Chapter 3
Narrativity in Complex Systems

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3.1 Introduction

Humans undoubtedly have a *narrative mind* (Bruner, 1990)—we like, tell, and understand *stories* starting from a very early age (Egan, 1986, 1988). We use narrative for making sense of our environment; it has been argued that we get to know other humans and our humanity through hearing stories (this is the *Narrative Practice Hypothesis* formulated by Hutto, 2007, and Gallagher & Hutto, 2008). Importantly, stories create worlds to be explored and experienced in parallel to our physical and social worlds (Caracciolo, 2014).

So, how does this relate to our interest in complexity? If we deal with humans or human-related affairs, including affairs where humans interact with nature and technical artefacts, we quickly are confronted with *complex systems*. [We shall not attempt to define complexity in any systematic and formal way (for more background, see Zeyer, this volume, and Andersson et al., 2014). We take complex systems to be *dynamical systems* that exhibit several if not all of the following features: (1) they are not composed of the same elements over and over again; rather, they are

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made of elements having (strongly) different properties; (2) interactions between elements lead to feedback that is complicated in some sense (mathematically speaking, feedback leads to nonlinearities); (3) their structure and behaviour are not strictly stable; their structure can change (evolve) over time; and (4) components in a system can come together by chance and for only very brief periods, maybe just for creating a single event (the components form an *ephemeral mechanism*; see Glennan, 2010). From a dynamical modelling perspective, we may summarise the view taken here by saying that complex systems and processes are those that are both hard to model *and* difficult or even impossible to predict. Obviously, there are *degrees* of complexity.] Therefore, we might wonder if, and if so, how and to what extent our narrative mind can help us deal *scientifically* with complexity. This and what this means for education are the questions we would like to address in this chapter.

A First and Brief Answer We compose an answer largely from a small number of observations of scientific and narrative practice, and how these issues are related to each other. First, laypersons and scientists equally appeal to *mechanisms* when attempting explanations of observed behaviour and phenomena. Mechanisms are thought of as be*ing composed of material parts interacting to produce observed behaviour*. Switching on an electric light in a room might serve as a simple example. However, the search for mechanisms has become important in sciences other than the basic ones, such as health and environmental sciences. We may hear a medical researcher say that "mechanisms of autoimmune diseases are not very well understood".

Second, our mind creates notions of *agency* and *agents* that are active in mechanisms. [Our second observation is closely related to the question of causation in dynamical systems. Naturally, mechanistic approaches have their versions of how to understand causation (Craver & Tabery, 2019), one of which is of particular interest to us: in activity-based accounts, causation is understood in terms of productive activities (such as hydrogen bonding, transfer of momentum, and flow of heat). Our approach to causation is close to this but includes an account of how activity is represented in imagination. We shall see that models of dynamical systems introduce (immaterial) forces of nature that are characterised in imagination as agents active in mechanisms. Naturally, a scientist creating a model of a mechanism might understand this implicitly and will arrive at the same result as one who thinks explicitly in terms of forces of nature as agents. Our insistence on this additional step is grounded in concern with cognition and learning; even more important, it is the step that makes modelling an explicitly narrative affair.] We see forces at work in and between the parts of a mechanism that are represented as (more or less) powerful agents. Wind, rain, light, heat, and electricity come to mind as examples of forces of nature—anger and fear; justice and the market; and music, dance, and sculpture are psychological, social, and cultural forces. Models of mechanisms appeal to these agents and in this manner explain activity in a mechanism. Note that if the interactions between agents and between agents and elements of environments are even just moderately complex—mathematically speaking, nonlinear—events can become unpredictable. Here is a first source of complex behaviour.

Our third observation concerns the fact that humans deal with the experience of agents acting in scenes mostly in *narrative ways*, by telling stories of the adventures of these agents. [We may be inclined to reserve the notions of agent and agency for intentional (animal and human) agents. However, analysis of how we speak about natural (and social, cultural, and psychological) phenomena demonstrates that we invariably make use of the imagery of agents and agency. These notions are clearly prescientific, but they reappear in (physical) science in a form that frees them from goal-directedness and intentionality (see the last two paragraphs of the following story and Fuchs, 2006, 2010). In macroscopic physical science, agents representing forces of nature are more or less intense, extended, and powerful (Sect. 3.4).] We can draw a parallel between the scientific practice of modelling and simulation of dynamical systems and narrative practice. Stories heard or read lead to the construction of mental models which we call story-worlds (Fuchs, 2015). A story is a tale of concrete events playing against the backdrop of a story-world. This view of stories as prototypical narratives is analogous to scientific practice: we can compare a (formal, mathematical) model to a story-world and a simulation of such a model to a "tale" of concrete events against the backdrop of the model. Just as hearing or reading of a story suggests a story-world, dealing consciously and narratively with simulations—by explicitly treating a simulation as a story—leads to the creation of model-worlds in the mind of the analyst.

The fourth observation brings us right back to the first: there are *ephemeral mechanisms* where chance brings together the parts of a mechanism for one-time, short-lived, unpredictable, and historical (natural) events (Glennan, 2010). In other words, there is unpredictability in the composition of scenes and number and properties of agents, i.e. in the composition of model-worlds. Here is a second source of complexity.

In summary, we suggest that we are led to narrative understanding of (complex) systems by introducing the notion of forces imagined as agents active in possibly ephemeral mechanisms. Our mind creates story-worlds (environments populated by agents) which are excellent representations of models whose simulations work as stories told against the backdrop of the story-world.

Ideas of how to deal practically with the foregoing observations in educational settings are transformed into a *five-step heuristic strategy* which will be outlined in this chapter.

A Day in the Life of a Tree Let us start the discussion of these questions with a brief story of things happening in and around a tree. We shall use the narrative as a guiding example throughout. It is a story about a natural system *without* direct involvement of humans, and as such it tells about events in a *moderately complex* system.

> It was in early summer; the day had started with a thunderstorm. It had been unseasonably hot already for days. The thunderstorm brought only very short relief. The sun dried up the land very quickly, and temperatures began to climb.
>
> In front of the old farmhouse stood a giant linden tree. The leaves were still a light green, and the tree had started to flower; it smelled lovely. The tree with its wide branches created a large shady space. The family had gathered under the tree for a slow day and a late brunch. The parents looked up and discussed harvesting the linden blossoms when time had come, for the tea they liked to drink.

