Lifelong Learning, Empirical Modelling and the Promises of Constructivism

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Abstract—**Educational technology is seen as key for lifelong learning, but it has yet to live up to expectation. We argue that current learning environments are typically oriented too much towards structured learning to meet the needs of the lifelong learner. Environments for lifelong learning demand a higher degree of autonomy for the learner, must be open to eclectic sources, support soft informal learning activity, and accommodate evolution both in the experience of the learner and in the context in which this occurs. We propose sense-making through the construction of suitable interactive artefacts as a core activity for lifelong learning, and discuss and illustrate how this can be supported using Empirical Modelling. The merits of Empirical Modelling as a constructivist approach are assessed with reference to a criterion recently proposed by Bruno Latour, namely, the extent to which it strengthens five guarantees, taken together.**

Index Terms—**Lifelong learning, constructivism, Empirical Modelling, experiential learning, educational technology**

I. Introduction

The term ‘lifelong learning’ has become prominent within the educational community and in government proposals. In the UK, the Secretary of State for Scotland has declared that “Life-long learning is a feature of modern life and will continue to be so” [1]. The epithet ‘lifelong’ is somewhat difficult to interpret, as—to judge by its application!—it can refer to all kinds of learning—encompassing pre-school, school, higher and further education, as well as both formal and informal learning. For the purposes of this paper, ‘lifelong learning’ will be taken to mean *learning activity that takes place as a part and expression of living*. This accords with the popular archetype for lifelong learning: adult education outside the schooling years through work (e.g. in training courses) and also for pleasure (e.g. night classes, etc). It also embraces the kind of unsupervised, self-motivated learning that is associated with over-a-lifetime learning of specialist disciplines, hobbies and skills outside the classroom.

The role that educational technology can play in supporting lifelong learning has yet to be clarified. There are reasons to suppose that current technology is well-suited to supporting independent learning activities on the periphery of established educational frameworks, but optimism is tempered by the knowledge that educational technology has yet to live up to its expectations within these frameworks. This ambivalence about the potential of technology is reflected in the observation by the British Educational Communications and Technology Agency to the effect that: “There is some evidence of the use of ICT in traditional teaching, and some blended learning is taking place. However, ICT and e-learning are still largely peripheral to classroom teaching and are most widely used for additional support activities to extend independent learning” [2]. Internet use has of course played a most significant part in such "additional support activities", but has been problematic in relation to learning because of issues concerning organisation and validation that are compounded by the predominantly passive way in which document technology has so far been deployed. The limitations of current models for e-learning are confirmed by recent research findings revealing that greater online interaction does not significantly improve student grades [3]. Though there has been a trend towards many more online students and classes, there have also been exceptionally high drop-out rates—up to 80%—for online courses [4].

This paper is a revised and extended version of [5]. It argues that adapting the traditional e-learning environment to support lifelong learning is exceptionally challenging because of the mismatch between the characteristics of lifelong learning and the underlying model of knowledge behind conventional computing platforms. In some respects, a more appropriate orientation is found in the computing technologies behind recreational activities such as game-playing (cf. [6]), digital photography or electronic music. The principles that are emergent in these technologies have yet to be properly recognised, and are in tension with the established framework of computing. They reflect a significant shift in emphasis: where classical computer science focuses on abstract formally mediated interpretations of linguistic constructs and algorithmic processes, the focus in software for recreational use is upon what computing technology affords by way of concrete experiences and interactions to give direct support to cognitive processes. This is to view a product of computing technology first and foremost as a physical artefact, interactive environment or microworld.

From a learning perspective, there has been a parallel shift in emphasis from static cognitive structures to cognitive processes within certain theories of learning in developmental psychology, as, for instance, within the *constructivist* tradition of the Geneva school [7]. This shift in emphasis is broadly evident in research such as that of Karmiloff-Smith and Inhelder [8], where learning is studied as "the interplay between the child's action sequences and his implicit theories which the observer infers from the sequences rather than from his verbal comments". More specifically, it relates to Papert and Harel's vision [9] for *constructionism* as a form of "learning-by-making" that entails "building knowledge structures ... in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe."

The thinking that underlies classical computer science suits the instructionist metaphor, but an alternative vision for computation is needed to liberate the constructionist ingredients essential for lifelong learning. Where the archetype for classical computer science is a 'program' that performs a specific function on the basis of well-established knowledge about its domain of application, the archetypal computer-based artefact for constructionist use has the characteristics of what Gooding in [10] describes as a construal: "Construals are a means of interpreting unfamiliar experience and communicating one's trial interpretations. Construals are practical, situational and often concrete. They belong to the pre-verbal context of ostensive practices." [10:22]; "... a construal cannot be grasped independently of the exploratory behaviour that produces it or the ostensive practices whereby an observer tries to convey it." [10:87].

Building on critiques of conventional programming in support of constructionism [11], this paper advocates model-building based on Empirical Modelling (EM) principles as an alternative approach that is particularly well-suited to the demands of lifelong learning. EM aims at the development of computer-based construals whose significant features, interactive responses and behaviours stand in an intimate relationship to those of an external referent. This relationship is mediated through observables associated with the EM construal that have direct counterparts in the referent. This association is moreover grounded in the immediate experience of the modeller in the sense that there is a correlation between the observed and imagined patterns and agencies of change that link the observables in the construal and those that link the observables in its referent.

There is a crucial distinction to be made between modelling in EM and the traditional mathematically-based modelling that is commonly associated with computing applications. EM is in some respects a more primitive activity that is topical prior to the elaboration of a theory, in keeping with Gooding's observation [10:88] that: "Construing may be thought of as a process of modelling phenomena while the conceptual necessities of theory are held at arms length." In this paper, the principles of EM are introduced and illustrated through studies in construal relating to clocks and Sudoku puzzles. Its credentials as a constructivist approach are then evaluated with reference to a criterion recently proposed by Latour [12].

