Construals as a Complement to Intelligent Tutoring Systems in Medical Education

Meurig Beynon[1], Will Beynon[2]

[11]Computer Science, University of Warwick, Coventry CV4 7AL
{wmb@dcs.warwick.ac.uk}
[2] University Hospitals Leicester, Leicester, UK
{willmeurig@gmail.com}

Abstract. This paper elaborates on ideas presented in two papers [6,7] prepared in connection with the 11th International Conference on Intelligent Tutoring Systems held in Crete in June 2012. The overall conference theme, as set out in the Call for Papers [27], was co-adaptation between technologies and human learning. To achieve co-adaptation in building an Intelligent Tutoring System (ITS), it is essential to reconcile machine and human perspectives on 'knowledge' and 'intelligence'. Following well-established principles of Empirical Modelling (EM), we propose to address this integration by using the computer to make *construals*: interactive environments in which human agents acting as model-builders can explore the observation, dependency and agency that underpins their understanding of the subject domain. EM principles are particularly relevant to domains such as medicine where reasoning draws both on scientific knowledge and on human experience and judgement that is ever evolving. This is illustrated with reference to a construal of malaria, currently under construction, that has the potential to bring together many perspectives – both contemporary and historical – on this extensively studied disease. Our prototype exploits a web-enabled variant of EDEN – the principal EM tool – which enables many agents to participate in the process of adaptation.

Keywords: intelligence, adaptation, construal, technology-enhanced learning, learning environments, observation, dependency, agency, Empirical Modelling, medical education, malaria

1 Introduction

In supporting co-adaptation in an Intelligent Tutoring System, the conceptual framework surrounding 'knowledge' and 'intelligence' has a critical role. The well-known problems of adapting software to meet new requirements suggest that something richer than the conventional conceptual framework for computing applications is appropriate. Where a traditional computing system is conceived as a 'program' that reflects a paradigm of 'computational thinking', Empirical Modelling (EM) [26] proposes a broader perspective on computing based on the more primitive notion of 'construal'. A *construal* is an interactive environment in which a human interpreter can experience metaphorical counterparts of the different states and transitions between states they encounter in a phenomenon they wish to understand.

In this report, we explore and illustrate the potential for exploiting construals to support learning activities in which adaptation to new information or agent behaviours is essential. Construals have evident practical advantages over the more inflexible procedural programs of traditional computing. Moreover, as we shall demonstrate, experientially-mediated construals seem better-oriented semantically than program-like functional abstractions in some learning contexts – and especially those where adaptation is essential. In particular, human intelligence in any domain involves more than can be expressed in terms of knowledge of recipes for achieving clearly specified goals. Working with construals enables us to exploit the computer in ways that reflect this broader vision for intelligent interaction.

The key idea behind making construals using EM is that we make sense of phenomena by thinking about putative causes – what is acting in the situation to make changes (*agents*); what these actors are deemed to 'sense' and respond to (*observables*); and how agents' actions immediately affect several observables simultaneously in predictable ways (*dependencies*). Medicine appeals as a subject domain in which the notions of agency, observation and dependency are most topical. A conventional ITS is an excellent way to support medical education where learning terminology, factual information and standard protocols is concerned. But both clinicians and researchers can also benefit from complementary learning resources that help to exercise and develop informal and tacit knowledge that may guide their judgement. A construal fulfils this role by inviting engagement from learners with many different goals, levels of expertise, and varieties and degrees of experience. Rather than supplying definitive answers, this activity provokes questions, and in the process forces the learner to reflect upon their knowledge and experience. Such reflection is a vital component of medical education, where educators must learn to cope with emerging science, evolving practice, and ever-changing contexts. This is illustrated by the online construals of malarial infection to be described in §4 below. We first give a brief introduction to EM.

2 The principles of Empirical Modelling

The principal goal – or aspiration – in Empirical Modelling is to develop an interactive artefact (a 'construal') that reflects and communicates the modeller's understanding of – or "intelligence about" – a current situation. The word 'aspiration' is to be preferred to 'goal', as creating a perfect and comprehensive construal is acknowledged to be impossible. The notion of 'intelligence about a situation' is to be preferred to 'understanding of a situation' as the former suggests knowledge whose significance is not necessarily fully appreciated or associated with a specific purpose. This is consistent with the dictionary concept of 'intelligence' as *the capacity for understanding; ability to perceive and comprehend meaning* [25] and the idea of intelligence as implicit – and perhaps secret – information that is gathered because of its potential strategic value.

Figure 1 depicts the key ingredients in making a construal using EM: the **construal**, its **referent**, and the **context** within which the **modeller** interacts with both.

The construal takes the form of an interactive artefact constructed on the computer. The figure is intended to represent a 'live' correspondence that the modeller experiences as a result of interaction with the construal and with its referent (see [4] for further explanation of the nature of this correspondence).

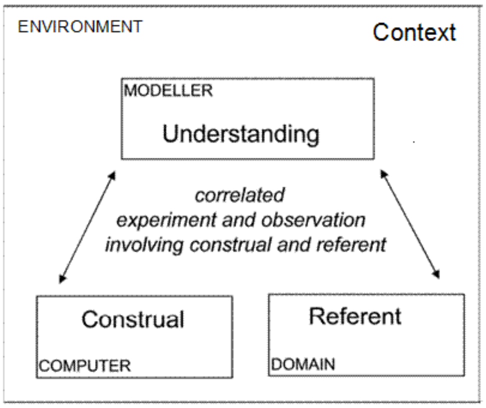

Fig. 1. Empirical Modelling for making a construal: a modeller's perspective

Intelligence about the current situation is tacit in the construal in much the same way that intelligence is tacit in a spreadsheet. This intelligence encompasses 'what if?' knowledge: "what would happen were I to act in the following way in this situation?". Because an EM construal is more primitive than a spreadsheet and does not have a standard structured interface, it invites free open-ended interaction with broad potential for interpretation.

In the construal, the current situation is reflected by a family of *observables* that have counterparts in the referent. An observable is an entity to which an identity and current status can be attributed. The observables within the construal are subject to *dependency* relations, whereby changing the value of one observable leads directly and 'instantaneously' – or at any rate without any possibility of interruption – to the updating of other observables. All state-changing actions made by the modeller in essence take the form of modifying the current values of observables and/or the dependencies to which they are subject. Dependencies, like observables, have direct counterparts in the referent. They reflect the ways in which changes to observables are characteristically synchronised in the current situation.

The range of state-changing actions that can be effected by the modeller is broad. Modifying the current values of observables or the dependencies might be interpreted as reflecting a change of state of the referent. It might alternatively be refining the correspondence between the construal and the referent. Such refinement could take the form of introducing a 'new' observable relating to the current situation. It might entail improving the way in which observables are realised visually or can be changed via an interface. It may be a corrective action – revising an incorrectly specified dependency, or correcting a misapprehension about the nature or even the identity of the referent.