> As the family went after their business, the tree silently worked. What water the roots could find made its way to the leaves where it combined forces with air and sunlight to produce all the fuel the tree needed for its growth and the growth of its blossoms. Or the water combined with heat and evaporated. During such a hot day, the tree literally spewed a huge amount of water and heat into the dry air and so made the space under its branches even cooler and more comfortable.
>
> As the Sun made its path across the sky, the heat started becoming oppressive. The people under the tree first did not see it, but clouds grew to a threatening height in the sky and changed the light. In the afternoon, the wind had picked up and all of a sudden, it became dark. The family fled into the farmhouse as lightning could be seen and thunder rolled over the land. All of a sudden, they heard a deafening clap and the sound of an explosion and braking—a lightning bolt had struck their linden tree. The tree was split right down the middle, parts of it were set on fire. Fanned by the wind, the fire roared, and sparks were flying at the farmhouse …

Before we get down to describing and arguing what the story tells us or proves about our issue, let us draw your attention to just a few elements that will be brought up again in the following sections. First, as a prototypical narrative, the story has a traditional structure: there is a beginning that defines a setting; expectations of some future event are formulated; and events continue and culminate in a possibly unexpected ending.

Second, there are entities in the story, not least the tree itself. The words and sentences draw attention to a gestalt—the tree—that is perceived as a *system* that presents us with a number of interesting *phenomena* (giving shade, growing leaves and blossoms, evaporating water, and cooling the space underneath it), all operating concurrently. Third, the tree is made of *parts that interact* and so create the phenomena; together, this gives us the appearance of *mechanisms* at work in the system.

Fourth, in the middle of the story and again at the very end, for brief moments, a *shift of perspective* to a different group of characters or *agents* is taking place. Water, air, sunlight, and electricity are called upon and said to be responsible for important processes taking place in and around the tree. Finally, there is an unexpected and quite *unpredictable event*—the tree is hit by lightning, starts burning, and might, quite possibly, set the farmhouse on fire as well.

Note that there are parts and aspects of the story that should be called *scientific*—they suggest certain images and an understanding of phenomena and causes that are instrumental to scientific approaches to the system described here. One of our goals is to show how stories create an experience that helps us build models of complex systems as a form of understanding.

Narrative and Complex Systems Narrative and science appear to be entwined in a relation of *necessity* in the case of complex systems (Fig. 3.1). Complexity is easily experienced if we are interested in *real-world applications* and do not restrict our attention to idealised textbook examples. [Our assumption that science and narrativity are intimately linked is motivated by an enactive approach to embodied cognition (Varela et al., 1991; Di Paolo et al., 2018): systems and processes are linked to narrative cognition through basic forms of *experience*. We use the term *experience* in Dewey's 1925 sense as the result of *feedback* in *action-perception loops*, occurring between an organism and its physical, social, psychological, and cultural-linguistic environments. Alternatively, we might call experience the *unified action* *of perception and conception* (Fuchs et al., 2018).] Moreover, complexity arises quite directly when humans are part of a system. Since we commonly tell stories when dealing with human affairs, complexity and narrative seem natural allies.

Therefore, we shall argue here that explaining and understanding the experience of complexity *require* a narrative approach; conversely, it is narrative experience and understanding that *enable* us to deal with complex systems (Fig. 3.1, left). [In this chapter, we take this fundamentally optimistic attitude toward the possibility of narrative sense-making of complex systems and behaviour. We shall discuss important reasons for assuming that complexity and narrativity are compatible in important ways. However, there are reasons for treating this issue more cautiously. Depending upon our perspective and depending upon what we consider to be the most important aspects of complex systems, we might hypothesise that our cognitive system is fundamentally limited in understanding complexity (Walsh & Stepney, 2018). For example, if we define a complex system as one that exhibits *emergence*, we might conclude that a narrative can deal only with the emergent behaviour and cannot be used to explain the mechanism (the interactions of the parts of the system) that leads to this emergent behaviour—real understanding eludes us; all we can do is develop a sense of wonder for the relation between the hidden "real" causes and what we see emerging (Walsh, 2014). Obviously, we do not (fully) share this concern. Our work, and recent developments in the philosophy of mechanisms (Glennan, 2017), allows for greater optimism; see, in particular, Sect. 3.6 in this chapter.]

How does this assumption relate to traditional scientific approaches to complexity? A typical scientific approach to *real-world examples* of systems and processes that may or may not involve humans makes use of modelling and simulation of dynamical systems (see relation (a) in Fig. 3.1). We indirectly deal with what we perceive as complex systems by representing their real-world examples as formal dynamical models.

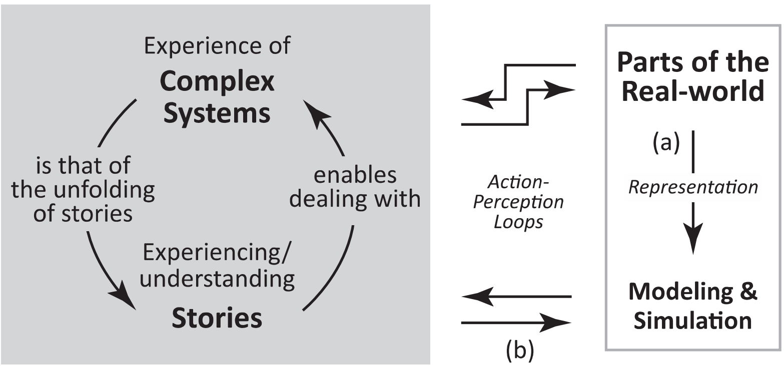

Fig. 3.1 Narrative experience and understanding are deeply related to our experience of complex systems (left, shaded box). This relation is mediated by the relation between narrative practice and the practice of modelling and simulation of real-world systems. Framed part (right): traditional approaches to working with complex systems

This state of affairs is certainly a stumbling block for a pedagogy of complexity in school science. Modelling and simulation of dynamical systems are not commonly considered accessible to most learners. [However, a pedagogy of dynamical modelling was developed decades ago in the field of *system dynamics* independently of narrative concerns; see, in particular, the *System Dynamics in Education Project* (SDEP) at MIT (1996) and Forrester, 1961. System dynamics modelling is used in certain fields of research and some areas of (science and social science) education. Most importantly, work in system dynamics has led to the development of computer programs for creating and simulating dynamical systems that include simple to use graphical user interfaces.] If we can show, however, that *these techniques are fundamentally narrative acts* (see the feedback relation (b) in Fig. 3.1), modelling, both informal and formal, is opened up to a larger group of learners. If we recognise this possibility, we can do more than just *argue* that narrative and complex systems require each other—we can then *demonstrate and explain how we can deal narratively with complexity*, and we can sketch a pedagogy that need not be unnecessarily formal.

