Chapter 7

Constructivist computing†

The term constructivism does not occur with great frequency in this thesis before the current chapter, but many of the discussions are closely related to issues in constructivism. The aim of this chapter is to introduce some of the relevant constructivist literature and to show how this relates to the practice of EM. Rather than take a stance on any particular decomposition of constructivism, the idea of constructivism is taken as a complete attitude or approach, as supported by Bruno Latour in his attempt to rescue constructivism [Lat03]. EM will be shown as supporting the five guarantees sought by Latour. This has led Beynon to propose that the EM approach be referred to as a constructivist approach to computing, or 'constructivist computing' [Bey07c].

Discussions on and relating to constructivism in the educational literature are vast and seem to be ever expanding with the addition of new variations of constructivism as pointed out by Phillips in his paper "The good, the bad, and the ugly: the many faces of constructivism" [Phi95]. Phillips compares constructivism to a secular religion because it has many sects "each of which harbors some distrust of its rivals" [Phi95]. Educational theorists and practitioners, sociologists and scientists, have all popularised and criticised constructivism as well as interpreting it differently according to the specific needs of their area. It has been applied so broadly that to talk of constructivism is to enter into the debate of 'which constructivism?' and justification is sought for the adoption of a particular form. Constructivism has been popular in the area of computing and educational technology as can be judged, for example, by the research relating to Papert's 'constructionism' [PH91] (as described in §1.2.1). Such widespread application (and mis-application) of the term 'constructivism' has led many people to question its status as a prominent theory of learning. The title of Phillips' paper—the good, the

†This chapter is an extended exposition of part of a joint paper published in the Journal of Computers [BH07].

bad and the ugly—reflects the changing mood surrounding constructivism, with Phillips suggesting that currently we might be experiencing the 'ugly' side. However, as Phillips notes, ideas closely related to constructivism continue to be the subject of vigorous debate [Phi95].

The application of EM to education and learning can be seen as having much in common with constructivism (see for example the discussion by Roe [Roe03:c.4]). However, previous connections with constructivism have been criticised for not being clearly aligned to a particular group of constructivists. In a book entitled "Constructivism for education" [SG95], Steffe highlights some of the conflicting epistemologies discussed by different groups of constructivists. She also stresses the need for research relating to constructivism to be aware of these conflicts [Ste95]. One solution to this problem is to join a particular group of constructivists and adopt a specific attitude to constructivism (e.g. radical constructivism). Another solution is to neglect the connection with constructivism altogether and join the critics of 'ugly' constructivism. Neither of these solutions appear to offer any contribution towards understanding EM with respect to learning.

7.1 Introducing constructivism

7.1.1 The constructivist idea

According to the well-known constructivist von Glasersfeld, the basic tenet of constructivism is that individuals are not born into the world pre-installed with rules, mechanisms, skills, and knowledge [Gla90]—individuals are unlike a computer that comes installed with software and ready-loaded with data. Neither do individuals acquire skills and knowledge in neatly packaged boxes by some kind of transfer—unlike the way a program or files are installed into a computer. Instead, the majority (the amount depends on which constructivism you follow) of knowledge is constructed by each individual in response to personal experiences. Piaget is generally credited with first formalising this way of thinking about how we construct knowledge from his studies of children [Pia29] and his essays on biology and knowledge [Pia71]. He suggested that learners internalise knowledge in two ways: assimilation and accommodation. When a learner assimilates, she is interpreting events in terms of her own understanding, fitting the experience to the mental model, thus strengthening her understanding of the experience [Pia71]. When a learner accommodates, she is changing her understanding of the world to accommodate the event, fitting the mental

model to the experience, thus learning something new from the experience [Pia71]. This implies that the knower, the known, and the outside world, all can play a part in any construction or reconstruction of knowledge within the learner (and the interplay of these influences is also important, as described further by Latour [Lat03]).

EM is not concerned with the transfer of 'prescribed' knowledge to a 'passive' individual. The aim of this work is to address a more fundamental issue that is close to the constructivist idea: How can EM support the active personal construction of knowledge by model-building? Sense-making plays an important role in model-building with EM. Likewise, Piaget typically depicts the child learner as an individual creative scientist struggling to make sense of phenomena in the world [Pia29]. EM is offering support for learners in this role.

7.1.2 The many forms of constructivism

In this section, some of the many forms of constructivism are reviewed. Ernst von Glasersfeld's *radical constructivism* [Gla90] is perhaps the most famous form of constructivism, and is seen as the most extreme. He states the basic principles as:

> *1. Knowledge is not passively received either through the senses or by way of communication. Knowledge is actively built up by the cognizing subject.*
> *2. a. The function of cognition is adaptive, in the biological sense of the term, tending towards fit or viability; b. Cognition serves the subject's organization of the experiential world, not the discovery of an objective ontological reality.*
> [Gla90]

Von Glasersfeld goes on to argue that to adopt constructivism seriously, the principles have to be radical because they are "incompatible with the traditional notions of knowledge, truth, and objectivity" and therefore require "a radical reconstruction of one's concept of reality." [Gla90].