II. Technology and Lifelong Learning

Technology as a medium for communication is the current driving force behind lifelong learning. There are two aspects to this communication. Computers have become popular for the distribution of information since the birth of the World Wide Web, and are now commonly used as resources of downloadable course material. Developing web resources is perceived as enabling learning outside the classroom, allowing learners access to information in an ubiquitous manner. Computers have also been used for two-way communication in environments where students and teachers can interact. Such communication in support of e-learning can be synchronous, asynchronous or a combination of both. For example, a teacher can communicate with a student by email or organise an online session to instruct many students at the same time. This potentially provides universal access for learners to teachers and virtual classrooms.

Organised learning activity that exploits technology as a communication medium in these ways is not well-matched to the needs of the lifelong learner. Typical e-learning environments are best-suited to supplying the framework for the systematic exposition of a discipline. Such environments perform best where the learner 'begins at the beginning' and follows the prescribed learning paths sufficiently conscientiously to enable the system to build up a useful learner profile at every stage. Ideally, it should be possible for the learner to enter the framework at any point without having to incur a large overhead in supplying the contextual information about their learning status that is required by the system. In practice, any customisation of resources to the learner has to rely heavily upon the previous history of interaction with the learning environment. This has proved to be one of the problematic issues for e-learning environments, accounting for the frustration felt by learners who wish to engage with advanced topics, but are first obliged to perform routine exercises in order to inform the system of their status.

In the context of lifelong learning, the casual use of the internet both to acquire information and to use or download interactive 'learning objects' has greater promise as a model for e-learning. Though the web does not necessarily provide the electronic analogue of an accredited teacher or secure classroom, nor the structured framework of a school curriculum, it meets the needs of the independent learner in some respects. The choice of resources offers the opportunity for self-directed learning; material is generally more self-contained and can be accessed and adapted as required; the range of perspectives represented can be rich and wide. As in “the university of life”, these potentially dangerous characteristics are virtues for learners with the appropriate level of discrimination and experience. The limitations of the web as a medium for lifelong learning relate primarily to the predominantly passive and unstructured nature of the learner’s interaction.

Both e-learning environments and the web typically offer relatively limited and closed forms of interaction for the learner. Because so much lifelong learning is self-motivated, a greater degree of autonomy in interaction is desirable. The environment that best suits the lifelong learner is then one that contains elements that are constructivist in spirit [7,9], and gives opportunities for learning by building. Since lifelong learning also typically takes place in close association with concrete external activities, it is natural to consider using microworlds to provide a virtual environment within which exploratory learning can take place in context.

III. Model-building for lifelong learning

The concept of lifelong learning clearly invokes an evolution over time, both in respect of the learner’s experience and of the context for learning. Such evolution is of course conceived in traditional environments for e-learning, but is typically constrained to follow prescribed paths. In such environments, the learner is exposed to new concepts, experiences and contexts in a systematic fashion, and the exposition is managed in such a way as to keep track of the learner’s performance. But whereas the classroom learner’s experience is shaped in an artificial closed environment, that of the lifelong learner is not. A mature listener who takes up an instrument late in life may appreciate certain specialist elements of musical composition and interpretation better than a young teacher. A schoolboy experienced in IT may have a good practical grasp of principles of relational database design without being familiar with the formal notion of functional dependency. The lifelong learner frequently combines a sketchy explicit understanding of fundamental principles with a depth of experience and a familiarity with practical contexts of application that seems incongruous and inappropriately advanced.

In these circumstances, the e-learning environment that is designed to suit the learning purpose best under stereotypical conditions is no longer necessarily effective. It may be appropriate to address topics in any order, to make opportunistic, serendipitous links, or to change the strategy mid-process in the light of developments in the open world outside the classroom. Such issues can only be addressed to a limited degree by the preconceived design of an e-learning system. It is hard enough to develop adaptive systems that are selective and discriminative when the learning trajectory has been comprehensively monitored; it is impossible when the learner’s engagement is casual and incidental to much broader interaction in the outside world. In the typically informal and unstructured setting of lifelong learning, the onus of bridging the gap between standard textbook knowledge and procedures and their often disguised or distorted real-life counterparts then has to fall upon the learner.

Such ‘soft’ learning needs can be addressed by developing technology to support the learner in sense-making activities. In a lifelong learning setting, this sense-making can take many forms. It may involve making a model of a situation drawn from the learner’s working environment that can be used to gain a deeper understanding of what relationships and mechanisms are at work. Alternatively, it may involve a process of concretization: constructing a physical artefact to embody an abstract process whose practical relevance and application is obscure. As a prominent component of much lifelong learning is the exposure and rationalisation of activities and concepts of which the learner already has implicit informal knowledge, the construction of models and artefacts cannot in general be based on a pre-existing theory. As in constructionism, the process of building can itself be a process of active learning, through which connections are made and relationships between different experiences come to be better understood.

The nature of the model-building activity that can meet the lifelong learner’s requirements is depicted in Figure 1. The term *artefact* is used to refer to the model that the learner builds in order to stress its physical experiential character. As discussed above, the artefact is built with some experience to be explored and better understood in mind. The experience to which the artefact itself refers may relate to a situation, to an abstract procedure, or to a phenomenon: to respect such generality, the neutral term *referent* has been adopted. The referent could be something physical, or, in the case of an artist, the referent could be an emotion or idea that their artefact will convey. The learner develops tacit knowledge of the artefact and referent through exploratory interaction motivated by establishing a close correspondence between experience of the artefact and experience of the referent. The layering in the diagram is used to convey the idea that the relationship between the artefact and its referent evolves dynamically. The context in which the artefact and referent are being experienced is constantly changing, and invokes a change in the implicit knowledge of the artefact. As is to be expected in the lifelong learning setting, both the experience of the learner and the context for the exploratory interaction develop over time.