At the same time, narrative is also the gateway to formal work in the sciences of complex (and not so complex) systems. The stories we have in mind are not meant to be tools for "unscientific" work that lacks depth and weight. Basic human experience connects science and narrative most deeply by making modelling and simulation of dynamical systems a narrative affair—this is the feedback relation (b) shown in Fig. 3.1 (see Corni, 2013; Fuchs, 2015; Corni et al., 2018; Fuchs et al., 2018, 2020; Corni & Fuchs, 2020, for a more detailed discussion of this crucial link).

Structure of the Chapter To sketch a practical path from real-world examples via storytelling and modelling to complex systems (Fig. 3.1)—one that works also for education—we shall first explain how to put order into the perception of systems (Sect. 3.2; step 1 in our heuristic strategy) and then how to "decompose" a (complex) real-world system into mechanisms for the phenomena exhibited by the system (Sect. 3.3; second heuristic). In other words, we distinguish between a system and mechanisms used to explain its phenomena: "A mechanism for a phenomenon consists of entities (or parts) whose activities and interactions are organized so as to be responsible for the phenomenon" (Glennan, 2017, p. 17).

Thinking in terms of mechanisms constitutes a somewhat "material" way of dealing with systems. It turns out that, in general, more is required for creating models of a mechanism. We need to perform a basic cognitive operation, *figure-ground reversal*, where the parts of a mechanism become the (back-)ground and agents, as representatives of forces (of nature) appear as new figures in our imagination (Sect. 3.4). This is our third heuristic: learn how to "see" these agents, and learn about their properties and their environments. Dynamical models are in some sense representations of our imagination of what these agents are capable of doing in their environments.

This is where narrative and storytelling or, more generally, the theory of narratology comes to play an important role (Sect. 3.5). We have to learn to distinguish between a concrete story told and a story-world conjured up in our mind by the story. We can then draw an important analogy between story and story-world, on the one hand, and simulation and model, on the other. Learning about this is our fourth heuristic strategy.

The line of thought going from systems to mechanisms to models and narrative thought works for simple systems. Complex systems may present us with a bigger challenge. If sources of complexity have to do with a system evolving or learning, and with chance occurrences and events, we need to extend the notion of mechanism to include what Glennan (2010) calls *ephemeral mechanisms*: an ephemeral mechanism is one that constitutes itself for only a brief moment, possibly to create an event just once, possibly by chance. Learning that we can continue to think in terms of mechanisms, forces of nature, and models, but accepting that a mechanism can be ephemeral, is our fifth heuristic (Sect. 3.6). Finally, in Sect. 3.7, we draw some conclusions for educational settings.

3.2 The Notion of System

Humans perceive (complex) units in their natural, social, cultural, and psychological environments. We can call these units *systems*. Systems are therefore perceptual units or gestalts. [When dealing formally with systems, we describe a system as consisting of (interacting) elements. However, we wish to stress what happens in experience when we encounter nature or fellow humans and their cultural creations. Experience creates mental units that might stimulate our curiosity and, only upon analysis, are seen as consisting of (interacting) elements.] Our story gives us a chance to "see" a tree; we recognise cows grazing in a pasture; we "see" a particular building in a city, etc.

It is no contradiction to say that we see a perceptual unit as presenting us with a number of phenomena and allowing us to see that it is composed of parts. Gestalt perception goes from the whole to its parts, not the other way. We can also divide a system into subsystems where each subsystem will again be composed of interacting parts.

A system presents us with—usually more than one—phenomena proceeding in parallel. The linden tree creates shade; it grows leaves that will die again late in the year and adds to its wooden structure; it grows blossoms; it takes up water from the ground, evaporates it, and uses part of it in photosynthesis with air and sunlight. To use an altogether different example, a tiger will be seen as a system where movement, sleep, hunting, feeding, and digesting are some of the phenomena that can be observed.

We can also go the other way, not from a system to subsystems but from a system to larger systems where the first system is a part. [This does not contradict the idea of gestalt perception. Perception (or, more generally, experience) takes place at different scales (Fuchs et al., 2020); what will be picked out as a gestalt is not predetermined by nature.] Our tree interacts with the ground, with the water cycle, with the atmosphere, with the sun, and possibly with humans. This allows us to create the notion of a system involving the tree, water cycle, atmosphere, and sun; the tree is a subsystem in this larger system.

While this step, the creation of order in our experience (by identifying systems, the phenomena they support, and subsystems), is important in a pedagogy of dealing with complex systems, it is not the main concern of this chapter. Still, we want to point out that dealing with this issue in the classroom cannot be neglected—it is the first step in a heuristic strategy for working with and on complex systems.

3.3 Complex Systems, Mechanisms, and Models

Let us consider the tree in the previous story and the phenomena it supports. The tree can be considered a complex *system* for the simple reason that it exhibits not just one but at least a few rather different behaviours. It is a living system that produces not only seasonal changes but also secular change over a lifetime. This is very different from systems typically considered in physical science such as a planet moving around the sun, charge flowing through a wire, and the reaction of hydrogen gas and oxygen gas to form water, etc.

If we want to understand the tree, we cannot do this by taking it as a unified single apparition. By calling the tree a system we might be inclined to do this, but it will not work—we need to visualise its parts. We also need to see the different phenomena the system is producing, and we should study these phenomena. We have to do this separately for each phenomenon, certainly before we attempt to put them all together again to get an understanding of the unified whole (the system).

When we follow how scientists investigate a system's phenomena, we notice that they frequently make reference to *mechanisms*. [In recent years, philosophers who have been observing the practice of scientists in fields such as biology or neuroscience have proposed a philosophy of mechanistic thinking and explaining (see Bechtel, 2008; Craver, 2009; Bechtel & Richardson, 2010; Glennan, 2017.] We are told that we have to find a mechanism behind a phenomenon if we want to explain it; it is said that the mechanism causes the phenomenon. We know that this is how it is done in scientific practice when we consider terms such as evaporation, phase change, photosynthesis, respiration, capillarity, lightning, combustion, etc. Each of these refers to a mechanism, and in each we find parts that work together to produce the effects and phenomena we are interested in.