The emphasis is placed on the individual as the constructor by von Glasersfeld. The effects the social environment have on the construction are not seen as being different from the effects from the environment taken as a whole [Gla90]. In Ernst's article on radical constructivism [Ern95], he discusses seven other forms of constructivism that place emphasis on different factors in the environment as playing a crucial role in knowledge construction.

As described by Galloway in article on Lev Vygotsky, *social constructivism* is based on Vygotsky's findings in developmental psychology that social context plays a central role in the process of making meaning [Gal01]. In Vygotsky's Zone of Proximal Development

(ZPD) theory [Vyg78], the individual has a set of already acquired skills (things that can be done on one's own) and a set of skills yet to be acquired (things that cannot be done even with help). In between these two groups is a set of skills that can be done with some help, and Vygotsky calls this the Zone of Proximal Development. Learning or development is the process by which things move from the ZPD to the set of acquired skills, a process which needs a More Knowledgeable Other (MKO) [Gal01]. As development progresses, new skills yet to be acquired move into the ZPD enabling the individual to continue to learn at an ever greater depth.

The basis of social constructivism is the idea that individuals, being inherently social beings, participate in the learning of a collective knowledge. The relationship is reciprocal in that individuals learn from the collective, just as the collective is constructed by the social group of individuals. Stronger forms of social constructivism view all knowledge as socially constructed—great scientific theories are the constructive work of groups of individuals comparable to great works of literature, and classroom textbooks do not contain the absolute truth but are a representation of the knowledge of many individuals. Such views are expressed in a book by Latour controversially entitled *Laboratory life: The social construction of scientific facts* [LW79].

In another form, Vanderstraeten describes Dewey's philosophy as 'transactional constructivism' [Van02], referring to learning as a process of interaction (or transaction) between organism and environment. Vanderstraeten argues that Dewey's approach is constructivist because it implies that knowledge is not external, mind or organism independent, but is a relationship between actions and their results.

In a survey of the varieties of constructivism, Dougiamas builds on the well-known forms of constructivism to introduce other forms [Dou98]. After social constructivism he introduces cultural constructivism, which builds on social constructivism by emphasising the role of culture in constructivist learning [Dou98]. Critical constructivism is another flavour [Dou98] further building on social and cultural constructivism. There are others.

Phillips attempts to bring some order and clarity to the 'which constructivism' debate by introducing three dimensions on which to locate the different forms of constructivism [Phi95]. The first dimension has at one extreme the constructivists who focus on individual understanding (such as Piaget) and at the other the constructivists who focus on public knowledge (social constructivists). The second dimension can be characterised roughly as "mind as master versus matter as master", where on one side is the view that when

knowledge is constructed it is chiefly influenced by the knower (or knowers) and on the other side is the view that it is imposed by nature (outside influence). The third dimension is related to the nature of the knowledge construction activity; at one extreme the construction activity can be described in terms of individual cognition, and at the other extreme the activity can be seen in terms of social processes. Phillips maintains that all flavours of constructivism can be located on these three dimensions [Phi95].

As explain earlier, there is pressure in the educationalist community to be aligned with a particular constructivist camp. For example, an article by Confrey [Con95] (in the same book as Steffe's discussion on the problems of constructivism [Ste95] mentioned earlier) expresses serious doubts about the compatibility of radical constructivism and social constructivism, even going as far as to say that the underlying theories are contradictory. EM faces criticism for not claiming to be constructivist but not adopting a clear theoretical basis by aligning with any particular group of constructivists. However, as will be shown in the next section, EM can offer a unique perspective on constructivism that does not require association with a particular group of constructivists. Instead, the EM approach is supported by a theoretical basis provided by the philosophy of William James [Bey05a]. Following Latour's suggestion, the quality of EM as an approach to constructivism can be determined, not by how well aligned EM is to a particular flavour, but by how well it strengthens the core constructivist idea [Lat03].

7.2 An EM perspective on constructivism

The principles of EM have been strengthened by the connection Beynon makes with a philosophic attitude, termed Radical Empiricism, developed by William James at the beginning of the 20th century [Bey05a]. Both EM and RE promote an attitude towards the nature of knowing that is radically different from typical approaches to knowledge representation in computing [Bey05a]. The close relationship between EM and Radical Empiricism is highly relevant to, and offers some fodder for, a discussion of constructivism from an EM perspective.

7.2.1 Introducing Radical Empiricism and pure experience

Radical Empiricism (RE) and EM are connected through their shared interest in rooting knowledge in personal experience [Bey05a]. EM as an approach to learning focuses on personal exploration, sense-making and individual understanding, which leads on to the

argument in this thesis that the three key characteristics of EM activity are experimentation, flexibility and meaning. Beynon describes the important role of experience in EM activity:

> "The product of an EM exercise is first and foremost to be regarded as a source of experience whose interpretation by the modeller is not preconceived, but is to be established in the mind of the modeller through an association between experience of the model and experience external to the model." [Bey05a]

The nature of EM activity, as described by Beynon, is partially evident pictorially in the illustration of the model-builder in relation to the artefact and the referent (see Figure 2.5 on page 39). One of the key points of EM is that there is a relationship between knowledge of the artefact and knowledge of the referent such that interaction with the artefact can inform knowledge of the referent and interaction with the referent can inform knowledge of the artefact. In essence, there is an intimate connection between experience of the artefact and experience of the referent.

