Chapter 2

Empirical Modelling in support of learning

The challenge introduced in Chapter 1 is for educational technology to support more of the everyday aspect of learning that is evident in the *eight significant characteristics of learning*. The following introduction to Empirical Modelling describes the principles, tools and characteristics that are fundamental to Empirical Modelling practice, and which have strong connections with the eight significant characteristics of learning described in Chapter 1.

2.1 Introduction to Empirical Modelling

2.1.1 Modelling state-as-experienced

Empirical Modelling (EM) is a collection of principles and tools that are fundamentally concerned with *modelling state*. In computer science, state is usually associated with the specification of formalised abstract behaviours. This view of state is concerned with procedures for *preconceived* interaction, all of which are *objectively* interpreted with respect to the computer as a 'state machine'. EM is concerned with state in a much broader sense. When referring to modelling state in EM, it means state in its more everyday sense—that is, the condition or status of things as they are *subjectively* and *empirically* apprehended. This type of state, which Beynon refers to as *state-as-experienced* [Bey07a], is open to many kinds of interpretation based on personal observations and experiences.

As an approach to computer-based modelling, EM is not primarily aimed at developing abstract behaviours. EM is concerned with constructing and engaging with concrete situations using computer-based artefacts. To achieve this, EM activity is focussed on creating computer-based artefacts that capture state-as-experienced. These artefacts (or models) typically offer the flexibility of human interaction in the world, in contrast to the rigid tightly-constrained behaviour of a computer program. For this reason, EM artefacts often invoke personal, subjective, particular, provisional and tacit interpretations that reflect the open-ended nature of human interaction.

The construction of computer-based artefacts for modelling state-as-experienced is underpinned by well-established principles defined by Beynon & Russ [EMW]. These principles are predicated on the basis that an artefact is a collection things that can be observed—called *observables*—and that have counterparts in a set of definitions in the computer. Each definition takes the form:

$$v \text{ } is \text{ } f(x_1, ..., x_n)$$

where $x_1, ..., x_n$ correspond to observables, and the value of v is updated instantaneously whenever $x_1, ..., x_n$ change. In this way, a set of definitions can be viewed as representing a *state* together with a family of atomic state-changes. Artefacts are then constructed in a *fluid* activity involving the creation and manipulation of definitions. The act of creating a definition, or making a redefinition, represents a *state-change.* Meanings and relationships develop through interaction with the artefact occurring from state-change. This continuous activity develops a closer and closer correspondence between the artefact and the set of definitions.

To differentiate EM artefacts from more general terms, such as 'models' and 'programs', the term 'construal', as interpreted by David Gooding, has been adopted by Beynon [Bey07a]. Gooding's use of the word 'construal' refers to the artefacts and the interaction with the artefacts that are developed by experimental scientists in the early stages of exploration of phenomena:

> "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." [Goo90:p22]; "... a construal cannot be grasped independently of the exploratory behaviour that produces it or the ostensive practices whereby an observer tries to convey it." [Goo90:p88]. (Something *ostensive* is direct or demonstrative [OED:*ostensive*].)

In the same sense, an EM construal can refer to all aspects of an artefact, including the current set of definitions, the history of interactions or redefinitions, and the relationships between experiences with (or expectations of) the artefact and experiences with (or expectations of) the world. Therefore, EM construals are *personal*, *subjective*, *particular to circumstances*, *provisional* and *tacit* [Bey07a].

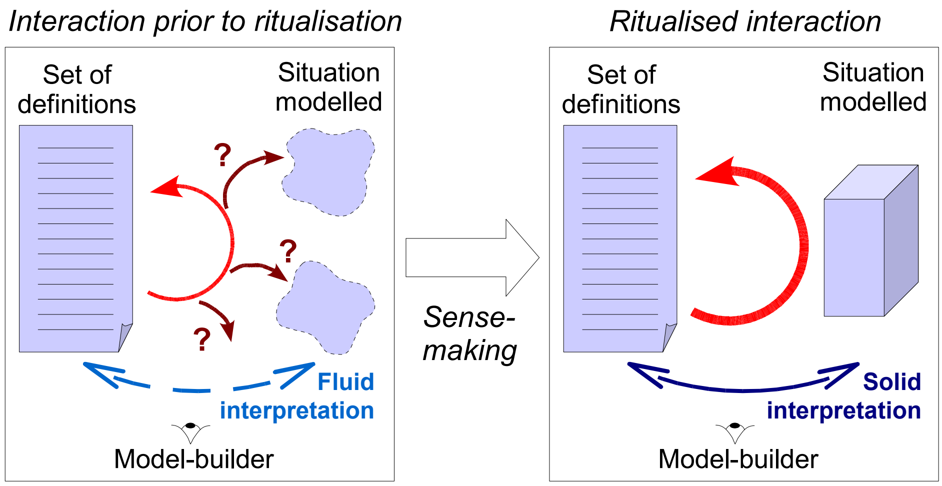


Figure 2.1: The nature of EM activity.

When construals correspond closely with a situation that is familiar and well understood, we can interpret this to mean that there are well-established patterns of interaction—this will be referred to as *ritualised interaction* because, due to repetition, the interaction with the artefact becomes stereotypical and automatic. Traditional programming is concerned with creating artefacts that support such ritualised interaction. The nature of EM activity means that it is well-suited to interaction that is *prior to ritualisation*. Such interaction is speculative and exploratory, and might involve the negotiating of meaning in situations that are not familiar or well understood. The character of interaction prior to ritualisation is illustrated in the left-hand side of Figure 2.1. In such interaction, it is appropriate for the construal to be personal, subjective, particular to circumstances, provisional and tacit.

The right-hand side of Figure 2.1 illustrates interaction that has been ritualised, where the construal corresponds closely to the situation and this relationship is well understood. This typically means that the key observables in a situation have been clearly identified and have counterparts with fixed interpretations in the construal. Moving from pre-ritualised interaction to ritualised interaction involves becoming familiar and developing understanding of the artefact and situation—it involves sense-making. Such activity is associated with starting from a rough, provisional correspondence between definitions and situation, and through interaction, arriving at a solid correspondence between definitions and situation. Figure 2.1 illustrates the overall movement from the left-hand side to the right-hand side.

The evolution of an EM construal (from pre-ritualised to ritualised interaction) is a particularly fluid activity that occurs through creating, manipulating and observing an artefact that is reflected in a set of definitions. The natural flow of interaction (creating, manipulating and observing) is particularly important for sense-making and learning.

