Dynamic systems theory: a tool for understanding development and education

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What explains why some children acquire a particular profile of skills and knowledge whereas other children don't? Why do some educational treatments have positive effects and others not, or why do they have an effect in some children and not in others? What explains the nature of the interaction between a teacher and students and where do the differences in this interaction come from? These and comparable questions are interesting from a purely academic point of view, but also and more importantly from an applied point of view, because the correct answers to these questions can provide practitioners with usable knowledge, i.e. help teachers and educators to better teach and educate, to pursue their goals in a more efficient way and help define goals that are at the same time valuable and reachable.

The nature of the knowledge retrieved in the context of such complex action as teaching or educating children is incredibly diverse and practically unlimited, in the sense that almost any kind of knowledge can eventually help to decide which action to perform in a particular context. In that regard, one can ask oneself whether relatively *abstract* knowledge about *general* principles and models of teaching and education can in principle be usable, more than just in the service of a posterior justification of one's actions. We believe that such general knowledge is actually of considerable practical importance because it functions as a framework that helps select and trigger practical knowledge in the course of action. Such general frameworks have been discussed under various terms, such as "worldviews", "paradigms", "frameworks of discourse" and so forth. They help us understand and explain reality and by so doing guide our activities.

Theories and models: their role in action

In a context that involves scientific knowledge, explaining and understanding are based on theories and models. Scientific theories are general, coherent structures of knowledge that are consistent with facts. Scientific models are based on theories. Models are representations of some part of reality, in principle in some "tangible" form, implying that you can do something with it, namely to "make facts" or "make knowledge" about the modeled part of reality, without having to turn to that reality directly. A good model "makes facts" that correspond with the reality it describes and thus helps us understand that reality: the facts that characterize that reality are now based on or founded by our model and are thus, in that sense, "under-stood".

Models and explanations for that matter, are simplifications: they reduce a reality that is so diverse and complex that it far exceeds the limits of our human cognitive resources. They reduce it to something that can – almost literally – be grasped and managed. A simplification leaves out a host of details and thus makes a choice as to what is important or not. In that sense, a model defines or specifies what is important, essential or characteristic in a phenomenon. How does such "defining" knowledge function in concrete action, e.g. concrete teaching or the actual design of educational programs?

The classic developmental psychologists, such as Piaget and Vygotsky, have emphasized a defining relationship between knowledge and action, namely that knowledge comes forth from action and that its nature is to function as part of action. Especially the first aspect is important. New knowledge is based on action, action schemes that are transformed into knowledge. Vygotsky in particular has emphasized that such formative action is guided and structured by physical semiotic tools. These principles do not only hold for children, they are applicable to all situations in which learning takes place, including the learning of experts in teaching and educational science. After all, in their original form, the words “explanation” and “understanding” refer to some form of action (to make plain, as in “explanation”; understanding defined as “grasping”).

Against the background of this action-oriented view on understanding and explanation, this chapter tries to accomplish three goals. First, we will explain basic features of dynamic systems theory and how they relate to teaching and education; second we will show how understanding of a dynamic systems approach can be acquired and applied by means of “guided” activities, namely by experimenting (or playing) with simulation models (which are physical semiotic tools); third, we will explain how such knowledge is indeed usable in the context of teaching and education.

Dynamic systems theory as an approach to teaching and learning

The phrase *dynamic system* contains the words *dynamic* – referring to the Greek “dynamikos”, which means “powerful” – and system – a word that stems from a Greek verb that means “to combine”. Thus, a dynamic system is a combination of things to which certain “powers”, i.e. forces apply. We shall call something a dynamic system if it consists of components that exert specific influences or forces upon one another and by doing so, change each others’ and their own properties.
The aim of a dynamic systems model is to try to capture the basic dynamics of a phenomenon in its most essential form, that is, by reducing the complex world to the minimal set of essential components that are necessary to explain, i.e. generate the characteristic form of the dynamics. In this sense, a dynamic systems model (dynamic system for short) is not a “description” of reality in the classical sense. Its aim is to form the conceptual basis of something that can actually *do* something, namely generate the phenomenon of interest, for instance in the form of a simulation.

All this sounds – and is – very abstract and we will try to make it concrete by giving an example of a dynamic systems model of a process of teaching and learning. The model is broadly inspired by a Vygotskyan approach and has been described elsewhere (Van Geert, 1991, 1994, 1998).