Take evaporation of water from a leaf. It involves the leaf, water, and warm and relatively dry air. There is an interaction between the water and the air leading to the transformation of water into vapour and the transport of vapour into the air surrounding the leaf. [Somehow, heat is also involved in what is going on. We shall consider this aspect in the next section where we introduce the notion of forces of nature as a feature of perception.]

Or consider the larger scale process producing the winds that blow fresh air past the leaves. The mechanism behind this phenomenon joins land, air, sunlight, the gravitational field of the earth, and outer space in a concerted action. Sunlight heats up the ground, and the ground heats the air which then expands and moves upward. In the uppermost layers of the atmosphere, the ascending air radiates toward space, cools, and descends again, creating a closed loop of air flowing.

Clearly, seeing phenomena playing out in complex systems and then identifying mechanisms behind these phenomena is an important scientific heuristic: it is a step toward clearly specifying separate phenomena in systems and getting ready to study and explain them.

Mechanisms and Models An important aspect of the idea of mechanisms that underlie and explain phenomena has to do with models of mechanisms (see Glennan, 2017). A scientific explanation takes the form of a model, which raises some issues relating to mechanisms and models that are important to our theme.

Let us first clarify the following point. The models we have in mind and that play a role in our heuristic strategy are created for mechanisms and not for systems. We normally do not make this distinction when we speak about science and scientific approaches; nor should we necessarily have to do so. However, for our purpose, it makes sense to distinguish between systems, mechanisms, and models and make clear that *a model is created for a mechanism that has been identified to be at work in a system*.

Second, it is important to understand the role of (dynamical) models that are based upon finding and explaining mechanisms. Identifying a mechanism for the first time is a qualitative affair—it is not clear if the use of a mechanism so identified will be productive in a particular scientific study. Clarifying what a mechanism is and how it works requires creating an abstract model for it. The model is the tool that tells us what (kind) the mechanism is and how it works.

Third, if we were to try to create a model on the basis of typical narrative descriptions and explanations given of a mechanism and a phenomenon it produces (such as the one presented above for the production of winds), we will run into problems—there is no direct path from the description to the model. [To understand this point, we need to differentiate between different types of narratives (see below and Sect. 3.5 for detail). In contrast to prototypical narratives—actual stories—narrative descriptions and explanations do not create story-worlds in our imagination. Dynamical models are based upon full-fledged story-worlds.] Take the simpler example of a car running into a sitting car and pushing it off the road. A mechanism involves the two cars interacting and the ground they move on. However, when we create a mathematical model of the event, we introduce another entity, namely, *momentum*, and a quality, *speed*. The model is formulated in terms of momentum and speed, and the cars do not appear as such in the model (they are described solely by a constitutive parameter called *mass*). The question is how does the notion or image of momentum appear in the human mind? We shall answer this question in the next section (Sect. 3.4).

Narratives Told About Mechanisms Usually Are Not Stories We need to briefly consider an issue in narratology that will be dealt with in more depth in Sect. 3.5. Let us turn to the question of the form and role of narrative in the descriptions of mechanisms and the processes they are responsible for. A description in natural and relatively informal language certainly has a narrative quality. Narratives are sometimes said to describe a chain of events. To be explanatory, each of the links in the chain should be subject to some law (of physics, chemistry, human behaviour, etc.). The narrative description of the production of winds in the atmosphere given above is of this sort. We have a narrative of the activities of the parts of the atmospheric “wind mechanism”.

But does this make a story? Apparently not. Stories have different qualities and different powers. A concrete narrative, if it is a story, will in general not be “explanatory” in the simple sense of chaining events by laws.

So, one way of seeing what is missing when we study phenomena at the level of mechanisms can be understood from the perspective of (forms of) narrative: *a story is a narrative, but narratives need not be stories*. Apart from recounting and chaining events, a prototypical story involves agents that experience events, and events are caused by tensions (Herman, 2009; see Sect. 3.5 for more detail). Momentum in models of collisions of cars is such an agent. In other words, our argument for a narrative approach to (complex) systems requires *proper stories*—tales—and not just any form of narrative.

Summary Our second heuristic consists of *the qualitative approach of associating mechanisms with phenomena*; in practice, we want to do this by telling an explanatory narrative in the form of a chain of events where each link in the chain is explained qualitatively in terms of one of the interactions taking place in the mechanism; remember that such a narrative is not a prototypical story.

3.4 From Mechanisms to Forces of Nature

Something is missing when we study phenomena at the level of mechanisms. We can once again turn to the story of the linden tree. There are narrative elements that go beyond the description of a chain of events. Consider the third and fourth paragraphs of the linden tree story. Ever so gently, the words hint at the existence of entities other than the material parts that constitute a mechanism. While the latter are made up of branches, leaves, water, or air, the former are called light, heat, wind, water, air, and electricity. [Note that water and air appear in both lists; this is no mistake. Water and air appear as material elements of a mechanism *and* as “non-material” entities together with entities such as heat, light, and electricity. We call the latter *forces* (of nature) and talk about them as if they were *agents* in (natural) processes. Substances have a dual nature; they appear to us as both material parts and non-material forces. With heat, cold, light, or electricity, we have less of a problem in this regard.] [There is another feature of the list of forces of nature presented here that needs explaining. Why do we have wind and air? From a pre-scientific perspective, the answer is fairly simple: wind refers to the phenomenon of “moving air”, whereas “air” as a force refers to a chemical substance that is at once a material part and a force of nature.]

Forces of Nature The description creates an image of *agents* and *agency*: these new entities are powerful agents that act in a natural environment whose parts can be identified as parts of a mechanism. Our imaginative rendering of what is going on in and around the tree results from an important form of human experience: the interaction of our bodies and our physical and social environments leads to what we call the perception of *Forces of Nature* (Fuchs, 2006).

When we consider nature and talk about it, we apparently see forces at work such as wind, water, light, soil, humidity, electricity, gravity, or motion, and we describe them and their actions as if they were (powerful) *agents*. Moreover, when we talk about these forces and use our talk as part of an explanation of what is going on around us, we do this in the form of proper *stories* (Fuchs, 2015; Fuchs et al., 2018). To see what we mean, we should just compare the third paragraph of the linden tree story to the narrative description of the production of winds given in Sect. 3.3.

Shifting the Burden of Causality What is missing when we analyse phenomena in systems as being caused by mechanisms is the perception of forces (of nature) at work in these mechanisms. We could say that we shift the burden of causality—we shift causation from the parts of a mechanism to these agents; we hold these forces responsible for what we see happening in a mechanism. It is not the moving car that forces the sitting one off the road; it is the momentum of the first that is imparted to the second.