As argued by Beynon, RE is useful for "developing a deeper understanding of the primitive concepts of EM" [Bey05a]. This is because the relation between one experience and another is fundamentally important to RE as it is important to the principles and practice of EM. James identifies RE with the notion that knowledge or knowing is made by relations between experiences, experiences that may arise from relations themselves [Jam12:p30]. This is how James describes "an experience that knows another" [Jam12:p32]. For James, all aspects of knowledge or knowing can be put into experiential terms, and thus he refers to it as "a philosophy of pure experience" [Jam12:p45].

The importance of experienced relations to EM is evident when considering the substitution of an experience of the artefact for an experience of the referent. From a Jamesian "pure experience" standpoint, such a substitution is not only natural (in terms of knowing) but also beneficial: "By experimenting on our ideas of reality, we may save ourselves the trouble of experimenting on the real experiences which they severally mean." [Jam12:p32].

7.2.2 Reconciling RE with constructivism

Constructivism is generally expressed within a dualistic framework. The differences amongst constructivist approaches, as introduced in §7.1, are described by Phillips in terms of dualistic issues: focus on private versus focus on public; mind as matter versus mind as master; and construction as individual versus construction as social [Phi95]. Such opposing viewpoints are not easily reconcilable with a mainstream philosophic attitude.

In RE, James offers a non-dualistic pragmatic perspective on the nature of knowing. By adopting the idea of 'pure experience' there is a wide scope for what is classed as 'real': "the relations that connect experiences must themselves be experienced relations, and any kind of relation experienced must be accounted as 'real' as anything else" [Jam12:p22]. Private knowledge (criticised as potentially being within a dream world of no substance) and public knowledge (criticised as a socially constructed phenomena of no substance) can be experienced and therefore have equal status from an experiential perspective. The dualistic debate, common in constructivism [Phi95], on the status of the mind as either all powerful or subject to external forces of nature is irrelevant as experienced relations can be seen as caused by both internal states of consciousness [Jam12:p7] and external perceptions [Jam12:p28].

If constructivism were expressed in Jamesian terms then there might be fewer arguments amongst the opposing constructivist camps. By taking a RE attitude, the classification of constructivism, into Phillips's three dimensions for example, is an experienced relation. Whichever view of constructivism is observed, it is an experienced relation as 'real' or valid as any other. Given the large body of research on each of the many flavours of constructivism, there is clearly some benefit in the differentiations that are made between them. It seems quite natural, from an RE perspective, that scientists may wish to take a different view of constructivism from educationalists.

In an article that directly examines the relationship between RE and radical constructivism [Phi02], Phillips takes the view that RE is more *radical* in terms of its conception of the nature of knowing, whereas radical constructivism has a more mainstream (not so radical!) philosophical attitude. Equally though, Phillips believes that James would not have any difficulty with von Glasersfeld's suggestions for education implied by radical constructivism, so although they disagree on fundamentals, they can agree about the practical issues in education [Phi02].

7.2.3 Relevance for EM

As explained by Beynon [Bey05a], EM is built on the philosophy of RE from the initial idea that the development of knowledge is firmly rooted in personal experience, through to the precise details of James's attitude of 'pure experience' that all knowing and learning can be seen as a continuous stream or transition of 'experienced relations'. From this, the fundamentals of EM can be seen as radically different from the nature of knowing

typically referred to in conventional approaches to knowledge representation in computing [Bey05a].

The significance of the connection between EM and RE can be appreciated when considering the potential of EM as an approach to constructivism. Due to RE's non-dualistic attitude, the classification of approaches to constructivism is just another experience, and therefore is not susceptible to the concerns surrounding which constructivist approach is 'correct' or 'better'. In following RE's attitude of 'pure experience', EM can likewise be seen as not primarily concerned with being associated with a particular constructivist camp.

There is still a need to show that EM is constructivist in spirit. The eight characteristics of EM, classified into experimental, flexible and meaningful characteristics, share many links with constructivism, from being concerned with 'learning through physical construction' to 'learning being a personal experience'. However, to evaluate EM as a possible constructivist approach, a stronger method for appraisal should be considered. For this it is helpful to refer to Latour later in this chapter.

7.3 Constructivism and Latour's guarantees

If Phillips attempts to draw out the differences and incoherence in the varieties of constructivist thought [Phi95] then Bruno Latour takes a different approach in emphasising their collective integrity for strengthening the constructivist idea [Lat03]. For Latour, the arguments around constructivism are a natural process in coming to understanding: "Everywhere, building, creating, constructing, laboring means *to learn how to come sensitive* to the contrary requirements, to exigencies, to the pressures of conflicting agencies where none of them is really in command." [Lat03]. Latour considers it a naturally constructivist tendency to be arguing about 'which constructivism'—where none really fit every situation.

