter, we have tried to illustrate and substantiate the following main ideas[2]. First, the theory we have should structure not only the questions we ask but also the methods we use to answer such questions. All too often, methodology is seen as an independent body of best practices to empirically answer questions, irrespective of the theory from which such questions originate. In addition, as far as the user is concerned, methodology is customarily seen as a closed

[2] we thank the editors of this book for having pointed out these main trends in our work.

system of procedures out of which the user must choose. New methods, in this view, are developed by methodological specialists, such as statisticians. What we have tried to demonstrate in our work is that methodology is basically open-ended, and that new methods are developed in answer to theory-specific questions and problems. Methodological innovations must primarily come from the researchers themselves, who see the need for particular new methods in light of the theories they try to develop. If one has questions about how processes unfold over time, one should use — and eventually develop — methods that are suited for answering these questions, and that are most often not the standard methods of the dominant research practice, which are typically designed for answering questions about statistical differences between group data.

Second, and related to the latter point, processes as described by a complex dynamic agent theory are phenomena that occur in "individuals" i.e., they pertain to individual cases (e.g. a specific individual, a specific class of students with their teacher etc.). Hence, the design and methods we use should be person- and interaction-oriented rather than population-oriented. As the so-called ergodic theory (Molenaar & Campbell, 2009) clearly states, findings on relationships between variables based on associations in a population are almost always of an entirely different kind than the relationships and mechanisms found on the level of the individual, specific process. In order to understand such processes, one should study individuals and their interactions. This recommendation often clashes with the classical requirement of generalization, "does your finding apply to the population?". However, in our view, generalization is first of all based on the relationship between an underlying theory — which must be general — and an empirical design, methodology and findings (Van Geert, 2011). Empirical generalization to the level of the population is based on knowledge about processes occurring in individuals and individual cases, and can therefore only be achieved by accumulating many such individual based studies and by trying to find commonalities as well as differences.

In a paper published in 1943, Kurt Lewin (1943) said that "A businessman once stated that "there is nothing as practical as a good theory"" (page 118) (which, by the way, means that the famous quote is not originally from Lewin but from some nondescript businessman whom Lewin happened to know)… But we could just as well end this chapter by saying that an *educator* once stated that "there is nothing as practical as a good theory"….