Basic conceptual model of teaching and learning

The system of teaching-and-learning consists of a variable that refers to a teacher or instructor and a variable that refers to a student or apprentice (we will use the words “instructor” and “apprentice” as generic terms). The system is called the teaching-learning system, referring to the fact that teaching and learning stand in a mutual dynamic relationship to one another.

We begin with the observation that the instructor has a goal and that the apprentice has not yet reached that goal. We further assume that we have a measurement device, i.e. a “ruler” by means of which we can quantitatively specify the level of the instructor’s final goal, the apprentice’s current level and the level instantiated in any particular act of instruction. The issue of rulers for specifying goal structures and levels is of great importance (see the chapter of Fischer et al.). For the sake of model building, we do not need to ask ourselves how such a ruler should exactly look like (although we will need to specify the ruler once we apply the model to real teaching and learning).

Our dynamic system can be represented in a geometric form as a two-dimensional space, with the horizontal axis representing time, and the vertical axis the ruler specifying among others, the goal level and the student's current level (see figure 1, the line that corresponds with the "current moment", the remainder of the figure will be explained later in this section).

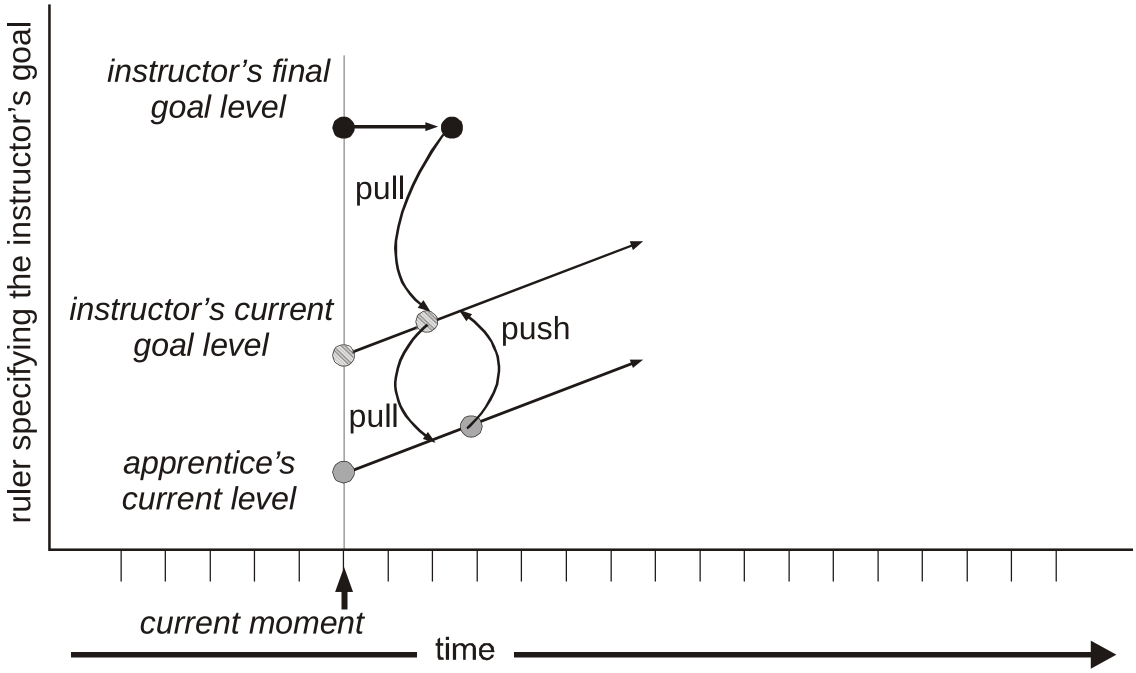

Figure 1

A basic principle of learning is that the apprentice's level (skill, habits, behavior, …) can be changed by making the apprentice do something, for instance by making him solve a problem, imitate or rehearse what the instructor has been doing, and so forth. What the instructor wants the apprentice to do must be relatively close to what he is already able to do, or else he will not be able to do it (this is reminiscent to Vygotsky's notion of the zone of proximal development). Thus we must add another element to our dynamic system, which is what the instructor wants the apprentice to do, i.e. the current requirement or current (i.e. temporary) goal set by the instructor. This current goal must be ahead of the apprentice's current level, but within the apprentice's reach (with "within reach" dependent on properties of the apprentice). It must also be closer to the final goal level than the apprentice's current level (see figure 1; the current-moment line).

