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Anticipatory Systems in Physics

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Research Paper

Abstract: The aim of this paper is to clarify the role of anticipation of systems in physics. Previous work on the subject (DuBois, 2000) selected certain types of systems as anticipatory, but the argument here establishes that all dynamical systems in physics are necessarily anticipatory.

In what is now considered his seminal work on the nature of anticipation, *Anticipatory systems*, Robert Rosen offered a succinct view on what separates anticipatory systems from non-anticipatory ones:

> "An anticipatory system is a system containing a predictive model of itself and/or of its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a latter instant." (Rosen, 1985, p. 341)

While it is not my intention here to analyze the implications and adequacy of Rosen's definition or to assess the types of systems that can be properly called anticipatory, it is important to recognize that this definition sets up an implicit agency within these systems "which allows [them] to change state". This agency is able to modify its own state while having and being cognizant of a predictive model of the situation it is in. Rosen's definition excludes systems that do not contain such agency. Presumably for him a falling rock would not qualify as an anticipatory system while a human being would, since the rock does not have an agency with a predictive model of itself, while humans, at least most of the time, do.

Reflecting on the motion of simple physical systems, like a falling rock, raises the question whether simple non-agential systems have any sort of anticipation over their future states. An investigation into the dynamics of physical systems in fact reveals that a type of anticipation exists for all systems. I show that all physical systems are anticipatory because they include final conditions in the constitution of the system itself and because motion requires the existence of external frames of reference.[i] To begin to make the case that all physical systems are anticipatory I offer a brief history of the role of frames of reference in the physics of motion. I show that in classical mechanics the potential energy of a system provides the dynamic and anticipatory elements of the system. After showing that there must be an external frame of reference for a system to have motion, I will clarify that this is not solely part of the epistemology of the system, that is, it is not just a limitation on the model of our systems, but rather that it is part of the system in nature, an ontological claim. For this I need to appeal to relativity and quantum mechanics, since classical mechanics ultimately remains ambiguous about this question. A brief analysis of EPR style measurements reveals that this fundamental anticipation is ontologically necessary part of all physical systems. In sum, I show how this development leads, particularly after the advent of relativity and quantum mechanics, to a conception of a dynamic 'physical system' that is fundamentally anticipatory.

Specifically I show that all physical systems *rely* on their future state for their present constitution and thus have a fundamental anticipation. This reliance does not imply backward causation, that future events are the cause of present ones, but as the analysis shows, that the state of possibilities of future states does form part of the present state of the system. There is a significant ontological role of *possibility* or *potential* in the present constitution of a system. In addition, this broader or more fundamental conception of anticipation is compatible with Rosen's definition since the latter becomes a special case of fundamental anticipation. Daniel Dubois has recently argued for a similar broadening of the concept of anticipation. (Dubois, 2000) His claim is that anticipation as defined by Rosen relies on models of prediction within the system and that such systems are not as 'strong' (henceforth, weak anticipatory systems) as systems where the prediction occurs within the system itself without the model. In a complementary paper I show that Dubois's argument is problematic in some fronts, yet effectively makes a similar claim about fundamental anticipation than the one I propose here, mainly that "anticipation has a physical background."[ii]

One clear benefit from introducing this broadening of the meaning of anticipation lies in the recognition that fundamental anticipation is part of all physical systems will help form a more coherent and continuous account of the evolution from simple to complex systems without the need of unnecessary and hard to justify ontological dichotomies between anticipatory and non-anticipatory. The implicit suggestion behind fundamental anticipation is to stress that the differences are of degree rather than kind. This suggestion does not imply, however, that the differences do not become significant as systems become more complex and that new emergent properties can appear to enable systems to gain control over their futures. All systems have fundamental anticipation, but Rosen's type of anticipation refers to systems that are anticipatory in a more controlling and effective way. This effectively removes the problem of creating an ontological dualism organism/non-organism or anticipatory/non-anticipatory.