2.1.2 Definition-based notations

The notion of a construal as captured by a set of definitions necessitates methods or notations for creating, manipulating and observing definitions. A number of notations have been developed for a wide range of modelling activities. Beynon refers to these notations as *definitive notations* due to the fact that they are definition-based [Bey07a]. Some notations are general purpose, like DoNaLD (Definitive Notation for Line Drawing) which is used to create line drawings [Yun90]; some notations have a more specific purpose, like the %analog notation created by Charles Care for experimenting with the components of an analogue computer [EMP:analogCare2005].

The primary general-purpose notation is EDEN (Engine for DEfinitive Notations), which was developed by Yun Wai Yung [Yun90]. The EDEN notation is the most primitive and can be used for the definition of base values (e.g. numbers, characters and lists).

The next general-purpose notation is DoNaLD which can be used to create drawings based on points, lines, arcs and other basic shapes [Yun90]. An example of a set of definitions in DoNaLD is shown in Figure 2.2(a). The definitions describe lines and circles that relate to a clock face containing an hour hand, a minute hand, and marks for the quarter positions. The artefact that reflects the set of definitions is shown in Figure 2.2(b).

Another general purpose notation is SCOUT (definitive notation for SCreen LayOUT) which was designed by Yun Pai Yung [Yun93] for arranging windows (including viewports for DoNaLD drawings) on a screen. A complete list of standard notations can be found in the EDEN documentation [EMD]. It is important to note that these notations are still at an experimental prototype level. There is still a lot to understand about the design of definitive notations, for which there is little precedent in traditional programming language design.

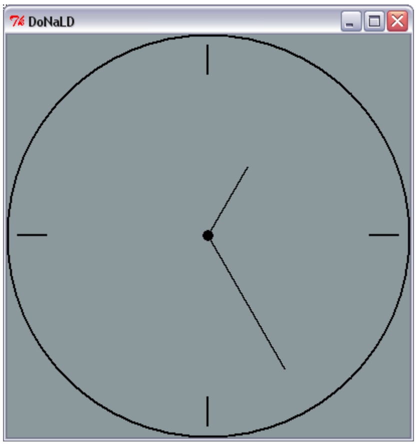
One of the major contributions to the development of definitive notations is a framework for creating and manipulating notations within EDEN—enabling model-builders to develop their own definitive notations (in principle) 'in the flow of modelling'. This is based on my work on an *agent-oriented parser* (AOP) [Har03], that was originally prototyped by Chris Brown [Bro00]. The AOP has led to many innovative models (e.g. the Wumpus model [EMP:wumpusCole2005]) and a number of new definitive notations (e.g.

```
int radius
point centre
radius = 400
centre = {400, 600}

line facemark9, facemark6, facemark3, facemark12
circle face, shaft
facemark9 = [centre-{radius-20,0}, centre-{radius-80,0}]
facemark6 = [centre-{0,radius-20}, centre-{0,radius-80}]
facemark3 = [centre+{radius-20,0}, centre+{radius-80,0}]
facemark12 = [centre+{0,radius-20}, centre+{0,radius-80}]
face = circle(centre, radius)
shaft = circle(centre, 10)

int hour, minute
line hourhand, minhand
real hourangle, minangle
hour = 1
minute = 30
hourhand = [centre, centre+{radius div 2.5 @ hourangle}]
hourangle = float(hour) div 12 * -2*pi + 0.5*pi
minangle = float(minute) div 60 *-2*pi + 0.5*pi
minhand = [centre, centre+{radius div 1.3 @ minangle}]
```

(a) DoNaLD definitions describing a clock face.



(b) An EM construal of a clock face.

Figure 2.2: An example of using the DoNaLD definitive notation to create an EM construal.

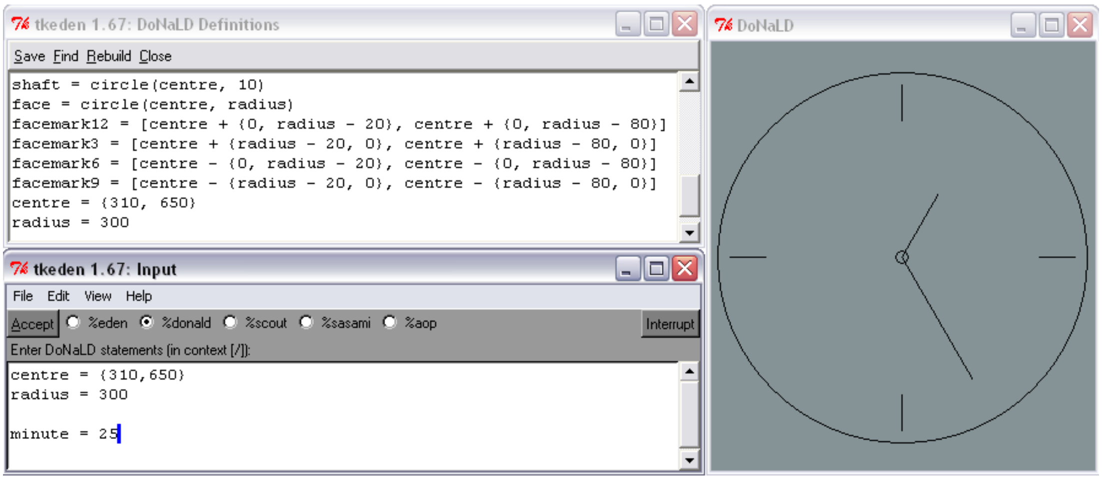


Figure 2.3: The **tkeden** tool for creating EM construals with definitive notations.

the HTML notation described in Chapter 4). The GEL (Graphical Environment Language) notation [EMP:gelHarfield2006], for creating graphical user interfaces, is one of the notations that has been developed as part of this thesis using the AOP, and that has been used to create and explore many of the models described in this thesis. An introduction to the GEL notation can be found in Figure 4.5 on page 93 and more information is available in the documentation [EMD]. The importance of such auxiliary definitive notations is in the scope they afford the model-builder to exploit richer metaphors in the construction of artefacts.

2.1.3 Tools for modelling state

A number of tools have been developed for EM†. The most widely used and the most extensively developed is `tkeden`. The `tkeden` tool runs on Linux, Mac OS, Unix & Windows and is freely distributed under the GNU General Public License‡. The tool incorporates a number of standard notations, such as EDEN, DoNaLD and SCOUT, as well as other domain-specific notations including those created using the AOP, such as GEL. A significant role for the notations is providing visualisation of state that promotes the experiential rather than the symbolic aspect of the artefact. As illustrated in Figure 2.2(b), visualisations can be expressive without being highly realistic [Bey05b].