This is the type of reasoning used in the construction of dynamical models of mechanisms identified in simple or complex systems (Fuchs, 2002; Dumont et al., 2014). A force of nature such as heat is characterised in terms of three main aspects: intensity and tension, quantity or size, and power. [For heat, there is an intensity of heat (temperature), and associated with it is a thermal tension (temperature difference) which is visualised as the driving force of thermal processes. Second, we create a concept of a quantity of heat which is called caloric (in formal thermodynamics, this is called entropy; Fuchs, 2010). Caloric is contained in materials, it flows into and out of these, and it is produced in irreversible processes. Finally, we realise that the power of a thermal process (Sadi Carnot's "puissance du feu"; Carnot, 1824) is proportional to both the magnitude of a flow of caloric and the temperature difference (tension) it flows through. We might add to this list special properties of caloric: among others, it makes bodies warm, lets them expand, and might melt or vaporise them.] To give an example, a quantity of heat is contained in a body, it flows in and out, its amount sets the temperature of the body, and this sets the temperature difference with the environment, which determines flows of heat, etc. (Notice the appearance of feedback in this description.)

Armed with such images, we can create formal dynamical models of thermal systems and processes. We now want to answer the question of how we arrive at a visualisation of agents as representations of forces (of nature) and their activities after we have identified a mechanism in a complex system. What is the relation between "seeing" mechanisms and imagining forces of nature at work?

Figure-Ground Reversal To answer this question, let us describe and explain the process of evaporation of water from a leaf in warm, dry air from both perspectives. If we consider the mechanistic approach, we are inclined to say something like the dry air "turns" the water in the leaf into vapour, and the dry air "sucks" the vapour out of the leaf. Moreover, the transport of vapour into the air increases the humidity in the air near the leaf.

Note what is fundamental here from a perceptual standpoint. The material entities that make up the mechanism are the *figures* that appear against a (back-)ground. The *ground* can be imagined as a potential landscape—an imaginary or virtual space defined by intensities (levels) through which the figures move or are moved (Fig. 3.2, left)—the objects change their states. In the example of evaporation from a leaf, the air is a figure that moves "up" in the "humidity-landscape". Leaf and air interacting are seen as causing the virtual "movement" of the air.

On the other hand, if we describe the same phenomenon from the viewpoint of forces of nature, we get a different kind of rendering that suggests a different perceptual perspective. The fact that the air receives vapour from the leaf whereupon its humidity goes up is explained by appealing to water (or vapour) being an agent that follows a gradient of humidity going from high (water in the leaf) to low (vapour in the relatively dry air). [More formally, the gradient is one of chemical potential. The chemical potential of saturated water in the leaf is higher than that of water vapour in not yet saturated air.] If we shift our attention to heat as an agent, we see caloric being produced in the leaf as a consequence of light being absorbed; the caloric is first stored in the leaf and then flows down a temperature gradient into the water, raising its vapour pressure. This is the beginning of the process whereby vapour flows from the leaf to the air. [Deichmann, 2014 has created a visualisation of

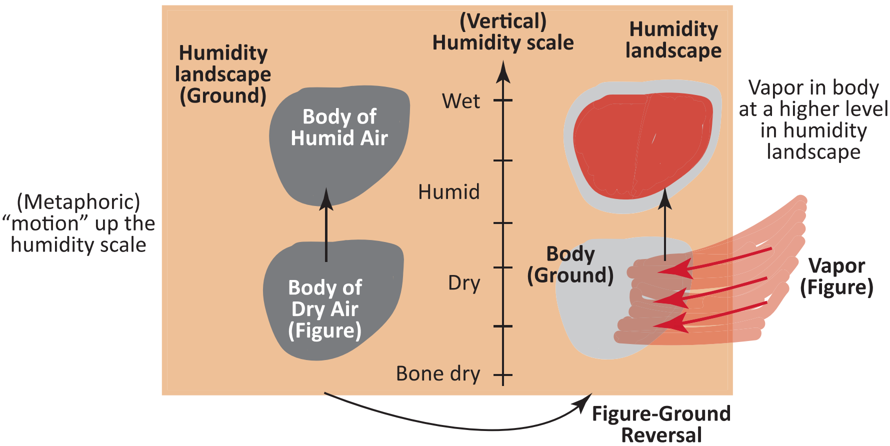

Fig. 3.2 Symbolic representation of the act of figure-ground reversal in the case of humidifying air. Before the experiential shift, we perceive a body (of air) that is first dry and then humid. After the shift, the body has become the (back-)ground. Now, vapour is the figure that enters the body, is stored, gets more concentrated, and therefore appears at a higher level of humidity

processes that uses the perspective of forces of nature in the form of an animated story of an inventor trying to invent a perpetuum mobile.]

In this short sequence, we see that leaf and air have become the perceptual (back-)*ground* relative to which light, heat, and water (vapour) are going through activities—they are visualised as agents, i.e. they have become the *figures* in our perception. In other words, the move from thinking in terms of mechanisms (as consisting of material elements) to imagining forces of nature is the cognitive act of *figure-ground reversal* (Fig. 3.2). This act is the origin of imaginative entities (agents) created by our mind. These agents have three traits (and related properties): they are characterised by *size*, by *intensity* (or tension), and by *power* (which actually depends upon size and intensity; Fuchs, 2006, 2010, 2011).

Summary Let us finish this section by describing briefly what all of this tells us about the structure of models of mechanisms in dynamical systems. Such models are representations of the activities of agents (i.e. forces of nature) set in, and constrained by, a natural, technical, or social environment. Cast in terms of figure and ground, a model contains specifications of the *(back-)ground* (typically expressed by parameters such as sizes, geometries, material properties, resistances, capacitances, etc. of the physical elements of a mechanism) and a rendering of the properties of the *figures* (agents) and their interactions both with each other and with the ground (i.e. the environment). Together, they define what we can call the natural, technical, or social *scene*. Performing mental figure-ground reversal is our third step in the heuristic strategy.

3.5 Modelling and Simulation as Narrative Acts

Identifying mechanisms and perceiving forces of nature do not, by themselves, force us to explicitly use a narrative approach to scientific practice. We need to dig deeper into the relation between cognitive effects of narrative and the methodology of modelling and simulation (of dynamical systems) if we want to see how they depend upon each other (see the feedback loop (b) in Fig. 3.1).