1. The Role of Frames of reference in Physics

In his *Physics* Aristotle promoted the idea that earthly motion had the natural tendency downward to the center of the earth with rare exceptions, which, like fire, tended toward the perfectly circular motion of the celestial spheres. The center of the earth was simultaneously the center axis of the perfect rotation of heavenly bodies and the point of convergence of the motion of most earthly things. In the Aristotelian picture, henceforth, the center of the earth became the *de facto* absolute frame of reference from which all motion was determined.[iii] (Barnes, 1984)

Almost two thousand years later Copernicus famously dethroned the earth's center from its status as the preferred frame of reference in favor of the sun as the new center of the universe. This simple but fundamental conceptual shift was not complete, however, since motion was still set in relation to an ontologically preferred center. The conceptual disruption of no longer having the long presumed unique center and unique frame of reference for all motion, however, opened up the possibility of further questioning basic assumptions about space, time, and motion.

In his *Dialogue Concerning the Two Chief World Systems*, (Galileo, 1962) arguing against those that proposed that a cannonball fired from a cannon facing the direction of rotation of the earth would land closer to the cannon than if it was facing away, Galileo postulated that unaccelerated linear (inertial) motion cannot be distinguished from rest unless an external frame of reference was specified: the principle of relativity.[iv] A consequence of Galileo's principle is that an inertial system does not have a velocity unless a reference frame is specified to determine it. Or, more dramatically, that a system has all possible velocities in reference to all possible inertial frames of reference that can be used to determine that inertial motion. Thanks to Galileo we learned that inertial motion, the velocity of as system, is only a property of that system if a reference frame is specified. Clearly, at least for specifying inertial motion, there does not seem to be an absolute frame of reference. The property of 'having motion' depends on an external frame of reference and the choice of frame is arbitrary.

Newton in his *Principia* argued for motion to be ruled by a gravitational force of attraction. (Newton, 1995) There is a physical effect at a distance. Newton's law of gravitation along with his newly developed calculus (it was also independently invented by Leibniz) offered a precise means of calculating accelerated motion for all systems due to gravitational forces. Unfortunately Newton argued via his famous rotating bucket example that accelerated motion can only be explained in reference to a fixed independent frame of reference, the background of absolute space and time. Space (and time) becomes the absolute preferred reference frame of frames. There can be many frames of reference since there are many sources of gravitational attraction but they are all inevitably fixed to absolute space and time.[v] There was once again a fixed frame of reference for motion. It was suspected, moreover, that there was no real inertial motion, since all objects experience some sort of acceleration due to the indiscriminate and long range of gravity. Inertial motion was an idealization and the relativity principle of Galileo was an apparent consequence of such a non-realistic aspect of motion. This is precisely the view that many held in the 19th century when they proposed the aether as the actual medium that embodies the frame of reference for all types of motion. The accepted view became that once the aether was found, Galileo's principle of relativity would be overturned and clearly revealed to be an unnecessary idealization. The story, however, did not turn out to be like this and the principle of relativity, rather than being dismissed as the conceptual basis of motion, took an ontological turn when experiments to find the aether turned out negative and when a young patent clerk in Bern successfully expanded Galileo's principle of relativity into electrodynamics.

2. The Concept of 'System' in Mechanics

The historical lesson so far is that to assess the motion of a system one must specify first an external reference frame and that different frames of reference may give different accounts of those properties. Yet, we have not entertained how this story connects with the question of whether simple physical systems are anticipatory in a fundamental way or not. This is because this historical prelude offers a way to consider with precision what constitutes a physical system. Shorty, we will see that a physical system, by its very nature, is necessarily anticipatory in a fundamental way.

Etymologically the term 'system' comes from the greek *systema* which is a compound of *sy*- (together), -*ste*- (to stand), *and –ma* (the result of action). A system is the result of action of standing together. For Aristotle any action indicated motion. In his *Physics* he argued that motion entailed an actual element and a potential element. A falling rock is in motion because the actuality is its potentiality of being somewhere else. Therefore, for Aristotle, motion is the state where the future belongs to the present.[vi] In his *Metaphysics* Aristotle stressed that motion must consider the whole process as a unity and not just as independent parts (like Zeno famously tried to do in some of his paradoxes). And hence, to consider a system is to consider a system with its potential to do work or be in motion.[vii] Leibniz, among others, applied Aristotle's idea of potentiality for the description of dynamic systems and thus it began to percolate into mechanics (later in the 20th century Heisenberg also credits Aristotle's concept of potentiality for his view on the meaning of the state of the system in quantum mechanics). (Heisenberg, 1960)

Rankine initially coined the concept of energy in modern physics in the 19th century to speak of a system's ability to do work, specifically steam engines, and he explicitly credited Aristotle for the idea of *energeia*. Like Aristotle, Rankine conceived of energy as the aggregate of the system's current work, its kinetic energy (KE), with its future ability to do work, its potential energy (PE). In addition, the contributions of Hamilton and Lagrange in the formation of a more general conception of mechanics offered a simple way to account for systems under gravitational or mechanical influences. The overall state of the system was given by a function (the Lagrangian L or Hamiltonian H) and these functions were soon interpreted to be connected to the concept of energy of the system.

