A Unified Perspective on Explaining Dynamics by Anticipatory State Properties[*]

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Abstract. In Cognitive Science, recently Dynamical Systems Theory (DST) has been advocated as an approach to cognitive modelling that is better suited to the dynamics of cognitive processes than the symbolic/computational approaches are. Often the differences between DST and the symbolic/computational approach are emphasized. However, if two approaches are used also their commonalities can be analysed, and a unifying framework can be sought. In this paper the possibility of such a unifying perspective on dynamics is analysed. The analysis does not only cover dynamics in the cognitive discipline, but also in other disciplines: Physics, Mathematics and Computer Science. The unifying perspective warrants the development of integrated approaches covering both DST aspects and symbolic/computational aspects.

1 Introduction

Due to dynamics the world occurs in different 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 recognized and emphasized as a central issue in describing cognitive processes; for example, (Port and Gelder, 1995; Kelso, 1995). Van Gelder and Port, (1995) emphasize and position dynamics as opposed to the symbolic/computational approach and the connectionist approach. The *Dynamical Systems Theory* (DST) is advocated as a new paradigm that is better suited to the dynamic aspects of cognition.

The notion of a state-determined system lies at the heart of DST. This type of system is based on the assumption that properties of a given state fully determine the properties of future states. Taking this assumption as a premise, in this paper the explanatory problem of dynamics is analysed in more detail. The analysis of four cases within different disciplines (Cognitive Science, Physics, Mathematics, Computer Science) shows how in history this perspective has led to a number of often used concepts within these disciplines. In Cognitive Science

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the concepts desire and intention were introduced, and in classical mechanics the concepts momentum, energy, and force. Similarly, in Mathematics a number of concepts have been developed to formalise the state-determined system assumption. Derivatives (of different orders) of a function, and Taylor approximations are examples of such concepts. Furthermore, also transition systems, a currently (within Computer Science and related areas) popular format for specification of dynamic systems can be interpreted from this perspective. One of the main contributions of the paper is that the case studies provide a unified view on the explanation of dynamics across the chosen disciplines. All approaches to dynamics analysed in this paper share the state-determined system assumption and the (explicit or implicit) use of anticipatory state properties. Thus it places explanation and modelling of cognitive phenomena on one line with explanation and modelling of other phenomena in Nature.

Within Cognitive Science realism is one of the problems identified for the symbolic/computational approach, i.e., how do internal states described by symbols relate to the real world in a natural manner. As DST is proposed as an alternative to the symbolic/computational approach, a natural question is whether for DST the realism of the states can be better guaranteed. As a second main contribution the paper provides an evaluation of DST compared to the symbolic/computational approach, which shows that in this respect, i.e., for the realism problem, DST does not provide a better solution than the other approaches. This shows that DST and the symbolic/computational approach not only have the state-determined system assumption and the use of anticipatory state properties in common, but also the realism problem.

2 Dynamical Systems Require Anticipatory State Properties

Assuming that the world (including the mental world) occurs in different states (i.e., states at different points in time that differ in some of their state properties), and 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 first candidate, and for dynamical systems they are assumed to form the only candidate source. Thus, to analyse the claims underlying Dynamical Systems Theory, 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 (or combinations of 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 on the next state: *anticipatory state properties*. If such state properties (historically sometimes called *potentialities*) 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. In Ashby (1960), a similar claim is expressed as follows:

'Because of its importance, science searches persistently for the state-determined. As a working guide, the scientist has for some centuries followed the hypothesis that, given a set of variables, he can always find a larger set that (1) includes the given variables, and (2) is state-determined. Much research work consists of trying to identify such a larger set, for when it is too small, important variables will be left out of account, and the behaviour of the set will be capricious. The assumption that such a larger set exists is implicit in almost all science, but, being fundamental, it is seldom mentioned explicitly.' (Ashby, 1960), p. 28.

Ashby refers to Temple (1942) and Laplace (1825) for support of his claims. He distinguishes phenomena at a macroscopic level for which his claim is assumed to hold from phenomena at the atomic level, for which the claim turns out not to hold.