Before Latour attempts to rescue constructivism, he explains some of the reasons why it has become a dangerous, and often despised, word. First Latour attacks the misinterpreted use of 'social' often prepended to 'constructivism'. He argues that the word is taken to mean that "the construction is made of social stuff ... a material so light that the slightest wind would dismantle it". Therefore opponents considered social constructivism not strong enough to build "the house of science ... made of solid walls of facts" [Lat03]. Second, Latour argues that the idea of construction in social science wrongly implies an all powerful

maker or builder. Whereas in reality, "if there is one thing toward which 'making' does not lead, it is to the concept of a human actor fully in command ... the constructor has to share its agency with a sea of actants over which they have neither control nor mastery" [Lat03]. Third, Latour describes how the 'construction' metaphor has led to opponents incorrectly assuming that constructions can easily be de-constructed. He explains that the 'de-constructionists' are all too eager to see a construction as a sign of weakness and as something to be reduced to ruins "in order to give way to a better and firmer structure untouched by human hands".

Latour aims to rescue constructivism, from the three problems above, by drawing on the core idea of constructivism and showing that different approaches can all coherently agree with the core idea. In determining the extent to which the constructivism is achieved, approaches to constructivism can be evaluated in terms of how each strengthens these five guarantees, *taken together* [Lat03]:

1. Certain ideas or things should not be allowed to be disputed, and should be acknowledged as a stable reality.

2. A revision process should be maintained to make sure new claimants are able to challenge areas which the established order has not taken into account.

3. Understanding of the world is composed progressively, it is not already there once and for all.

4. It is essential that there is no clear separation between the human and non-human (words and worlds, nature and culture, facts and representation).

5. It should be possible to differentiate between good and bad construction, and specify the quality of the 'good common world'.

7.4 Modes of application for EM construals

In order to reflect on EM's constructivist ingredients, it is helpful to consider the contrast between a traditional program and an EM construal (or model). This is best appreciated by considering five different but interrelated modes of application:

- Realising an established construal

- Developing and critiquing a construal

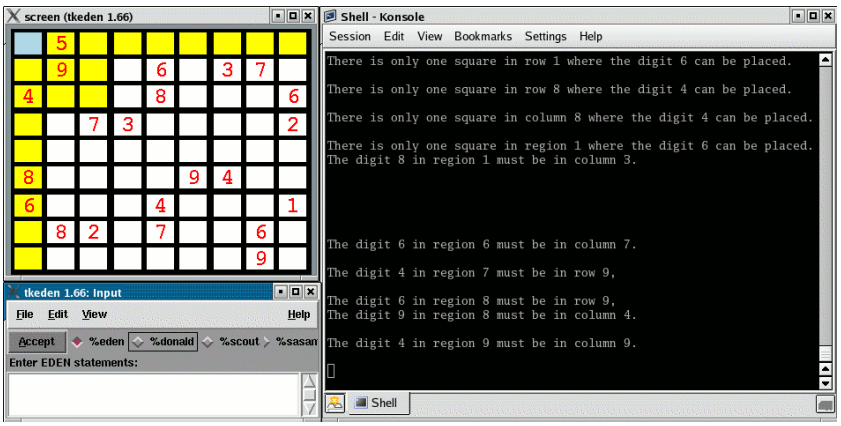


Figure 7.1: The original sudoku model by King [EMP:sudokuKing2007].

- Exploring speculative construals
- Blending mind and machine in construals
- Auditing a construal

These modes of application will be briefly discussed in turn, and related to exercises in EM that have been associated with an extended study of Sudoku puzzles and their solution by a number of student authors over the last two years. Screen-shots taken from various models that have been developed are depicted in Figure 7.1 and Figure 7.2. Figure 7.1 shows a basic EM model of Sudoku puzzles that was developed by King [EMP:sudokuKing2005]. Those depicted in Figure 7.2 (b) and (d) subsume King's original model simply by extending its basic set of definitions. In the next section the relevance of these modes of application will be formalised in comparison to Latour's guarantees.

7.4.1 Realising an established construal

EM can be conducted with an explicit referent and goal in mind. It may be that the nature of the relevant observables, dependencies and agencies at work in the application is well-accepted and understood. The objective of the modelling may be to achieve realism by some criterion: whether to be a good likeness or to fulfil a recognised function of an object.

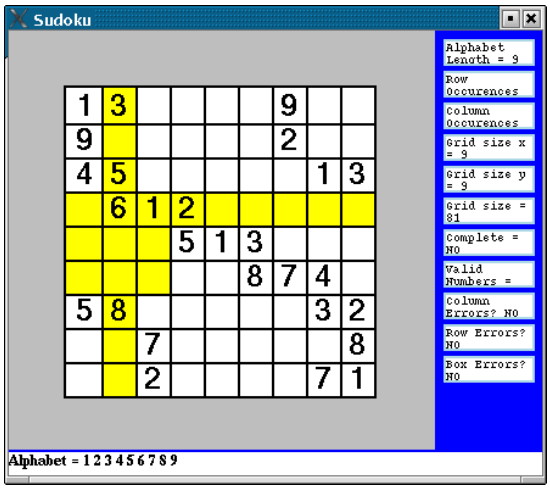
In King's model [Kin07], dependency serves to maintain the relationships between observables that are characteristic of the Sudoku puzzle: for instance, ensuring that the displayed information about current possibilities is kept up-to-date when a new digit is entered. King's model is a 'vanilla' model whose primary function is to give book-keeping support to the manual solution of a puzzle. In its most primitive form, this entails being