Modelling activity of this broad nature is not normally foregrounded in the use of spreadsheets – though it features in exploratory modelling with spreadsheets and is typically what setting up a standard spreadsheet from first principles entails. In making an EM construal, the modeller exploits the breadth of the state-changing mechanism to interact as if in the role of other state-changing *agents* that can act in the current situation. This makes it possible to explore the nature of the potential agency latent in a situation. The scope for making several modifications to observables and dependency simultaneously also allows multi-agent interaction to be simulated.

In EM, the semantic relation that links the construal to the referent is informal in character. It is a relation that is experienced by the modeller because of the way in which observables and dependencies have been configured and agency is enacted. Like its referent, the construal presents itself to the modeller in a particular state that may or may not be familiar. Though some aspects of the current state are explict in what is directly observed, some are latent, and are only elicited through interaction. What the modeller recalls from previous interactions is highly significant in this process of elicitation, and shapes what is meant by the modeller's **Understanding** in Figure 1.

In much the same way that an experimental scientist fashions interactions with the world so as to replicate situations and sustain interpretations, the modeller can – if they choose to – craft the context for interaction with a construal, and so temper its meaning (cf. Figure 1 and the account of Keer's ant navigation construal in [13]). In this way, EM can be seen to complement other forms of model-making. For instance, by rehearsing particular sequences of interaction and interpretation, the modeller may be able to identify standard processes that are program-like in character. By restricting interaction with the construal to such processes, the modeller may then be able to use the construal to implement traditional mathematical computer models. This discretionary way in which interaction can be framed in order to give new and alternative meanings to a construal establishes what is referred to in Figure 1 as the **Context**.

A striking feature of human intelligence is our capacity to hold more than one plausible interpretation in mind, even though in some cases these are contradictory. With reference to Figure 1, this capacity relates to making speculative shifts in context that are consistent with what is actually directly observed in the current state, but reflect different perceptions about the likely consequences of interaction. Uncertainty about interpretation of this kind is commonplace in the experience of the clinician, for whom the same symptoms can be associated with quite different diagnoses and clinical problems. This highlights the role of the EM construal as a form of mental model of a situation that can guide strategic decisions concerning functional goals. In this role, the EM construal is as much oriented towards being prepared for what the modeller does not know as with representing what they *do* know.

3 Relating making construals to Intelligent Tutoring Systems

We envisage construals as interactive environments that are co-constructed by agents with different kinds and levels of knowledge and expertise. For instance, the agents making the construals of malaria to be discussed below might ideally include clinicians, medical researchers and patients as well as EM experts. Each agent will attend to different sets of observables and dependencies, and their understanding of the domain as mediated by the construal will be expressed in a similar way. Specifically, each agent will have become familiar with particular ways of interacting with the construal and interpreting the associated state changes.

In [17] Chapter 18, Nkambou et al characterise ITSs as "complex computer programs that manage various heterogeneous types of knowledge, ranging from domain to pedagogical knowledge." Making construals is not as sharply focused an activity as 'developing a program'. As will be illustrated below, the co-construction activity naturally generates many variants from an initial single construal. Though these construals themselves do not fulfil the same functions as a well-developed conventional ITS, their construction is highly relevant to the successful development of an ITS for an ill-defined domain. The process of making construals is itself a form of exploratory and collaborative learning in which the primary emphasis is on rehearsing and orchestrating the evolving experience of many different human agents. It illustrates a way of giving computer support for developing and managing understanding that is outside the scope of traditional approaches to knowledge engineering and software development (cf. [9,19]). The construals it produces, when sufficiently mature, are themselves a valuable resource for creating a traditional ITS in which more formal representations of knowledge and learning activities can be deployed.

Making construals has distinctive qualities as an alternative approach to ITS development. The same construal can support interactions by human agents acting in many different roles, each according to their particular skill and expertise. Every interaction takes a similar form, and involves one or more (re)definitions of dependencies performed simultaneously. In this way, activities that would conventionally be clearly differentiated in character and carried out sequentially, as when moving from knowledge engineering to software development to deployment for learning in developing an ITS, can be addressed in a uniform manner and performed in parallel. Each agent has an individual conception of the construal that is informed by their history and memory of interacting with it and interpreting these interactions. Intelligence about the construal is in the first instance concerned with having valid expectations about how it will respond to probing interactions. Because the perspectives of different agents are implicitly defined by possible interactions, they are fluid in nature and do not need to be consistent in order to co-exist. For this reason, ITS development based on construals offers better prospects for addressing the challenges identified by Nkambou et al [17] in Chapter 18. In particular, the loose and pragmatic association of different agent perspectives it affords may be helpful in achieving the integration of heterogeneous methods and tools across levels that is demanded in Woolf's framework of intelligent tutor building blocks [24].

Making construals is rooted in an epistemological framework that relates all "knowing" to connections that are given in the experience of the model-builder. As depicted in Figure 1, the modeller directly experiences the connection between the experiences offered by the construal and its referent. This semantic stance, central to William James's *radical empiricism* [12], is in line with Lanier's interest in exploiting computing technology without privileging formalism over human experience (cf. [14,7]). This may be seen by some as disqualifying an account of ITSs based on construals as a potential candidate for the "theoretical foundation" for ITSs sought by Self in [23]. Our aspiration is that such an account can nonetheless provide foundational principles that do full justice to the breadth of concerns, from the most abstract and to the most pragmatic, in ITS research.

A satisfactory semantic account of ITSs must address a challenge identified by Nkambou et al [17, Chapter 2]: bringing together the different epistemological traditions represented in philosophy, psychology and education sciences and in AI and cognitive sciences "so as to effectively meet the requirements associated with the development of a rich knowledge model and the inferential mechanisms associated with ITSs". Nkambou distinguishes two levels within classical knowledge engineering methodologies – the epistemological and the computational, and observes that "in relation to ITSs [the former] has not received any special attention". By contrast, making construals foregrounds the epistemological analysis that precedes the adoption of methods and formalisms required at the computational level. With reference to Figure 1, as stable coherent contexts for interaction of agents acting in the domain emerge, it becomes possible to refine the understanding of the knowledge, skills and perceptions required of each agent. The concept of "knowledge" being invoked here is highly nuanced in the way that Nkambou et al highlight as essential in designing ITSs. Knowledge may relate to the empirical fact of being aware of dependency relations, for instance, or – at the other extreme – to knowledge that can be expressed in a propositional form. For certain domains, it is realistic to expect that construals can be developed to the point where it becomes possible to frame ontologies, and to express methods for performing tasks in terms of these.

As has been argued elsewhere [1,5], EM construals are exceptionally well-qualified for supporting learning activities of a primitive and experientially-oriented nature because of the distinctive epistemological framework surrounding their construction. This claim may seem bold, but is quite consistent with James's views on the fundamental significance of adopting the stance on knowing that radical empiricism commends. It is most natural for construals to be developed in ill-defined domains, and there are clear links between making construals and the ill-defined task structures in what Lynch et al [15] (cited in Fournier et al [17: Chapter 5]) characterise as 'design domains' and 'analytical domains'.