3 Explaining Changed States by Introducing Potentialities

In this section only concepts that relate to states are included in the ontology to conceptualise reality. We focus on the possibility to include concepts in the ontology to conceptualise states that are useful to describe properties of changed states. Aristotle did introduce such a concept; he called it *potentiality* (to move), or movable. The difference between the arrow at rest and the snapshot of the moving arrow at time t at position P is that the former has no potentiality to be at 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 a different position P':

Why is the arrow at t' at position P'?
The arrow is at position P' at t' because
at t it was at position P, and
at t it had the potentiality to be at P', and
at t nothing in the world excluded it to be at P'

Aristotle did not only consider changes of positions (due to locomotion), but also, for example, a young man becoming an old man, and a cold object becoming hot. For each of these types of changes a specific type of potentiality is considered; e.g., the potentiality to be at position P', the potentiality (of a young man) to be an old man, the potentiality (of a cold object) to be hot. In general, if the potentiality (occurring in a state S) to have state property X has led to a state S' where indeed X holds, then this state property X of state S' is called the *fulfilment* or *actualisation* of the potentiality for X occurring in state S.

4 Mental State Properties as Potentialities

In the previous section the 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. For example, for a person B which has the capability to move:

Why is person B at t' at position P'?

Person B is at position P' at t' because

person B was at position P at t, and

at t person B had the desire to be at P', and

at t nothing in the world excluded B from being at P'

The type of explanation discussed in Section 3 has some similarity to an explanation of human behaviour from internal mental state properties such as desires. In the example, the desire (which is often considered as a kind of future-directed mental state property) 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. For example:

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. (Aristotle, 350 BC, *De Motu Animalium*), Part 6

He describes what today is often called *means-end reasoning*. He explicitly summarises that 'things in the soul' control action:

Now there are three things in the soul which control action and truth - sensation, reason, desire. Of these sensation originates no action; this is plain from the fact that the lower animals have sensation but no share in action. (Aristotle, 350 BC, *Nicomachean Ethics*), Book VI, Part 2

Based on Aristotle's analysis the pattern to explain motion of animals or humans is as follows:

at any point in time

if A has a desire D

and A has the belief that X is a (or: the best) means to achieve D

then A will do X

This form of analysis has been called 'practical syllogism'.

5 Giving Potentialities a Place in Physics

In later times successors of Aristotle, such as René Descartes (1596-1650), Christiaan Huygens (1629-1695), Isaac Newton (1643-1727) and Gottfried Wilhelm Leibniz (1646-1716), among others, have addressed the question how to further develop the phenomenon of change or dynamics and, in particular, the concept potentiality within physics. Contributions of these will be discussed in this section and in Section 8.3; for more specific references, see there. Indeed they succeeded in giving certain types of potentialities a well-respected place in modern physics (actually in more than one way).

5.1 Potentialities in Physics

Descartes 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. Thus he related the vague concept potentiality to other, better known concepts. Notice that this anticipatory state property 'quantity of motion' is a *relative* potentiality: the actualisation of a given quantity of motion entails being at another position as specified by this quantity relative to the current position (and not as being at some absolutely specified position). Descartes also expresses a law of conservation for this quantity of motion.

In modern physics this 'quantity of motion' concept is called *linear momentum*, or just *momentum*, and the conservation, for example, during elastic collisions, is called the 'law of momentum conservation'. Newton incorporated this notion in his approach to motion. This is one way in which a concept 'potentiality' was given a well-respected place in physics, in particular in classical mechanics.

Huygens (1629-1695), and later his student Leibniz (1646-1716), used a different way to give a concept 'potentiality' a place in physics. Leibniz called this concept *vis viva* (*living force)* or *motive force*, or *moving force,* or *force of motion*, or simply *force* or *power*. Leibniz claimed that the potentiaility 'motive force' was propertional not with velocity as in the case of 'quantity of motion', but with the square of velocity. In this way Leibniz put the foundation for the law of conservation of energy, in this case involving kinetic energy (which actually was later taken $1/2$ mv^2) and potential energy, and exchange between the two. For more details, see the extended version Treur (2005).

