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Classical and Non-Classical Representations in Physics

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ABSTRACT. Dynamical representations used in physics are analysed from a "second order" viewpoint, as distinction systems constructed by an observer in interaction with an object. The creation, conservation and destruction of distinctions can be understood on the basis of a distinction dynamics. The fundamental mechanism is the variation through recombination and selective retention of closed combinations. The conservation of all distinctions is shown to provide a demarcation criterion, distinguishing classical from non-classical representations. Different non-classical representations (thermodynamics, quantum mechanics, relativity theory, ...) are classified on the basis of which distinctions they do not conserve. It is argued that the specific structures of these non-classical representations can be reconstructed by studying the properties of non-trivial closure.

KEYWORDS: second order cybernetics, constructivism, distinction systems, physics, non-classical theories, distinction dynamics.

Introduction

Systems science (including cybernetics) is not a traditional discipline concerned with the study of a particular domain, but a meta-discipline, concerned with the domain-independent modelling of general systems (Van Gigh, 1986). As such, it does not aim to find the one true representation for a given type of systems (e.g. physical, chemical or biological systems), but to formulate general principles about how different representations of different systems can be constructed so as to be effective in problem-solving.

This meta-theoretical point of view is emphasized in particular in the so-called “second order cybernetics” (von Foerster, 1979; 1981), which studies how observers construct models. In contrast with the traditional realist epistemology, a model is here not supposed to be a homomorphic image of a part of reality, which the observer passively apprehends, but an active construction of the observer, which allows him to find coherence between his different observations, and thus to adapt to (i.e. find equilibrium with) the environment as he (subjectively) experiences it (von Glasersfeld, 1988). The present approach differs from more “idealistic”, “subject-oriented”, or “social” constructivist approaches (e.g. Gregory, 1986; Maturana and Varela, 1979) by emphasizing that the construction of knowledge is based on an *interaction between subject and object*, or more generally between different systems, without an a priori distinction between “observer” systems and “observed” systems: it hence cannot be understood by looking only at the subject, or at the (social) interaction between different subjects (”social construction of reality”).

This constructivistic approach towards theory-building, together with specific concepts and formalism developed in systems science, makes it possible to study some traditional problems of

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epistemology and philosophy of science in a novel way. The preferred subject of traditional philosophy of science is formed by the theories of physics, in particular classical mechanics, quantum mechanics and relativity theory. The reason to prefer physics to, say, geography or psychology, is that physics is the most developed of the traditional disciplines, and as such proposes theories which are well-structured, explicit, and well-confirmed. This makes it easier to analyse the specific features which determine the success (or failure) of a theory.

This analysis of physical theories has brought a wealth of fundamental concepts and principles useful for theory-building, yet there remain some problems which have resisted more than half a century of epistemological investigations. These conceptual problems are exemplified by the interpretation of quantum mechanics and its paradoxes (Jammer, 1974). The inseparability of observer and object in quantum mechanics appears particularly difficult to assimilate to a realistic framework, while the alternative non-realistic interpretations appear far-fetched, heterogeneous and hazy. Though the paradoxes of quantum mechanics are the most spectacular expression of the difficulties in interpreting physical theory, the problem is more general, and can be expressed as the incompatibility between different classical and non-classical ways of representing physical phenomena. Classical models, based on a mechanistic and deterministic world view, are in general easy to understand intuitively, though physicists are aware of their limitations. Non-classical models, on the other hand, often behave counter-intuitively, and are difficult to integrate with other classical or non-classical theories.

The objective of this paper is to analyse the differences between the different classical and non-classical representations in physics, on the basis of a second-order conceptual framework, in the hope of elucidating some of the fundamental problems which traditional epistemology appears unable to solve. The framework is based on the concept of *distinction*, which is an elementary unit of cognitive structuration, whose construction can be understood by the principles of an interactive *dynamics of distinctions* (Heylighen, 1989b; 1990b). A physical representation can then be analysed as a distinction system, to be defined in the following section.

Dynamical representations as distinction systems

Physical theories are ways to represent dynamical systems in the most precise way possible, in order to allow prediction of the future states of the system, given knowledge about the present state. Such a model of a process will be called a *dynamical representation*. It can be viewed as a particular case of the more general concept of an “adaptive representation”, which is a model of how an actor can adapt to a changing environment (Heylighen, 1990b).