In [17], Fournier et al identify five approaches to "representing and reasoning on domain knowledge in ill-defined domains". These include three classical approaches – *model-tracing*, *constraint-based modelling* and *expert systems* – and an additional approach of *partial task modelling*. The fifth approach is a hybrid of the other four. It is not appropriate in the first instance to regard making construals as 'representing' and 'reasoning' about domain knowledge – the associations that are depicted in

Figure 1 are much too loosely and intuitively prescribed to merit description in these terms. Nor are construals typically or necessarily built with a specific task in mind. But, as illustrated in previous work on EM – and despite the radically different epistemological orientation – there are significant points of similarity between making construals and each of these approaches. For instance:

- **Model-Tracing:** Modelling by networks of dependencies to which automatically triggered agent actions can be attached is in many aspects akin to rule-based modelling. Rules that can be invoked to maintain a dependency relation can be explicitly framed for instance. The crucial difference is that dependencies in general express relationships of a subjective character relating to the perception of an agent as to how changing the status of one observable will be perceived to affect that of another. This complements the syntactic nature of rule-based development by foregrounding semantic relationships in the way that is highlighted in Figure 1.

- **Constraint-Based Modelling (CBM):** CBM is an excellent example of the principle of shifting the focus from a procedural to a state-based view that is commended by EM. In elaborating a construal, it is often appropriate to apply the technique characteristic of CBM, viz. to introduce agents that monitor higher-level observables concerned with relationships between more primitive observables and exploit these observables in creating additional dependencies or actions. The motivation for the emphasis CBM places on 'capturing domain principles' is clear where there is a mature understanding of the domain. Such techniques can also be used more broadly in the process of identifying and circumscribing the domain, and as a way of critiquing domains whose conceptualisation is unsatisfactory. In this connection, it is interesting to contrast the well-known SQL Tutor with the SQLEDDI environment described in [8], in which the deficiencies and logical flaws in SQL as a vehicle for relational algebra are exposed.

- **Expert Systems:** The same principles that are deployed in CBM to give feedback to the learner can be used more pro-actively to guide or automatically invoke remedial actions. The way in which making EM construals provides a conceptual framework for exploiting expert systems is illustrated in the treatment of the elevator design problem (cf. Rothenfluh et al [22]), as described in [10].

In each of these comparisons, it should be borne in mind that making construals is primarily conceived as a manual activity that involves step-by-step engagement of the model-builder. Only when certain kinds of sequences of interaction and interpretation have been identified as routine is it appropriate for these to be incorporated into a construal by introducing automatic agency. This occurs for instance when these interactions are tracing autonomous behaviour in the referent or correspond to activities that have become so familiar to the modeller that they are no longer the subject of reflection. But this limited degree of automation typically falls far short of the kind of computational activity that is invoked in a fully-developed conventional ITS, and its primary purpose is to assist understanding in the process of designing an ITS rather than to deliver functionality and performance in its targetted deployment.

This distinction is illustrated by comparing the automation of routine interaction sequences commonly practised in EM with the process of deriving such sequences by data mining or machine learning techniques, as is characteristic of the Partial Task Modelling approach [17: §5.3.4].

Making construals can also be related to specific kinds of teaching model identified by Fournier et al in [17: §5.4]. For instance, making a construal resembles inquiry learning [17: §5.4.3] in that it characteristically provokes questions rather than providing knowledge to the learner. It is also well-suited for structuring learning around collaboration, since making a construal is most effective when the model-builder is obliged to exchange information and ideas with others, whether when communicating about their individual construal or engaged in collaborative construction.

4 Construals of malaria

The role for EM construals in learning is unlike that of a typical ITS in several respects. The interactions with a construal that support learning need not have the familiar well-rehearsed characteristics of a preconceived 'use-case' – learning through the *elaboration* of a construal is normal and may be more significant. There may be no specific level of understanding at which the construal is pitched – the intention is that the construal invites open-ended interaction from learners with potentially very different expertise and that the experience of interacting with the construal can be educational for both expert and novice. In this section, we describe two prototype construals that illustrate these characteristics. Though they are simple in nature, they could in principle be the basis for more sophisticated construals constructed with input from many different modellers with complementary expertise. Our chosen theme is understanding of malaria – the malaria construal in §4.2 will be used to illustrate construction from an EM perspective, and that in §4.3 from the perspective of a modeller with more medical expertise.

4.1 Adopting an EM perspective on making a construal of malaria

The principles discussed in §2 are practically supported by several EM tools. To use these tools effectively, it is necessary to adopt a particular approach to modelling. The discussion of Figure 1 in §2 emphasises the way in which the observables in the construal are directly experienced by the modeller as counterparts of real-world observables as-of-now. In the light of this, it is natural to consider malaria as a process defined by a characteristic sequence of states.

In the initial phase of making the construal, a standard depiction of the stages in human malaria infection was consulted. This was taken from the account of the life cycle of a malaria parasite published online by the US National Institute of Allergy and Infectious Diseases [28], as reproduced in Figure 2. The objective was to make a construal whose current state would reflect the possible stages of malaria infection, as determined by the point reached in the life cycle of a malarial parasite.

Before discussing the EM construal itself, it is instructive to consider the way in which the schematic diagram in Figure 2 acts as an aid to learning. This diagram is not a formal representation and its interpretation is quite loose and in some respects problematic. The larger circular feature with numbered stages, together with the small circular feature on the left, clearly represents the life cycle. It is unclear to what extent the 'blood-coloured' portion that corresponds to the human phase of the life cycle is intended to be interpreted as depiction of the bloodstream. The way in which a physical representation of the liver has been superimposed on the diagram in the vicinity of Stage 2, the way in which sporozoites enter and merozoites leave the liver, and the way that human red blood cells are depicted, strongly suggests the role of the bloodstream as a medium for transport. On the other hand, the sequence of three liver cells associated with the human liver stage is clearly intended to represent the process of schizogony, rather than the physical movement and transformation of a liver cell through the liver. The same applies to the sequence of five blood cells depicted in the small circular feature that represents Stage 3. And though it might appear that one and the same human body is involved in when the mosquito ingests and injects the parasite, this is of course not the most appropriate interpretation.