Figure 2.3 shows the `tkeden` tool with a simple model of a clock. The bottom left window is the input box where definitions can be entered in a particular definitive notation. In Figure 2.3, the input box currently contains buttons for the EDEN, DoNaLD, SCOUT, SASAMI and AOP notations, but there is potential for new notations, such as GEL, to

†For a complete discussion of the history of EM tools, see Ward's PhD thesis [War04].
‡The `tkeden` tool is available from: `www.dcs.warwick.ac.uk/modelling/tools`.

be introduced on-the-fly. The top left window contains a full list of the current definitions in the environment. The DoNaLD window on the right is the artefact that is described by the DoNaLD definitions. As discussed above, EM construals are created and manipulated through definitive notations and therefore the `tkeden` environment is conceptually relatively simple, requiring only the input box for making definitions and redefinitions.

The key features of the `tkeden` tool are that the interaction between model-builder and artefact is continuous and unconstrained. The fluid nature of EM activity is well accommodated in `tkeden`. Model-building proceeds from a rough, provisional set of definitions that have a loose correspondence to a situation to solid, well-understood set of definitions that have a strong correspondence to a situation. When the definitions of an artefact are recorded or saved, it represents only a snapshot of the EM activity. The `tkeden` tool records the history of redefinitions which affords the possibility of returning to previous significant states.

The `tkeden` tool described above is the most common environment for model-builders. However, there are other variants of the tool. These include an extended version of `tkeden`, called `dtkeden`, with distributed communication features, enabling models to be created across multiple machines. Chapter 5 explores the use of `dtkeden` for collaborative model-building.

2.1.4 More background on EM

EM is the result of 20 years of computer science research led by Beynon & Russ at the University of Warwick [EMW]. The motivations for EM are discussed, for example, in Beynon's lecture notes on modelling for concurrent systems [Bey07a] and in King's thesis [Kin07]. Rungrattanaubol offers a detailed exposition of the principles of EM in its relation to conventional approaches to computing in her thesis entitled, *A treatise on Modelling with definitive scripts* [Run02]. An alternative introduction to EM from an educational perspective is given by Roe [Roe03:p6]. A detailed account of the design and implementation of `tkeden` and other EM tools is given by Ward [War04].

2.2 Eight characteristics of EM

The following discussion introduces EM with particular reference to eight characteristics, summarised in Figure 2.4, that are relevant to the eight significant characteristics of learning set out in Chapter 1. The correspondence between the eight characteristics of EM and

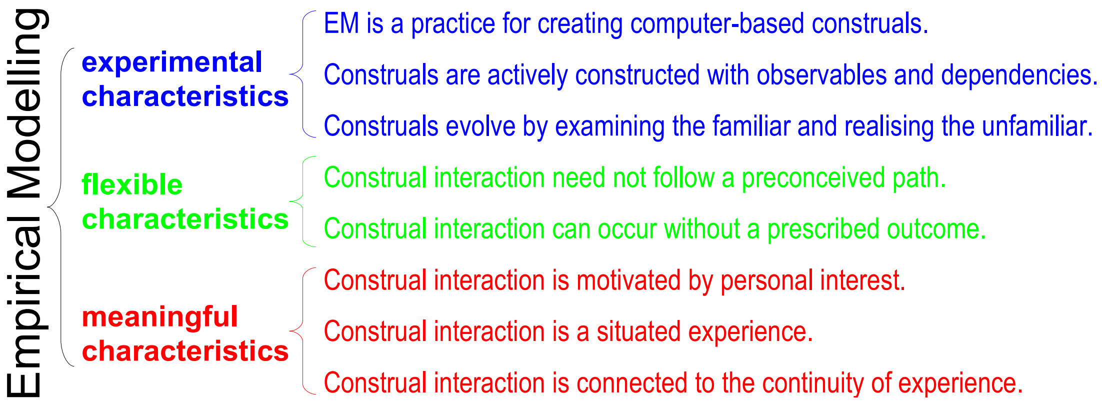


Figure 2.4: Eight characteristics of EM.

the eight significant characteristics of learning can be observed by comparing Figure 2.4 to Figure 1.3 on page 16. The table in Figure 2.8 on page 53 clearly illustrates the connection with references to the relevant section where each characteristic is discussed.

2.2.1 EM is a practice for creating computer-based construals

In a modern world where it is common for people to use computers to create documents, presentations, graphics, websites, and programs—*to produce some readily useful output*—examples of the use of computers for understanding and sense-making are much less prominent. In respect of educational technology, the exploratory use of spreadsheets discussed in §3.4 is one example. Previous work by Beynon, Russ & McCarty has shown the need for more attention to the use of computers for sense-making [BRM06], and it has been argued that the current foundations of computing are ill-suited to supporting sense-making [Bey07a]. EM is suggested as offering an alternative perspective on computing that is well-aligned with the needs of sense-making.

Empirical Modelling, as the name suggests, is concerned with *creating* and *using* computer models that are empirically developed. The word *empirical* can have several meanings, but here it is taken to mean that the modelling activity is *guided by practical experience, not theory*. EM was originally developed as a way of representing concurrent systems. Not the abstract formal models of concurrency associated with, for example, Hoare's CSP [Hoa85], but concurrent systems in a broader sense as found in everyday experience that include people, nature, and constructed artefacts together [Bey07a]. Beynon refers to this as 'common-sense concurrency' and views EM as a means for representing an "external observer's conception of a concurrent system, as it evolves, typically incrementally, through experience of the system" [Bey07a]. Constructing models that reflect common-sense con-

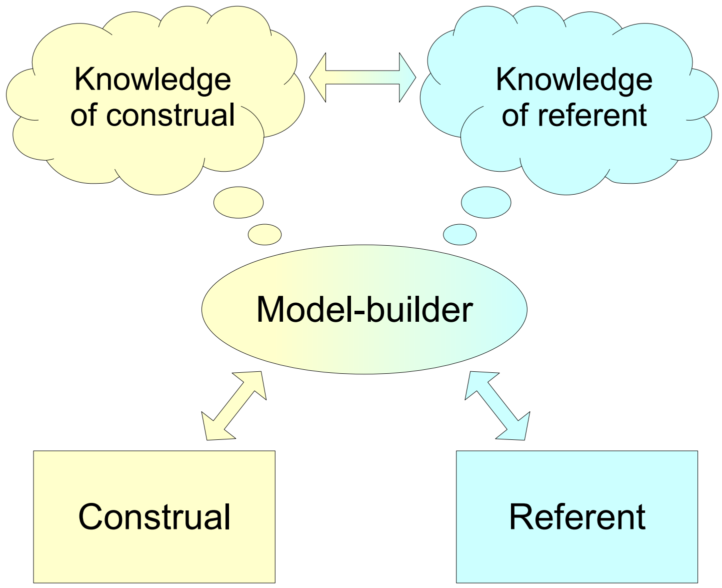


Figure 2.5: A learner constructing an construal relating to a referent.

currency can be beneficial where sense-making is important, such as: determining the requirements for a piece of software, reconstructing historic events, analysing a archaeological dig, designing a socially-aware robot, or learning to speak a foreign language.