In a study of practices of computational physics and the use of large-scale simulations of complex processes, such as the creation of snowflakes, Wise (2011) has shown how story-like patterns arise from the generation of bundles of (simulated) trajectories—simulating computer models is a narrative act.

Conversely, in the field of economic theory, Morgan (2001) has demonstrated how economists tell stories of economic systems to help create models of these systems. In the natural sciences, we can see how stories are used to understand basic phenomena (Corni, 2013) and historical natural phenomena (Norris et al., 2005). These studies show how we arrive at models from stories. This is similar to the role of our own story of a linden tree—stories appear to suggest models. But how do they do this? Here are two points that we believe answer this question and are of practical importance.

Stories as Prototypical Narratives First, experience and conceptualisation of forces of nature connect science and narrative: forces of nature, represented as agents acting and suffering in natural and technical environments, deliver a necessary ingredient of *stories*. Stories, as prototypical members of the category of narrative structures (Herman, 2009), are characterised by events that are caused and experienced by agents and by tensions that cause events (remember that agents are subject to tensions).

Stories and Story-Worlds Second, and partly as a consequence of the first point, an important analogy can be drawn between narrative practice, on the one hand, and modelling and simulation, on the other: telling a story is like creating a simulation of a model, and a model is like the story-world that is conjured up in the mind of the person hearing or reading the story. In order to make this analogy clear, we need to understand what is meant by *story-world* (see Fig. 3.3). In *Story Logic*, Herman (2002) defines *story-worlds* as follows: "[…] storyworlds [are construed] as mental models […] supporting narrative understanding" (p.17). He writes that:

> [I]n trying to make sense of a narrative, interpreters attempt to reconstruct not just what happened—who did what to or with whom, for how long, how often and in what order—but also the surrounding context or environment embedding existents, their attributes, and the actions and events in which they are more or less centrally involved. […] storyworld points to a way interpreters of narrative reconstruct a sequence of states, events, and actions not just additively or incrementally but integratively or "ecologically"…. (pp. 13–14)

This description of a story-world sounds very much like that of a model created of a mechanism for a phenomenon presented by a (complex) system.

We can now understand the analogy between a concrete simulation of a given model and a concrete story told against the backdrop of a story-world. After all, a simulation traces the development of agents (their properties, i.e. extensions or amounts and intensities)—it traces the events they are causing and experiencing.

To understand narrative practice, it is important to see it as a *union* of storytelling *and* construction of story-worlds; and to understand the scientific practice in the field of real-world systems, it is important to see it as a *union* of simulation *and* model building.

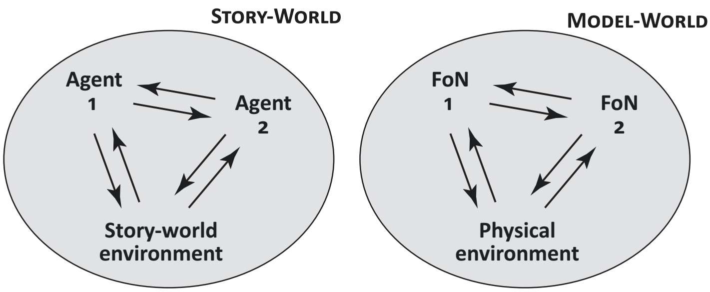

Fig. 3.3 Analogy between story-worlds and model-worlds. A story-world describes agents in an environment. Agents interact with each other and with the environment. These interactions are commonly described by fairly stable rules. In a model of a mechanism, Forces of Nature (FoN) replace agents, and a physical environment is analogous to a story-world environment

Summary All of this suggests that a story is a tale that evokes a scene (story-world) which is the source for models of mechanisms, told as a tale of forces of nature; the models are then the explanatory engines that can be used to recreate the story (i.e. the simulations) and create new stories (new simulations).

In practical terms, this means that, in an educational setting, we should make an effort to train students in creating stories of events in complex systems that have enough detail to suggest a rich story-world consisting of a story-world environment and agents (Fig. 3.3, left). The richer the story, the more suggestive it will be, the more it will tell us about how to create a possible model of mechanisms at work in the system. This is our fourth step in the heuristic for dealing with complex systems.

3.6 Complexity and Ephemeral Mechanisms

Our discussion of a narrative approach so far works for simple to (moderately) complex systems that exhibit relatively stable mechanisms and behaviours obeying relatively well-defined rules. This does not mean, however, that there cannot be exceptions—even simple and well-behaved, stable mechanisms can break down; cars break down and so do hearts (see Glennan, 2017). However, there is more to life than that.

Remember the story of the linden tree—it ends in a bang. At the end of the day, the tree is destroyed by a lightning strike. First, this is an example of an event that would be difficult if not impossible to predict. Second, what is happening here is clearly not the result of the breakdown of a mechanism—it is caused by the interaction of several mechanisms creating a larger mechanism in a system that includes the tree, the land, and the atmosphere.

Note the element of *unpredictability*—many systems that are justly called complex bear the characteristics of events like the one in the last part of our story. [Unpredictability alone does not make a complex system. To give an example, in radioactive decay there a simple process that is subject to randomness and makes single events unpredictable. Conversely, a complex system need not be characterised by randomness (remember the case of deterministic chaos).] Does this mean that explanation in terms of mechanisms, forces, and models breaks down in the face of complex systems? Let us first see how the event of the demise of the linden tree fits in with the idea of mechanisms.

What we have here is a system that is anything but stable. [Maybe we should not even speak of a system any longer since the term usually suggests a relatively stable assembly of parts (Glennan, 2017).] The mechanism that is held responsible for the destruction of the tree includes the thunderstorm, a lightning bolt, and the tree. This mechanism, the *concrete* case of the local thunderstorm on that day, generating the lightning strike and hitting the tree at that very moment so precisely that it kills the giant tree, is what Glennan (2010) calls an *ephemeral mechanism*.

Such mechanisms are created ad hoc, maybe by a generous dose of chance, and they do not persist—they are usually short-lived, and their activity takes place in a relatively limited spatial region. Glennan describes ephemeral mechanisms as having three main characteristics:

1. The interactions between parts can be characterized by direct, invariant, change-relating generalisations.
2. The configuration of parts may be the product of chance or exogenous factors.
3. The configuration of parts is short-lived and non-stable and is not an instance of a multiply realised type.

Obviously, this tells us that we can continue to think in terms of mechanisms even when faced with unique, historical, and basically unpredictable events—chance has to do with the constitution of the mechanism, not with its functioning which still works according to rules.