As a result of performing the required activity, for instance with the help of the instructor, the apprentice will incorporate, in some way or other (there are various possibilities, but how it actually happens does not matter here), the skill, action or knowledge that he was made to practice or act out. Thus, the student's current level will be attracted towards the current goal level, and it will move towards that level with a particular speed (the rate of change). In dynamic systems terms, the instructor's current goal or current level of instruction (which will change as learning progresses) is an *attractor* for the *apprentice*'s current level.

In this dynamic system, two important parameters related to the apprentice can be distinguished. The first is the *rate of change*. It relates to ease and rate of learning, and is thus related to psychological variables such as intelligence, domain-specific intelligence or knowledge, motivation, and so forth. The second is the *maximal distance* between the apprentice's level and the current goal level beyond which the current goal level of the instructor no longer acts as an attractor for the apprentice. Put differently, all instruction that is within that distance can make the apprentice learn. The maximal distance relates to psychological variables such as intelligence (but it requires other components of intelligence than those that are involved in the rate of learning, for instance), the ability we intuitively call "talent", and so forth.

It is easy to see that the learning will come to a standstill once the apprentice has reached the level set by the instructor's current goal level, demands or requirements. Thus, in order to keep the learning going, the instructor must adapt the current goal level to the apprentice's increasing skill of knowledge level. That is, as the apprentice progresses, the instructor will move his current goals closer towards the final goal level. Thus, the *instructor's attractor* is a level of instruction (teaching, giving help, …) between the final goal level and the apprentice's current level. The force that makes the current goal level move is the apprentice's progress.

The model is represented in figure 1. It shows how the instructor's level is pulling the apprentice towards it, and how the instructor level at the same time is pulled towards the final goal level and pushed in that direction by the progress made by the apprentice.

The whole process is *iterative or recursive*: the apprentice learns something new, which motivates the instructor to move the instruction to a higher level, which enables the apprentice to learn something new, and so forth. This iterative character is characteristic of dynamic processes in general.

Thus we see a dynamics consisting of two mutually influencing forces: the apprentice's level and the instructor's current goal level, i.e. current instruction level. This mutuality refers to another general property of dynamic systems, namely that of *distributed causality*, i.e. a causal process distributed over the instructor and the apprentice, in which one cannot work without the other. It also refers to the particular meaning of "context" in dynamic systems: the context of one variable or force is in fact the other variable or force. Thus, the context (the other variable) is co-dependent on the variable at issue and on its turn that variable is altered by the context (the other variable). In a practical situation of teaching and learning, the effective teaching "context" is to a considerable extent determined by the way the apprentice interprets the teaching, reacts to the teaching and so forth. On the other hand, these interpretations and reactions will change as a consequence of the teaching.

As stated before, the instructor must change the current goal level in function of the apprentice's progress. This change can occur with different rates, comparable to the differences in rate by which the apprentice moves towards the current goal level. In a school curriculum, the rate refers to the increase in the level of the instruction given to the students over the various lessons. The rate can sometimes be too high; many students seem to have this feeling in statistics classes, for instance. They can follow in the beginning, but then the leaps from one lesson to the next seem just too great. This *rate of current goal change* or *rate of instruction change* is in fact the third parameter of our dynamic system. Table 1 summarizes the components and parameters of the dynamic teaching-learning system.

	apprentice	***instructor***
level	current level of knowledge, mastery or skill	current goal level, i.e current level of teaching, instruction, help...
attractor	instructor's current goal level	level between final goal level and apprentice's current level
parameters	rate of learning, progress rate	rate of current goal change
	maximal current-goal distance	

Table 1

Applying the dynamic system to various forms of teaching and learning

The reader might object that the dynamic model explained in the preceding section might describe what happens in a tutorial situation, with a single tutor and student, or describes the way teaching occurs with a private teacher. What about all the other forms of teaching, learning and education, that are far more common than these two? Our answer is that the core of the dynamic system is the structure of levels (the “forces”), attractors, parameters and relationships. This structure can be instantiated in various ways. The essential aspect is the adaptive nature of the teaching-learning system. Highly protocolled forms of curriculum-guided teaching and learning that proceed irrespective of what the students actually learn, do not provide a good example of the dynamics. However, there exist many forms of adaptive teaching and learning to which the dynamics can be applied. One is a strongly teaching-oriented form (the tutorial or private teaching we already mentioned) where the current goal level, including instruction and help, is primarily under the control of the instructor. However, we already noted that this instruction level, which forms the apprentice’s context of learning, is always to a considerable extent a construction of the apprentice himself. For instance, if the apprentice hears only half of what the instructor is saying, it is the half that he hears that will affect him. The context is what you make out of it, not what it objectively is.