Models or artefacts that are constructed using EM can have a number of characteristics (as explained in this chapter) that differentiate them from uses of models in computer science and, more generally, computing. The word *construal* is used to describe the computer-based artefact that the EM model-builder constructs to avoid confusion with the more general term model. A construal is a computer-based artefact created or used by a person engaging in EM activity. An EM activity is one where the emphasis is on using the construal for *understanding* and *sense-making*, as opposed to necessarily producing a useable artefact. That which the construal relates to in the world is called the *referent* (coming from 'that which is referred to') as depicted in Figure 2.5. The construal is built with some experience to be explored and better understood in mind. The use of the word construal emphasises that the model is a personal interpretation of the experience by the model-builder. The experience to which the construal itself refers may relate to a situation, to an abstract procedure, or to a phenomenon. Therefore the referent could be something physical, or the referent could be an emotion or idea to be conveyed in an construal. The learner develops tacit knowledge of the construal and referent through exploratory interaction motivated by establishing a close correspondence between experience of the construal and experience of the referent. The bottom half of Figure 2.5 highlights the essential elements of an EM activity where a model-builder is interacting with a construal that corresponds to a referent. In this activity the model-builder's understanding and experience play a crucial role. Experiences of the interplay between the referent in the world and the construal in the computer, at the top of Figure 2.5, can inform the model-builder's interaction with and construction of the construal.

EM's approach to learning is constructionist in spirit [BR04] [BH05b]. In contrast to traditional ET that exploits a constructionist idiom which is primarily concerned with artefact construction, ET based on EM principles promotes constructionist activity that is essentially concerned with negotiating meaning and sense-making. Well-known examples of constructionist learning environments include Logo, Agentsheets and Toontalk. These are discussed in contrast to EM by Roe [Roe03]. In particular, Roe points out that Toontalk and Agentsheets rely too heavily on the computation metaphor [Roe03]. The limitation of these environments is that they use methods based on traditional procedural programming for construction—a foundation that this thesis has argued is ill-suited to everyday learning and sense-making. EM, with its focus on the experimental aspects of model-building, is better placed to offer support for constructionist learning environments and fulfil the characteristic in §1.2.1 that *learning occurs when constructing artefacts in the world*.

2.2.2 Construals are actively constructed with observables and dependencies

Given that EM is concerned with composing construals for sense-making, it is of primary importance that model-building enables relations and meanings to be negotiated. As introduced in §2.1, a construal is a collection of things that can be observed and manipulated—called *observables*. These observables can be represented by a set of definitions which describe the relationships between observables using *dependency*. The observation and manipulation of definitions is occurs through *agency*. Observables, dependencies and agency reflected in a construal can capture the scope of an external observer's interpretation of a concurrent system in an everyday sense [Bey07a].

From the viewpoint of an external observer, observables are features of the environment that can be ascribed an identity [Bey07a]. The identification of observables arises from interaction with a referent, as in Figure 2.5. An observable could represent a value (e.g. 360), a property (e.g. has wheels), a quantity (e.g. £125,000), a description (e.g. sleek), a colour (e.g. red), a relative measurement (e.g. fast), a perceived feeling (e.g. scary), or an event (e.g. I saw a Ferrari). Observables are often subjective as they reflect a personal meaning for the model-builder that has developed over a series of interactions. Current EM tools are implemented on a digital computer and therefore the representation of observables are rather primitive, however the intended meanings of such observables can reflect quite detailed ideas in the mind of the observer. The level of detail of an observable depends very much on the observer and the motivation for studying a given referent. Depending on the interests and skills of the observer, observations may be made on different levels (e.g. "the meteorite is the source of the light, and the meteor is just what we see").

The external observer, during the course of many interactions with an everyday concurrent system, is likely to develop expectations with respect to observations. For example, I am accustomed to associate the swiping of my university card at the door of the department with the opening of the door. These indivisibly perceived changes, where the observer would be surprised if expectations were unrealised, can be described as *dependencies* [Bey07a]. Such expectations, or dependencies, reflect reliable patterns of state-changes arising from a series of interactions. Thus, a dependency is a description of how changes to observables are linked to one another. In everyday concurrency, observations are related to each other in that a change in one observable often leads to a change in other observables. The perception of dark clouds overhead often coincides with the subsequent falling of rain (event), which often coincides with cars switching their headlamps on (description) and, if driving, a sense of caution on the road (feeling). Each of these dependencies may be reliable observations that have been made according to history of interactions. A point to be discussed later is that these dependencies are not 'set in stone'—at any time during the model-building, maybe in response to new observations, the relationships may be changed.

In EM, *agency* is associated with the attribution of state-change [Bey07a]. Whereas concurrent specification languages often ignore the notion of an agent, in an everyday view of concurrency it is natural to attribute the change of state to an object or entity [Bey07a] (e.g. "candy weighing both of my pockets down"). Changes to observables can occur in any number of ways. For this reason, EM takes a very liberal view of what constitutes *an agent*, because an agent is anything that has *the capacity to change state*. In everyday living, people have the potential to (and regularly do) change the state of the world. People regularly change state as they move about their daily business, they can choose to switch the heating on or off, to place rubbish in a litter bin, to speak out against something or someone, or to keep quiet and do nothing—every action has an effect on state†. Animals too have this capacity to affect the world, as do weather systems, plants, bacteria, diseases and many other things. In many cases we do not understand why these effects take place (e.g. freak weather like the Tsunami caused by the Indian Ocean earthquake in 2004). It may turn out that through subsequent iterations with the referent that acts of agency could be observed as complicated dependencies at a more primitive (e.g. atomic) level. However, from the point of view of an external observer, there will often be acts of state-change whose origin are unknown or not important at the current time. For example, my grandmother might perform perceived random acts of gratitude, such as giving me chocolates, where the causes are not relevant to me. Take the weather as another example of agency, and its forecasting: studied since Robert Fitzroy headed the first meteorology department in the British government in 1854 [Bur86], still today, it is often not even possible to explain the causes of freak weather, let alone predict the weather accurately on a daily basis. It is important to acknowledged that common-sense concurrency is not a closed system but is open to agency from the outside (e.g. from people or the weather).