A representation should here not be understood in the sense of a homomorphic image of an objective, external reality, but as a system designed to give a more or less precise, mathematical shape or structure to the associations between different observations (this is similar to the sense of “representation” as it is used in mathematics, or in the phrase “knowledge representation”, cf. Heylighen, 1990b). For example, it is possible to construct a representation of a “black box” system just by establishing mathematical relations between the inputs to which the system is submitted and the outputs which are observed. This representation may be adequate in predicting the behaviour of the system, without therefore implying any correspondence between the formal components of the representation and the (hidden) material components of the system.

Let us analyse the standard components of a dynamical representation. First there are the *objects* representing the system to be modelled or its components. Objects might stand for electrons, molecules, planets, etc. Objects are characterized by variable properties or *predicates*, such as position, mass, charge, velocity, ... The attribution of a particular predicate to a particular object, e.g. electron e has position P, determines an elementary *proposition* describing the system. Propositions can be combined by means of logical connectives (conjunction, negation, disjunction ...) in order to form compound propositions. A proposition which gives all the information one can get about the system at a particular instant in time is called the *state* of the system. The set of all possible states is called the state space. The evolution of the system can then be described by a time-parametrized trajectory in the state space, representing the states of the system at subsequent instants. In order to determine the trajectory, one needs two further structures: operators and dynamical constraints. An *operator* is a transformation or transition rule mapping initial states onto subsequent states. A *dynamicalconstraint* is a selection criterion which determines which of the possible state transitions corresponding to different operators will actually take place. Dynamical constraints usually have the form of either 1) differential (or difference) equations, relating the predicted state transition (time derivative of the state) to the present state, 2) conservation principles, stating that a certain global property of the system, e.g. energy, must be conserved during the transition, or 3) variation or optimization principles, stating that that transition will occur which minimizes (or maximizes) a certain function of the transition parameters.

These different components of a dynamical representation correspond to ways of structuring the domain of experience (i.e. the possible observations and their relations) in such a way that the resulting system is as simple, precise, and reliable as possible. Since a representation is necessarily less complex than what it is to represent (the whole actual and potential domain of experience), this means that a number of observed features must be abstracted out, by putting different phenomena, which are similar with respect to the problem one tries to solve, into the same class, and by *distinguishing* this class from other classes of phenomena. The distinctions can be conceived as elementary structurations of a domain of experience (Spencer Brown, 1969), hence as elements or units of representation. A representation as a whole can then be analysed as a network of distinctions connected by certain relations, i.e as a *distinction system* (Heylighen, 1988).

The components of a representation correspond to particular types of distinctions. An object corresponds to a distinction between the focus of attention (figure, pattern, system) and its background or environment. A predicate corresponds to the distinction between the class of all objects with a certain property and the complement of that class. A proposition corresponds to the distinction between the truth of a certain description and its falseness (or truth of the negation of the proposition). Time corresponds to a distinction between past, present (i.e. simultaneity) and future. An operator corresponds to a distinction between the state before the operator was applied and the state afterwards. A dynamical constraint corresponds to a distinction between an allowed state transition, and an impossible one.

The philosophy behind the present analysis is that distinctions are not objectively given, that there is no one good way to make distinctions. A distinction is constructed by the observer in interaction with the system. As such, a distinction is always to a certain degree subjective, depending on the goal the observer has in mind while modelling the system, but it is not arbitrary, because not all distinctions will allow to find coherence between the different observations performed on the system. Since all phenomena in the universe are by definition different, the number of potential distinctions is infinite. A representation of (part of) that universe is necessarily finite, and hence the number of distinctions an observer will make, will be infinitely smaller than the total number of distinctions he *could* make. How distinctions are made (i.e. which distinctions out of the infinite number of potential distinctions are selected), and how they are connected, will determine the structure of a representation, and hence its adequacy in predicting the observed behaviour of the system. In order to understand in which ways distinctions can be made, we must examine the general principles underlying the dynamics of distinctions.