Take for instance learning of skills in the context of *guided participation* (Rogoff, 1993). In this practical context, the instructor carries out a complex activity, for instance preparing a meal or repairing a broken windowpane. In guided participation, the “instruction level” presented to the apprentice who participates in the activity is determined by both the instructor and the apprentice. In his perception of the complex skill, the apprentice will automatically simplify and reduce that skill to those aspects or elements he can grasp, i.e. to something that is relatively close to his current level of independent action. As the apprentice’s skill increases, it is likely that new aspects of the complex skill will be noticed or perceived, which will act as a more advanced level that serves as the new attractor. In guided participation, the skilled person can help the apprentice by reducing the apprentice’s range of action, by simplifying the tools used (as with children who use toy knifes and utensils when they help their parents cook), and so forth.

Toys provide a good example of cultural artifacts that help specify the apprentice’s current goal level and imply a particular level of self-defined instruction. For instance, when a four-year-old plays with a toy electric cooker to prepare meals, the toy oven allows the child to act out certain aspects of the real cooking, such as preparing and heating the plates, but the temperature will never go beyond a very safe level. As the child's skill increases, the toy cooker might loose its attractiveness and the child might begin to assist the parents in preparing real meals. In our view, the simulations that we hope the reader will carry out after having read this chapter, are very much like toys. They simplify reality but conserve those aspects of reality that are essential to it. By playing with the simple simulation models, one can obtain a better understanding of the way the model describes reality and then proceed to real situations or more complex models.

Note that Piaget has focused strongly on the dynamics of assimilation and accommodation, which is very close to the mechanism just described, namely the child "reducing" the complexity of the world to something it can grasp (assimilation) but that nevertheless contains enough novelty to act as a powerful attractor of its current level of action or understanding.

The dynamic model is highly "pedagogically optimistic" in that it assumes that the apprentice will automatically comply with the instruction, or that the instructor will automatically adapt to the apprentice's level. In reality, however, apprentice and instructor have their own concerns, i.e. their own goals that they wish to pursue, which do not necessarily coincide with the educational goals (for a general dynamic model and simulation model of concern-driven behavior, see Steenbeek and van Geert, 2004). However, the concerns of the participants are examples of factors that map onto the model's parameters. For instance, just like intelligence (among others), the apprentice's concerns form a psychological factor that contributes to the apprentice's rate-of-change parameter.

Finally, the dynamic model is individualistic: it describes the relationship between a single apprentice and a single instructor. In reality, most teaching and learning involves groups (of students, for instance). However, the group is nothing but a collection of apprentice-instructor dynamics. The core features of the dynamics remain the same. Differences might occur in the instructor's attractor, which might depend on some sort of "average" of apprentices' current levels. In addition, the apprentice's peers might contribute to the teaching-learning process by helping define the instruction level (e.g. in the form of peer assistance).

In summary, the core of the dynamic model is its dynamic structure, which is open and flexible enough to be applied to a wide variety of teaching-learning situations, provided they are adaptive in nature.

We will now proceed to our second goal, namely to show how understanding of a dynamic systems approach can be acquired and applied by means of "guided" activities, namely by experimenting (or playing) with simulation models.

Understanding the dynamic model through simulation

General aspects of the simulation model.

Before one can run simulations with a dynamic model, it has to be translated into a form that can generate output. The common strategy is to transform the conceptual model into a set of coupled mathematical equations, which are then transformed into a computer program that the user can work with. For more technical details, we refer to the web-text “A model of learning and teaching”. The simulation model describes both variables – the apprentice’s and the instructor’s level – by means of a logistic equation that incorporates the relations explained in the conceptual model. It is based on three major parameters – the apprentice’s rate of change, i.e. learning or acquisition rate; the maximal distance at which the instructor’s level can still act as an attractor for the apprentice’s level and finally, the rate of adaptation of the instructor’s level to the change in the apprentice’s level. The user of the simulation model can manipulate these three parameters (in the Excel model, this is done by means of three scrollbars).

