Modelling Dynamics of Cognitive Agents by Higher-Order Potentialities

Tibor Bosse[1]

[1]Vrije Universiteit Amsterdam
Department of Artificial Intelligence
De Boelelaan 1081a, 1081 HV Amsterdam
The Netherlands Tel. +31 20 598 77{50,63}
http://www.cs.vu.nl/~{tbosse, treur}

Jan Treur[1,2]

[2]Utrecht University
Department of Philosophy
Heidelberglaan 8, 3584 CS Utrecht
The Netherlands Tel. +31 6 15028916
{tbosse, treur}@cs.vu.nl

ABSTRACT

In the development of disciplines addressing dynamics, such as Mathematics and Physics, a major role was played by the assumption that processes can be modelled by introducing certain state properties (also called potentialities) that anticipate in which respect a next state will be different. The current paper is a first exploration of this perspective to analyse and model dynamics. Potentiality-based modelling subsumes quantitative, numerical modelling approaches, such as Dynamical Systems Theory (DST), and qualitative or symbolic modelling approaches to dynamics, such as BDI-modelling, and is applicable to model dynamics in a wide variety of (cognitive and noncognitive) disciplines. Thus, the modelling of dynamics of cognitive agents can be fully integrated with the modelling of other phenomena in Nature.

1. INTRODUCTION

Dynamics of the world shows itself by the occurrence of different world states, i.e., states at different points in time that differ in some of their state properties. In recent years, within Cognitive Science dynamics has been recognised and emphasised as a central issue in describing cognitive processes [9]. Van Gelder and Port [6] propose the Dynamical Systems Theory (DST) as a new paradigm that is better suited to the dynamic aspects of cognition than symbolic modelling approaches. However, as DST commits to the use of quantitative methods (differential and difference equations), it is often considered less suitable to model higher cognitive processes such as reasoning and language processing. DST is based on the notion of a state-determined system: a system in which properties of a given state fully determine the properties of future states; cf. [3], p. 25; [6], p. 6. This means that for state properties that are different in a future state, state properties in the given state can be found that somehow indicate or anticipate these differing (changed) properties in the future state. This idea closely relates to the concept of *potentiality* that goes back to Zeno and Aristotle [1]: if a potentiality *p* for a state property *a* occurs in a given state, then in a next state, property *a* will occur. A potentiality can be considered a kind of anticipatory state property: a state property anticipating the different state property (in the changed state).

The current paper contributes a first exploration of the notion of potentiality with respect to its use as a basis for modelling the dynamics of cognitive agents. A methodological perspective is described to analyse and model these dynamics in terms of potentialities. This modelling perspective subsumes both quantitative approaches (such as DST) and qualitative or symbolic approaches to modelling of dynamics. Given that the perspective subsumes DST, which since long has proved its value for quantifiable areas within a wide variety of disciplines, the scope of applicability of the proposed method includes disciplines such as Physics, Chemistry, Biology, and Economics.

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2. POTENTIALITIES

Given a particular state that just changed with respect to some of its state properties, it is natural to ask for an explanation of why these new state properties occurred. In a state-based approach, as a source for such an explanation, state properties found in the previous state form a primary candidate. A main question becomes how to determine for a certain state that it is going to change to a different state, and, more specifically, how to determine (on the basis of some of the state properties in the given state) those state properties for which the new state will differ from the given one. This poses the challenge to identify state properties occurring in a given state that in some way or the other indicate which of the (other) occurring state properties will be different in a subsequent state; by having these properties, the state anticipates the next state: anticipatory state properties. If such state properties are given, anticipation to change is somehow encoded in a state. The existence of such properties is the crucial factor for the validity of the assumptions underlying the Dynamical Systems Theory [3, 6]. It indicates the possibility to include concepts in the state ontology to conceptualise state properties that are useful to describe properties of changed states. Aristotle did introduce such a type of concept; he called it *potentiality* (to move), or movable. For example, the difference between an arrow at rest at position *P* and the snapshot of a moving arrow at time *t* at position *P* is that the former has no potentiality to be at some different position *P'*, whereas the latter has. This explains why at a next instant *t'* the former arrow is still where it was, at *P*, while the latter arrow is at *P'*.