Nowadays we still follow pretty closely this description of state. Specifically, if the system is considered closed, that is, the boundaries of the system are not broached by external influences, then the total energy (E_T) is conserved and one can safely define the energy of the system in terms of its kinetic and potential energy[viii]:

$$E_T = KE + PE$$

In systems where gravity is the only relevant force or field in play (mechanical systems), the kinetic energy is defined as:

$$KE = \frac{1}{2}mv^2$$

where m is the mass of the system or entity and v is its velocity. Often, the quantity of mass times velocity, quantity of motion or momentum (p) is preferred when speaking about energy since it is also conserved.

$$p = mv$$

Since the property of velocity of a system is dependent of an external reference frame and momentum is simply its product with the mass of the system, momentum also needs an external frame of reference before it can be a meaningful concept. From the frame of reference of the system itself, the momentum is always null as well.[ix] It is only when an external frame of reference is specified, and the choice is still arbitrary, that we can speak of a system having momentum.[x]

The kinetic energy in terms of the momentum is then:

$$KE = \frac{p^2}{2m}$$

This means that the kinetic energy of a system, being the square of the momentum over the mass, also depends on an appropriate choice of an external frame of reference.

Similarly the potential energy of a system will depend on the choice of reference frame. Imagine a rock falling from a cliff. It has a potential energy

$$PE = mgh$$

where h is the distance of the *projected* fall to the bottom of the cliff, g is the gravitational field assumed to be constant in this scenario, and m is the mass of the rock. Similarly as with the kinetic energy, the potential energy depends on the choice of external frame of reference and this choice depends on the anticipation of where the system will be evaluated. The potential energy of a system needs to have an external frame of reference and the choice of frame will determine its value. Both kinetic and potential energy have no meaning unless an external frame of reference is selected. Choosing the frame of reference is akin to choosing the initial *and* final conditions of a system. Since the total energy of this system is the sum of kinetic and potential energy, then, to speak meaningfully of the energy of a system we must assume the existence of an external frame of reference that provides with a non-null value of energy. Hence, the total energy of a system depends on the initial as well as final conditions. Thus the system can be said to be anticipatory since it is defined in terms of its total energy.

This does not come to any surprise or controversy to anyone who has thought through their first lessons in physics. One learns that the concepts of velocity and energy are arbitrary and only meaningful if a frame of reference is specified. Yet the attempts in the 19th century to eliminate the principle of relativity should give us pause. Is it that this relativity is a byproduct of our model of reality rather than an aspect of reality itself? In other words, do reference frames play solely an epistemic role, one that helps us specify certain properties of systems like velocity and momentum, or do they also have an ontological role, where not only they help specify these properties but are needed in the very reality of motion? Is the suggestion then that frames of reference exist independently in nature? What sort of ontological role do reference frames play for motion, besides being a helpful (epistemic) tool for physicists using them to meaningfully speak of velocity and other properties? Yet to render them as mere epistemic tools of our models, would this suggest that velocity and energy are just but helpful fictions? What is the ontological import of such relative (or relational, if one prefers) properties such as velocity, momentum, or energy? Let's turn to the developments of the physics of motion early in the 20th century.

In attempting to reconcile the successful theory of electromagnetism, which as succinctly stated by Maxwell's equations proposed the existence of a preferred and absolute speed c for electromagnetic phenomena in a vacuum, with Galileo's principle of relativity, which denied that such preferred absolute speed could exist, Einstein formulated his Special Relativity Principle where he kept intact both Maxwell's theory and Galileo's principle but denied instead that absolute simultaneity of events exists. That is, an event's duration or time elapsed needs to be specified in relation to an external reference frame and, thus, time was no longer an absolute and independent facet of our universe. Not just motion is in need of frames of reference, but the time of an event is also necessarily tied to frames of reference. Further consequences of this were that long conceived-to-be intrinsic or primary properties of systems, extension and mass, can no longer be so except by approximation. It no longer makes sense to speak of the extension or total mass of a body unless a reference frame is specified.[xi] Later Einstein extended this insight to systems experiencing acceleration in General Relativity with even more dramatic results. Rather than finding a way to dismiss the importance of Galileo's principle of relativity, Einstein's contribution enhanced the ontological status of the concept that motion and other properties of systems are inherently relative to an external reference frame. (Einstein, 2005)