The user will probably ask what it means when he or she sets a parameter to a specific numerical value. To understand what happens, it is important, first, to remember that the parameters are related to psychological variables in various ways. For instance, the apprentice’s learning rate is a function of his intelligence, motivation and so forth. Thus, increasing the rate corresponds with a range of possibilities: by increasing the rate, one can study what happens if the apprentice is more intelligent, or more strongly motivated, or a combination of the two, etc. Second, the meaning of the numerical values is “relational”. Thus, increasing a parameter value from 1 to 2 for instance, means to double the strength of the relationship that the parameter controls. A very interesting property of dynamic systems, however, is that the *effect* of such changes is not always proportional to the magnitude of the change. This property refers to the *non-linear* nature of (many) dynamic systems.

The goal of the simulation is to show that a dynamics such as this one, which is not overly complicated, nevertheless displays a wide variety of qualitatively different patterns. These patterns are not “pre-wired”, that is, there is no instruction that tells the program “on value x of parameter A, show qualitative pattern M”. The patterns arise spontaneously, given specific parameter values. The spontaneous occurrence of qualitatively different patterns is characteristic of dynamic systems and refers to the fundamental property of *self-organization*. The didactic purpose of the simulation is to give the user an active feel of what it means to try to control a dynamic system, with its intrinsic properties of self-organization and non-linearity, organized on the basis of a general model of teaching and learning.

An overview of simulation results

We will now give a short description of the various qualitative patterns that the dynamics produces. Open the Excel file and begin with the “default values” for the three parameters. We call these the default values because they produce a simple, expected pattern, namely an S-shaped growth curve for the apprentice’s level of knowledge, skill or mastery, and a comparable curve for the instructor’s level, which stays ahead of the apprentice, until they both reach the pre-established final goal (see Figure 2, chart 1).

While keeping the other two parameters constant, gradually reduce the *maximal distance*. That is, simulate a situation in which the apprentice needs a level of instruction that is increasingly closer to his current level of mastery, knowledge, skill or performance. As the distance parameter reaches the value 2.25, the pattern changes into a two-step process, with an intermediary plateau (see Figure 2, chart 2). Suddenly (at value 2.2) that pattern changes into an S-shaped pattern again, but with a final level that lies considerably lower than the intended final goal state (note that the final goal state that the instructor uses has not changed, it is just not possible for the system to reach it; see Figure 2, chart 3). As you go on reducing the maximal distance parameter, the system's final state stabilizes at increasingly lower levels.