3. HIGHER-ORDER POTENTIALITIES

The effect of a potentiality on a future state can be described by relating its occurrence in the present state to the occurrence of a certain state property in the future state. This specification can be viewed as the definition of what it is a potentiality for. A more complicated question is how to specify when (under which past and present circumstances) a potentiality itself will occur. For the case of empty space, where an object is assumed to have no interaction with other objects, a potentiality to change position is present because it was present at an earlier point in time and persisted until *t* (inertia of motion). However, if the potentiality in a new state is different from the earlier one, a question becomes why this is so. This leads to the question addressed in this section of how a *changed potentiality* can be explained. An answer to this question is the use of *higher-order potentialities*. The idea behind this is simple: to obtain an explanation of changed state properties over time, potentialities were introduced. Potentialities are also changing over time. As they are considered state properties themselves, it would be reasonable to treat them just like any other state property that changes over time. This means that for a potentiality $p^{(1)}$ a so-called *second-order potentiality* $p^{(2)}$ is introduced to explain why $p^{(1)}$ may become changed over time. And of course this process can be repeated for $p^{(2)}$, and so on. This leads to an infinite sequence of *higher-order* potentialities, $p^{(1)}$, $p^{(2)}$, $p^{(3)}$, $p^{(4)}$, …, where for each natural number n the potentiality $p^{(n)}$ is called an *n-th-order potentiality*. Using such higher-order potentialities, the idea is the following:

- for a certain point in time *t0* the occurrence of a state property *a* is determined by the state at a previous time point *t1* < *t0*, in particular, by the occurrence of the first-order potentiality $p^{(1)}$ for *a* at that time point *t1*.
- the occurrence of the first-order potentiality $p^{(1)}$ at *t1* can be determined by the state at a time point *t2* < *t1*, in particular by the occurrence of its own potentiality which is the second-order potentiality $p^{(2)}$ for *a* at *t2*.
- and so on.

This process can be visualised as depicted in Figure 1. In this figure, the *x* at the lower-left can be ignored for the moment.

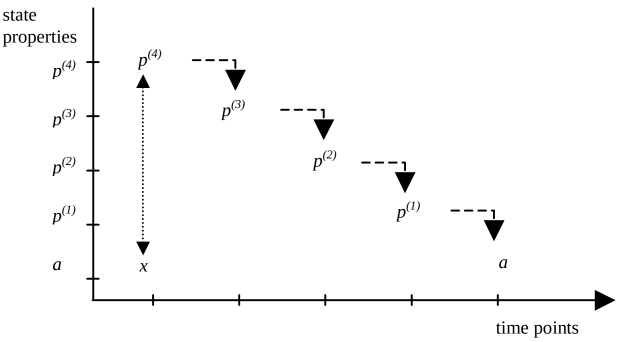

Figure 1. Dynamics based on higher order potentialities

This shows how the concept of potentiality to explain change of a certain basic state property *a* can take the form of a single entity, for example one number, to indicate what a changed property in an immediate subsequent state will be. Moreover, this can be extended by a large number of other (higher-order) entities, the occurrence of which can explain changed basic state properties *a* in future states.

Strange as the idea of an infinite number of higher-order potentialities may seem at first sight, in mathematical context (in particular in calculus) this has been worked out well (using infinite summations). For the discrete case, the idea of difference tables for functions has been developed. These differences play the role of relative potentialities: they indicate the next value not in an absolute sense, but in comparison to the current value. For the continuous case, higher-order potentialities have been formalised in the form of (higher-order) derivatives of a function. The (first-order) derivative of a function at a time point t gives an estimated measure of how the function will change its value in a next time point. The well-known Taylor series [12] for sufficiently smooth functions (at least infinitely often differentiable) shows how changes of the value from *t* to *t'* (within some given neighbourhood of *t*) depend on all (higher-order) derivatives:

$$f(t') = f(t) + \Sigma_k\ f^{(k)}(t)(t' - t)^k / k!$$

This expression shows how the (relative) potentiality at *t*, defined by the combination of all (infinitely many) higher-order potentialities, determines the changed state at the future time points *t'*.

In later times, successors of Aristotle have addressed the question how to further develop the phenomenon of dynamics (or change), in particular within Physics. They developed classical mechanics based on certain types of potentialities. For example, Descartes [4] took the product of mass and velocity of an object as an appropriate foundation for its potentiality to be in a changed position, or 'quantity of motion'. In modern physics this 'quantity of motion' concept is called *(linear) momentum*. This is one way in which a concept 'potentiality' (for change of position) was formalised in physics, thus providing one of the cornerstones of classical mechanics. Leibniz [7] formalised the notion of potentiality for changed position in a different manner by the product of mass and the square of velocity, what later got the form of the notion of kinetic energy, another cornerstone in Physics.