The dynamics of distinctions

Cinematics of distinctions

Let us first formulate some general principles about the way distinctions change or maintain. The cinematics of distinctions can be viewed as a general description of possible processes involving

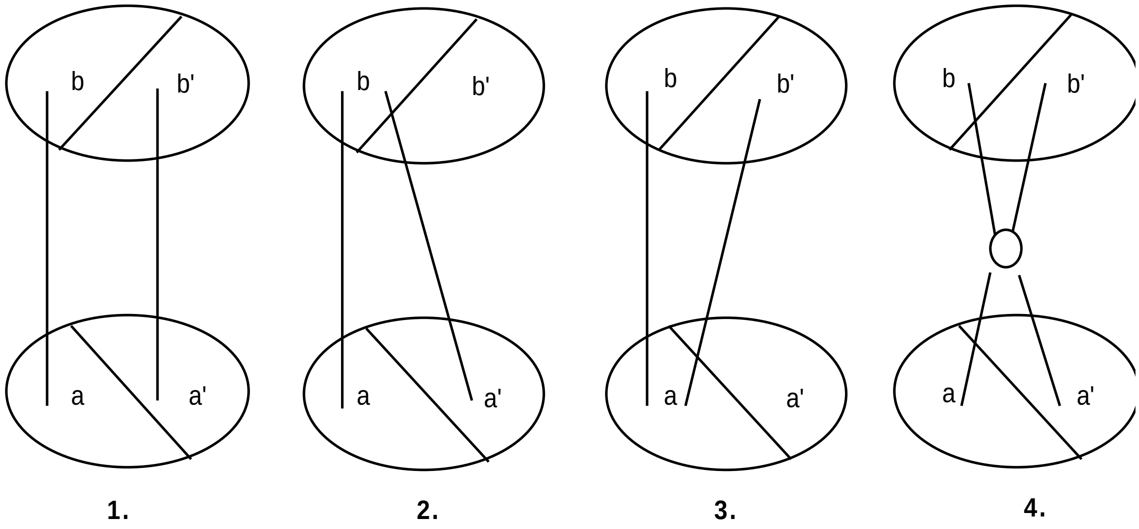

Figure 1: four basic types of distinction processes:
1. conservation, 2. destruction, 3. creation and 4. creation-and-destruction.

distinctions. For a given type of distinction there are four types of processes (cf. Heylighen, 1989b):

1) conservation of the distinction; this can be modelled by a one-to-one, bijective function, corresponding to a process which is reversible and predictable;

2) destruction of distinctions, but without creation of new ones; this can be modelled by a many-to-one, surjective function, corresponding to a process which is predictable but irreversible;

3) creation of new distinctions, together with maintenance of the existing ones; this can be modelled by a one-to-many relation (not a function), corresponding to a process which is reversible but not predictable;

4) creation of distinctions together with destruction of distinctions; this can be modelled by a many-to-many relation, corresponding to a process which is irreversible, and unpredictable.

These 4 types of processes can be easily represented by denoting a single distinction by the couple (a, a') of a class a and its complement a' (Heylighen, 1989b; 1990b). Conservation of the distinction means that the couple is sent bijectively onto another couple (b, b'): $a \rightarrow b$, $a' \rightarrow b'$. The other types of processes are depicted in fig. 1.

By considering different types of distinctions, a much more complex classification of distinction processes can be made. For example, a process can conserve type A, destroy type B, and create-and-destroy type C, hence it could be characterized by the combination A.1, B.2, C.4. Moreover, the class of the process may vary according to the time interval, so that a particular type of distinction is conserved during interval [t_1, t_2], but destroyed during the subsequent interval [t_2, t_3].

Variation and selection

After classifying possible distinction processes (cinematics), we must understand the constraints which will select the actually occurring processes out of the potential ones (dynamics). In order to do that we will assume that general processes belong to class 4., and that it is possible to conceptually separate the phases of creation and of destruction of distinctions. The creation phase may be called “variation”, since it creates a variety of distinct configurations or “variants”. *Variety* (Ashby, 1964) can here be understood as a measure of the amount of distinct configurations. The second phase may be called “selection” since it reduces variety by selectively eliminating certain variants, thus destroying distinctions.