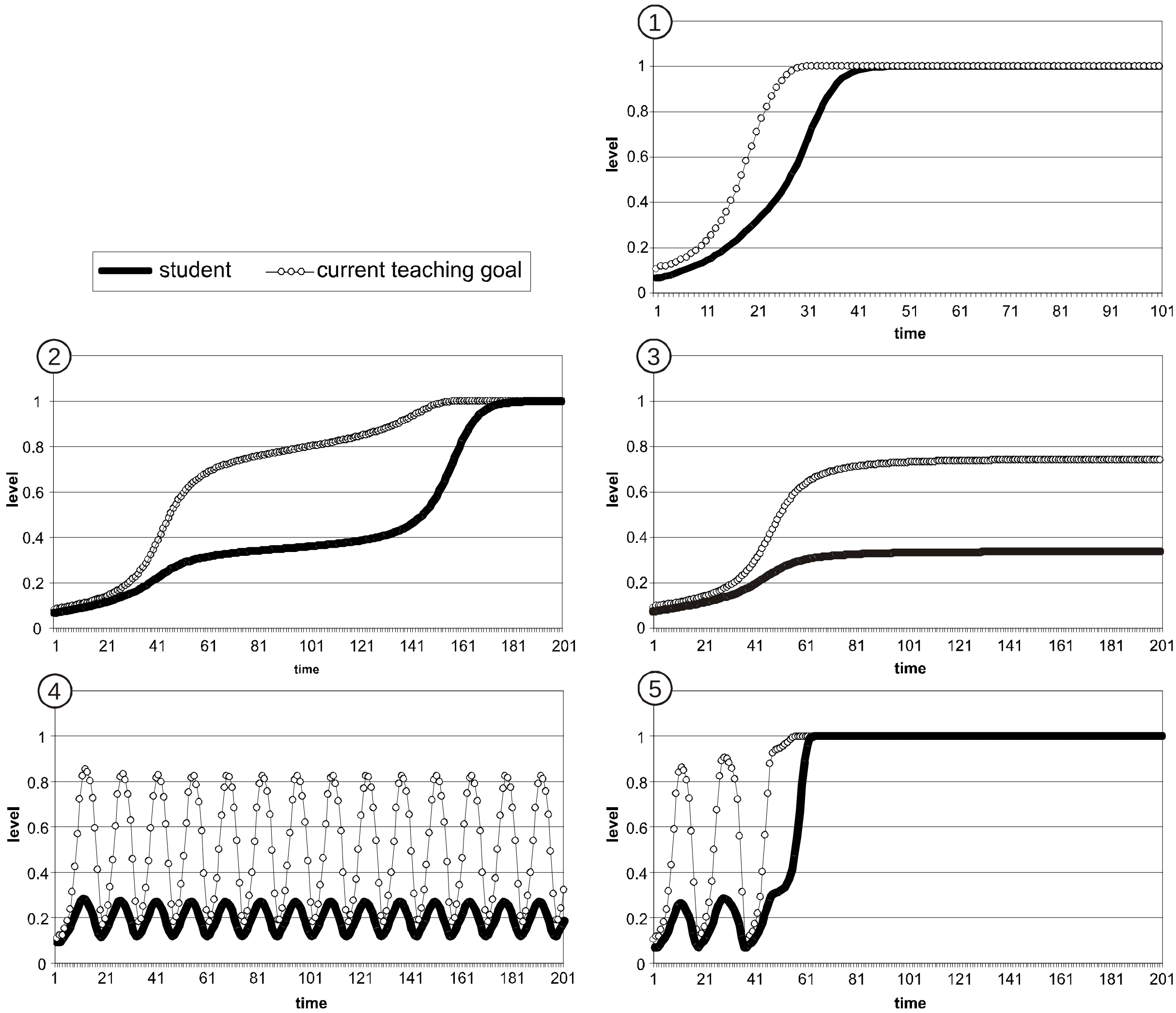

Figure 2

Restore the maximal distance level to the 2.1 value and now change the *instructor's rate of adaptation* by gradually reducing it. With just a little reduction, you see that the system suddenly restores its ability to reach the final goal state, in the form of the two-step process we already observed (Figure 2, chart 2). Thus, a decrease in the instructor rate of adaptation compensates for the negative effects of the reduction in maximal distance. However, proceed with the gradual reduction of the rate of adaptation: it now takes increasingly longer time to get the learning off the ground, but at the value of 8.5 the system stabilizes onto a situation where almost no learning takes place. Thus, the positive effect of the reduction of the adaptation rate isn't but a local effect, occurring as long as the instructor's rate of adaptation is sufficiently high. This phenomenon nicely illustrates a major feature of a dynamic system, which is the *non-linearity* and *localness* of the effects. Thus, one cannot generalize the principle “If the system stabilizes at a level lower than the desired (final) goal level, reduce the rate of adaptation of the teaching level”. This principle works only in a limited (but fortunately rather broad) region of the parameter space. The practical meaning of this model observation is that for specific contexts (i.e. not necessarily all contexts), the effect of particular educational interventions have a desired effect only in specific circumstances, i.e. under specific dynamic contexts.

Finally, take a maximal distance of 3.1 (around the default value) and an instructor’s rate of adaptation of 20. If this rate were to apply to a school curriculum, it would refer to one that “goes too fast” i.e. where the increase in complexity or demands on the students increase too rapidly over the successive lessons taught (remember the earlier example of the statistics class). With a default learning rate of 0.15, the corresponding trajectory is S-shaped increase that stabilizes on a level well below the desired goal level (i.e. at a numerical value of around 0.2 for the apprentice and a level of around 0.6 for the attainable goal level, whereas the actual goal level lies at the value 1). Now check whether an increase in the apprentice’s rate of learning will solve the problem: gradually increase the apprentice’s rate of change (learning rate). It seems that an increase in the learning rate does not have the desired effect: as you reach the value 0.3 the system runs into a cyclical pattern, i.e. a pattern of ups and downs with an increasing frequency (Figure 2, chart 4). The cycle is stable, i.e. it remains a cycle for at least a very long period. However, if the learning rate of the apprentice further increases and reaches the value 0.34, the pattern suddenly switches to two cycles followed by a rapid increase of the apprentice’s level to the final goal level (see figure 2, chart 5). Slightly increase the rate parameter (by 1 step of the scroll bar) and the number of cycles needed to reach the goal level increases, increase the parameter further and the number of cycles decreases. It is clear that with these parameter values we have reached a *chaotic region* of the dynamics. In this region, it is no longer possible to practically predict what will happen if only a small change occurs in one of the parameters. From a practical point of view, all regularity is gone (check this by a gradual increase of the learning rate parameter; this loss of predictability can also be checked by activating the model’s randomization factor; see the web text for further explanation).
Hoping that the readers have been intrigued by this description and have played with the simulation model themselves, we now want to proceed to our third goal, which is to explain how such knowledge is indeed usable in the context of teaching and education.