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Figures

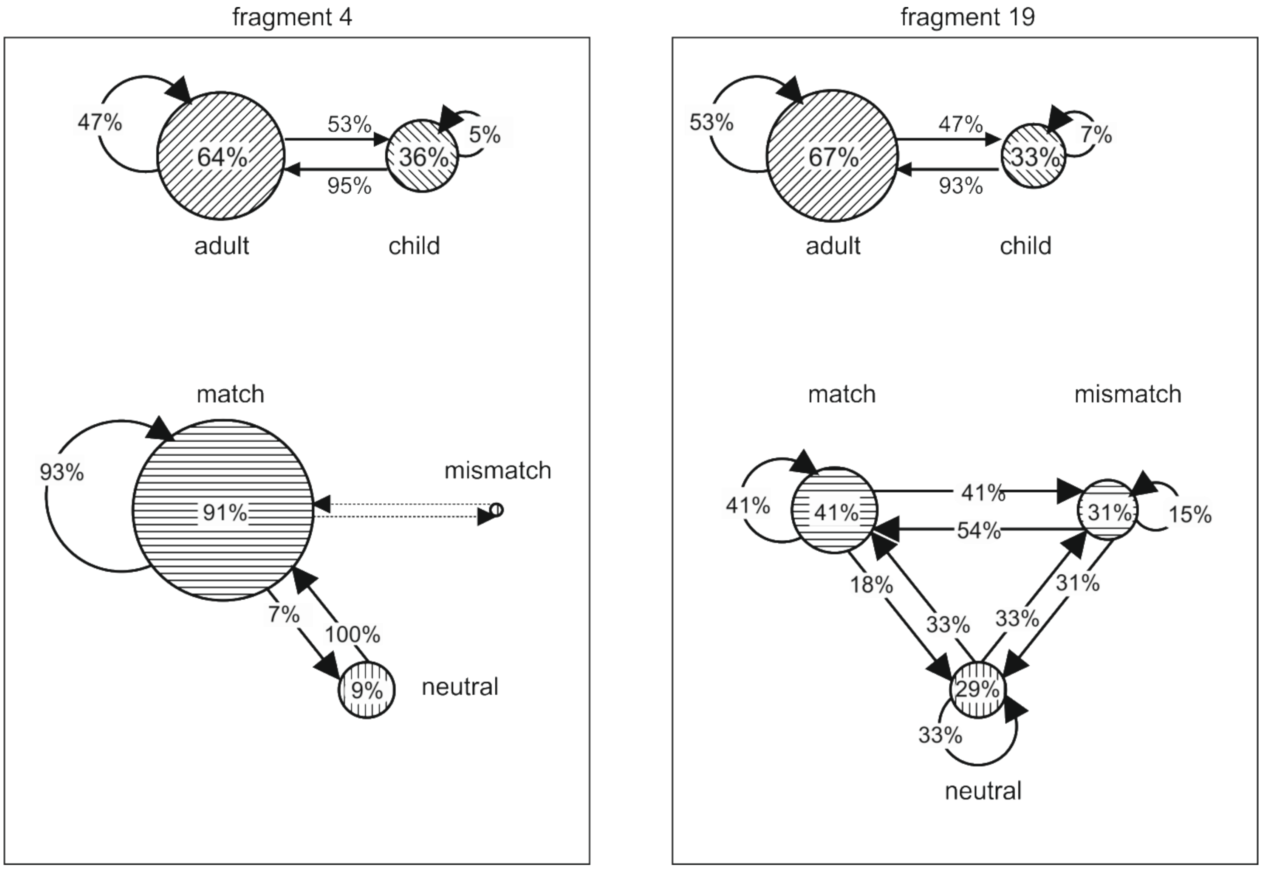

Figure 1. Two transition graphs, which are graphical representations of the sequences of events that take place during a lesson, before a transition (fragment 4, on the left) and after a transition (fragment 19, on the right). The above figures show the number of self-iterations (which more or less stay the same); the figures below show the matches, neutral matches and mismatches between utterances of the teacher and utterances of the student (ratio significantly changes).

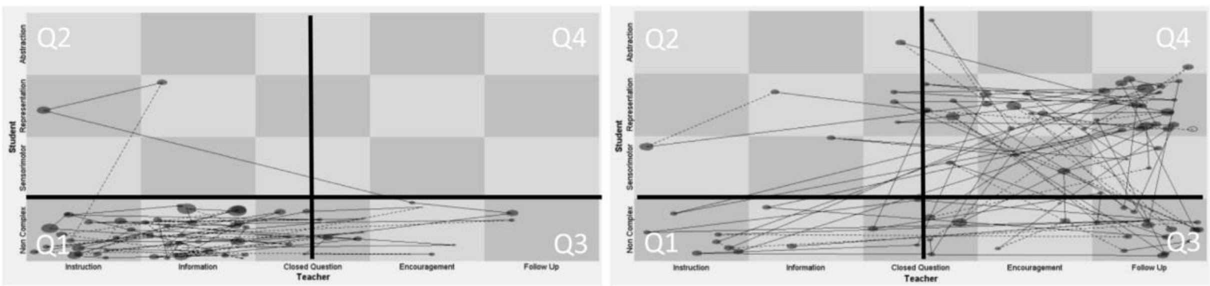

Figure 2. An example of using State Space Grids (SSG) to depict the quality of the interaction dynamics between students and teacher in two different primary school classes, during science education. The student utterances are depicted on the y-as using an ordinal scale of scientific understanding (non-complex; sensorimotor; representation; abstraction). The teacher utterances are depicted on the x-axis using an ordinal scale of extent of stimulation (instruction; information; closed question; encouragement; follow up).

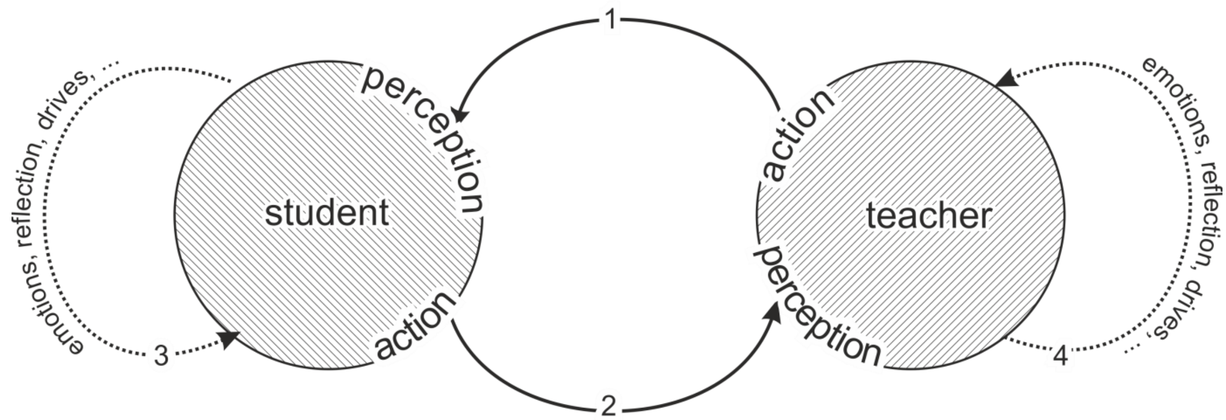

Figure 3. Educational interaction patterns emerge out of the actions of participants (e.g. a teacher and a student). Actions take the form of iterative perception action loops (e.g. a teacher's perception of an educational opportunity in the preceding action of a student) followed by an action of educational support, which is then perceived by the student as either helpful or not, and followed by an action of the student. In addition to these between-person loops, the interaction pattern is also based on the within person loops that contribute to the dynamics of the interaction. These within person loops take the form of emotional appraisals, drives and motivation, cognitive reflections about the nature of the interaction of the possibilities for action so forth.