IV. Illustrating EM for lifelong learning

Traditional e-learning environments rely upon crafting the learning context through imposing specific patterns of interaction. This is a good strategy when learning activity can follow a preconceived plan. Such environments can be built by traditional programming, where construction is driven by identifying the required use-cases and optimising for these.

By contrast, the experienced lifelong learner will typically bring an individual, possibly idiosyncratic, perspective to bear on issues to be learnt. To accommodate this, a learning artefact for lifelong

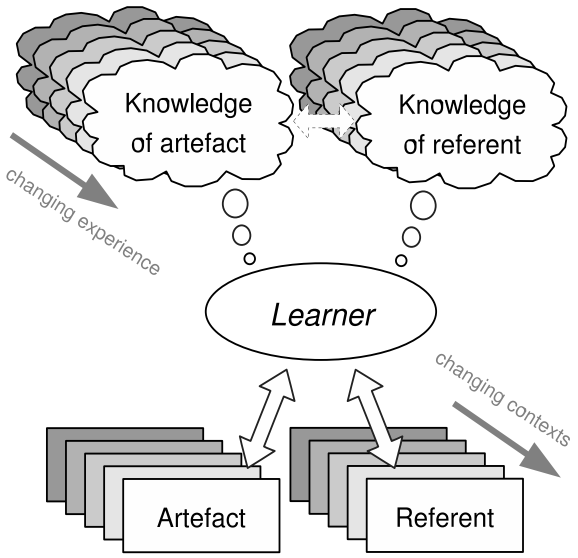


Figure 1. Learning through model-building

learning needs to be conceived in quite a different way from a conventional program. As discussed in more detail in previous papers [11], Empirical Modelling (EM) is an alternative approach to computer-based model-building that suits the constructivist vision of learning depicted in Figure 1. EM entails the development of *construals*: interactive artefacts that embody the learner's personal understanding of a situation or referent. Such construals are developed by imitating the relations between observables, dependencies and agent actions that are identified as characteristic of the referent. The process of identification and construction resembles that involved in developing a spreadsheet, and leads to a network of observables (cf. spreadsheet cells) and dependencies (cf. relationships between cells) that are expressed in a family of definitions, or *definitive script*. The versatility of EM as a vehicle for learning is consistent with other findings relating to the application of spreadsheet principles in learning [13].

An extended example will serve to illustrate the principles of EM in relation to lifelong learning. The theme of this example—that of learning about time and clocks—is too simple to be fully representative of the applications of EM to learning (cf. [14]), but highlights many of the essential characteristics.

As remarked above, the sense-making activity depicted in Figure 1 can reflect many different kinds of learning. Relevant topics might relate for instance to: being familiar with clock mechanisms; understanding the relationship between digital and analogue representations of time; appreciating how the analogue clock concretizes abstract relationships in modular arithmetic; or knowing how to tell the time in different languages and in different time zones. In a lifelong learning context, each learner will bring a different orientation and experience to these diverse perspectives on clocks and time. The process of construal that EM supports reflects this rich and potentially confusing combination of concerns. The various perspectives and their interrelationships are reflected in variants of what can be regarded as one

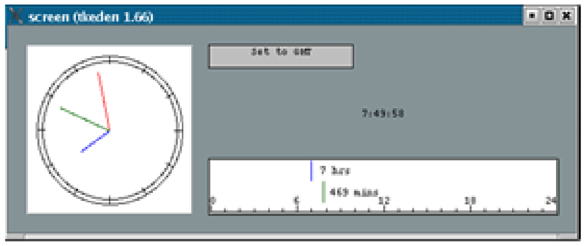


Figure 2. A variant of the clock model

model, as developed in different directions according to the learner's particular needs. An important feature of this model is that in principle it concurrently offers the same potential for redefinition and adaptation to all participants in the learning—whether model-builder, teacher or learner. In this way, it can serve in many different educational roles as a learning artefact—some aspects being developed autonomously by the learner, some supplied by an expert modeller, and some adapted and customised by a teacher.

The simplest form of sense-making model takes an analogue clock as its referent (cf. the left-hand side of Figure 2). As shown in Figure 3, the relevant observables in this context include the time as shown on the clock, the centre point of the clock face, the angle of the hour and minute hands, and the line representing the hands. Relevant dependencies link the hour and minute hands to the centre point and the angle of the hands, which in turn depends on the time in terms of hours and minutes. This may also depend on the current time in a variety of ways according to the status of the clock. For instance, the clock may be stopped, fast or slow, or refer to a distant time zone. To reflect the physical integrity of the clock, the positions of the marks on the rim and the lengths of the hands depend upon the radius of the clock face. In developing the EM construal, the geometric elements of a line-drawing to depict the clock can be specified (e.g.) as points, lines and circles whose attributes are linked by definitions to scalars and textual data that represent times, dimensions and other geometric attributes such as colours and linestyles. Full details of the definitive script together with notes on its development can be found in the EM archive [15] as `clockBeynon2001`.

The merits of the EM construal as a learning artefact relate to the open-ended interactions that it enables. Though the clock exhibits standard modes of interaction and behaviour, its observables, dependencies and the agency to which it is subject are all open to revision at the discretion of the learner—whether or not they respect the boundaries of commonsense. This is in keeping with the principle that the engineer learns most not just by observing the clock in normal operation, but by dismantling and rebuilding it, and the user learns most by interacting with the clock in exceptional contexts and exploratory ways.