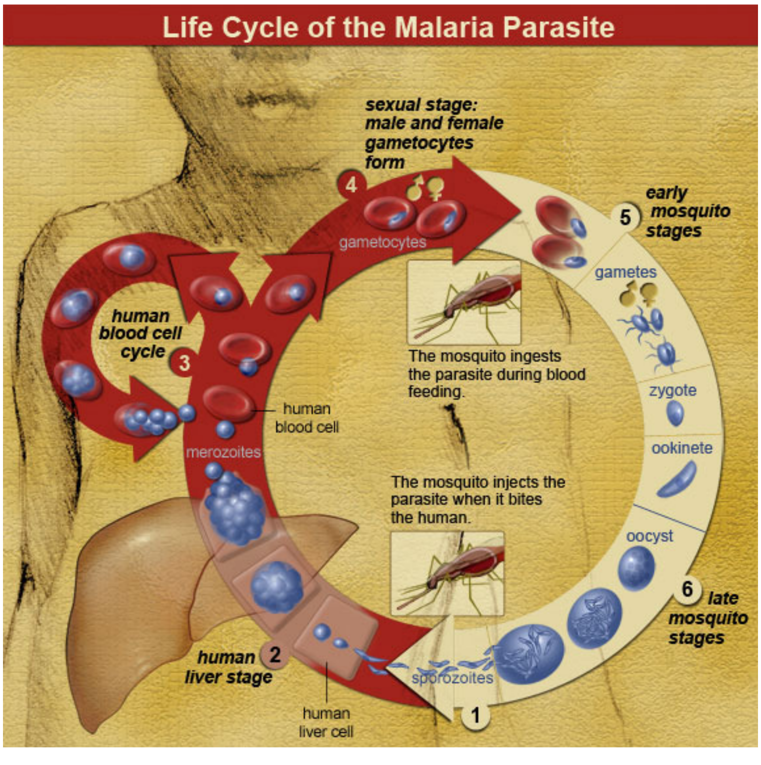

Fig. 2. The NIAID's depiction of the life cycle of the malaria parasite

In addition to these ambiguities that arise from over-loading features with meanings, there are ambiguities that stem from what has been omitted. There is no concept of the actual time involved at each stage. The number of instances of parasite subdivision that are associated with Stage 3 is unspecified, as is the way in which the different stages may be synchronised. The depiction of a few ‘representative’ blood cells gives no indication of the scale of the infection process. The stages of the mosquito phase of the life-cycle are even more sketchily depicted, and omit all details of the insect physiology.

The qualities of Figure 2 as a learning aid are typical of representations based on visual metaphors. Despite the ambiguities and omissions, which can be problematic if analysed in detail, the learner is able to grasp the image as a whole and exploit the relationships it embodies. For instance, the geometric layout conveys the sequence of stages in the cycle, whilst the symbolic elements in the diagram focus attention on the most relevant features associated with the life cycle (e.g. the blood cells, the liver, the sporozoites and merozoites).

In moving towards an EM construal for malaria, it is necessary to establish the kind of state-by-state correspondence that is depicted in Figure 1. In Figure 2, many states and perspectives have been conflated. The figure represents *all* stages of the lifecycle and no particular one is singled out. The right-hand side of the figure gives information about stages that are of primary interest to the epidemiologist rather than the cliinician. A step towards separating these different views is illustrated in Figure 3. This is a screenshot from a very simple construal that has been constructed by adapting the content of the NIAID webpage from which Figure 2 has been extracted. In this construal, which can be accessed online via the link at [29], there is a single observable called ‘stage’ whose value can be set by using the mouse. The corresponding components of the Life Cycle diagram and the descriptive text that accompanies it are then automatically highlighted by dependency.

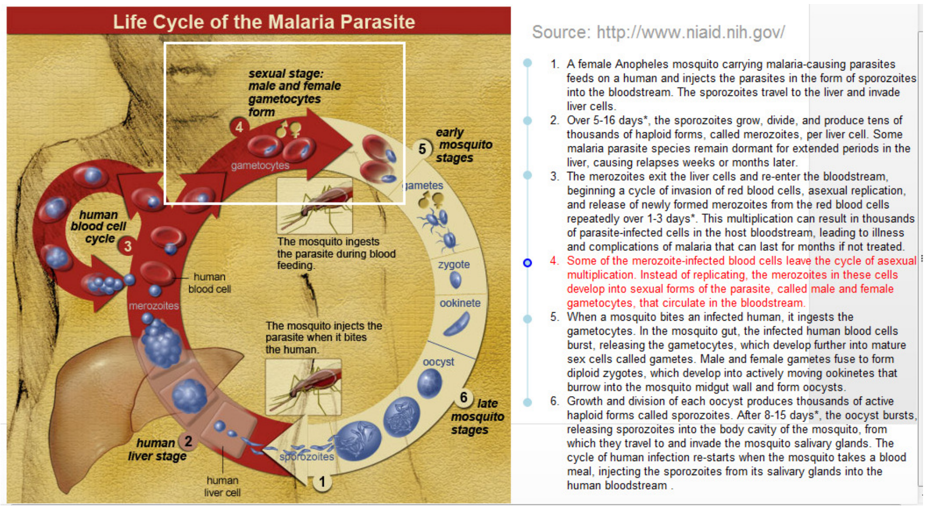

Fig. 3. Adapting Figure 2 to make a simple construal

4.2 A generic construal of malarial infection

The simple construal of malaria in Figure 3 is a first step towards making a construal that can support interactions from the perspectives of many different agents. The diagram and text in Figure 3 give only a loose, informal impression of each stage of the life cycle. To make the construal more useful as an aid to communication and learning in medical education, it is necessary to sharpen the focus and to give a richer and more precise account in observational terms. From the clinical perspective, the emphasis should be on the human phase of the life cycle. In order to make a connection with the condition of a malaria patient, the state of the infection must be described in more exact and informative terms than feature in Figure 3.

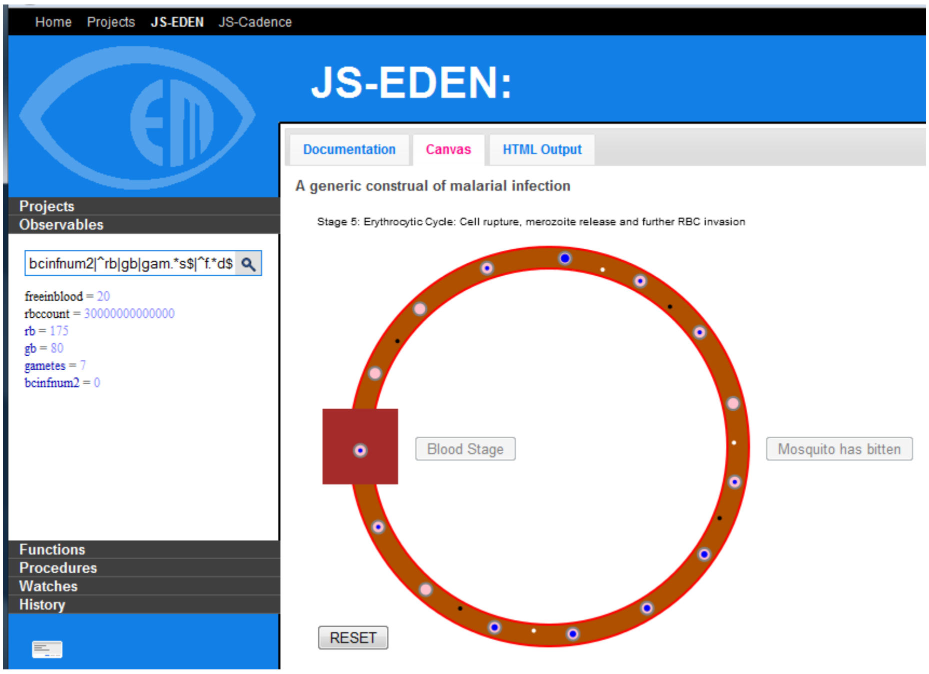

Fig. 4. A simple generic construal of human malarial infection

Figure 4 is a screenshot from a second online construal of malaria. This construal ("the GMI construal") has an automated behaviour that reflects the progress of a generic malarial infection, as associated with the human phase of the life cycle of the malaria parasite depicted in Figure 3. The GMI construal traces the stages of the infection using metaphor in much the same way that is used in Figure 3. For instance, a blood cell is represented by a pink circle. An infected blood cell is then represented by a pink circle enclosing a blue circle to represent the merozoites within it. Male and female gametes are represented by black and white circles. These circles are placed within an annulus that metaphorically represents the bloodstream. Whereas merozoites circulating in the bloodstream are explicitly represented in Figure 3, we have instead chosen to represent the presence of merozoites in the bloodstream by modifying the colour of the annulus, which is initially pure red, but acquires a larger green component as the infection progresses. With these conventions for interpretation, the visual state of the construal as a whole can then be interpreted as representing a particular stage in the infection. For instance, Figure 4 is a snapshot representing a point in the blood stage where there are infected blood cells and gametes as well as a large number of merozoites circulating in the blood.