able to set up and store positions electronically, to record the sequence of steps and recover configurations. The state of the Sudoku puzzle can either be manipulated in a 'user/designer mode' through mouse interaction with the grid, or changed by typing new definitions into the interpreter input window. (The latter being the way in the model was originally constructed, and through which it remains wide open for further modification in much more radical ways.) The model is readily extended to perform functions that require automation; for instance, displaying the list of digits that is not already represented in a region, row or column associated with a selected square (see Figure 7.1). Introducing such functionality involves the discretionary addition of definitions to the 'vanilla' Sudoku model. Adding automatic agents to implement simple rules (such as entering a digit where every other digit appears in an associated region, row or column) is straightforward.

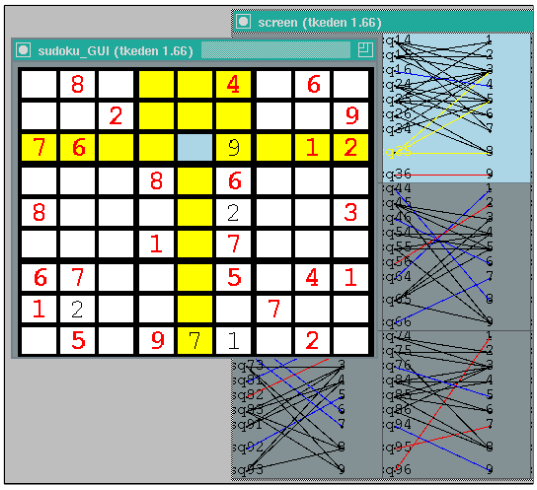
7.4.2 Developing and critiquing a construal

As construals, EM artefacts exhibit relationships between observables, dependencies and agents that embody a form of explanation. It may be that such explanations for the current state of affairs are uncontroversial, perhaps to the point of being seemingly beyond question. In some cases, certain features may be the very features that are deemed to define a referent. Nonetheless, building an EM artefact makes it possible to explore what might be termed "the neighbourhood of its referent in the space of sense" [Bey01]. This may entail adopting different viewpoints on the referent, probing accepted hypotheses and exposing alternative explanations. This is especially useful in a design context, where such investigation can lead to innovation.

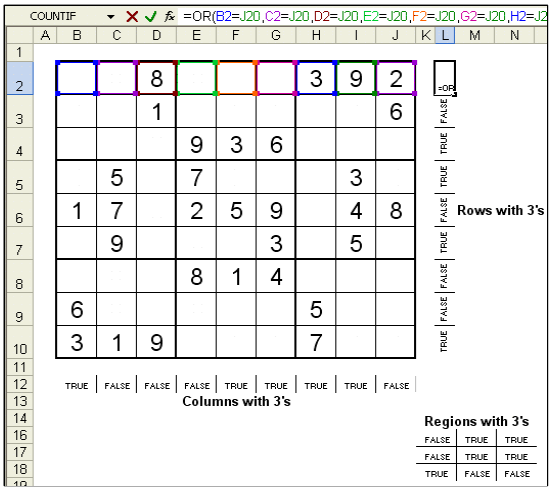
Rumsey's Doku builder (Figure 7.2(a)) demonstrates some of the potential for developing King's initial Sudoku construal. It allows a modeller to set up grids of different sizes and to generalise the principle of the Sudoku puzzle by using a different alphabet or modifying the solution constraints. Rumsey's model is oriented towards puzzle-building rather than solution, so that it deals with states of affairs of peripheral interest in the conventional model. For instance, the possibility of overwriting given entries and of processing states where there are conflicting entries is routinely considered. Note that the distinction between Rumsey's model and King's model is primarily concerned with how the modeller has exercised his discretion in developing and registering different paths through possible changes of state. For instance, it is quite possible to change the initially fixed digits through the graphical user-interface in King's model, but this is not consistent with the



(a) The Doku builder for generalised Sudoku puzzles



(b) Linking Sudoku with combinatorial graphs



(c) Studying Sudoku solving with a spreadsheet

(d) Exploring solving strategies based on colour

Figure 7.2: EM construals based on or inspired by King's Sudoku model.

established construal of 'solving a Sudoku puzzle'.

7.4.3 Exploring speculative construals

The characteristic primitive activity in EM is the construction of artefacts that exhibit patterns of dependency that invoke some external experience in the modeller's mind. For instance, a few simple geometric objects, such as lines and circles, when appropriately animated, can invoke a person running. Though no animation may be strictly necessary for this association to be made, the distinctive semantic foundation for EM rests on the observation that EM artefacts admit open interactions that disclose semantically significant dependencies between the positions of geometric elements. The fact that in the geometric figure "the head" moves with "the body" in a characteristic way is evidence to distinguish the figure from a randomly generated configuration of points and lines that fortuitously resembles a person running. Apart from such potential associations given in experience, there is no other necessary reason why an EM artefact should be interpreted in a specific way. This means that, at its most primitive, EM can be conducted in a purely speculative way, as a search for convincing associations. Parallels may be drawn with primitive activities in experimental science and engineering, where the goal is to reliably identify the key observables associated with a phenomenon with a view to incorporating them into an embryonic theory or design.