Observables, dependencies and agency (ODA) are the three concepts in EM that can be used to represent concurrent systems in an everyday sense. An EM tool, such as `tkeden`, provides an environment in which a model-builder can experiment with patterns of ODA. The construction of a construal is achieved by creating and manipulating sets of definitions that correspond to ODA. In `tkeden`, observables can be identified as values, strings, or lists (for example)—like the cells in a spreadsheet. Dependencies, being the relationship between observables, can be identified as definitions that relate two or more observables. A dependency definition indicates an expectation, that when one observable changes, a change also occurs in the other observable—like functions between spreadsheet cells. When considering agency, it may come from outside the computer-artefact in the form of mouse movement, mouse button clicks, keyboard presses, or input from other devices. These actions could be automated or semi-automated by the model-builder in such a way that they become *agent actions* within the model thus creating internal agency. Agent actions can be defined in a model as a sequence of redefinitions that are triggered when a condition occurs (i.e. an internal observation is made). If we take the example of modelling the driving of a car, then we might start by controlling the car with external agency by letting

† As reflected in the Buddha's description of Kamma: "When this is, that is. From the arising of this comes the arising of that. When this isn't, that isn't. From the cessation of this comes the cessation of that." AN 10.92 (Pali Canon)

the model-builder control the inputs to the car driving activity (i.e. steering, accelerating and braking). The model-builder could use the patterns of redefinitions that she makes to automate or semi-automate the driving activity. Initially these patterns may be quite simple, for example: "when approaching a corner, apply the brake". Further refining of the model might take into account many more factors that could affect the agent's control of the car (e.g. weather conditions, the position of other cars on the road, the driver's knowledge of the car, or the driver's mood)†.

Numerous notations exist for constructing construals based on ODA. As introduced earlier, EDEN, SCOUT and DoNaLD [EMD] are three basic notations that are used in the `tkeden` tool. Detailed explanations of these and other notations used for creating sets of definitions corresponding to ODA are covered by Ward [War04]. Some of the notations developed by the author are discussed in Chapter 4.

The ODA that are reflected in a construal correspond to ODA in the concurrent system through the model-builder's continual interaction with the construal. ODA are essential ingredients for model-building because of the close correspondence between the ODA reflected in the constual and the ODA in the referent. In Figure 2.5, the construal is linked to the referent by this correspondence through ODA. In this way, interaction with ODA in the construal develops knowledge of the construal which is linked to knowledge of ODA in the world or referent. This characteristic of EM as an active construction of a construal using ODA on the part of the model-builder is related to the characteristic of *learning involving an active construction of understanding* on the part of the learner described in §1.2.2.

2.2.3 Construals evolve by examining the familiar and realising the unfamiliar

Given an environment for constructing construals that reflect observables, dependencies and agency in an everyday sense, EM's contribution to the construal creation process is now considered. In EM, as with any other sense-making activity, we usually start with that which we already know, have an understanding of, or are familiar with. By examining the familiar, we are able to see what we do know about the subject, and what we do not know. In some cases, our subject might be very well known, but in others we might be exploring it for the very first time. An inexperienced architect may well explore his subject, the design

† A model about braking distances was created as part of an undergraduate project for WEB-EM-3 [WEBEM3].

of a library for example, in some confusion and with no previous experience of making a plan of a library to draw upon. Generally though, the architect is not completely lost as he has other experiences that might be relevant: his training as an architect, experience from designing other architectural plans, visits to his local library. A more experienced architect may well have designed many libraries, knowing exactly what is required of him and his design, but still by exercising the familiar he will come across areas of the design that he needs to make sense of, and make a decision, to continue his design. This act of sense-making, by exercising the familiar to explore the unfamiliar, is what we are 'making use of', encouraging and enhancing in EM through the use and creation of construals.

When creating a new construal, I am encouraged to start with what I already know or something I am familiar with. If I know the subject well, then it is relatively easy to highlight observables, dependency and agency, and therefore I can begin to build an EM construal by defining various observables and dependencies, and maybe later automating some aspects of agency. If for example, I started to create a construal of a bicycle, I might begin with a simple definition taking account of the wheels, their sizes, and the number of gears. Depending how well I know the subject, within a short while I would reach the edge of my understanding. This is what Vygotsky would call the Zone of Proximal Development [Vyg78] as mentioned in §1.2.3. On my bicycle, although I might be aware that the more force I exert on the pedals the faster I will go, I cannot immediately formalise this into a more accurate form such as the relationship between force and velocity. I have a vague idea of the relationship, but it remains unfamiliar territory. This is the point at which I move from creating a construal of a familiar subject using ODA, to exploring patterns of ODA in my construal that fit the unfamiliar territory (that which is not formally known to me). The unfamiliar is no longer a complete blank because I have the springboard of the familiar ODA on which to base my experiments with other patterns of ODA. I can also draw on other experiences, or other people, or other models, to compare to my own experiences with the construal. By exploring and experimenting with different patterns of ODA, and comparing it to my familiar understanding and experiences from the world, I am usually able to gain a little more familiarity of the subject. In order to become more familiar with the bicycle construal, I can experiment with different dependencies and draw on my experience of riding a bicycle to make sense of the relationship between the pedals and the speed of the wheels.

The process of acknowledging the familiar and exploring the unfamiliar is not a one-off

1. Initially I do not know what is unfamiliar or not known to me.
2. I start by creating a construal using ODA of that which I am familiar.
3. By exercising the familiar, I find the edge of my familiar understanding and discover that there are things which are unfamiliar or not known to me.
4. I explore and experiment with different patterns or compositions of ODA.
5. By relating experiences of the construal with experiences in the world, I can become more familiar and make-sense of the subject.
6. I repeat the process, exercising the familiar including any new aspects of the construal.