The basic dynamical principle governing this process states that those variants will be eliminated which are unstable (i.e. which tend to spontaneously disappear because of their own internal dynamics, or because they are not adapted to their environment). The stable ones, on the other hand, will be selected and hence "survive". This principle is just a simplified, tautological version of the Darwinian principle of natural selection. "Tautological" does not mean "trivial", however. The value of a tautology resides in its use as rule for "rewriting" and thus simplifying a description, in the same sense as the laws of logic (e.g. the laws of de Morgan, or the principle of contradiction) are tautologies, but yet are very useful when making complex inferences. In this way a tautological principle can be used to connect several descriptions by showing that the one can be deduced from the other one. If the origins of those descriptions are far apart, then the result of this connection is not trivial at all, and can sometimes even be considered as an important break-through.

In order to allow such non-trivial inferences we must analyse in more detail what are the mechanisms of variation and the criteria of selection (”stability”). The selection we want to understand is not so much the selection of a separate variant, but of the distinction between the variant and its environment. In other words, we are looking for a criterion for the invariance of distinctions. This invariance can be defined mathematically by means of the concept of (relational) *closure* (Heylighen, 1989a, 1990a).

Closure

In mathematics closure can be defined as an *operation* C on sets, C: $B \rightarrow B^*$, with the following properties:

1) $B \quad B^*$ (monotonicity)
2) $(B^*)^* = B^*$ (idempotence)
3) $B \quad D \quad B^* \quad D^*$ (inclusion preservation)

A set B is called *closed* if $B^* = B$. Intuitively such a closure of a set means that somehow "missing elements" are added to it, until no more of them are needed. For example, in topology, if you want to "close" an open set, you must add the boundary to the set itself. However, the general definition does not tell us what would be missing, or when we should stop adding elements. Intuitively, a subsystem B of a global system S of elements and relations (or–more generally–*connections*) is closed if B can be externally distinguished from its complement ($S \backslash B$) in an invariant way, whereas the internal distinctions between the elements or subsystems of B are not (or less) invariant. Examples of closure are the transitive or cyclical closure of a relation, or the closure of a group of transformations under its composition operation (Heylighen, 1989a;1990a). There are many different types of closures, but in this approach we will restrict ourselves to the ones which can be found in formal theories of physics.

Closure can be understood as an *internal* stability criterion, leading to selection, for a particular variant D of a subsystem distinguished from its environment, but it can also provide a criterion for the adaptation or "fit" of the variant D to one or more other systems $E, F, G, ...$, *external* to D, so that $\{D, E, F, G, ...,\}$ would together form a higher-order closed system D'. In that case it is not so much D which is stabilized, but the relation between D and $E, F, ...$, and hence the compound system D'. It may well be that D itself loses its invariance within the larger system D'. For example, in a unicellular organism, the cell forms an (organizationally) closed unit, which is stabilized by homeostatic mechanisms. However, in a multicellular organism, it is the whole of all cells which forms a closed entity which is to be maintained, and this stability of the whole is relatively independent of the continuous destruction (through aging or natural processes) of many of the cells which constitute its parts.

Variation in this framework can be modelled by considering change as the result of changed relations between invariant elements (closed subsystems or "modules"), in other words as the *recombination* of modules. For example, sexual reproduction which is one of the basic variation mechanisms in biological evolution consists of the recombination of chromosomes from two organisms. This is an example of external variation, whereby the modules to be recombined with the original modules come from outside the original closed system (organism), and hence are in certain respect “new” or “unpredictable”. In a dynamical representation, on the other hand, variation is modelled by a transition between states, whereby a state is determined by a specific combination of elementary propositions, consisting of objects and predicates, e.g. “the particle has position x” & “the particle has momentum p”. A new state will consist of a different combination of objects and predicates. This is an example of internal variation since all the possible predicates and objects are already contained within the representation system as a whole. This may be called the closure of the state space: no (internal) variation process can generate a state which does not belong to the state space: though the state changes, the state space itself is invariant.

