Understanding artefacts and phenomena through EM
Internal Combustion Engine and Transmission

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Abstract

Throughout history, humans have always been faced with the challenge of understanding new artefacts and phenomena, whether out of necessity or interest. A picture paints a thousand words, but surely in our day and age, we can do better than a picture – in this paper, we explain why the principles of Empirical Modelling are extremely valuable to the process of understanding new artefacts. We illustrate our discussion through the use of a model of an automobile's internal combustion engine and transmission. Finally, we describe certain limitations encountered during our modelling activity, and speculate about the bright-looking future of the discipline.

1 Introduction

From ancient physicists such as Archimedes understanding buoyancy, to driving school pupils across the world today understanding how gears work, learning about new objects is, and always has been, an everyday task.

In this paper, we show that the principles of Empirical Modelling can be applied to the task of understanding new objects, phenomena and concepts. By way of illustration, we use a purpose-built model of an automobile's internal combustion engine, transmission, and instruments.

Modelling an internal combustion engine was already attempted by Allderidge (1998), but the hardware available at the time could not run the model without first being compiled to an alternative platform (DAM). Today's hardware has made this possible, and our model can be considered as Allderidge's model's spiritual successor. We show how interacting with this Empirical Model, or "cognitive artefact" (Beynon, Cartwright, 1995), facilitates the process of understanding the way it functions.

2 Understanding an Artefact

Artefacts of our universe have a particular structure, which can be described in EM terms. Understanding this structure leads to understanding the artefact.

2.1 The structure of "*things*"

Artefacts, phenomena, events, objects, or more crudely just "things" – there exists an unlimited number of them, and yet they can all be described with three simple concepts. Regardless of their complexity, all artefacts consist of a collection of component agents, the observables that they own, and the dependencies between them.

In our engine model, one of the agents is the exhaust valve: one of its observables is whether it is opened or closed, and this observable is dependent on the state that the four-stroke cycle is currently in.

By using the EM concepts of agency, observable and dependency, the structure of "anything" can be described, from physical notions such as buoyancy discovered by Archimedes over two thousand years ago, to the internal combustion engine, invented in the form in which we know it by Nikolaus Otto in 1867.

2.2 The process of understanding

The ways in which humans cognitively process and understand new artefacts is a huge research topic of itself. Having described the structure of "things" in terms of EM concepts, we can see that to understand these "things", it is essential to understand their structure.

The first step consists in understanding observables. A valve on the engine can be open or closed. The accelerator pedal can be totally pushed down, not pushed down at all or anywhere in between. The engine runs at a certain speed, called RPM (revolutions per minute). These are some examples of observables in our ICE model.

The second step consists in understanding the dependencies between these observables. Depressing the accelerator pedal will have the effect of injecting more gasoline/air mixture into the cylinders, which in turn will make the engine run faster, and therefore increase RPM. Consequently there is a dependency between the accelerator pedal and RPM.

The process of understanding is a bottom-up procedure. We start by understanding individual component agents by understanding their observables and the dependencies between them, and when we understand all component agents, we understand the artefact as a whole.

2.3 A picture paints a thousand words

There are many different ways of explaining something to someone. From instruction manuals, through lectures and presentations, to schematic diagrams, humans have always looked for different and better ways to transfer understanding.

An intuitive attempt might be to vocally explain to someone how an artefact works. The vocal explanation might be complemented and enhanced by the addition of pictures or sketches to convey meaning visually. When introducing me to the concept of *engine braking*, my driving instructor retrieved the scrapbook she always had in her car's door pocket, and sketched a diagram similar to Figure 1 to illustrate why the lower gears (which have a larger diameter than higher gears) produce less revolutions of the wheels for a revolution of the crankshaft, thus reducing the speed of the car on a downshift.

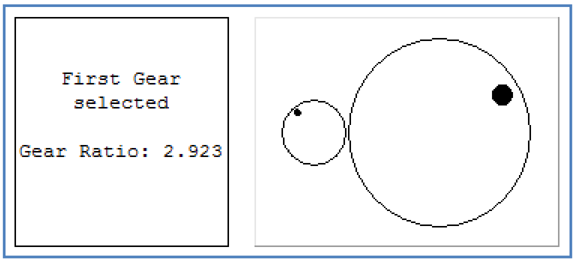

Figure 1: Transmission Gears

It is said that "a picture paints a thousand words", and indeed in many occasions, a diagram or picture can greatly facilitate the assimilation process.

But even my instructor's picture, useful though it was, did not help my understanding of how the car reacted to engine braking as much as actually trying it out for myself. Shifting down a gear whilst going down a slope and noticing for myself how the car's speed immediately decreased allowed me to understand the concepts my instructor had described in a way that no picture or text could have done.