Figure 2.6: A generalisation of experimental EM activity.

exercise that will result in the subject being understood. (No results are guaranteed.) Rather, it is a process that continually occurs throughout the creation of a construal and throughout the sense-making activity. Neither the familiar nor the unfamiliar can be separated, they both depend on one another for the sense-making activity to proceed as shown in Figure 2.6. The activity in Figure 2.6 is a continuous cycle in which the familiar informs the unfamiliar and the unfamiliar forms the familiar.

Schrage, who discusses models in his work on innovation [Sch99], writes in *Serious Play* that:

> "...the real value of a model or simulation may stem less from its ability to test a hypothesis than from its power to generate useful surprise. Louis Pasteur once remarked that 'chance favors the prepared mind.' It holds equally true that chance favors the prepared prototype: models and simulations can and should be media to create and capture surprise and serendipity [...] That's why Alexander Fleming recognized the importance of a mould on an agar plate and discovered penicillin." [Sch99:p117,119,125]

Figure 2.6 taken with Schrage's sentiments shows a clear connection with learning in relation to the 'realising the residue' characteristic of learning in §1.2.3. The first three of the characteristics of EM emphasise the *experimental* nature of EM activity that plays an important role in supporting learning as characterised in Chapter 1.

2.2.4 Construal interaction need not follow a preconceived path

In this section it will be shown that construals for sense-making involving the exploration of the unfamiliar (as described in the previous section) should be approached without a preconceived plan. Computer artefacts that are thought-out or preconceived in advance do not encourage the sense-making activity during the creation of the artefact. The common practice of computer scientists dictates that computer artefacts should first be specified, then designed, and finally implemented. This implies that the sense-making or understanding is done at the beginning, and the final stage is a 'simple' translation of a design on paper to a program in the computer. It disregards the essential need for sense-making in the implementation stage. There are some good reasons for disregarding sense-making when the final product is of primary importance, but when the focus is on using the computer for understanding a subject, following a preconceived path can subvert the sense-making activity. Therefore, in EM it is important that construal interaction does not necessarily follow a preconceived path.

Neither is there a particular way in which EM construals have to be created (no given recipe) nor does the model-builder have to preconceive of a way to create her construal (no need to design a recipe). There is no need for a recipe for creating a construal, the recipe arises from the cooking. The cooking being the activity of creating a construal using ODA by paying attention to the familiar and the unfamiliar.

Traditional programming is like making a victoria sponge; follow the recipe and, depending on the ingredients and your skills, you will end up with a cake. EM does not offer any particular advantages for following a recipe because the path is preconceived and well-understood. However, EM is appropriate when you want to find out what makes a good victoria sponge, when you want to understand how to make a good victoria sponge, and when you want to make sense of the relationship between the ingredients and a good victoria sponge. This activity does not follow a preconceived path, it requires the model-builder to practice what is already familiar about making a victoria sponge, experiment with different patterns of ingredients (ODA), and relate new 'victoria sponge' experiences to previous baking and tasting experiences.

As EM activity is concerned with interaction that is often *prior to ritualisation*, as depicted in Figure 2.1, it is well-matched to the characteristic, described in §1.2.4, that *learning need not follow a preconceived path.*

2.2.5 Construal interaction can occur without a prescribed outcome

A construal is never considered finished because it has no prescribed outcome, in the same way that learning is never finished (as described in §1.2.4)—there is always more to 'make sense of'.

Following on from the characteristic of EM that construal interaction need not follow a preconceived path, a further step can be taken to describe that it is not even necessary for a construal to ever be considered finished. This theme is partly developed in Beynon's paper on *Liberating the computer arts* [Bey01]. The reason for this is self-evident from the description of the sense-making activity. Making sense of a subject is a never-ending process of continually expanding understanding into ever more unfamiliar territory. A construal being a computer artefact for making sense of a subject, it follows that the activity is open-ended and the construal need not be constrained to achieve any particular result. Contrast this with traditional programming where the expected output is a program that can be used by others, and there is clearly a need for the program to, at some point, be considered finished, useable or sellable. In order to produce a finished product, it makes sense that the product be specified or thought-out prior to the programming activity in such a way that the programming activity has a clear prescribed outcome. The specification then becomes the guide by which the programmer knows what a finished product should look like, and hence they will also know when it is finished. As described in the previous section, it is likely the programmer will employ some standard methods to assist in achieving the finished product (e.g. object-oriented programming) following some particular development methodology as discussed later in §3.1.

Although a construal may never be considered finished, it does not mean that it is not useable. It can be useable throughout the interaction, simply because it is the experience through interaction that enables the model-builder to develop understanding. It is not the finished product itself which is most important, it is the meaning that the construal can give, or has given, to the model-builder. Therefore the construal does not require any specification, nor does the construal need to be thought out in advance. The 'thinking' of how to create the construal is part of the sense-making activity. Any pre-thought-out specification for the construal is liable to restrain and subvert the creation of the construal. This approach of not asking for a prescribed outcome is evident in particular scientific discoveries. For example, when Faraday discovered electricity, he had not set out to find electricity or produce it, he was looking at other phenomena—trying to make sense of them—when he became aware of what later became known as electricity [Goo90].

The above discussion indicates a similarity to the characteristic, described in §1.2.5, that *learning occurs without a prescribed outcome*. Taken together, the two characteristics of EM described as ‘’ and ‘’ promote a particularly flexible attitude to model-building in which the process or outcome can be completely open-ended. These flexible characteristics of EM play an important role in supporting everyday learning which is explored further in Chapter 4.

2.2.6 Construal interaction is motivated by personal interest

In the previous five sections it has been shown that EM is an experimental approach to model-building (§2.2.1,§2.2.2,§2.2.3), and that it is an approach that demands a high degree of flexibility (§2.2.4,§2.2.5). Next, the reasons for creating construals in this way are examined. One of the reasons is that construals are intimately connected to the person interacting with them. They are tools for understanding and making-sense things in the world (as well as in the computer). The fact that they are very personal to the model-builder is why they are useful for sense-making. The meaning of the construal is constructed by the person creating the construal—it is subjective—and the sense-making occurs in the interplay between construal and referent as perceived by the model-builder.

Given the personal nature of construals, it follows that construals may be linked to personal experiences and personal interests. Empirical Modelling is successful when it is motivated by personal experiences and personal interest (as discovered in the ‘Introduction to EM’ module discussed in §6.1). Creating a construal of something you are not interested in—not meaningful—is unlikely to inspire great exploration or connect well with previous experiences. But with a subject in which the model-builder is personally interested—is meaningful—there is more motivation for exercising the familiar and better potential for exploring unfamiliar territory on the edge of the model-builder's understanding.