By way of simple illustration, in the clock model as described above, the positions of the hour and minute hands are independently determined by the current time. In practice, the hands of a mechanical clock are linked so that you can move the minute hand and the hour hand

```
/* observables defining the position of the clock*/
point centre
centre = {500, 500}

/* observables defining the time to display */
int hour, minute
hour = 1
minute = 30

/* dependencies defining the angle of the hands */
real hourangle, minuteangle
hourangle = float(hour) div 12 * -2*pi + 0.5*pi
minuteangle = float(minute) div 60 *-2*pi + 0.5*pi

/* dependencies defining the lines representing the
hands */
line hourhand, minutehand
hourhand = [centre, centre + {200 @ hourangle}]
minutehand = [centre, centre + {400 @ minuteangle}]
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
/* a redefinition of hourangle */
hourangle = (float(hour)+float(minute) div 60)
                     div 12 * -2*pi + 0.5*pi
```

Figure 3. A fragment and a redefinition from the clock script.

moves at a slower (but proportionate) rate. The clock artefact can be adapted to exhibit this behaviour by using the redefinition in Figure 3 to establish a dependency that links the position of the hour hand to that of the minute hand. Underlying the design of the analogue clock as an engineering product are simple principles to connect elapsed time in hours and minutes modulo the number of minutes in an hour and hours in a day. The abstract relationships between 'time as recorded by hours and minutes elapsed in a day' and 'time as displayed on digital and analogue clocks' are given concrete expression in the variant of the original clock model shown in Figure 2. This variant is derived simply by visualising scalar relationships that are already explicit in the original clock model.

By way of further illustration, the time as shown on the clock can be redefined in such a way as be totally independent of the current local time, or so as to reflect the time in another time zone. The significance of specifying the time difference between Japan and UK time as plus 9 hours, rather than minus 15 hours, or even plus 5 hours, exposes the physically constrained and socially constructed nature of world time. The focus on clocks and time in physical and cultural context is well-oriented to lifelong learning, where contextual factors potentially both enrich and obstruct understanding. For instance, it is indicative of the imperfect and potentially confusing nature of learning to read clocks in a real-world setting that (e.g.) the hour hand may be misaligned so that it is not quite vertical at midday etc. It is easy to tweak definitions to imitate this condition, or to express more dire forms of mechanical failure, as when the minute hand comes loose and hangs vertically downwards.

The EM construals described above illustrate how Figure 1 applies both to the modelling of a concrete

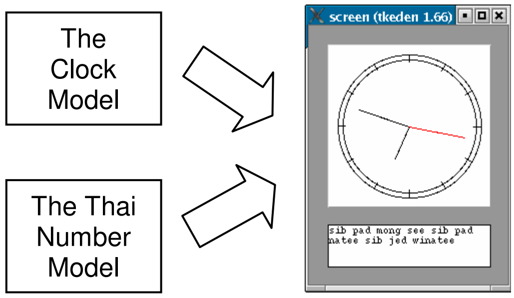


Figure 4. A blend of two construals.

referent, and to the concretisation of abstract relationships. Because of the dynamic and provisional nature of the relation between artefact and referent in Figure 1, it is also possible to regard it as a framework within which two or more artefacts can be combined and can evolve into a new learning artefact. Previously, an EM artefact for learning about counting in different languages was built [16]. By placing this artefact in conjunction with the clock artefact and adding new observables and dependencies it is relatively easy to derive an artefact for telling the time in different languages (as well as different time zones). Figure 4 depicts the artefact displaying the time in Japan whilst expressing the time in Thai.

V. MODES OF APPLICATION FOR EM CONSTRUALS

The contrast between a traditional program and an EM construal is best appreciated by considering five different but interrelated modes of application:

- Realising an established construal
- Developing and critiquing a construal
- 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. Screenshots taken from various models that have been developed are depicted in Figures 5 and 6. Figure 5 shows a basic EM model of Sudoku puzzles that was developed by King (see `sudokuKing2005` in [15]). Those depicted in Figures 6(b) and (d) subsume King's original model simply by extending its basic set of definitions.

A. *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 [17], dependency serves to maintain the relationships between observables that are characteristic of the Sudoku puzzle: for instance, ensuring