The reason for this, in the words of David Kolb (1984) is that "learning involves transactions between the person and the environment". However a textual or vocal description, a picture, or even a video is a one-sided exchange: the human takes in information from a source, but does not interact with it. The subject is not able to interact with the artefact being explained; unfortunately, it is in this interaction which resides the most potential for learning and understanding.

However, EM and EM tools provide a framework to enable and understand the valuable transactions between the human and referent through the process of building and interacting with a construal. Empirical Models are "are cognitively rich because they result from extensive experience of the model and the referent through interaction by a human modeller in the course of identifying relevant observables and experimenting with dependencies" (S. Russ, 2007).

2.4 An Empirical Model paints more

A picture may paint a thousand words, but EM paints many more, because it "gives priority to our direct experience of phenomena" (S. Russ, 2007), allowing us a two-way interaction with the construal in a way that no text, picture or video could ever provide. In his paper, Steve Russ continues to explain how EM is "particularly appropriate for new phenomena, or phenomena which are as yet little understood". This further supports our view of EM as a tool for understanding artefacts through two-way interaction with a construal representing the artefacts themselves.

While any artefact or phenomenon can be modelled with EM, mechanical and engineering models are particularly well suited due to the elegant way in which Empirical Models can represent the dependencies between different mechanical parts. For example, the ICE part of our engine model (Figure 2) allows the user to explore through experimentation the relationships between the valves, spark plug, piston, and crankshaft, as well as the cylinder's current stroke. The user can change any of the parts, and see how this change is propagated through the system in a ripple of dependency.

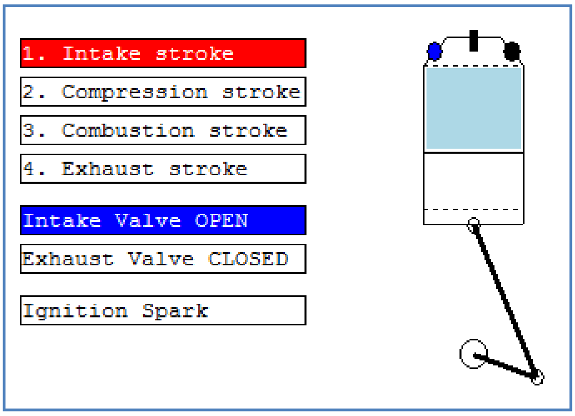

Figure 2: Animated engine cylinder showing four-stroke firing sequence

Many other modellers have taken advantage of the high value of EM principles in the modelling of mechanical artefacts. Ian Bridge's Vehicle Cruise Control model (W.M. Beynon, I. Bridge, Y.P. Yung, 1992) demonstrates how they can be applied to forces such as gravity, friction and acceleration, and a student even developed a general purpose Newtonian Mechanics Workshop for Web-EM-4 (Anon., 2008).

Experimenting, "the act of taking an action whose effect is unknown", is the process that leads to sense making (W.M. Beynon, S.Russ, 2008). Not only is it a process which cannot be carried out with conventional explanatory methods, it is also the most valuable one, and one which EM provides.

When chemists wish to learn more about a certain substance, they experiment with it to discover its properties and to observe how it reacts, using various tools such as test tubes, beakers and flasks. *Tkeden*, the most important piece of software to come out of the EM project, is the Empirical Modeller's tool for learning about artefacts: it is to the Empirical Modeller what the beaker is to the chemist. In time, it might even be any Computer Scientist's tool, and not restricted only to Empirical Modellers.

For example, in our engine model, a number of experiments can be carried out to enhance the user's understanding of how gears affect RPM and vehicle speed, such as shifting into a different gear, and observing the effects of the change on the tachometer and speedometer (Figure 3).

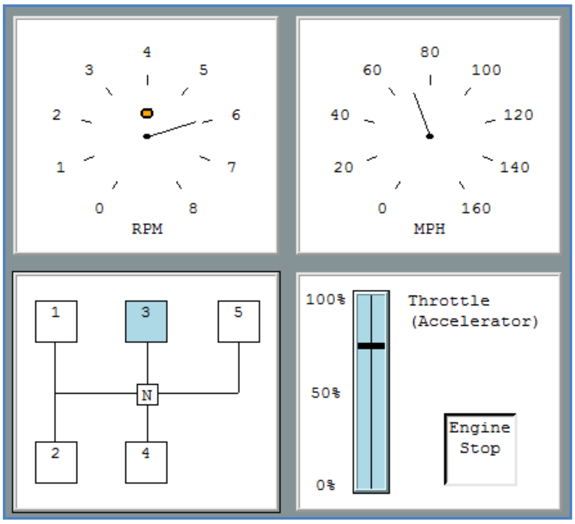

Figure 3: Instrument Panel (tachometer, speedometer, H-shifter, throttle and ignition)

2.5 How LSD can help

Using a digital watch construal to illustrate their discussion, Beynon, Cartright, Sun and Ward (1999) explain how mechanical artefacts can be modelled as "Interactive Simulation Models (ISM)". These convey information about artefact states in a way far superior than state charts by allowing the user to interact with the artefact, but they also allow the user to interact with the artefact in ways which go beyond the original modeller's intended simulation.