As shown in Figure 2.1, EM activity is concerned with the sense-making involved in progressing from interaction prior to ritualisation to ritualised interaction. Such progress involves exploring particular situations in a construal—exploration that is motivated by personal interest in the particular situation. The importance of personal interest in EM activity is relevant to learning, and demonstrates an association with the characteristic, discussed in §1.2.6, that *learning is motivated by personal interest.*

2.2.7 Construal interaction is a situated experience

In the previous section it has been acknowledged that construals are personal tools for understanding and sense-making, and if we stop there then creating construals might be seen as a private solitary activity. Although this act of making sense of a subject is very personal, it need not be totally confined to one model-builder per construal. In this section I shall explain that construals can be shared amongst model-builders, and that construals can be moved in and out of different contexts.

It is helpful to note the similarities between a construal and a story. A construal is an EM artefact that enables the model-builder to convey meaning. A story is similar in that it is used to communicate the meaning in a situation or an event. Neither the construal nor the story are necessarily precise or formal in any way. Both are open to interpretation by either the model-builder in the case of the construal, or the story-teller and listener in the case of the story. Each time a story is recounted, it is a unique explanation of the situation, but sufficiently similar to be recognised when heard again. So it is with construals. A model-builder's construal is unlikely to be the same for every interaction, and in many cases it is desirable for the construal to change, elaborating the details of the construal as the model-builder becomes more familiar with his subject. A construal can be looked at from different contexts, in order to explore other meanings for the construal. A simple example of this is in the jugs model to be examined in §3.2, where liquid in two jugs can have a different meaning in completely unrelated contexts such as the displaying the chords on a violin. A construal, although a personal artefact, can take on new meanings in a different context or situation from that which the model-builder created it, just as a story can invoke new meanings in a different context.

Stories can be taken up by other people, and construals can too. Construals taken up in this way by new model-builders are not necessarily used in exactly the same way as before or in the same context. The evidence that I have of this is that EM construals are often revisited by different model-builders. New model-builders nearly always incorporate the old construal into their own construal, or they use the old construal as a basis for further creation. I relate this to the way that people tend to remember stories that are relevant or interesting to them, that is stories that can be put in a personal context. When a model-builder take on a construal, it needs to be taken into context for it to have some meaning. Sometimes this new meaning is not all that relevant to the previous model-builder's meaning. So a construal, although a personal artefact, can take on new meanings with a different model-builder.

When a story is written down, it is similar to creating automation. In conventional software development this forces the user to 'use' the program exactly as specified by the programmer. Automation allows users to follow a specific line of interaction, but EM model-builders, unlike typical users of programs, do not necessarily have to follow the specific path laid out for them by the automation (they are free to intervene at any point)—just as someone reading a story is free to skip over sections of the story, read it backwards or in any order, as well as to try to interpret the story in whatever way they wish. The distinction between EM and software development is taken up further in Chapter 3.

The emphasis of this characteristic is on the nature of EM activity to treat construals as embedded in a particular situation or context, and that a construal used in a particular context is unique. This is closely connected with the characteristic of learning, as described in §1.2.7, that *learning is a situated experience.*

2.2.8 Construal interaction is connected to the continuity of experience

A construal's association with sense-making requires that experience plays a fundamental role in the creation and use of such artefacts. Of course, experience plays an important role in any interaction between user and computer, but as Beynon, Russ & McCarty show, traditional methods for constructing computer-based artefacts (i.e. programming) attempt to separate the experience from the construction process in a way that EM subverts by the fluid nature of its activity [BRM06]. As illustrated in Figure 2.1, the sense-making that is involved in moving from interaction prior to ritualisation to ritualised interaction is a continuous and unconstrained activity. In this way, EM offers a different perspective on the role experience plays in interactions between model-builder and computer, one that views experience as central to such interactions. As described by Beynon [Bey05a], the EM approach relates to the philosophy of James' in his work on Radical Empiricism [Jam12]. Beynon argues that a construal should support the superabundant and dynamic nature of personal knowledge: "What there is to be known of Coventry is more than I can ever experience, and my personal knowledge is established, maintained and revised dynamically through my ongoing interactions with it" [Bey05a].

The Experiental Framework for Learning (EFL) introduced by Beynon [Bey97] and subsequently elaborated on by Roe [Roe03] describes different categories of learning as shown in Figure 2.7. These categories range from activities concerned with concrete situations and private experience to activities relying on formal languages and public knowledge. Roe states that learning begins from private experience: "Preliminary interactions

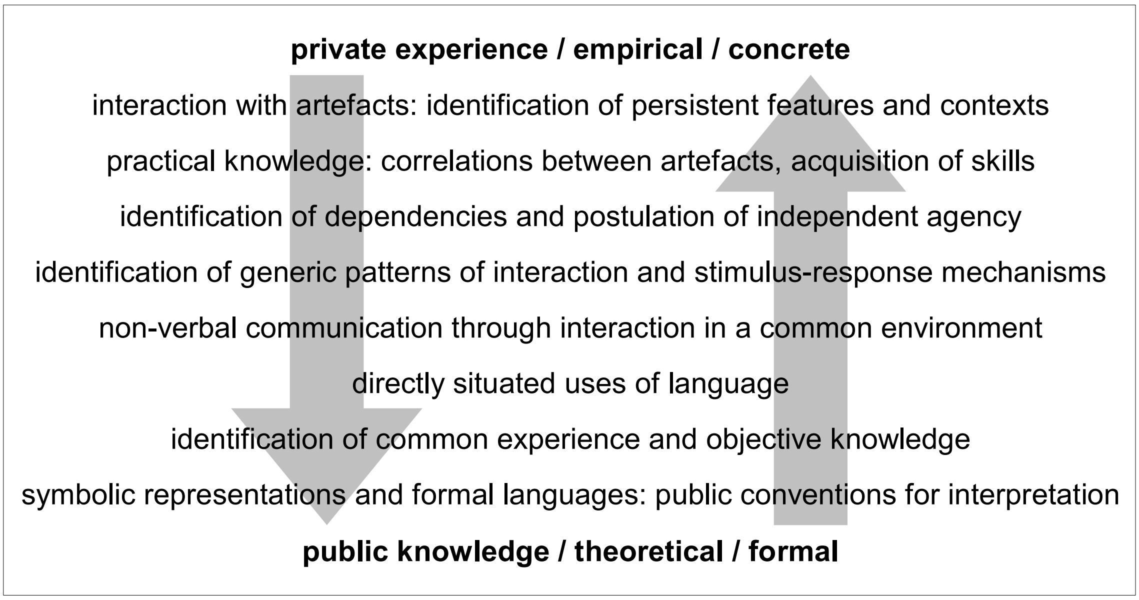


Figure 2.7: The Experiental Framework for Learning (EFL).