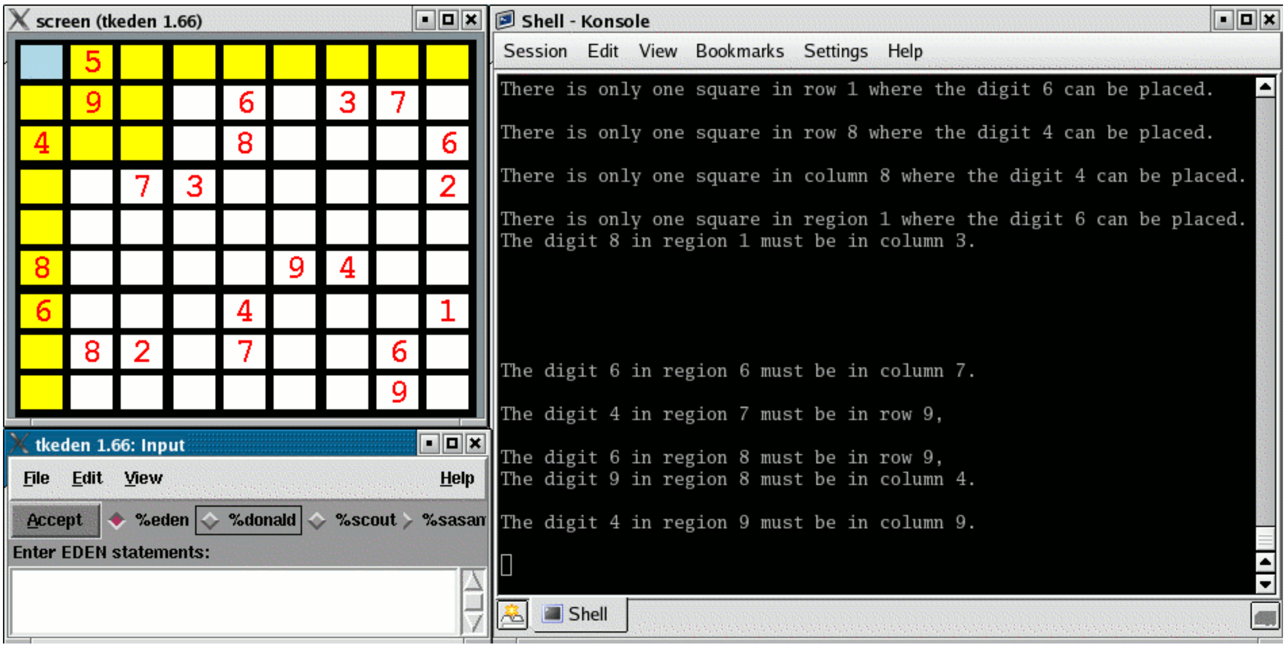


Figure 5. King's Sudoku model.

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 5). 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.

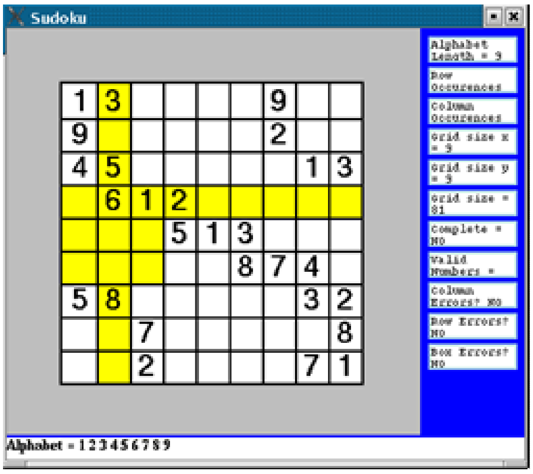
B. Developing and critiquing a construal

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" [18]. 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.

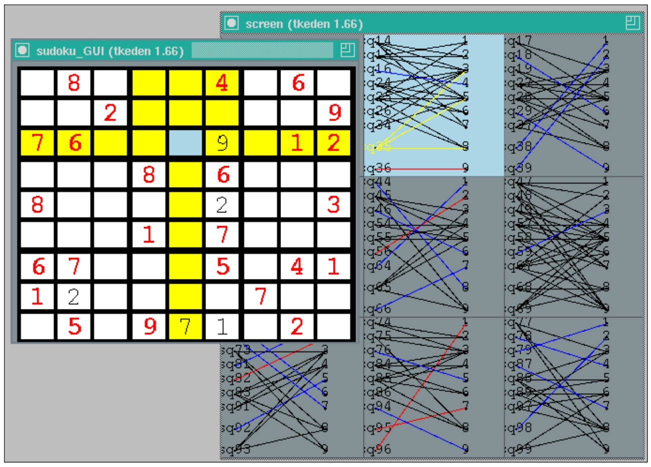
Rumsey's Doku builder (Figure 6(a)) demonstrates some of the potential for developing King's initial Sudoku construal. It allows a modeller to set up grids of different sizes and to generalise the principle of the Sudoku puzzle by using a different alphabet or modifying the solution constraints. Rumsey's 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 established construal of 'solving a Sudoku puzzle'.

C. Exploring speculative construals

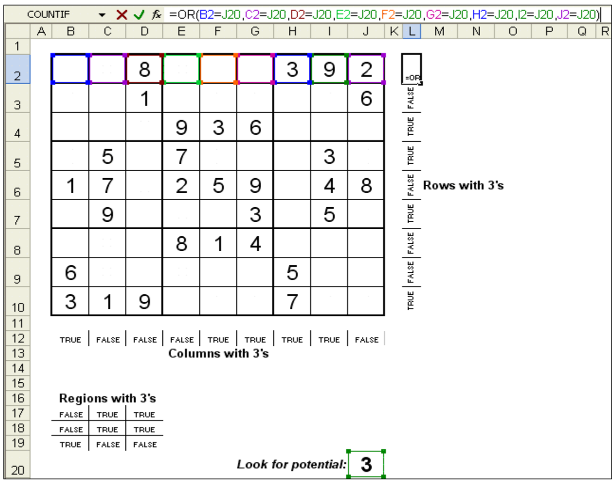
The characteristic primitive activity in EM is the construction of artefacts that exhibit patterns of dependency that invoke some external experience in the modeller's mind. For instance, a few simple geometric objects, such as lines and circles, when appropriately animated, can invoke a person running. 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



(a) The Doku builder for generalised Sudoku puzzles



(b) Linking Sudoku with combinatorial graphs



(c) Studying Sudoku solving with a conventional spreadsheet

(d) Exploring solving strategies based on colour

Figure 6. EM construals based on or inspired by King's Sudoku model.

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 6(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 [19].

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 6(c) was developed in a speculative manner by the second 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.

D. 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 6(d), developed by the authors, 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.

E. *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 [20], 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" [21:160].

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 [17]. 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.

VI. LIFELONG LEARNING, EM AND CONSTRUCTIVISM

Lifelong learning is a natural setting within which the interaction between everyday learning from experience and book learning is topical. In applying EM principles to study this interaction, it has been helpful to frame discussion in terms of a family of learning activities that range from the experiential to the propositional (cf the Experiential Framework for Learning (EFL) in Figure 7). EM is unusual amongst conceptions of computing in placing its primary emphasis on the experiential roots of knowledge. As has been argued elsewhere [22], this establishes strong links between EM and a constructivist stance on learning [11,14] that is rooted on a philosophical position with many points of contact with the Radical Empiricism of William James [21]. Neither of these links is of itself sufficient evidence that EM is well-conceived, since constructivist perspectives are the focus of fierce and longstanding controversy [23], whilst Radical Empiricism has been amongst the few relatively neglected components of James's legacy [24].