Though the concept of the Sudoku puzzle is narrowly defined, it has been the focus of a number of open-ended investigations. Figure 7.2(b) is a model developed by Efstathiou with several exploratory objectives: connecting Sudoku with the mathematical theory of matching in bipartite graphs; better understanding the connections between informal inference rules and concepts from discrete mathematics; evaluating a definitive notation for combinatorial graphs developed as an extension to the standard EM interpreter [Efs06].

An underlying theme in the construals relating to Sudoku is that, though the puzzle is tightly constrained, the nature of the rules that can be applied in its solution is open-ended. It is clear that the approach to solution and the capacity to recognise rules differs from solver to solver. All strategies rest on being able to build upon simple self-evident observations about state to derive useful consequences. The Sudoku model in Figure 7.2(c) was developed (using a general spreadsheet environment as described in §3.4) in a speculative manner by the author with a view to better understanding how self-evident observations can cumulatively inform steps in solution. In this context, the

associated dependencies were modelled using a conventional spreadsheet application. Elementary observations that can be made about the current state of the puzzle, such as 'row 1 contains 2, 3, 8 and 9', were maintained on separate layers of the spreadsheet, and significant inferences were subsequently derived by constructing other dependencies to link entries across several layers.

7.4.4 Blending mind and mechanism in construals

The concept of EM is predicated on human engagement, perception and interpretation. The notion of a dependency appeals to the idea that one change entails another in the view of a specific agent. The ground for such a notion of indivisibly coupled change is either the direct experience of the modeller ("pressing the switch puts the light on") or an experimentally informed construal that projects such coupling of change into the environment of an independent agent ("in the view of the engine management system the car is moving when the engine is running and the clutch is engaged"). That changes are perceived as indivisibly coupled has conceptual, physiological and technological components. On this account, sense-making in EM necessarily involves a blending of human and non-human agency. Some applications of EM may be primarily concerned with investigating this blending of aesthetic and experiential with mechanical and symbolic worlds.

The distinction between human and non-human perspectives on construal is highlighted in Sudoku by the fact that—in a well-posed puzzle—the precise content of any square can be inferred. In effect, the content of every square is logically dependent on the digits in the initial grid. There is no way that such dependency is directly mediated in the experience of the solver however. Even an experienced solver can only appreciate how a few specific inferences apply in a current situation to infer a new value in the grid. The boundary between what the machine automatically supplies by way of support for the solver and what the solver might be expected to observe can be adjusted by deploying different strategies for dealing with rules and inferences.

The colour variant of Sudoku depicted in Figure 7.2(d), developed by the author [EMP:coloursudokuHarfield2007], illustrates a subtle variation on this theme. A specific colour is associated with each digit, and the background colour for each blank square is a mixture of the colours associated with digits that do not already appear in the same region, column or row. The distribution of colours in the grid provides global information about the possible entries in locations that proves to be a valuable aid to solution. At

each step, dark squares offer the best prospects for making a new entry. A black square indicates that an error has been made. Being obliged to place a digit in a brightly coloured square suggests that a speculative step has been taken. Strategies for solution can be suggested by looking at the disposition of hues in regions, rows and columns. The process of choosing the colours to be associated with the nine digits was necessarily empirical in nature, and remains subject to further refinement. Subsequent extensions of this model allow the solver to manipulate the association of colours to digits and their luminance in a dynamic fashion, potentially enabling richer strategies.

7.4.5 Auditing a construal

EM is as much—or more—concerned with the processes of construction as with the product. McCarty, writing in the context of humanities computing [McC05], has emphasised the importance of modelling in helping us to appreciate 'how we know what we know'. The incremental construction of an EM artefact is associated with step-by-step empirical validation of how its states correspond to those of its referent. Where appropriate, these steps can be retraced in auditing a construal. The closely parallel role played by 'informal' artefacts in the exposition of a mathematical proof highlights the complexity and subtlety of the relationship between abstract propositions and the experiences that can convince us of their validity. The premise that underlies this aspect of EM is that espoused by William James in his philosophic attitude of Radical Empiricism: "Everything real must be experiencable somewhere, and every kind of thing experienced must somewhere be real" [Jam12:p160].

As the Sudoku exercises illustrate, EM activity broadly informs the quality of the construal from all the above perspectives. Problematic elements in a construal reveal themselves in interaction. They may be associated with imprecise or incorrect definitions in the construal itself. For instance, a mistake in defining the initial colour mix within the colour Sudoku model was disclosed when two squares that patently admitted the same possibilities had different colours. Significantly, such a problem could be resolved by redefining the colour mix function on-the-fly, then resuming the Sudoku solving activity without abandoning the stream of thought [Kin07]. The problems in developing a construal may also be attributable to the referent. For instance, Efstathiou's model led to the identification of a puzzle that was apparently not well-posed in that its solution required guessing and an extended back-tracking search. In this context, the way in which non-

obvious facts about a state in solving a Sudoku puzzle can be inferred from simple self-evident observations can itself be viewed as an integral part of the EM activity. Note that EM offers no magic wand for conjuring dependencies; it only supplies the conceptual framework within which they can be most effectively exploited. This is illustrated by the difficulty of recovering from a mistaken step in Sudoku without exploiting access to information not directly accessible to experience.