If we apply the idea of ephemeral mechanisms to the concept of story-worlds of forces of nature, we can expand the image we have sketched in this chapter—we can introduce the concept of *ephemeral story-worlds*. Remember, a story-world is an *environment* populated by *agents*. Stories, i.e. possible behaviours, are developed against the background of such a story-world. Unpredictable behaviour can come about in several ways. It does not just result from the form of the rules that govern the interactions between participants and objects in the story-world (see the feedback loops in Fig. 3.3), such as feedback that leads to complex behaviour (deterministic chaos) or stochastic processes (i.e. relations between agents and agents and their environments having stochastic components); it arises as well, and maybe very importantly, from chance in *constituting* the story-world (i.e. a story-world environment *with* agents).

However unpredictable the chance constitution of the story-world, the ephemeral mechanisms it represents can still be understood. There is nothing about the meteor striking the Earth that led to the demise of the dinosaurs—if this is what actually happened—that cannot be talked about and understood. Nothing about it is not physical or biological. We understand the forces at work, and we know about their interactions with each other and the environment. All of this allows for an explanatory story to be told.

Glennan (2010) has introduced the idea of ephemeral mechanisms in the context of historical explanation. Histories often involve humans, but they need not do so—we are accustomed to think of the history of the universe, the life of stars, and the history of our planet or of non-human life on Earth. Many of the events and chains of events are punctuated by unpredictable phenomena—they would be explained in terms of ephemeral mechanisms and recounted in the form of stories emerging from story-worlds that have an ephemeral constitution.

Note that stories are the perfect repositories for systems and phenomena with a historical perspective. Indeed, it is hard to think of complex systems not to demonstrate at least an element of historicity; therefore, and just on this account alone, narrative seems to provide a powerful tool for working with systems derived from the real world.

Summary Unpredictability does not fundamentally keep us from explaining and understanding. We can create stories that suggest ephemeral story-worlds. The rules that normally apply to the interactions of agents and environments still apply. This means that we can learn about complex systems even though they very often exhibit unexpected and unpredictable behaviours. We simply need to learn what is chancy and unpredictable about events, and that such aspects do not negate productive knowledge gained from simpler systems and cases.

3.7 Conclusion: Complex Systems in Education

Although we have described mostly general issues of how narrative relates to complex systems, our concern has always been with education. Over the years, the authors have engaged in teaching the science of everyday simple to complex dynamical systems to engineering students and to student teachers. In recent years, a methodology for dealing with applications, ranging from renewable energy engineering, through the physiology of mammals, to the Earth's climate, has been developed. This methodology has been presented here as a heuristic strategy in five steps:

Step 1: Observe and identify phenomena and foreground a system that is associated with these phenomena.
Step 2: Identify mechanisms for the phenomena the system presents us with.
Step 3: (Learn to) perform a figure ground reversal to let forces of nature appear as agents acting in these mechanisms.
Step 4: Tell stories about the phenomena and use the stories to construct story-worlds; learn how to translate the story-worlds into model-worlds that represent the properties of agents and environments and their interactions. Use the models for simulations and analyse these simulations as additional stories told about phenomena the system can present us with.
Step 5: Learn to recognise ephemeral mechanisms and how to create ephemeral story-worlds. Realize that the steps 1–4 in our heuristic of dealing with (complex dynamical) systems also work in the face of ephemeral mechanisms.

Here is a very brief concrete example of how we use stories, such as the one about the linden tree, in our courses for student teachers of primary school (much of the work described in the following is done in laboratory sessions accompanying the basic lecture of the course; Corni & Fuchs, 2020).

The story serves several distinct but related purposes. It connects a student as directly as is possible to a natural scene—short of experiencing it physically; it allows a listener to become emotionally and imaginatively engaged; it creates experientiality that lets systems emerge in our mind (a tree and a thunderstorm); it alludes to mechanisms (uptake of water, photosynthesis, evaporation) and feedback dynamics; and it lets forces of nature emerge and emphasises their agent-like character. [It has been pointed out how important and powerful nurturing empathy in science education concerned with complex socio-scientific issues can be (Zeyer & Dillon, 2019). We can stress here the role of emotion and imagination for both empathy and rationality. As we have written elsewhere, "Stories of forces of nature may very well be the siblings of typical stories children all over the world are exposed to. What we hope to achieve is that students see nature—and through it, science—in a new light. It is not any longer a world that is so totally different from the society of our fellow human beings. Nature is filled with agents with whom we can interact—communicate. We feel we are in a position to understand and predict the behaviour of these agents (folk physics) just as we wish to predict human behaviour…" (Fuchs et al., 2018).]

We make our students aware of all these aspects and invite them to engage in a number of analytic and constructive activities that demonstrate how such a story can be used in their future classrooms with young learners. Important activities include an analysis of story structure and how this lets agents and (feedback) dynamics emergence; the search for metaphoric elements that render in imagination the properties and activities of agents representing forces of nature such as humidity, heat, and electricity; and identification of examples of how agents interact to create a complex system. Above all, the structure of the linden tree story gives our students a chance to become aware of ephemeral mechanisms.

We then use the results of such analyses to introduce students to the science of (some of) these forces and the art of consciously creating story-worlds or mental models that become the foundations of more formal models. In the case of teacher students, we use system dynamics modelling tools for creating models of simple systems such as water in a glass evaporating as the humidity of the surrounding air changes.

In conclusion, our experience has told us that the often rather difficult task of creating and using models of dynamical systems can be taught rather successfully to a wide(r) range of audiences if it is treated narratively rather than as a purely formal exercise. While dynamical models are often used for dealing with relatively simple systems, the methodology is indispensable for working scientifically with complexity.

Maybe this is one of the most important things we can learn from dealing with complex systems by using a narrative approach. Stories we hear as children or read as adults teach us that life cannot be predicted, and so, predictability usually breaks down in scientific "stories" as well. If we take a narrative approach to complexity, a view of science as giving us "the" truth about nature and allowing us to predict the future—a view that is all too often alienating for many learners—can be effectively balanced by a more humane view of what we, as a species and a culture, are capable of knowing and doing and how and why.

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References

Andersson, C., Törnberg, A., & Törnberg, P. (2014). Societal systems: Complex or worse? *Futures, 63*, 145–157. doi:https://doi.org/10.1016/j.futures.2014.07.003. Accessed 18 Jan 2021.

Bechtel, W. (2008). *Mental mechanisms. Philosophical perspectives on cognitive neuroscience*. Psychology Press.