To appreciate the relevance of EM to constructivism more fully, it is helpful to contrast the discussions of constructivism in Phillips [23] and Latour [12]. From Phillips's account, the breadth of possible interpretations of the concept of 'construction' is apparent. For instance, a constructivist viewpoint may be more or less concerned with the constraints imposed by nature in relation to human creation; it may also place its primary emphasis on the individual or the socio-political construction of knowledge. But whilst Phillips stresses the potential danger of incoherence that these diverse viewpoints present, Latour acknowledges their potential integrity, setting out to rehabilitate construction as "the collective process that ends up as solid constructs through the mobilization of heterogeneous crafts, ingredients, and coordination" [12]. In Latour's vision, the potential for conflict between disparate agencies, perspectives and constraints is of the essence: "Everywhere, building, creating, constructing, laboring means *to learn how to become sensitive* to the contrary requirements, to the exigencies, to the pressures of conflicting agencies where none of them is really in command." [12].

EM is proposed as an enabling technology that can assist construction consistent with Latour's broad vision. The process of EM engages with all kinds of issues that can be encountered in learning activities within the EFL:

- the manner in which the qualities of the artefact depend upon the reliability of the machine and the skill of the human modeller,
- the constraints that the environment places upon interaction with its referent,
- the authenticity of the individual experience of conjunction between the artefact and its referent,
- the role that repetition and public communication play in validating what is learnt,
- the significance of social conventions and protocols in sense-making.

These issues are typical of the obstacles that lie in the way of an effective construal. There is then no single variety of constructivism that is endorsed by EM; the resolution of each and every issue is a matter for pragmatic empirical evaluation, and may invoke natural laws, human skills, individual and socio-political elements according to what appears to be the most appropriate identification of constraints and attribution of agency in the particular situation.

With a view to promoting the credentials of EM in relation to the authentic ideals of constructivism, this concluding section relates EM to an agenda set out by Latour [12]. In it, Latour calls for constructivist proposals

private experience / empirical / concrete

interaction with artefacts: identification of persistent features and contexts

practical knowledge: correlations between artefacts, acquisition of skills

identification of dependencies and postulation of independent agency

identification of generic patterns of interaction and stimulus-response mechanisms

non-verbal communication through interaction in a common environment

directly situated uses of language

identification of common experience and objective knowledge

symbolic representations and formal languages: public conventions for interpretation

public knowledge / theoretical / formal

Figure 7. An Experiential Framework for Learning (EFL).

to be evaluated with reference to how they treat five guarantees. In the five subsections below, each of Latour's guarantees will be briefly introduced and discussed in its relation to lifelong learning and 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*.

A. *Acknowledging a reality*

The first of the guarantees to which Latour refers in his analysis of constructivism relates to the need to acknowledge stable ingredients in knowledge. Latour's concern is that the underlying concept of constructivism naturally invites a complementary process of 'deconstruction' that can be entirely destructive: "If X is constructed, then I can easily 'deconstruct' it to dust" [12]. An authentic constructivist approach should in some aspect strengthen the guarantee that—within the established order—certain things, whether deemed to be constructed or not, can be accounted *real*: "[they] should not be allowed to be disputed and should be used as the indisputable premise of other reasonings" [12].

This quality of a constructivist approach is of particular interest to the lifelong learner. Unlike the schoolchild, the typical lifelong learner comes to a topic with well-established ideas that are rooted in extended experience, and that often serve as an independent reality against which abstract teaching is to be judged. Where the schoolchild will conjure with ideas without deep regard for whether they square with experience, and may be persuaded of theories that find little practical endorsement, the lifelong learner is obliged to challenge or reject what is in conflict with experience that has been hard-earned and tested in practical situations. With or without supporting theoretical knowledge, what they have observed in practice has an incontrovertible practical usefulness and relevance that any acceptable theory has to accommodate.

The notion of “constructing a reality” is well-represented in EM. It is an activity that is associated with the identification of a context for interaction that is empirically established as offering coherence and stability (see Figure 7). Such a reality is shaped by a family of observables, dependencies and agents whose primary characteristics are not negotiable, at least in the sense that they underpin the integrity of the artefact. Within the semantic framework of EM, an artefact acquires meaning by virtue of a correspondence—itself experienced by the modeller—between interaction with the artefact and interaction with its referent. The quality of this correspondence, and the modeller’s capacity to experience it, develops as the modelling activity proceeds. At its core, certain elements of this correspondence—having being so extensively rehearsed and consistently interpreted—come to be taken for granted. This is not to say that—within the EM framework—these characteristics of the artefact cannot in principle be rendered otherwise—only that (without more radical change to the established order) this would have the effect of undermining its capacity to invoke what had previously seemed to be its external referent.

B. Admitting the possibility of revision

Latour’s second guarantee complements the first:

“in spite of the indisputability insured by the [first guarantee], 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. And “voice,” of course, is not limited to humans.”

The first and second guarantees appear at first sight to be paradoxical if taken together. The qualification that sidesteps this paradox is in the clause “which the former established order had not been able to take into account”, since it indicates a radical shift in perspective. The expression ‘the established order’ has already been borrowed from Latour [12] in the preceding discussion of the status of reality in relation to lifelong learning and EM.