In contrast with Figures 2 and 3, the construal depicted in Figure 4 gives richer scope for dynamic interpretation. The way in which the state of the construal changes over time not only reflects the overall stages of infection, but the underlying processes involved. These include asexual reproduction of merozoites within a blood cell, leading to the destruction of the cell and the release of merozoites into the bloodstream, for instance. Since the human observer can exercise independent control over the construal, it is possible to reflect the distinction between state change that occurs automonously from state change that requires an external agency – as when a mosquito first bites. To some degree, there is also scope to show the impact of clinical intervention. For instance, the effect of eliminating free merozoites from the blood can be simulated by making a single redefinition, and the temporary impact this has on the progress of the infection is appropriately reflected in the behaviour of the construal.

Despite being much more expressive, the GMI construal shares some of the limitations of the construal in Figure 3. The visual elements circulate in the annulus in way that suggests an ongoing cyclic process that is ambiguously interpreted as related to the circulation of the blood – as when the sporozoites first travel to the liver – or to the cycle of infection associated with the asexual multiplication of merozoites. It is plausible to regard a unit increase in the radius of a blue circle in Figure 4 as representing a doubling of the number of merozoites with a blood cell, but these representations of blood cells – like those in Figure 3 – are essentially iconic. For instance, the GMI construal depicts the number of merozoites inside an infected blood cell as building up to the point where the blood cell bursts. This bursting of an infected cell is represented visually as if a new uninfected cell had taken its place. For this reason, it is not possible to reconcile this behaviour in the construal with an interpretation of Figure 4 in which the iconic blood cells depict the level of parasitaemia. The mechanisms by which the state changes in the construal are effected are in any case too crude and random in character for sensible interpretation in quantitative or temporal terms.

The construal in Figure 4 can be inspected online via the link at [29]. As shown in Figure 4, the observables in the construal can be viewed by opening the Observables panel on the left, and using the search box at the top of the panel to select observables of interest. Some of the key observables in the model are documented in the webpage that can be accessed in a model README via the HTML Output tab. As explained in this README, particular families of observables can be selected for display in the

Observables panel on the RHS by entering a suitable regular expression in the textbox at the top of the panel. Such a use of regular expressions is illustrated in Figure 4. The webpage displayed in Figure 4 enables the human observer to interact directly with the model via the buttons on the canvas, but this is only the most limited and obvious mode of interaction. The definitions of observables in the Observables panel can be retrieved and edited whilst the model is active. It is also possible to bring up an Input Window through which new observables and dependencies can be introduced at any time. Such use of the Input Window is illustrated in Figure 5 below.

Appreciating the informal uncircumscribed nature of the interface to the modelling environment is essential to grasping the role of construals. Open-ended interaction via the Input Window is the dominant activity in the construction of a construal. Buttons are typically introduced to the interface only to give support for specific forms of agency, affording interactions that are particular significant or useful, or cannot be mediated conveniently or quickly enough using textual input.There is not in general a clear end-point to the development of the construal, and many agents can contribute to its elaboration at any time.

These issues can be illustrated with reference to the GMI construal. In the construal, the number of merozoites in the blood stream is estimated by the observable `freeinblood`, which can be thought of as the binary logarithm of that number. It is difficult to gauge how to maintain this observable without considering more realistic mechanisms of infection and it was in fact added only after the more specific construal to be introduced in the next section had been developed. A clinical intervention that eliminated free merozoites from the bloodstream might be simulated by setting `freeinblood` to zero. In the GMI construal, the value of `freeinblood` has a dramatic impact on the colour of the annulus, which is appropriate in so far as this colour is intended to make the presence of free merozoites readily apparent. The dependency that specifies the colour of the annulus in this case is not so appropriate from the clinical perspective, where the principal concern is to correlate the visualisation with the condition of a patient, and the presence of a few merozoites in the bloodstream may be asymptomatic. An alternative dependency proposed in [7] has been used in the construal depicted in Figure 5.

4.3 A construal of *Plasmodium Vivax* malarial infection

Without further elaboration, the abstract account of EM construals in §2 and the simple illustrative example in §4.2 do not do justice to the richness and subtlety of our mental models. Some of the issues can be highlighted by looking more critically at the example construal in Figure 4.

The discussion of Figure 1 in §2 emphasises the way in which the observables in the construal are directly experienced by the modeller as counterparts of real-world observables as-of-now. In relation to Figure 4, it is not clear what perspective would enable a modeller to have such direct experience.

Observables of many different kinds are associated with understanding malaria. These can be classified according to the role of the modeller (e.g. malaria patient, a clinician, medical researcher etc.), the nature of their observation, and the other agents relevant to the modelling context (e.g. the Plasmodium parasites and associated hosts in their many different forms, the mosquitoes that carry and transmit the infection).

For the patient and clinician, key observables are the symptoms and clinical consequences of malaria – relapsing fever, small vessel ischaemia, splenic pain, haemolysis and anaemia etc. For the medical researcher, observables might relate to parasitic load, cell-signalling, pathogen-host interactions at the cellular level, or statistical data derived from epidemiological studies.

To interpret Figure 1 as it applies to a malaria construal, it is most natural to think of the referent as "a specific instance of malarial infection at a particular moment in time". But the artificial probabilistic mechanisms that are used to animate the stages in the parasitic life-cycle in Figure 4 are quite unsuited to modelling the impact of a malarial infection. In making a better construal, the modeller potentially has the current status of any of the above observables in mind. Relevant observables range from the patient's current temperature or likely haemoglobin to the current level of parasitaemia and the biochemical interactions that are as-of-now occurring. Yet – though observables of all these kinds can inform the modeller's mental model – the modeller cannot actually apprehend them all in one and the same state.

The 'constructed' – rather than 'objective' – nature of the modeller's perception of state can be highlighted in many other ways. The modeller's observation is informed by a complex aggregation of present and past experiences, some necessarily "second-hand" in nature. Part of the process of construal is an account of observations and interactions that cannot be directly experienced by the modeller, but are postulated to be 'experienced' by another agent. What is more, the correspondence between the state of the construal and the state of the referent is sketchy and in some aspects problematic. The status of trillions of red blood corpuscles cannot possibly be depicted using a 'representative' few. There are many different manifestations of malaria, four relevant parasite species and perhaps 70 Anopheles mosquito species each with different characteristics and behaviours. On this basis, it is not clear in what sense the construal in Figure 4 has been conceived with a "specific instance of malarial infection at a particular moment in time". This motivates our final illustrative example of a construal.