3. The Concept of 'System' in Quantum Mechanics

In quantum mechanics the system is described by the state function Ψ. Operating on this function reveals the different properties the system may possess. The meaning of Ψ was and has been much debated. Schrödinger, who formulated the famous wave equation that gave Ψ its status, argued that it represented the actual state of the system. Later, not without many disagreements, physicists settled on the interpretation of Ψ given by Born, that the state function represented a state of possibility.[xii] Some, like Einstein, could never quite digest the idea that our best account of the state of affairs in quantum mechanics (the state of the system) is given by a set of probabilities. Einstein and others argued that quantum mechanics was an incomplete account of the world or that it merely indicated our state of 'knowledge' of the system rather than the state of the system itself. Others, like Bohr, wanted to simply accept this state of affairs of the reality of the state of probabilities without trying to probe too deeply into its consequences.

Clearly in quantum mechanics the state of the system is definitely a type of potentiality (this is what Heisenberg suggested after struggling with this problem for many years). This state of potentiality or superposition of possible states, as is often referred, is never observed, however, since interaction with any system actualizes or 'collapses' the superposition into one of the possible outcomes. Only 'measurement' actualizes the state of possibility. This is the well-known problem of measurement. Many possible solutions to this problem have been proposed, but no clear accord has been achieved yet. Nevertheless, what is clear is that, with the exception of those who argue that quantum mechanics is not a complete theory of nature, the rest agree about the ontological reality of Ψ as a state of potentiality (but there are different accounts of the details of what this state of potentiality entails). This potentiality is about future outcomes and clearly indicates that the present state of a system depends on the future possibilities. But what about those who object that quantum mechanics, instead of showing the state of reality is merely representing our state of knowledge of the system?

Einstein, Podolski, and Rosen (EPR) proposed a thought experiment to undermine the belief in the ontological lessons of quantum mechanics and thus in the idea that a system is the sum over all of its potential states. (Einstein et al, 1935) Using a variation of EPR based on David Bohm's version (which has in fact been recently carried out in experiment), consider a system S_0 made of positronium with total spin 0 (spin is a variation of angular momentum in quantum mechanics, which is conserved). After a bit, the material decays into a positron and an electron, we let them spatially separate a great distance away and then perform a measurement on the electron's spin (which can only have two possible values, up or down). Let's imagine it is up, $S^{\uparrow}$, then without the need to measure the positron, because of conservation of spin, we know the positron is down $S_{\downarrow}$ (up and down equal zero), thus conflicting with the idea that the only way to actualize a system is via interaction, since there was no interaction with the positron only the electron. Einstein et al suggested that this was a problem for quantum mechanics and that it must therefore be an incomplete account of nature given our expectations about reality that there can be no superluminal signaling between the electron and the positron. If you imagine that the positron is greatly separated from its electron sibling, then one can exclude any potential communication due to the upper limit on communications travel (the constancy of the speed of light). A physicist on sabbatical from CERN in the 1960's showed that some inequalities can be thought out that will allow the testing of these competing viewpoints. (Bell, 1965) In the 1980's several experiments were done that confirmed the quantum mechanical view and that Einstein's position was not really tenable. The solution seemed to be that somehow measuring the electron also measures the positron.

In EPR style experiments theorists often speak of action-at-a distance or non-local influences as to the explanation for why a measurement of an electron can affect the state of its far-away sibling, the positron. However, doing so assumes that it is congruent to treat the system S_0 as effectively separating into two different spatially separated systems $S^{\uparrow}$ and $S_{\downarrow}$. The main demand for consistently speaking of physical systems is that they don't get modified arbitrarily, so $S_1=S^{\uparrow} + S_{\downarrow}$. If that's the case, then we cannot speak of $S^{\uparrow}$ and $S_{\downarrow}$ as separate systems. $S^{\uparrow}$ and $S_{\downarrow}$ are entangled parts of S_1 which evolved from the closed system S_0. Once part of the system S_1 is measured, the whole system is interacted ("collapses") and produces an electron in one of the two allowed spin values $S^{\uparrow}$ and the positron in state $S_{\downarrow}$. This further foments the idea that the state of a system in quantum mechanics *is in nature* (that is, 'is ontologically' and not just 'is as conceived' or 'is epistemically') a state of potentiality where the actuality occurs when an interaction takes place. The state of the system prior to interaction/measurement depends on the future state of the system; it *is* the future state of the system. Hence, physical systems are ontologically anticipatory (and not just epistemically anticipatory as it could be the case in classical mechanics).