In the lifelong learning context, the established order refers to the perspective that the learner brings to the educational context. Whilst there can be no question that what the learner has experienced as robust and reliable knowledge in the school of life is indisputable, there are several ways in which its place in the established order may be called into question. A natural catalyst for such questioning is encountering a familiar topic in a new role. For instance, becoming a proficient pianist reinforces conceptions about the relationships between intervals (such as the self-evident fact that on a keyboard twelve intervals of a fifth span seven intervals of an octave) that are quite fundamental to musical appreciation of classical harmony. The fact that twelve fifths do not establish the same difference in pitch as seven octaves presents itself as a paradox to the pianist who tries to tune a piano. What to the performer is an essential presumption upon which a whole edifice of musical practice has been developed is to the tuner a fiction that has to be maintained by artful tempering of actual pitch (“well-temperament”).

EM addresses the issue of reappraising the established order in a quite different way from conventional programming. The artefact presents itself to the modeller at all times as a state, defined by the current values and dependencies of the extant observables, that is open for interaction and reinterpretation. Which interactions by way of redefinitions of observables the modeller exercises manually, or decides to invoke automatically, is a matter of discretion. In principle, there is no obstacle to the redefinition of any observable, or to the introduction of new observables. What guides the modeller is that the context and the capacity for interpretation remain consistent with the prevailing or emerging “reality”. Depending upon the stage of development of the artefact, and the state of affairs with which the modeller is engaged, there will be significant differences in respect of the balance between manual and automatic redefinitions and the degree of stability in the relationship between the artefact and its referent. Specifically, the patterns of interaction with the artefact and their interpretations may or may not be well-established and rehearsed, and the conception of its referent may or may not be precisely prescribed. This radical degree of flexibility is consistent with the exceptional capacity for changing context that computer-based technology now affords. For instance, a modern electronic keyboard can be switched from one tonal regime to another—in the process completely subverting its capacity for realising musical compositions that presume well-temperament. The term ‘reality’ in this context relates to a moulding and circumscribing of experience that is discretionary and admits unfathomable nuances.

C. The nature of the common world

Latour’s third guarantee relates to the quality of the common world:

“the common world is to be composed progressively; it is not already there once and for all.”

The emphasis in this guarantee is on “the unified world as a thing of the future, not of the past” and “the impossibility of absorbing the world—in the singular—in one single chunk.”

The archetypal school learning environment can readily promote the unified world of knowledge as *a thing of the past*. It is natural that formal education should stress the understandings and skills that have been established and inherited. This orientation is reinforced by the stress placed in much contemporary educational practice on learning as characterised by specific identifiable objectives and outcomes. The casual student is subject to accept this view, supposing that classroom theories about the established world have greater relevance to practice than proves to be the case.

It is easier to appreciate the unified world as a thing of the future—indeed in general as no more than an aspiration—from a lifelong learning perspective. More diverse perspectives and richer interactions with practice typically make it harder to build a coherent picture. Unified knowledge cannot be assembled within a pre-packaged, pre-fabricated framework. The subtle understandings of the world may build on what is already established, but also have to be wrested from confusion and paradox through activities that are unsystematic and opportunistic.

The distinction between book learning and "learning activity that takes place as a part and expression of living" can be appreciated with reference to the EFL in Figure 7. One trajectory for learning and teaching traces the establishment of understanding through learning activities that begin in the private subjective world (e.g. of the individual experimental scientist) and culminate in the articulation of a product that can be interpreted as belonging to the objective world of the established order. This trajectory is completed by organised activities aimed at unpacking this product and bringing it back into direct relationship with the personal experiences of learners. As discussed in detail in [25], such a trajectory can be viewed as a form of 'closed learning' that is predicated on what James in [21] characterises as 'understanding backwards'.

In contrast, and in keeping with James's philosophical stance in Radical Empiricism, EM supports learning activities that involve what James identifies as 'understanding *forwards*' [21:238-9]. Such learning activities are associated with the construction of interactive artefacts that embody the most primitive ingredients in a Jamesian conception of knowing. The semantic relation for an EM artefact is established in a mimetic rather than symbolic manner. Experience of interaction with the artefact stands in a relation to experience of interaction with an external referent, and this relation itself is given in experience. In establishing such 'conjunctive relations' [21], the builder can only take what is found—in her own personal experience—to be a reliable means to invoke an external referent. There is initially no presumption that such a relation will be recoverable in a different context, amenable to manipulation, or communicable to another person. An EM artefact may never acquire the coherence or closed quality of a world that has been unified.

D. The essential union of the human and the non-human

The fourth of Latour's guarantees is

"to ensure that there is no ... clear separation between words and worlds, nature and culture, facts and representation".

The discrepancy between the practice and the textbook—or even the manual—is a common focus of concern for the lifelong learner. A systematic exposition of theory in the classroom context gives limited preparation for practical application. A thorough exposure to practice gives only partial insight into theory. Marrying these two perspectives is typically a central motivation for the lifelong learner. Advances in technology repeatedly call the relationship between the word and the world into question highlighting their essential interdependence in unexpected ways. The database practitioner steeped in relational theory discovers that, in certain applications, the normalisation of relations is infeasible or that relational databases cannot be effectively used at all [26]. New technologies oblige a reappraisal of long-established conceptual boundaries. For instance, the possibility of gaining direct access to brain activity potentially offers new evidence that can challenge established assumptions about the way in which sensations are interpreted. This has profound implications for our thinking about language, nature and facts.

The separation of the word from the world is something that the established conception of computation promotes, though the practice of computing fights furiously to overcome it. In an orthodox conception of the semantic relation between a program and its operation in the world, programming entails expressing its required behaviour with reference to words (the programming language), nature (the computing hardware) and facts (the logical specification of its use). Software methods acknowledge the impossibility of arriving at such an expression without iterating between words and worlds, nature and culture, facts and representation. But the convoluted iterative character of the process by which this configuration is then established cannot disguise the fact that—as far as an accepted conception of computing is concerned—the result is an essentially dual object, part abstract specification and part concrete operational device.