Bechtel, W., & Richardson, R. C. (2010). *Discovering complexity. Decomposition and localization as strategies in scientific research*. MIT Press.

Bruner, J. S. (1990). *Acts of meaning*. Harvard University Press.

Caracciolo, M. (2014). *The experientiality of narrative. An enactivist approach*. de Gruyter.

Carnot, S. (1824). *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance* (R. H. Thurston, Trans. and Ed., Peter Smith, Gloucester, MA, 1977). Paris: Bachelier.

Corni, F. (Ed.). (2013). *Le scienze nella prima educazione. Un approccio narrativo a un curricolo interdisciplinare*. Erickson.

Corni, F., & Fuchs, H. U. (2020). Primary physical science for student teachers at kindergarten and primary school levels. Part I: Foundations of an imaginative approach to physical science. Submitted. *Interchange, 51*, 315–343.

Corni, F., Fuchs, H. U., & Savino, G. (2018). An industrial educational laboratory at Ducati Foundation: Narrative approaches to mechanics based upon continuum physics. *International Journal of Science Education, 40*(3), 243–267.

Craver, C. F. (2009). *Explaining the brain: Mechanisms and the mosaic unity of neuroscience*. Oxford University Press.

Craver C. F. (2015). Mechanisms in science. *Stanford encyclopedia of philosophy*.

Craver, C. & Tabery J. (2019). Mechanisms in science. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy* (Summer 2019 Edition).

Deichmann, M. (2014). *Im übertragenen Sinne*. Metaphern und Bildvergleiche in der Wissernschaft (Bachelor thesis). Zürcher Hochschule der Künste, Zurich. http://vimeo.com/98311515. Accessed 18 Jan 2021.

Dewey, J. (1925). Experience and nature. In J. A. Boydston (Ed.), *The later works* (Vol. 1, pp. 1925–1953). Southern Illinois University Press.

Di Paolo, E. A., Elena Clare Cuffari, E. C., & De Jaegher, H. (2018). *Linguistic bodies. The continuity between life and language*. MIT Press.

Dumont, E., Fuchs, H. U., Maurer, W., & Venturini, F. (2014). *From forces of nature to the physics of dynamical systems*. The 9th international conference on conceptual change, Bologna, Italy, August 2014.

Egan, K. (1986). *Teaching as story telling*. The University of Chicago Press.

Egan, K. (1988). *Primary understanding. Education in early childhood*. Routledge.

Forrester, J. (1961). *Industrial dynamics*. MIT Press.

Fuchs, H. U. (2002). *Modeling of uniform dynamical systems*. Zurich: Orell Füssli. Available at http://www.hansfuchs.org/MUDS. Accessed 18 Jan 2021.

Fuchs, H. U. (2006). System dynamics modeling in fluids, electricity, heat, and motion. GIREP invited talk, Amsterdam. In E. van den Berg, T. Ellermeijer, O. Slooten (Eds.), *Modeling in physics and physics education*. Proceedings of the GIREP Conference 2006, August 20–25, Amsterdam.

Fuchs, H. U. (2010). *The dynamics of heat*. Springer.

Fuchs, H. U. (2011). Force dynamic gestalt, Metafora e Pensiero Scientifico. In F. Corni, C. Mariani, & E. Laurenti (Eds.), *Innovazione nella Didattica delle Scienze nella Scuola Primaria: al Crocevia fra Discipline Scientifiche e Umanistiche* (pp. 8–18). Artestampa. ISBN 9788864620916.

Fuchs, H. U. (2015). From stories to scientific models and back: Narrative framing in modern macroscopic physics. *International Journal of Science Education, 37*(5–6), 934–957.

Fuchs, H. U., Contini, A., Dumont, E., Landini, A., & Corni, F. (2018). How metaphor and narrative interact in stories of forces of nature. In M. Hanne & A. Kaal (Eds.), *Narrative and metaphor in education*. Routledge.

Fuchs, H. U., Dumont, E., & Corni, F. (2020). Narrative minds in the construction and use of theories of forces of nature—A model of experience at different scales. In M. Sinding, A. Heydenreich, & K. Mecke (Eds.), *Narrative, cognition and science* (ELINAS series). De Gruyter, 2020 (to be published).
Gallagher, S., & Hutto, D. (2008). Understanding others through primary interaction and narrative practice. In J. Zlatev, T. Racine, C. Sinha, & E. Itkonen (Eds.), *The shared mind: Perspectives on Intersubjectivity*. John Benjamins.
Glennan, S. (2010). Ephemeral mechanisms and historical explanation. *Erkenntnis, 72*, 251–266.
Glennan, S. (2017). *The new mechanical philosophy*. Oxford University Press.
Herman, D. (2002). *Story logic*. University of Nebraska Press.
Herman, D. (2009). *Basic elements of narrative*. Wiley-Blackwell.
Hutto, D. (2007). The narrative practice hypothesis: Origins and applications of folk psychology. *Royal Institute of Philosophy Supplement, 82*(60), 43–68.
Morgan, M. S. (2001). Models, stories, and the economic world. *Journal of Economic Methodology, 8*(3), 361–384.
Norris, S. P., Guilbert, S. M., Smith, M. L., Hakimelahi, S., & Phillips, L. M. (2005). A theoretical framework for narrative explanation in science. *Science Education, 89*(4), 535–563.
SDEP MIT. (1996). http://web.mit.edu/sysdyn/index.html and http://web.mit.edu/sysdyn/road-maps/toc.html. Accessed 18 Jan 2021.
Varela, F. J., Rosch, E., & Thompson, E. (1991). *The embodied mind. Cognitive science and human experience*. MIT Press.
Walsh, R. (2014). Narrative in the face of complexity as a "limit-of-sense" phenomenon. *Narrative matters 2014: Narrative knowing/Récit et Savoir*, June 2014, Paris, France. hal-01076891.
Walsh, R., & Stepney, S. (Eds.). (2018). *Narrating complexity*. Springer.
Wise, M. N. (2011). Science as (historical) narrative. *Erkenntnis, 75*(3), 349–376.
Zeyer, A. (this volume). Coping with structural uncertainty in complex living systems. In A. Zeyer & R. Kyburz-Graber (Eds.), *Science | Environment | Health: Towards a Science Pedagogy of Complex Living Systems*. Springer.
Zeyer, A., & Dillon, J. (2019). The role of empathy for learning in complex Science|Environment|Health contexts. *International Journal of Science Education, 41*(3), 297–315.

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