Figure 5 is a screenshot from a construal of a Plasmodium Vivax malaria infection ("the PVMI construal") that was devised by adapting the construal shown in Figure 4 (this can be accessed via the link at [29]). The PVMI construal is intended to trace the stages in the development of a P. Vivax malarial infection from the point at which the sporozoites first enter the body to the point where the infection takes full hold over it. At this preliminary stage, the construal is still only provisional and incomplete – there are many ways in which it may be developed to add details and address limitations. Only very basic medical science and an easily accessible understanding of vivax malaria has so far been taken into account and applied.

The PVMI construal estimates the number of merozoites and gametes generated over time taking account of the likelihood of free merozoites being killed by the immune system, the number of red blood cells that can become infected, and the proportion of merozoites that reproduce sexually and asexually. The process of developing suitable metaphors to represent these processes is exceptionally challenging. There are 30 trillion red blood cells for instance [18] and at most a few million pixels on a standard computer screen. The timescale on which blood circulates round the body – once every 20 seconds – is quite different from the scale on which the P. Vivax parasite multiplies – once about every 48 hours – and the construal has to present state-transitions at an acceptable rate for the human viewer. As P. Vivax parasites preferentially infect young red blood cells, of which there are about a trillion initially, there is merit in distinguishing these from the rest. Red blood cells are renewed over a period of 120 days in health, a much longer period than that for which the infection is being tracked in this construal, and so older cells have in the first instance been neglected in modelling infection.

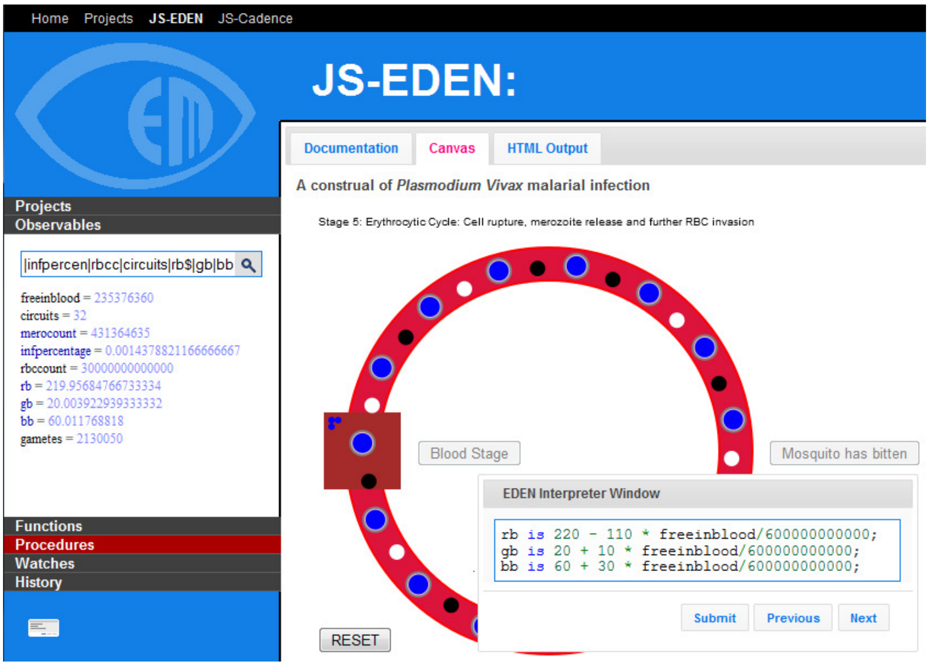

Fig. 5. A construal of human Plasmodium Vivax malarial infection

To interpret the construal, the viewer needs to appreciate the metaphors that have been used. The model has a dynamic circulatory behaviour to reflect the notion that the malarial infection is a cyclic and progressive activity. One cycle corresponds metaphorically to a period in the development of the P. Vivax parasite originating with the entry of merozoites into blood cells and terminating with the release of a cluster of merozoites from a schizont or the emergence of gametes. This leads to a dramatic increase in the number of merozoites in the bloodstream, which in turn initiates the next surge of infection of blood cells.

Although it does not represent the circulation itself, the red annulus in the construal metaphorically represents the blood within it; the pink circles populations of young red blood cells. Each of the fifteen circles represents a fifteenth part of the approximately one trillion cells that are most vulnerable to infection by merozoites in P. Vivax. There is no visual counterpart in the model for older red blood cells are not so vulnerable to infection, nor of individual corpuscles. The presence of merozoites within each of the fifteen clusters of red blood cells is metaphorically represented by blue circles that are placed on top of these pink circles. Like the red blood cells, the merozoites are so numerous that they cannot be visually depicted in a strictly proportionate manner. To overcome this problem, a logarithmic scale is used in the display. Each pink circle has radius 11 to indicate that it contains of the order of 10 to the power 11 cells. The radius of the blue circle that is superimposed is similarly specified according to the number of merozoites embedded within that population of cells.

Another significant feature of the infection process is the presence of merozoites and gametes within the blood stream. The same logarithmic convention that is used to depict red blood cells and merozoites is adopted to display the male and female gametes that are produced as the infection develops: these appear as black and white circles within the red annulus. A different metaphor is used to reflect the density of the merozoites free within the blood stream. The colour of the 'blood' within the annulus is modified as the number of merozoites increases, so that when the number of free merozoites is an N digit decimal number the 'blood colour' has a red component of 255-N*10 and a green component of N*15. In P. Vivax, the number of gametes in the bloodstream has been found to be very much smaller than the number of merozoites. Empirical studies estimate the median ratio of sexual to asexual parasites as 0.3% (0.07-6.2%) [20].

The mechanism that is used to update the infection status is invoked at the end of each cycle of infection. Mature erythrocytic schizonts, which in P. Vivax contain on average 16 merozoites, rupture releasing their contents into the bloodstream. In the course of a cycle, it is assumed that a certain proportion (1-gamma) of the merozoites are eliminated by the immune system, and that of the remainder a proportion (beta) enter the blood cells. Of those that enter blood cells, a small proportion (1-alpha) subdivide to form schizonts and even fewer generate gametocytes. The supply of young blood cells is also replenished.

5 More about the nature and role of construals

Making construals can be interpreted in two ways – as a potential basis for developing a conventional ITS and as an activity that serves an educational purpose resembling that of a conventional ITS in its own right. The former interpretation was the primary theme of §3; this section draws on the illustrative examples in §4 in discussing the latter.

The primary and most distinctive feature of the process of making construals is the emphasis placed on capturing meaning through experiential connections, and not in the first instance through formalism. This is significant both in methodological and epistemological terms. By comparison with the construals depicted in Figures 3 and 4, the PVMI construal – though still rudimentary in nature – is a basis for bringing together the perspectives of many different agents. It is possible to imagine how the construal could be elaborated to reflect the patient's likely symptoms, the real-time progress of infection, to simulate other variants of malarial infection, the impact of clinical interventions, and the interactions that occur at a molecular level, for instance. This illustrates how the elaboration and refinement of construals can prepare the ground for the specification of ontologies that enable the integration of agency in a conventional ITS, as discussed in §3. The virtue of the informal experiential semantics of construals is that it is not essential to develop such a specification in order to enable productive computer-supported communication between agents.