5.2 What Kind of State Property is a Potentiality?

Within physics, potentialities have found their place in different manners. Basic concepts in classical mechanics such as momentum, kinetic energy and force can be considered variants of potentialities. In Section 4.1 the first two of these concepts are discussed; the concept force will be discussed in Section 6.3 in the context of higher-order potentialities and exchange of potentialities by interaction. Both for momentum and kinetic energy a conservation law has been found, and both concepts can be expressed in terms of mass and velocity. Does this mean that in these two forms, potentialities have become genuine state properties, which are even definable in terms of other state properties? Even leaving relativity theory aside, this is not a simple question. A straightforward answer would be: indeed, potentialities are genuine state properties because they are defined in terms of mass and velocity which are assumed to be genuine state properties. For the sake of simplicity accepting this claim for mass, a question, however, remains what kind of state property velocity is.

A first approach is to take velocity to be distance traversed divided by time passed over some chosen time interval from t' to t; i.e.: v = (x(t) – x(t')) /(t – t'). This definition involves states at different points in time, so it is not based on one state at one time point. This notion of velocity actually is *velocity over*

the given time interval from t' to t, so a property of a sequence of states indexed by the time points of the interval, or, to simplify it a bit, a property of a pair of states for the starting point and the end point of the time interval. This is not what one would call a genuine state property.

A second approach is to identify velocity at some point in time with what a *speedometer* displays. Indeed at a point in time t the position of the pointer of a speedometer is a genuine state property. Would this offer an appropriate solution? A first objection may be that this property is just the position of the pointer, not velocity. For every type of object and speedometer a different state concept would arise: think of speedometers for cars compared to those of airplanes, ships, rockets; and what about the velocity of a bird or an approaching meteor. Even if for a certain class of objects, such as cars, a standardisation would be reached for a speedometer, then still the position of the pointer of the speedometer is itself not velocity; at most it has a *relation* to velocity. In particular, the pointer position itself does not affect the (changed) position of the car at the next instant; velocity does affect this position. However, for such a relation between pointer position and velocity we are still in need for a genuine state property velocity; apparently this problem was not solved by the pointer position.

As a further objection, the position of the pointer of a speedometer results from (or is affected by) the actual motion, so there is a small time delay between having some velocity and what the pointer displays. Therefore the pointer actually indicates speed over time points t' < t, which, although close to t are not equal to t. Thus the pointer position, which is a state property of the state at t, actually relates to states at t' < t , so even if it would be related to a certain velocity state property, this would be a state property of the state at some t' < t, not a state property of the state at t. This makes clear that the speedometer concept will not help to make velocity a genuine state property of the state at t.

A third approach is what is sometimes called the notion of *instantaneous velocity*. In modern physics and mathematics, for continuous processes that satisfy sufficiently strong conditions of smoothness, this is usually defined as a limit:

$$v(t) = \lim_{t' \to t} (x(t') - x(t)) / (t' - t)$$

Note that this limit is defined in terms of the whole family or sequence of states around t, i.e., in terms of the state properties $x(t')$ for all t' in a neighbourhood of t. In mathematical terms this limit can be defined as

$$\forall \varepsilon > 0 \; \exists \delta > 0 \; \forall t' \; [\; 0 < |\, t' - t\, | < \delta \Rightarrow |\, (x(t') - x(t)) / (t' - t) - v(t)\, | < \varepsilon]$$

It is clear that this statement refers to a whole sequence of states for time points t' around t. In this sense the notion of instantaneous velocity does not provide a better solution for a foundation of potentialities as genuine state properties than the other two approaches. Moreover, behind the assumption of smoothness some further assumptions are hidden, namely, to obtain such smoothness, either some inertia of speed has to be assumed (e.g., in free space), or otherwise a type of persistence of other state properties inducing velocity, which may be strongly situation-dependent.