are informed by our previous experience" [Roe03:p73]. We start to attribute meaning to elements of a construal and plant the roots of understanding. After a while we begin to notice patterns of observables, dependencies and agency that are common between experiences. As we make more sense of the subject, as we become more familiar with the subject, we are able to explain more clearly the relationships between observables. This corresponds to the downward arrow in Figure 2.7, in that concrete situations and private experience leads towards the formal use of language and public knowledge. At the same time, sense-making necessarily involves checking that a construal corresponds to the referent by comparing a chosen set of definitions to empirical evidence or private experience. Such learning activities can be associated with moving up through the different categories of learning in Figure 2.7 from the formal or public knowledge to the concrete or private experience. Therefore, the creation of construals is a down and up activity in the EFL. Experimentation through the creation of a construal is aiming downwards in the EFL to explore possible formalisations of ODA, observation through the interaction with a construal is poking upwards in the EFL to decide whether the ODA correspond to personal experiences. Roe refers to these activities as *abstraction* and *concretisation* respectively [Roe03:p76].

Experimental work by Piaget [Pia74] relates closely to the EFL in explaining the progression from tacit knowledge to explicit public knowledge. The work shows that there is a development gap between succeeding in performing an action and being capable of explaining the action. Experiments on young children discovered that almost none could describe verbally the movement of their hands and feet when walking on all fours, even after performing an example walk themselves [Pia74:p3]. Older children were able to correctly describe their behaviour. Another experiment [Pia74:p15] with children swinging and launching a ball on a piece of string shows that although competent at the skill of hitting a target, the children did not realise that the ball's trajectory was determined by both the release point and the direction of rotation. These examples (and others) show that children of different ages are not able to describe in language the skills that they have learnt. They have developed a practical level of knowledge (in the upper realm of Figure 2.7) but as yet have not progressed to levels further down the EFL. This is further evidence, in children at least, that learning starts from the realm of private experience in the practical/concrete sense, before moving towards public knowledge in an abstract sense.

Other work in the Geneva school by Karmiloff-Smith and Inhelder [KI75] points to the importance of "constructing and extending theories of action" for discovery in early childhood. This theory construction activity is evident in the downward movement of the EFL where similar or repeated private experiences are charactised in a way that can be more formally explained, such as developing an understanding from repeated experiences of rainbows occurring when bright sunshine follows heavy rain. Karmiloff-Smith and Inhelder also point out that scientists as well as children have a similar tendency to explain phenomena by constructing a unified theory and therefore it may be a deep-rooted function for learning and discovery [KI75].

EM can support the categories of learning in the EFL on all levels as demonstrated by Roe [Roe03]. Furthermore, the fluid nature of EM activity (as depicted in Figure 2.1 means that the learner can move between the levels (moving up and down the EFL) in the stream of model-building. The continuous and unconstrained interaction with a construal offers a model-builder the continuity of experience necessary for learning. In this way, EM is aligned to the characteristic of learning, introduced in §1.2.8, that *learning is a continuous experience.*

Characteristic of learning described in Chapter 1	*Related EM principle*
learning occurs when constructing in the world (§1.2.1) learning involves the active construction of understanding (§1.2.2) learning results from realising the unknown (§1.2.3)	construals are constructions in the computer (§2.2.1) construals are active constructions of meaning through ODA (§2.2.2) construals evolve by examining the unknown (§2.2.3)
learning need not follow a preconceived path (§1.2.4) learning occurs without prescribing an outcome (§1.2.5)	construal creation need not follow a preconceived path (§2.2.4) a construal is never finished (§2.2.5)
learning is motivated by personal interest (§1.2.6) learning is a situated experience (§1.2.7) learning is a continuous experience (§1.2.8)	construals are personal to the model-builder (§2.2.6) construals are personal to the situation (§2.2.7) construals are closely connected to continuing experience (§2.2.8)

Figure 2.8: The correspondence between EM and the characterisation of learning in Chapter 1.

2.3 Connections between EM and learning

2.3.1 The common theme of sense-making

In the discussion of the *eight characteristics of EM*, the word 'sense-making' has been introduced. Sense-making is a theme which runs throughout this thesis and is central to the EM principles and tools. It is taken literally to mean the activity of making sense of a situation or phenomena. As Beynon & Russ point out, building models is intimately connected to sense-making [BRM06], as will be demonstrated further in Chapter 3. Furthermore, sense-making is an important aspect of learning [Jon06:p3]. Jonassen relates sense-making to 'conceptual change', introduced in §1.1.4 as the mechanism underlying meaningful learning, and model-building using technology is one way for conceptual change or sense-making to arise in learners [Jon06:p3].

This thesis illustrates how EM can be used to help learners construct models of what they are studying or other phenomena of interest. Building models of phenomena and situations using EM tools facilitates the process of sense-making in learners.

2.3.2 Corresponding characteristics

There is a close correspondence between the eight characteristics of EM described above and the eight significant characteristics of learning as can be observed from Figure 2.8. This correspondence forms the basis for the argument that *EM is a suitable approach for* *supporting the experimental, flexible and meaningful characteristics of everyday learning.*

The discussion of EM in this chapter illustrates the point that EM is a learning tool that people learn *with*, not *from*. Therefore it is particularly well-suited to *supporting* ET with more of the characteristics of learning in the everyday sense—EM is less like Figure 1.2 and more like Figure 1.1. The integrated EM approach outlined in this thesis has advantages for supporting some forms of learning that assume the characteristics laid out in Chapter 1, but not necessarily for other forms of learning. While the following chapters demonstrate how EM helps achieve the eight characteristics set out in Chapter 1, it should also be admitted that EM might not be a suitable approach for all forms of education. It should be acknowledged that the goal is not necessarily to fit in with all forms of existing education, but to alleviate the tensions between technology enhanced learning and everyday learning. If EM can support more of the everyday aspects of learning then there is potential for the tensions to be reduced—in a way that might lead to a new paradigm for learning and education that is expected in the vision for ET discussed in Chapter 1. The next chapter is devoted to showing *why* EM is different to traditional ET, and the following chapters then demonstrate *how* EM is better suited to supporting the eight significant characteristics that are a feature of everyday learning.