The problematic semantic issues highlighted in §4.3 draw attention to the fundamental character of a construal, and its potential role in learning and communication. The correspondence between the modeller’s experience of the construal and the referent is always necessarily incomplete and in some aspects uncertain. This uncertainty is a positive rather than an undesirable feature in the learning context. The modeller is obliged to maintain the construal through carrying out confirmatory interactions and rehearsing interpretations. This activity provokes questions, and may lead the modeller to qualify their mental model in different ways, whether consolidating, refining, or softening the perceived connection between the virtual and real world.

In appreciating these qualities of the construal, it is essential to recognise that the way in which it is constructed is critically important. Computer simulations that animate specific configurations of observables, dependencies and agency are well-recognised as educational aids (see e.g. [32]). There is some controversy about the extent to which *using* such simulations assists deep learning, though it can clearly help to mediate established knowledge. *Building* the simulations arguably has greater educational value, but the key idea behind EM construal is that the nature of the construction is itself crucially significant where learning is concerned [2,3]. It is *because* EM construals are explicitly crafted as configurations of observables, dependencies and agencies open to direct inspection and revision by the modeller (cf. Figure 5) that they give rich support to the learner. This is in no way to detract from the importance of understanding specific ways of configuring agency so as to achieve particular functional goals as efficiently and reliably as possible, a task to which traditional mathematical models and computer programs are indeed in certain respects better-suited.

The maturity of a construal is reflected not only – or primarily – in its size and complexity as a computer-based artefact but in the range of interactions and interpretations that it can sustain. The fact that a construal can be developed through conceiving and affording richer and more fruitful modes of interaction and interpretation gives scope for exploring newly acquired understanding in an incremental evolving fashion – a feature that is especially topical in medicine because of the speed of developments in understanding disease and devising treatment. This characteristic is hard to illustrate directly since the most interesting aspects of these ‘live’ interpretative activities are concerned with fresh perspectives and insight. To appreciate what is involved in adapting construals to changing contexts over time, and their potential contribution to a conceptual framework for learning, it is helpful to consider construals of malaria from a historical perspective. As a thought experiment, let us imagine that the technology to support construal had been available throughout history.

Malaria is a condition that has been recognized for centuries. As described in [21], the first doctors were perhaps little more than naïve observers, for whom the only meaningful observables were the symptoms of a patient with malaria. In this context an appropriate construal could be no more than a record of the patient's symptoms over time e.g. in the form of a chart or diary. With reference to Figure 1, "the state of the infection" to which this construal refers would be similarly sketchily registered.

Until quinine – in the form of the so-called "Peruvian bark" – first became available, there was little that could be done by way of effective treatment [21]. It does appear, however, that a careful record of symptoms over time was significant. Riocco [21, p104] remarks upon the success obtained by the 'quack' Robert Talbor through secretly deploying this bark, and goes on to observe that: "His real secret was to administer a weaker dose than patients had hitherto been accustomed to, and to repeat it as often as necessary". This indicates how – even on the basis of very crude understanding of a phenomenon – it may be possible by careful observation to develop more effective program-like interventions to achieve a goal.

Understanding of malaria was to change radically after 1880 when Laveran first observed the parasite that causes malaria [21, p253] and subsequently after 1897 when Ross and Grassi uncovered the life-cycle of malarial parasites [21, Chap. 9]. The kind of construal that is depicted in Figure 3 became possible at this point.

It later became clear that there were several strains of malaria attributable to different species of Plasmodium parasites, and that these could be distinguished by their characteristic symptoms and course of the illness. For instance, in vivax malaria, the fact that parasites preferentially infect young blood cells limits the severity of the infection and accounts for a particular cyclical pattern of fever characteristic of this strain.

The elaboration of construals, illustrated in §4, that makes it possible to create one construal to support several different agent views and interventions could equally be applied to progressive modelling of the perspectives of human agents as they have developed over historical time. The technical devices that are represented in this revision and refinement of construals, such as adding new observables, specialising the context, adapting the metaphors, make it possible to develop construals that remain consistent and "backward compatible" as our understanding of a phenomenon deepens. The potential for integrating recent and historical views of malaria is easily demonstrated: a relatively simple further refinement of the PVMI construal might introduce dependencies to link likely symptoms with the current status of the infection and add time as a new observable so as to mimic the periodicity of the 'agues'.

Approaching system development through the informal integration of many different agent views is a way of reconceptualising systems by placing them within a much richer epistemological framework. The relevance of such a framework for medicine, and the supporting role that modelling can play, is highlighted in McKenzie's article *Why model malaria?* [16]. McKenzie's account endorses the spirit of 'making construals using EM' in several respects. As stated in the abstract, it "argues that models can be powerful tools for integrating information from different disciplines, and that advances in computer modeling can complement and extend classic approaches". It emphasises the benefits of constructing models even though they are incomplete or 'wrong', provided only that they "sharpen questions". It stresses the importance of grounding models in biology, the need for models that "incorporate the unwieldy, historically contingent formulations that so often fit our empirical understanding of biological phenomena" and that can change to reflect the fact that "biological conditions and knowledge rarely remain static even without intervention". Citing Ronald Ross's pioneering work on modelling malaria from an epidemiological perspective, McKenzie also identifies a key role for modelling in going beyond establishing that "a disease depends on certain factors" to determining "which influences are greater, on what scale, and how they interact" [16]. This is precisely the kind of analysis at which the identification and simulation of agency in making construals is directed.

Our aspiration in developing EM principles and tools is to provide a new framework for computer modelling in which to address the limitations of "models in classic mathematical forms based on analytically closed solutions" discussed by McKenzie [16] and that is complementary to more general program-like models in which user interactions and interpretations follow preconceived rules (see [4] for further discussion). The key shift in perspective for which the construals presented in this report establish proof-of-concept involves maintaining a live relationship between what is being constructed on the computer and the observation, experiment and intervention that informs the construction. The effect of this shift is to enable the modeller to think first-and-foremost in terms of observables and agents, and only subsequently – if, as and when appropriate – in terms of variables and processes of the mathematical or computer programming variety (cf. [11]).

By way of topical illustration, both the *a priori* and the *a posteriori* styles of modelling identified by Ross in his study of malaria (cf. [16: 511]) can be viewed as specialisations of the activity depicted in Figure 1. In *a posteriori* modelling, we observe the evidence, 'endeavor to fit analytic laws to them' and in this way try to infer the causes. In *a priori* modelling we presume to know the causes and set out to determine the expected consequences. And where developments such as the possibility that malaria can be treated by a vaccination that prevents all the known Plasmodium pathogens from invading blood corpuscles is concerned (cf. [30]), it is quite apparent from McKenzie's exposition of the complex epidemiology of malaria [16] that this demands something altogether richer than a 'program-like' account of the potential implications for medical practice.