Also second-order potentialities played a crucial role in the development of Physics, for example, to obtain the concept 'force'. Newton uses the term 'impressed motive force' to express the change of motion in his second law: 'The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed' [8]. This law expresses that the concept of force used by Newton directly relates to change of motion. For (quantity of) motion he gives the same definition as Descartes, i.e., momentum. For an impressed force the following definition is given: 'An impressed force is an action exerted upon a body, in order to change its state, either of rest, or of uniform motion in a right line'. These definitions show that the concept 'force' used by Newton as an addition to state ontology can be given a definitional relationship to 'motion generated in a given time'. This 'motion generated in a given time' can be considered a second-order potentiality for the first-order potentiality 'motion' or momentum. So, within classical mechanics, after the concepts 'momentum' and 'kinetic energy' which were added to the state ontology as specific types of (first-order) potentiality, the concept 'force' can be considered a third property added to the state ontology, this time as a second-order potentiality. Using this state ontology, Newton (and also Leibniz) developed mathematical techniques of calculus, such as differentiation and integration.

4. REDUCERS

As indicated in the previous sections, the idea of explaining changed states in terms of higher-order potentialities can be very useful. However, when each potentiality can only be explained by introducing another (higher-order) potentiality, the approach risks ending up with an infinite chain of explanations. Then infinitary mathematical techniques such as infinite summations are needed, as shown in the Taylor series. To avoid this, one of the higher-order potentialities often can be connected somehow to lower level potentialities and/or basic state properties of the world. To this end, the notion of *reducer* of a higher-order potentiality is introduced: a combination of lower level potentialities and/or basic world state properties that is equivalent to this higher-order potentiality.

An example in the domain of Physics illustrates this notion. Analysing the motion of planets around the sun, Newton found out that they can only follow their orbit if a second-order potentiality (i.e., a force) is assumed, in the direction of the sun [8]. Newton calculated (using his calculus under development) in detail that this force was proportional to 1 divided by the square of the distance. For example, for an object in space with mass *m* approaching earth (with mass *M*), Newton's law of gravitation for the motive force on the object is as follows (here x is the distance between the object and the earth, and c is a constant): $F = c\ mM/x^2$. Such a relation between the second-order potentiality force and basic state properties such as mass and distance shows how a higher-order potentiality can be reduced: in this case $c\ mM/x^2$ is a reducer for F.

To explain the idea of reduction, consider Figure 1 again. This time, pay attention to the additional (world) state property x, which is the reducer of $p^{(4)}$. For simplicity of the presentation we take an example where reduction only involves a basic state property, and no lower level potentialities.

5. POTENTIALITY-BASED MODELLING

Based on the idea of reduction, a generic method can be formulated to describe dynamics in terms of higher-order potentialities. The method involves a number of steps (also see Figure 1), roughly expressed as follows:

1. pick a basic world state property a of which the change over time needs to be modelled.
2. introduce a potentiality $p^{(1)}$ that explains the change over time of a.
3. can a reducer be found for the potentiality $p^{(n)}$ in the model that has the highest order?
   - 3a. *yes* -> introduce a reducer x that connects $p^{(n)}$ to a lower-level state property: in terms of world state properties and lower level potentialities; then end.
   - 3b. *no* -> introduce a potentiality $p^{(n+1)}$ that explains the change over time of $p^{(n)}$; then go to step 3.

To illustrate the idea of the method, suppose one wants to explain the fact that an object approaching the earth changes position over time (due to gravitation). In that case the basic world state property a would be something like 'object *O* is in position *P*' (step 1). Then, to explain the change over time of this state property, for the first-order potentiality $p^{(1)}$ a concept 'momentum' can be introduced (step 2). However, since no reducer of this potentiality can be found, a second-order potentiality $p^{(2)}$ is introduced to explain the change over time of a momentum, i.e. a concept 'force' (step 3b). Finally, a reducer is introduced for this second-order potentiality force: the expression $c{*}mM/x^2$ (step 3a). To summarise, this example shows how the change of a world state property in the domain of Physics can be explained and modelled in terms of higher-order potentialities.