In our engine model, which is an ISM, a user can experiment with the 5 available gears, but could also decide to introduce a sixth gear, or change the gear ratios. The referent modelled by a construal is usually a very limited part of the world; for ISMs, it is generally a mechanical artefact. But unlike a conventional programme, there is no limit to how far the construal can be developed – the referent can be expanded to a wider view of the world (or artefact) and the model expanded to depict a broader view of the referent.

LSD accounts (Meurig Beynon, 1986) are often used in ISMs (such as Bridge's Cruise Controller) to document the dependencies between observables and agents as envisaged by the ISM's original modeller. LSD accounts can greatly improve a user's understanding of a construal, and hence artefact, by acting as a high-level description of the referent in EM terms of agency, dependency and observables. An LSD account can both facilitate learning and understanding before a model is even started, as a form of pre-modelling planning exercise, as well as after a model is "finished"[1], by outlining the essential characteristics of the model.

For example, a simplified LSD account of the *transmission* and *H-shifter* agents of our engine model (Figure 4) displays the dependencies between the automobile's gear box and gear lever, by providing the user with a textual blueprint of these components of the Empirical Model. By describing the observables belonging to agents, and the dependencies between them, it acts as a specification of the referent from which a construal can be built, but it can also be extracted from the existing construal, and is therefore another means of explanation which complements the construal and facilitates the process of understanding the artefact being modelled.

```
agent gearbox {
  state
     current_gear
     gear_ratios[]

  oracle
     shifter_position

  handle
     current_gear
     rpm
     engine_status

  derivate
     rpm = gear_ratio[current_gear] *
        throttle
     current_gear = shifter_position
}

agent H-shifter {
  state
     shifter_position, positions[]

  handle
     current_gear

  derivate
     current_gear = shifter_position

  protocol
     change(shifter_position) ->
        update(current_gear)
}
```

Figure 4: Simplified LSD account of the gearbox and H-shifter agents

[1] We use quotation marks here as a model is never truly finished, only taken as far as the modeller wishes. Empirical Models can be extended without limit by taking a broader view of the referent.

3. Final thoughts and the future of EM

The principles of Empirical Modelling are hugely influential, and it seems surprising that they have not been more widely embraced by the computing community. While the tools which have come out of the EM project (in particular *tkeden*) have been invaluable in demonstrating these principles, they are now starting to look dated.

The multiple definitive notations, including *EDEN*, *Scout* and *DoNaLD*, impair usability and add complexity to what should be a straightforward, transparent process. Furthermore, some basic expected functionality is lacking. For example, when developing the engine model, we were surprised to find that there was no way of rotating a DoNaLD shape using the *rotate* function without creating a second instance of the shape, resulting in unwanted artefacts on the screen. A more complicated workaround had to be devised, which distracted from the EM activity.

Tkeden also makes extensive use of procedural-style constructs, such as *proc* and *func*, which are not really consistent with the dependency-based principles of EM. *Cadence*, the new research prototype, and potential successor of *tkeden*, promises to address some of these issues. However, when considering the choice of tools for our engine model, we opted for *tkeden* in large part due to the proven success of the *EDEN* notation.

However the principles of EM are still as sound as ever and full of currently untapped potential. Our view is that a dominant use of EM is assisting with the process of "sense-making", a field which has not really caught up with the advances of technology. When asked to assimilate something new, be it a mechanical artefact such as an automobile engine and transmission or a physical phenomenon such as Faraday's electromagnetism, we are often presented with a book, diagram, or instructional video. EM transforms the sense-making process into a two-way interaction, and opens up new ways for the creation of understanding through experimentation.

The contribution which EM can make to the process of understanding new artefacts and phenomena is massive. In the words of Steve Russ (2007), "the central process of EM is the interactive construction of an artefact that maintains a symbiotic relationship with the modeller's construal of a phenomenon". It is precisely this interactive process in which resides huge learning potential, and which allows for quick, effective and efficient understanding. And it is by understanding the structure of artefacts – the agents which compose them, their observables, and the relationships between them – through the means of experimentation, that we are able to understand the artefacts themselves. No instruction manual, diagram, or other conventional method will ever allow this; however EM does.

We believe that EM is still only beginning, and that in time the wider community will become aware of the value of its principles, and that in time EM will flourish and take its rightful place next to the other grand fields of computing.

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