There is no clear separation between the various modes in which EM construals are applied. As the Sudoku modelling exercises illustrate, many different interpretative aspects can be represented in one and the same activity, potentially simultaneously. A similar ambiguity arises in experiment, when what was first carried out with uncertain expectations of the outcome is routinely performed to confirm what—it thereafter seems—could hardly be otherwise.

7.5 EM and constructivism

The aim of this chapter is to demonstrate EM's capability for supporting the constructivist thought and practice. In Latour's vision for strengthening the core values of constructivism, he proposes that constructivist approaches be evaluated in terms of their ability to strengthen five guarantees. In each of the five subsections below, a guarantee is discussed with reference to construction using EM. According to Latour's criterion, the quality of EM as a constructivist approach can be gauged by how far it strengthens all five guarantees *when taken together* [Lat03].

7.5.1 Acknowledging a reality

The first of Latour's guarantees is that approaches to constructivism should acknowledge stable aspects of knowledge or reality where certain ideas, beliefs, and reasonings should not be allowed to be disputed. For Latour this means, "once there, and no matter how it came about, discussion about X should stop for good" [Lat03].

From a model-building point of view, it is essential that certain ingredients in a model should be accepted as stable (i.e. as a reality) in a model-builder's personal experience. During the construction of the Sudoku model, it was acknowledged that the rules of the game (i.e. played on a 9x9 grid, only one of each digit in each row, column and region) must remain stable in order for any further reasoning to take place. The activity of 'constructing a reality' involves the identification of stable patterns of interaction in terms

of observables, dependencies and agent actions. Once constructed, further preliminary model development on top of the stable *observables, dependencies & agency* (ODA) can take place, and as regular patterns emerge the stable aspects of the model (in terms of ODA) may increase. The extent to which ODA are considered stable corresponds to the experience of the model-builder's interactions with the model in relation to the referent.

In terms of learning, acknowledging a reality is related to the characteristic that learning involves *exercising the familiar* aspects of our understanding (see §1.2.3). The reality is that which is deemed to be stable, that which is deemed to be familiar and fairly well understood. These familiar aspects of knowledge can be framed in terms of observables, dependencies and agent actions, in order to mediate between the model and the referent (see Figure 5.14). A further aspect to this is model reuse, where a model is considered stable it can effectively be taken as a basis for further model-building, by different model-builders and in different contexts. As discussed by Latour, a stable basis is needed to encourage 'builders' to make further constructions—without an acknowledged reality constructions are susceptible to the exploits of de-constructionists [Lat03].

7.5.2 Admitting the possibility of revision

Despite the definite stance on reality taken by the first guarantee, the second admits the possibility of revision. Latour specifies that "a revision process should be maintained, an appeal of some sort, to make sure that new claimants—which the former established order had not been able to take into account—will be able to have their voices heard" [Lat03].

Where EM and traditional programming may stand on a fairly equal footing in terms of constructing a reality, EM has many advantages over programming when it comes to the possibility of revision. As has been discussed in Chapter 3 and Chapter 4, one of EM's powers is that within a model 'everything is up for grabs' at any time during construction and use (although no distinction is made between the two—see §3.1.5). This open-ended support for revision of a construction guarantees that appeals to the established order of things can be taken into account.

For Latour, constructivism does not mean that everything constructed can be 'de-constructed to dust', but that when experiences do not fit into the established order it should be possible to revise ideas, beliefs and reasoning to take account of new findings. It is common for our conceptions of the world to be slightly different, often a conception is *good enough* to work (just as the colour model was good enough to work for solving

Sudoku) and at other times a conception might not correspond with our expectations of the world. The latter case is when it is important to be able to revise ideas, beliefs and reasoning—not just for the sake of it—and it is when learning is most likely to occur. Latour states that this guarantee is a complement of the first, and in terms of learning it is related to exercising the familiar and examining experiences that do not fit the familiar, as introduced in the characteristic of 'learning results from realising the unknown' in §1.2.3.

7.5.3 Progressive composition of the common world

The third guarantee states that "the common world is to be composed progressively; it is not already there once and for all" [Lat03]. The emphasis in this guarantee is on "the unified world as a thing of the future, not of the past"

A learner constructing a model with EM can be compared to a scientist, constantly experimenting with phenomena leading to progressively deeper understanding. When the referent of a model is unclear or unstable in the reality of the model-builder, then a certain amount of experimentation must take place to develop a closer correspondence between the world (referent) and the model. EM environments encourage experimentation, as discussed in Chapter 2, because changes to observables, dependencies and agency are made on-the-fly and their effects can be immediately noticeable. Furthermore, as the model (and the understanding in the learner) is progressively composed, reliable patterns of ODA become stable realities from which further experimentation can take place.