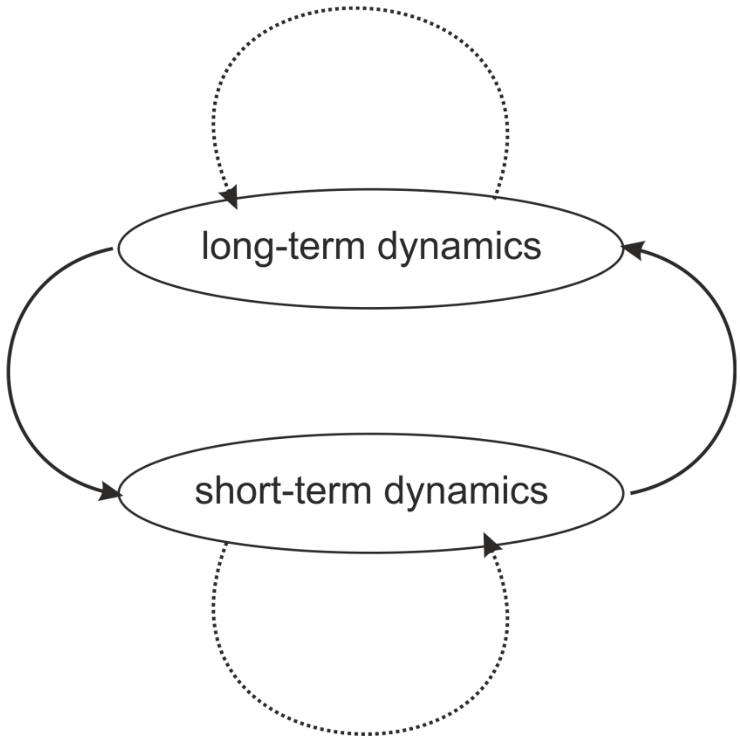

Figure 4A. Educational goals, intentions and concerns, and the educational skills necessary to achieve them, are characterized by a short-term dynamics (e.g. real-time interactions between the teacher and the student) and a long-term dynamics (e.g. the teacher's professionalization trajectory, or the student's learning-to-learn). Although the processes on the distinct timescales have their own internal dynamics (represented by the dotted arrows), there also are determined by the causal relationships between the processes on the long-term and short-term timescales.

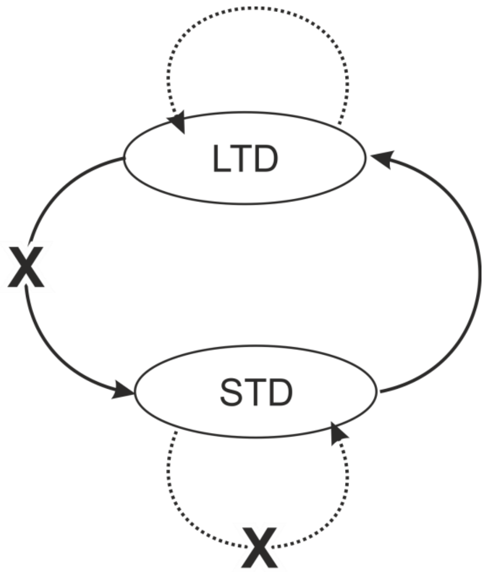

Figure 4B. The causal loops constituting the short-term or long-term dynamics of educational goals/intentions/concerts and educational skills can become disturbed if one or more of the loop components are hampered. For instance, if the causal link between the long-term dynamics (e.g. professional educational skills in a teacher) and a particular short-term dynamics (e.g. solving a particular educational problem with a difficult student) is hampered, the teacher is in fact unable to use his experience and skills to solve this particular problem. If a student fails to adapt to the teacher' s current assignments or explanations, or if a teacher fails to adapt to a particular student's current needs for solving a particular assignment, the internal short-term dynamics is disturbed, resulting in the (temporal or chronicle) inability to give and/or receive adequate educational support.

Table 1. Description of complexity level of students' utterances, derived from short term Skill Theory based measure (derived with permission from van Vondel, Steenbeek, Van Dijk & Van Geert, 2017)

Table 1b
Description of the complexity levels as expressed in students' verbal utterances.

Complexity level	Description	Examples
1 Sensorimotor	Simple connections of perceptions to actions	It [the paper] is *white*. It is *white* and that one is *yellow*. The paper collapses *because I blow*.
2 Representational	Go beyond current perception-action couplings	*I think* the paper will ascend. Because I blow, there is *more space* and then the *paper can go down*. Because I blow harder, the paper can drop lower.
3 Abstraction	Nonconcrete rules that also apply to other situations	Because the balance is gone … the air beneath the paper is pushed away [when I blow] … so … the *air pressure* drops down, but the pressure above the paper remains the same and thus pushes the paper down