In sum, the state of a physical system is anticipatory, not solely in our models or theories but in reality itself. The state of the system includes a potentiality, which reflects the role of possible future states in the current one.

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Notes

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[i] Specifically I will show that this anticipation is ontological, that is, it occurs in nature rather than being merely epistemological, that is, part of our conceptual models or theories. The argument will show that anticipation of this sort does not use or rely on backward causation, or the idea that the future causes the past/present, but rather that fundamental anticipation implies that the constitution of systems include possibilities of their future condition.

[ii] "Fundamental Anticipation of Physical Systems" (under review at Axiomathes). The main objection against Dubois lies in that his claim that models of prediction are substituted by certain type of relations (recursive, hypercursive, etc.) that procure the system with prediction of the future of the system without models. But it can be argued that these types of relations constitute, albeit simple, models for the systems therefore falling under Rosen's definition after all. This difference is simply not clear and not properly worked out. Furthermore, the notion of prediction in simple physical systems is not properly explained. How can a harmonic oscillator predict its future? How can a harmonic oscillating pendulum "know" (as Dubois uses it) its future state at a present time? Is he projecting an observer that can do this type of predicting and knowing? I think he inadvertently is.

[iii] Heavenly motion, could be argued, was also pinned to the reference frame of the earth, since perfect spherical motion of the celestial spheres occurred with the center of the earth as the center of the larger celestial sphere.

[iv] Fundamentally connected to his theorem of addition of velocities.

[v] We now know that Newton was aware of the physical and metaphysical implications of such background independent space/time, and was considered, reminiscent of his intellectual rival Leibniz's proposal, that space/time may need to be considered relationally.

[vi] Aristotle jointly entertained the ideas of *energeia* and *entelecheia* to explain the role of final causation in the formation of systems. Many scholars of Aristotle, including Aquinas, have struggled to make sense of his use of these terms. What's clear is that Aristotle conceived of the potential of an entity as relevant in the actual being of that entity.

[vii] Aristotle's account of motion generated much dispute through the years and even most modern accounts suggest that the way to interpret Aristotle's account of motion is to simply state that motion is a sort of actualization. (Ross, 1966, pp. 81-82) But this is a puzzling if not incoherent account of motion that leaves out the role of potentiality and some scholars have pressed deeper into Aristotle's analysis of motion to reveal a more complex view where motion is a combination of the actual and possible.

[viii] In this paper I explore the physics of anticipation in CM and QM. In a forthcoming paper, I tackle the role of anticipation in Statistical Physics and Thermodynamics, since these are, after all, the physics of systems open to interaction across their boundaries.

[x] As we have seen, after Copernicus de-centered the earth from its preferred metaphysical status, Galileo showed that a consequence of that de-centering was that velocities of bodies were not absolute but dependent of a frame of reference. At the risk of repetition and illustrating the obvious, consider a rock falling off a cliff at 60 mph relative to the frame of reference of the ground below. Equally valid would be to declare that its velocity is 0 mph in relation to itself since can choose any frame of reference to speak of the velocity of the rock. Yet, regarding motion, an internal reference frame of the system absolutely denies the existence of motion, hence it does not constitute an interesting or adequate frame of reference for discussing motion. The choice of frame of reference for motion has to be external to the system in consideration, since every system is at rest in reference to itself (we are always at 0 mph in reference to ourselves).

[xi] Appeals to claim that rest velocity (a sort of oxymoron), rest mass, proper length or proper time, which are the properties as measured from the reference frame of the system itself, are the new type of primary qualities does not work since ultimately this reference frame is one among the many that are relevant in a physical situation, even though often we can approximate to it.

[xii] Technically Born argued that Ψ represents the probability amplitude and that the square modulus of Ψ gives the probabilities of finding the system in one of its possible states.