In summary, it turns out that for all three approaches discussed the notion used to define potentiality for a state at one time point t takes into account different states, not only the one state at t. So, do we have to admit that addressing motion and change by extending the state ontology by some form of additional state properties for potentialities has failed? The answer on this question seems to be: yes and no. The answer is 'yes' in the sense that in the three possibilities considered there has not been found anything physically real in the state as a basis for a potentiality as a genuine state property. The answer is 'no' in the sense that the historical developments as discussed in this section have provided quite powerful mathematical means (calculus, differential equations) to model all kinds of problems in diverse application areas. In our daily life we all rely on artefacts constructed using classical mechanics; e.g., bridges, buildings, transportation means. Given that this conceptual machinery works quite well in predictions, makes that the question is still there: what is it that makes this machinery so successful?

6 Transition Systems and Potentialities

An often used method (in Computer Science and related areas) to specify how a state in a system may change is known as 'transition systems'. These are collections of specifications that each consist of a pair (φ, ψ), also denoted as $\varphi \rightarrow \psi$ and sometimes called a *transition rule* with antecedent φ and consequent ψ. In this specification:

- the first description φ indicates a combination of state properties for the current state
- the second description ψ indicates one or more state properties for the next state

The idea is that if the combination of properties specified in the first description holds in a (current) state, then in a next state the properties specified by the second description will hold. This is illustrated by a simple model of agent behaviour based on beliefs desires and intentions. Consider an agent walking down a street and observing an ice cream sign at the supermarket across the street he believes the supermarket sells ice cream. Based on this belief (b1) the agent generates a desire (d) for ice cream. Given this desire, and the belief (b2) that the supermarket is reachable (by crossing the street) the agent generates the intention (i) of having ice cream. Given this intention and the belief (b3) that no traffic is on the street he actually crosses the street and obtains the ice cream (e). In this case the state ontology is described by six basic state properties: b1, b2, b3, d, i, e. The simple scenario can be described in transition system format as follows:

b1 → d

b2 ∧ d → i

b3 ∧ i → e

Based on such a specification a trace of subsequent states is made as follows.

- Given a current state S, take the transition rules for which the antecedent holds in the current state. This is the set of applicable rules.
- Collect the consequents of all applicable rules and obtain the next state S' by modifying S so that all these consequents hold in S' (and the rest of S is persisting).

So, for example, the subsequent states for a given initial state for which the three beliefs hold are as follows:

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0 [b1, b2, b3]
1 [b1, b2, b3, d]
2 [b1, b2, b3, d, i]
3 [b1, b2, b3, d, i, e]
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How can this be interpreted in terms of potentialities. For example, consider state 1. As in the next state, state 2, state property i holds, in state 1 the potentiality for i to hold has to be present. On the other hand, i occurs in state 2 because of the second transition rule. Taken together this means that this transition rule can be interpreted for state 1 as indicating that, due to the occurrence of both b2 and d in this state, also the potentiality p(i) for i occurs in state 1. Similarly the other transition rules can be interpreted as indications of which potentialities occur in a given state. In general, according to this interpretation a transition system specifies for each state which potentialities occur: for each transition rule $\varphi \rightarrow \psi$, if in a state S its antecedent φ holds, then in this state S also the potentialities p(ψ) for ψ occur. Thus a transition rule $\varphi \rightarrow \psi$ can be interpreted as an implication $\varphi \rightarrow$ p(ψ), describing a logical relationship between state properties in a given state. In the example scenario the subsequent states can be described as follows:

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0 [b1, b2, b3, p(d)]
1 [b1, b2, b3, d, p(i)]
2 [b1, b2, b3, d, i, p(e)]
3 [b1, b2, b3, d, i, e]
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In principle, other variants of transition systems are possible as well, for example, for nondeterministic behaviour where only one (choice of an) applicable transition rule at a time is applied. The analysis of such variants is similar.

7 Conclusion

Dynamical Systems Theory (DST) has recently been put forward in Cognitive Science as an approach to the dynamics of cognitive processes, and proposed as an alternative for the symbolic/computational approach; for example, (Port and Gelder, 1995; Kelso, 1995; Gelder and Port, 1995). The notion of a state-determined system (Ashby, 1952) is central for DST; such a system is based on the assumption that properties of a given state fully determine the properties of future states. As DST has been advocated as a better alternative to symbolic/computational approaches, the question may be raised whether this fundamental assumption is what makes it distinctive from these other approaches.