The practical use of dynamic models and simulation models

An often heard objection against these dynamic models is that, instead of bringing usable knowledge, they preach passiveness and in fact reduce our understanding of reality. Anything goes: sometimes a change in a parameter causes this to happen, sometimes that. Or, there basically is nothing you can really do: what happens is caused by self-organization. This kind of objection is based on a serious misunderstanding of what dynamic models are trying to say and will in general not be uttered by those who have a practical understanding of how such models work. We have shown that – and in what way – the instructor is a very important factor in the dynamics. We demonstrated that the way the system self-organizes into various patterns is the result of how the instructor acts on the apprentice's activities (in addition to showing how the apprentice contributes to the pattern of self-organization). Moreover, dynamic models explain in which cases, and why, things can become uncontrollable or chaotic. They do not tell you that things are "always or mostly" uncontrollable and chaotic (for amateurs of action movies: the latter misunderstanding can to a considerable extent be attributed to Jeff Goldblum's impersonation of the chaos mathematician in Jurassic Park …).

A second possible objection might be more serious. When we explained this model to a colleague who works in an educational consultancy center – she is running a project to help teachers cope with bullying – she spontaneously replied "Well, this is what I try to accomplish in these schools, the description fits nicely with what I try to teach my teachers". If she is right, if practice already complies with the principles of dynamic systems, why bother with the complicated detour of models and simulations? The answer is that although educators and teachers might (eventually) act in accordance with dynamic systems thinking, there is still an unmistakable lack of a coherent framework that they can use to reflect on their educational or teaching actions and that corresponds with the dynamic features of that action. Classical developmentalists such as Piaget and Vygotsky have emphasized the importance of reflection that abstracts the core features of what one actually does, for advancing one's own development. This principle applies to children, but also to their educators. It is our belief that a dynamic systems model such as the one presented here can act as an adequate framework for reflective abstraction, thus helping to improve practice. Let us try to explain this a little further.

What apprentices and instructors alike are trying to do is to control a complex dynamic system, i.e. to pursue their own goals or concerns. It is our belief that the major *scientific* justification of the expectations about how to control a system – e.g. teach children, give therapy, and so forth – is mostly based on additive linear models, explaining that so much of the variance is due to factor A and so much to factor B, etc. This involves an image of reality where events, such as a sudden change, a regression, a cyclical pattern, are caused by some external force, such as a causal factor that pops up, an event that enters from outside and that causes the process to temporarily regress and so forth. Working and experimenting with dynamic systems can teach the user when, why and in what way qualitative patterns spontaneously arise out of the dynamics of the situation and thus are not necessarily caused by external factors or events. That is, the additive linear model may well apply to the overall pattern of relationships among variables defined on a population level, but the dynamic model is meant to apply to the individual processes that explain why such overall population pattern comes about.

More importantly, the linear model is not meant to serve as a model of educational action. If educators believe that events are caused by external factors that can be isolated and manipulated – as the linear and factorial models imply – they will try to identify and manipulate such events and causes and thus invest time and energy in the search for them. If one believes that the events of interest arise from the dynamics of the situation itself, one will invest time and energy in trying to understand the dynamics That is, the practitioner will try to find out where the dynamics can eventually be manipulated in such a way that the desired effect emerges out of the dynamic system in question. If the world indeed acts as a nonlinear dynamic system, a feeling of how nonlinear dynamic systems behave and how they can be controlled (or not) can make a major practical difference. Thus, the educators' explanatory frameworks should make clear to them how and when to create conditions under which self-organizational processes emerge, that lead to outcomes that approach their goals as closely as possible. Such understanding does not come from mere intellectual contemplation of those explanatory frameworks. Understanding comes from guided practice. Simulation in what is basically a toy world is a great tool for such guided practice and understanding.

In summary, if the dynamic model indeed describes what already happens in practice, it can serve as an adequate and usable reflective abstraction of those actions and thus will help to improve the actions of educators and bring them to a higher level of skill and control.

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