6. DISCUSSION

In this paper, the perspective to analyse and model dynamics in terms of (first- and higher-order) potentialities has been explored. This potentiality-based perspective played a crucial role in the development of Physics. These examples refer to motion of non-living objects. Another type of motion to be explained is motion of a living being. Often used explanations of human (or animal) actions refer to internal mental states: e.g., an explanation of human behaviour from internal mental state properties such as desires. The desire to be at *P'* plays a role similar to that of the potentiality for being at *P'*. Indeed, this similarity can be traced back in history, for example, to Aristotle: 'Now we see that the living creature is moved by intellect, imagination, purpose, wish, and appetite. And all these are reducible to mind and desire.' [2], Part 6. Here properties of 'mind and desire' are mentioned as the source of motion of a living being. He shows how the occurrence of certain internal (mental) state properties (e.g., desires) within the living being entails or causes the occurrence of an action in the external world. This indicates hoe the potentiality-based perspective can be used to model BDI-agents. Thus, the use of potentialities in a sense unifies different types of approaches (both symbolic approaches, such as BDI-modelling [10], and nonsymbolic approaches, such as DST [9]) to cognitive modelling that are often seen as mutually exclusive. For every (basic) state property that is changing over time, a potentiality can be added to anticipate its changes. As this (first-order) potentiality may also change, a second-order potentiality may be introduced to anticipate these changes. In principle, this can be continued indefinitely. However, in many cases there is no need to go this far. Often, after a few steps a reduction can be made in the sense that a higher-order potentiality turns out to be equivalent to a combination of basic state properties and/or lower level potentialities. Within DST this is where a differential equation comes in, reducing an *n*th-order derivative to lower level properties: the assumption of reduction is another assumption underlying DST. All in all, the proposed modelling perspective places the modelling of cognitive phenomena not in an isolated position, but fully integrates it with the modelling of other phenomena in Nature.

Analysing dynamics of a process in terms of basic world state properties and higher-order potentialities opens up the possibility to create an executable *formal specification* (and subsequently, *simulation*) of the process. This is the subject of current research. In addition, an interesting challenge is to apply the presented method to affective agent states (such as emotions and moods). It is claimed by many authors (e.g., [11]) that affective states have the potential to control agent behaviour; see [5] for an example application. Therefore, an obvious next step is to model affective states as potentialities as well, thereby providing more formal evidence of the above claims. This option will be explored in future work.

REFERENCES

[1] Aristotle (350 BC). *Physica* (translated by R.P. Hardie and R.K. Gaye).

[2] Aristotle (350 BC). *De Motu Animalium* On the Motion of Animals (translated by A. S. L. Farquharson).

[3] Ashby, R. (1952). *Design for a Brain*. Chapman & Hall, London. Revised second edition, 1960.

[4] Descartes, R. (1633). The World or Treatise on Light. Withdrawn from publication, 1633. Also in: Descartes, R. (1998), Descartes: The World and Other Writings (edited by Stephen Gaukroger). Cambrige University Press. (translated by M.S. Mahoney).

[5] Gebhard, P. (2005). ALMA - A Layered Model of Affect. In: *Proc. of the 4th International Joint Conference on Autonomous Agents and Multi-Agent Systems, AAMAS'05*, pp. 29-36.

[6] Gelder, T.J. van, and Port, R.F. (1995). It's About Time: An Overview of the Dynamical Approach to Cognition. In: (Port and van Gelder, 1995), pp. 1-43.

[7] Leibniz, G.W. von (1956). *Philosophical Papers and Letters*, LeRoy E. Loemker, ed., Chicago: University of Chicago Press, 1956.

[8] Newton, I. (1729). The Mathematical Principles of Natural Philosophy; Newton's Principles of Natural Philosophy, Dawsons of Pall Mall, 1968.

[9] Port, R.F., and Gelder, T. van (eds.) (1995). Mind as Motion: Explorations in the Dynamics of Cognition. MIT Press, Cambridge, Mass

[10] Rao, A.S., Georgeff, M.P. (1991). Modeling rational agents within a BDI architecture. In: R. Fikes and E. Sandewall (eds.), *Proc. of the Second Conference on Knowledge Representation and Reasoning*, Morgan Kaufman, pp. 473-484.

[11] Scheutz, M., and Sloman, A. (2001). Affect and Agent Control: Experiments with Simple Affective States. In: *Proceedings of IAT 2001*, World Scientific Publishers.

[12] Taylor, B. (1715). Methodus Incrementorum Directa et Inversa.