The answer to this question has been shown to be 'no'. It turns out that the state-determined system assumption, and the use of anticipatory state properties it entails, unifies different approaches to cognitive processes that are often seen as mutually exclusive. Moreover, it places the explanation and modelling of cognitive phenemena on one line with the explanation and modelling of other phenomena in Nature.

As within Cognitive Science one of the problems identified for the symbolic/computational approach is the problem of realism (i.e., how do internal states described by symbols relate to the real world in a natural manner), a further relevant question is in how far DST does better in this respect than the symbolic/computational approach: in how far is the realism of the states better guaranteed by DST.

Thus for the explanatory pattern for dynamics based on anticipatory state properties that is considered here, the commonalities were summarised for applicability in the different scientific disciplines Cognitive Science, Physics, Mathematics and Computer Science. One of the main contributions of the paper is that this provides a unified view on the explanation of dynamics across these different disciplines. This unified view is at a high level of abstraction; it does not deny that at more detailed levels there are differences between these disciplines as well. For example, some of the disciplines (Physics, Mathematics) allow for an appropriate form of quantification, whereas for other disciplines (Cognitive Science, Computer Science) such a quantification is not possible, or at least debatable.

The different examples in different disciplines show that the postulation of new anticipatory state properties in addition to the basic state ontology is a fruitful approach to describe dynamics based on the state-determined system assumption, as DST does. The question in how far these additional 'synthetic' state properties are genuine or 'real' state properties was shown to be a hard question that is not simple to answer, even in Physics. Nevertheless, the fruitfulness of having such state properties added is uncontroversial; for example we all trust artefacts in our environment that were constructed based on physics and mathematics using such state properties.

Given the assumption on state-determinedness, anticipatory state properties are essential to DST. In an explanatory context the question of realism of these anticipatory state properties in DST has to be answered. The analysis made in this paper, however, answers this question negatively. It is shown that even in Physics the foundational question on whether such postulated anticipatory state properties are genuine, real state properties cannot be answered positively.

As an evaluation of DST compared to the symbolic/computational approach, this shows that not only the two types of approaches have the assumption of state-determined systems, and the use of anticipatory state properties in common, but also share the realism problem: DST does not provide a better solution than the symbolic/computational approach. However, the investigations in the history of other scientific disciplines also have shown that this shortcoming does not necessarily stand in the way of fruitfulness of any of these approaches

within Cognitive Science. It may well be the case that DST will develop further, especially to address cases where the timing aspects are crucial, whereas symbolic/computational approaches will still develop further for other cases, for example, where more complex types of states are relevant, such as in reasoning or language processing.

Given that the approaches are not as exclusive as sometimes suggested, as shown by the commonalities found in this paper, integrated approaches will be developed, in which both DST aspects and symbolic aspects can be covered. Proposals for such integrated approaches can already be found, for example, in Sun (2002), or Jonker and Treur (2002, 2003) and Jonker, Treur, and de Vries (2002). In Jonker and Treur (2002) it is shown how the expressive temporal symbolic language TTL can be used to model cognitive phenomena, including their quantitative and continuous temporal aspects, and it is shown how DST techniques fit in this language. Sun (2002) claims that quantitative, continuous modelling approaches (such as DST) are suitable to address the implicit, non-representational internal agent states, whereas symbolic, discrete approaches are suitable for more explicit, representational internal agent states. He also shows the crucial role of the interaction between the two types of states, and is an advocate of hybrid modelling approaches where both types of aspects play a role.

Potentialities as postulated state properties often have relationships to other state properties of the state in which they occur (they can be said to be realised by these other state properties). But potentialities usually also relate, in a temporal manner, to state properties in other (past and future) states. These realisation relationships and temporal relationships can be exploited to obtain a further analysis of the foundational question. Such a further analysis is the focus of current research.

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