6 Conclusion

Work on EM construals for medical education is still at an early stage. EM's experiential perspective on computing practice exposes a gulf between our aspirations and current learning environments, not only in respect of EM itself but also of other approaches. By way of illustration, consider two of themes that were topical for the 11th ITS conference – "informal learning environments, where learning is a side-effect of interaction" and "multi-agent and service-oriented architectures" [27]. The very concept of "learning as a side-effect of interaction" is in tension with a program-like view of interaction, for which the context for human interpretation has first to be preconceived. Similarly, whilst a multi-agent architectural framework is most desirable as a basis for co-adaptation, mediating the interaction between agents “at the level of published functionalities” – as is characteristic of a service-oriented architectures – is semantically too restrictive. In effect, thinking of interaction between agents in these terms presumes that the ontologies required to address the communication problems have already been addressed (cf. §3).

EM construals lack the computational ingenuity of the machine learning that supports adaptation to different users etc in a conventional ITS within a functionally conceived framework. They nonetheless have rich promise for adaptation and co-adaptation from the *human* perspective. From our experience to date, the most conspicuous problem in making construals is that of developing interfaces for agents who do not have specialist EM expertise and cannot call upon an EM-proficient assistant. With more investment in interface development, EM tools promise to be the basis for a useful collaborative vehicle for bringing together the perspectives of many participants in the learning context, helping them to communicate, critique, refine and share their mental models. They will also promote that blending of virtual and real experience, of technical problem-solving with creative problematisation, and of scientific and human perspectives that is vital to fields such as medicine.

Acknowledgements

We are grateful to Tim Monks and Nicolas Pope for developing the JS-EDEN interpreter, and to numerous anonymous referees for their helpful feedback on the two papers on which this report is based.

References

1. Beynon, M.: Towards Technology for Learning in a Developing World. In Proc. IEEE 4th International Workshop on Technology for Education in Developing Countries, Iringa, Tanzania, July 2006, 88-92.
2. Beynon, M.: Computing technology for learning – in need of a radical new conception. In Journal of Educational Technology & Society, 10 (1), 94-106 (2007).
3. Beynon, M.: Constructivist Computer Science Education Reconstructed. HEA-ICS ITALICS e-Journal, Volume 8 Issue 2, June 2009, 73-90
4. Beynon, M.: Modelling with experience: construal and construction for software. Ways of Thinking, Ways of Seeing (ed. C. Bissell and C. Dillon), Springer-Verlag, 197-228 (2012).
5. Beynon, M. and Beynon, W.: A Conception of Computing with Promise for Medical Education, in Proc. 5th International Online Medical Conference (IOMC 2012), 3,4,10 and 11 March 2012, to appear in May 2012
6. Beynon, M. and Beynon, W.: Mediating Intelligence through Observation, Dependency and Agency in Making Construals of Malaria, in Proc. 11th International Conference on Intelligent Tutoring Systems, June 2012, to appear.
7. Beynon, M. and Beynon, W.: Construals to Support Exploratory and Collaborative Learning in Medicine, in Proc. Workshop on Intelligent Support for Exploratory Environments, June 2012, to appear

8. Beynon, W.M., Bhalerao, A.H., Roe, C. and Ward, A.: A computer-based environment for the study of relational query languages. In Proc. of the Teaching, Learning and Assessment in Databases Workshop, Coventry, UK, July 2003, 104-108.
9. Beynon, M. and Chan, Z.E.: A conception of computing technology better suited to distributed participatory design . NordiCHI Workshop on Distributed Participatory Design, Oslo, Norway, October 2006.
10. Beynon, W.M., Rasmequan, S. and Russ, S.: A New Paradigm for Computer-Based Decision Support. Decision Support Systems, vol 33 (2002) p127-142.
11. Beynon, W.M., Rungrattanaubol, J. and Sinclair, J.: Formal Specification from an Observation-Oriented Perspective. Journal of Universal Computer Science, Vol. 6 (4), 407-421, 2000.
12. James, W.: Essays in Radical Empiricism. Longmans Green and Co, London, 1912.
13. Keer, D., Russ, S., Beynon, M: Computing for construal: an exploratory study of desert ant navigation. In Procedia Computer Science, Volume 1, Issue 1, May 2010, 2207-2216.
14. Lanier, J.: You are not a gadget. Penguin Books, 2010.
15. Lynch, C., Ashley, K., Aleven, V., Pinkwart, N.: Defining Ill-Defined Domains; A literature survey. In: Proc. Intelligent Tutoring Systems for Ill-Defined Domains Workshop, ITS 2006, pp. 1–10 (2006)
16. McKenzie, F.E.: Why Model Malaria? Parasitology Today, **16**(12), 511-516 (2000).
17. Nkambou R., Bourdeau, J., Mizoguchi, R. *Advances in Intelligent Tutoring Systems*. Studies in Computational Intelligence 308, Springer-Verlag Berlin Heidelberg 2010
18. Pierige, F et al (January 2008). Cell-based drug delivery. Advanced Drug Delivery Reviews 60 (2): 286.95
19. Pope, N. and Beynon, M. Empirical Modelling as an unconventional approach to software development. Proc. SPLASH 2010 Workshop on Flexible Modeling Tools, Reno/Tahoe Nevada, USA, October 2010
20. Pukrittayakamee et al (Sept 2008). Effects of Different Antimalarial Drugs on Gametocyte Carriage in P. Vivax Malaria, Am J Trop Med Hyg, Vol 79
21. Riocco, F.: The Miraculous Fever-Tree: the Cure that Changed the World. Harper-Collins. (2004)
22. Rothenfluh, T.E., Gennari, J.H., Eriksson, H., Puerta, A.R., Tu, S.W., and Musen, M.A. Reusable Ontologies, Knowledge-Acquisition Tools, and Performance Systems: PROTEGE-II Solutions to Sisyphus-2. International Journal of Human-Computer Studies. 44(3/4), 1996, pp. 303-332.
23. Self, J.: Theoretical Foundations for Intelligent Tutoring Systems. Journal of Artificial Intelligence in Education, 1, 4, 3-14.
24. Woolf, B.: Building Intelligent Interactive Tutors: Student-centered strategies for revolutionizing e-learning. Morgan Kaufmann, New York (2008).
25. The free online dictionary, `http://www.thefreedictionary.com/intelligence`
26. The Empirical Modelling website, `http://www.dcs.warwick.ac.uk/modelling`
27. Call for Papers for the 11th International Conference on Intelligent Tutoring Systems, `http://its2012.teicrete.gr/`
28. Life Cycle of the Malaria Parasite, National Institute for Allergies and Infectious Diseases, `http://www.niaid.nih.gov/topics/Malaria/Pages/lifecycle.aspx`
29. Malaria construals in JS-EDEN: `http://www.dcs.warwick.ac.uk/~wmb/malaria/`
30. Malaria vaccination, `http://www.nejm.org/doi/full/10.1056/NEJMoa1102287`
31. The Open Clinical project at: `http://www.openclinical.org/whitepaper.html`
32. PhET, `http://phet.colorado.edu/`
33. The Virtual Physiological Human project at: `www.vph-noe.eu`