The third guarantee insists that there is no one specific understanding of the common world, but that understanding is to be built up progressively through experimentation. The range of use of the Sudoku models shows that there is no one specific use for a model in terms of learning. EM supports the development of understanding through progressive model-building founded on experimentation. The flexible characteristics of EM discussed in Chapter 2 ('creating EM construals is not a pre-thought-out activity' and 'an EM construal is never considered finished') describe the open-ended nature of model-building in supporting learning that does not necessarily follow a prescribed path and does not lead to a pre-specified outcome.

7.5.4 The essential union of the human and the non-human

The next guarantee emphasises the importance of the inseparable interaction between human and non-human agencies in the process of construction. For Latour this means

that approaches to constructivism should "ensure that there is no ... clear separation between words and worlds, nature and culture, facts and representation" and recognise that "humans and non-humans are engaged in a history that should render their separation impossible" [Lat03].

The immediate support that EM provides for Latour's fourth guarantee is that model-building is a personal activity, as discussed in the characteristic of 'an EM construal is personal to the model-builder' (see §2.2.6), that brings together the human and the non-human. Constructing a model involves the model-builder finding a correspondence between an experience in the common world and an experience with the model on the computer. EM necessitates a correspondence between the human model-builder and the non-human modelling environment, and between facts and representations. As can be seen by the number of students who prefer to start model-building from scratch, models often do not transfer easily to other human model-builders because they are part of a history that makes their separation difficult. Models are more special to their owners because they represent an acknowledged reality, a history of revisions, and a progression of experimentation.

As discussed in Chapter 2, EM supports learning that is motivated by personal interest, situated in a culture or context, and intimately connected with everyday experience. These three characteristics involve an essential correspondence between the learner, the referent, and the model (see Figure 2.5 on page 39). In this way, EM activity as characterised necessarily supports Latour's guarantee for respecting the inseparability of human and non-human agencies in the process of construction.

7.5.5 Differentiating between good and bad construction

The fifth and final guarantee ensures that constructivist approaches should enable the builders to appraise the quality of the construction. In Latour's words, "institutions assuring due process should be able to specify the quality of the 'good common world' they have to monitor" [Lat03].

EM as an approach to constructivism places the responsibility of auditing a model in the hands of the model-builder. Auditing constructions does not mean that at the end of the model-building exercise the model will be evaluated on its quality (although this may be relevant for education), auditing constructions is a process that goes on throughout the model-building where a model-builder is slowly developing an understanding of familiar

interactions. At the beginning of a model-building exercise this might involve testing primitive dependencies, such as the observation of the number 9 in a Sudoku square. Later on, confidence in these primitive foundations may lead to stable interactions on a more complex level, such as the solving of the complete Sudoku puzzle. As discussed in section §2.2.4, EM is more concerned with the process than it is with the product. The quality of a model is constantly appraised by the model-builder with respect to how well it imitates elements of the referent that the model-builder's attention is drawn towards. The accessibility of ODA in a model make it possible to mediate between states in the computer and states in the world, and therefore the quality of a model can be assessed by comparing observed dependencies in the model with those in the world.

In terms of learning, Latour's fifth guarantee is related to the second—it is when the quality of a construction is considered that there is potential for revision to take place. The fifth guarantee also ensures that the realities acknowledged (by the first guarantee) are reasonable and sensible constructions. By ensuring the quality of constructions, approaches to constructivism such as EM can reliably build upon previous constructions that have been historically stable. The extensions to Sudoku described above demonstrate the quality of the original Sudoku model for exploring a wide range of learning domains.

7.6 Towards a 'constructivist computing'

The five modes of application for EM construals in §7.4 were conceived with Latour's five guarantees in mind. The fact that all five modes can be represented within a single modelling exercise is evidence that EM is well-matched to strengthening each of Latour's five guarantees *taken together*.

Despite only mentioning constructivism in the final chapter of this thesis, it should be evident that constructivism is a topic intertwined with many of the issues throughout the thesis. The characterisation of learning in Chapter 1 pulls together constructivist ideas, the exposition of EM develops the idea of 'constructionism', and the other chapters are full of examples of construction. In the light of Latour's attempt to rehabilitate constructivism, Beynon has proposed that EM as a computer-supported approach to learning be renamed 'constructivist computing' [Bey07c]. There is potential for such a label to be misconstrued given the concern surrounding constructivism, but Latour's vision for the notion of constructivism and the five guarantees offer a solid support for 'constructivist computing'.

The reason for this exposition on constructivism is to show that EM is a constructivist approach without the usual baggage or arguments that surround the term. Without ignoring the many different forms of constructivism, EM has a unique perspective on constructivism—due to the foundation of Radical Empiricism—that means the many forms need not be seen as in opposition to the core idea. EM need not necessarily be aligned to any one constructivist camp—to show that it is a constructivist activity we need only show that it supports the five guarantees suggested by Latour. To enter into the constructivist debate is to miss the point that, as with all knowledge constructions, constructivism cannot be absolutely defined. Entering the debate is definitely not going to achieve a definition that will be accepted by all, forever; as von Glasersfeld suggests, the best constructivist practitioners can do is take on what seems most viable [Gla90].