By contrast, the EM artefact does not represent a closed behaviour but a *state of affairs*. The manner in which this state of affairs changes step-by-step is at all times live for the inspection, intervention and (re)interpretation on the part of the human interpreter, even though this change may be effected by non-human agency. And subject to the nature of the interpretation of the current state of affairs and the redefinition to be carried out such a change may reflect a routine transition to a new state (loosely analogous to a step in the execution of a computer simulation or program), a shift in conception (such as is involved in redesigning a program) or an exploratory step (such as is appropriate when identifying a requirement, or testing the capabilities of a piece of hardware). The blending of human and machine agency in this context has motivated Russ to classify it as "Human Computing" [27].

In so far as the significance of an EM artefact is entirely shaped by the autonomous interactions and interpretations of its maker, it is *constructed*. In its most primitive forms, it can serve to trace and record a succession of observations reflecting its maker's personal experience. If—through experimental interaction with the artefact and other human interpreters—these observations are seen to be a suitable basis for communication and sharing of perception of state, they may be deemed to be matters of fact about a common world. If and when an EM artefact has been elaborated in conjunction with familiar discretionary modes of interaction and observation that can be directly experienced as having counterparts in an external referent, it can be construed as a model of this referent. If the correspondence between the artefact and its referent is found to be sufficiently precise and constrained, it can be the basis for a formal characterisation of a behaviour of its referent (see [28] for an explicit example). In this way, EM can connect the primitive learning activities at the top of the EFL, rooted in the Jamesian "world of pure experience" [21], with those at the bottom of the EFL that engage with abstract propositions and objective facts. This is consistent with Latour's vision for the integration of words and worlds:

"Words and worlds do not represent two statues facing one another and marking the respective territories of two kingdoms—only to one of them will loyalty be sworn. Rather, words and worlds mark possible and not very interesting extremities, end points of a complex set of practices, mediations, instruments, forms of life, engagements, involvements through which new associations are generated."

The rich and subtle nature of the entities that lie between worlds and words is reflected in the semantic diversity of EM artefacts. The balance in emphasis between what can be construed as matters of observation and as propositions shifts in the process of progressive composition, as can the balance between human and non-human agency (cf. [29]). The use of the term "construal" indicates the role that EM artefacts play in the aspiration to reach understanding. As remarked in [27], the semantics of an EM artefact mirrors McCarty's vision for modelling [20]; there is in general no point of termination even where the referent is clearly identified from the first, and a model is to be forever interpreted as "a temporary state in coming to know".

E. Differentiating between good and bad construction

Latour's final guarantee is that "institutions assuring due process should be able to specify the quality of the 'good common world' they have to monitor."

As has been discussed in previous sections of the paper, assessing the quality of information and understanding is a particularly significant issue for the lifelong learner. Learning from eclectic sources without reference to a single assured authority puts the onus on the learner to evaluate her construals. Practical engagement in deploying theories and skills typically serves as a primary form of validation. Irrelevant or unhelpful theory falls out of focus; other book learning supplies the context of significant information that is used only occasionally for reference purposes; some is internalised to such a degree that it comes to be taken for granted. The manner in which domain understanding informs the learner's engagement will differ from learner to learner: just as one musician may play from music, another by memory, another by ear. Some aspects of a learner's domain understanding may be entirely idiosyncratic. The quality of such understanding will be gauged by how far it is coherent, communicable and objective in character and or helps to refine practical skills and enhance aesthetic enjoyment.

This pragmatic characterisation of the affirmed understanding of the lifelong learner is well-matched to the nature of an EM construal. In the progressive composition of a construal, a body of familiar interactions is built up. Initially, these interactions merely involve exercising primitive agency to confirm that particular patterns of observables and dependencies have been correctly expressed in the EM artefact. These basic dependencies and modes of interaction typically come to provide the primitive stable foundation for more sophisticated interpretations and applications of the model. The construction of the artefact proceeds through continuous refinement and exploration of the current state of affairs even as it is being experienced and correlated with experience of its referent. This builds a confidence in the underlying dependencies that becomes more assured with every interaction that is engineered to fulfil expectation. All the while, the context for the interaction, the precise nature of the referent, and the interpretation that conjoins the artefact to its referent are subject to revision, but generally in such a way as to respect or refine the correspondences that have already been wrought through previous experience.

Where there is discrepancy between what is observed and what is expected, the artefact, the referent, the interpretation and the context all have a potential role to play in its resolution. The semantic scope for discrepancies is exceptionally broad. It can encompass both basic failures in the construal (cf. the discussion of sailboat dynamics recounted in [30]), and trivial errors of transcription that affect observables invoked only in very specific circumstances. Dealing with such discrepancies involves tracing dependencies to their roots in observation and experiment. There is a close parallel with the way in which the lifelong learner becomes aware of misconceptions through encountering novel interactions and situations and adjusts her construal accordingly.

The five modes of application for EM construals in section V 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*.

VII. CONCLUDING REMARKS

Where current educational technologies are best oriented for well-planned and organised learning situations [31], learning in a real-world setting typically begins in some degree of chaos and confusion. EM principles and tools are still at an early stage of development, but show promise in supported learning activities that integrate educational modes, promote flexible opportunistic learning, and blend the concrete and the abstract across disciplines. These are qualities that can be most helpful in engaging the lifelong learner.

More effective communication of the underlying concepts, and better tools, are vital for the wider acceptance and adoption of EM. In this respect, linking Latour's five guarantees to EM practice is helpful, since the quality of his analysis of the constructivist ideal lends greater conceptual coherence to the breadth of activities represented in EM. In the longer term, we hope that EM can contribute to the rehabilitation of constructivist (or "compositionist") notions to which Latour aspires, and give greater prominence to the topicality of William James's philosophic stance.

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