The dynamics of distinctions formulated in this way is clearly interactive: variation consists of the recombination of (components of) systems, whereas selection is based on the “fit” of components or systems. No distinction creation seems possible without interaction between different components, but the components undergoing the interaction are themselves changed during the process. However, if we wish to understand knowledge, in the sense of an observer constructing a representation of an object, we will have to be more specific about interactions, and consider two interacting systems with stable, distinct roles in the process: subject and object, or observer and observed.

Interactive construction of distinctions

Let us first work out the case of two stable, interacting systems. For intelligent, “decision-making” systems (*actors*) the interaction process is sometimes called *conversation*, or dialogue. A single interact can be conceived as the sending of a message by system A to system B, followed by a response of B to A. The message arriving in B can be viewed as external variation, and will be either accepted or rejected (i.e. selection). If the message was not accepted, A will in general repeat sending new messages until one is accepted. If the message has been accepted, there will in general come a response or reaction which is a function of the accepted message. This new, transformed message can be viewed as external variation initiated by B. The interact (message-response) will in general lead to a new interact, i.e. A will send a new message or response to B, which is again a function or transformation of B's response. Eventually this variation-and-selection of messages may lead to the emergence of a “closed” message pattern, i.e. one which is accepted without further transformation by both systems. In this case the two systems may be said to be coupled—or to have reached an “agreement”—with respect to this invariant shared pattern.

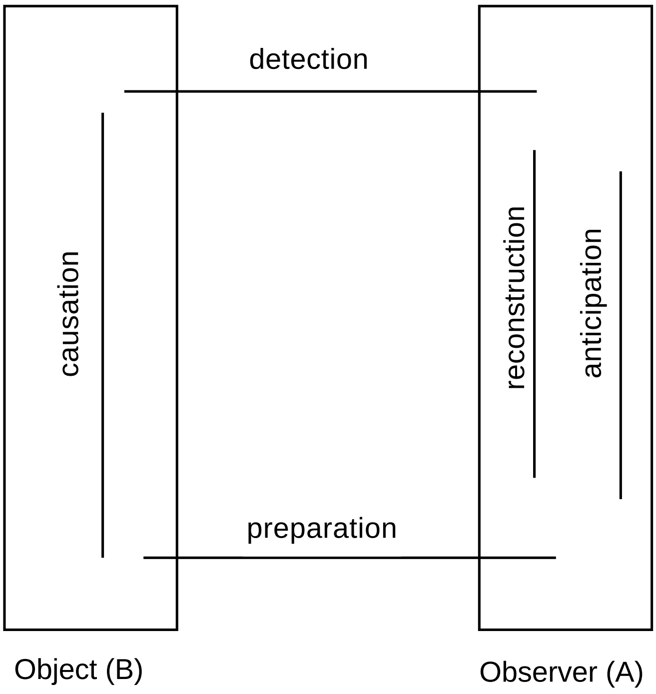

Fig. 2: the observation cycle

Let us assume now that *A* is the active system, the “observer” which tries to construct a model of *B*, which remains passive, just reacting to *A*'s actions, but not initiating any action itself. The messages from *A* to *B* correspond to preparations (input of *B*), where *A* tries to induce a certain state in *B*. The messages from *B* to *A* correspond to detections (output of *B*), where *A* registers the reaction (determined by *B*'s internal dynamics) to the previous preparation. The following conditions must be satisfied for a message pattern (distinction system) to be maintained during the whole interactive cycle (see Fig. 2) :

1) the initial preparation must be accepted by *B* (preparability of *B*);

2) there must be reaction of *B* which is a function of the state in which it was prepared: the internal dynamics of *B* must conserve certain distinctions inherent in the prepared state (minimal causality of *B*'s dynamics, cf. Heylighen, 1989b);

3) the reaction of *B* must be received by *A* (detectability);

4) the observed reaction must be coherent with *A*'s expectation or anticipation of the reaction, or, if *A* did not make an anticipation, it should be possible for *A* to explain or reconstruct the reaction on the basis of the preparation (coherence). This last condition may be further split up in two subconditions: a) it must be possible for *A* to generate distinct anticipations or explanations, without getting stuck in ambiguities or inconsistencies (internal coherence); b) the anticipated or reconstructed observation must be coherent with the actual preparation/detection (external coherence or correspondence).

Each of the four conditions (preparability, minimal causality, detectability, coherence) is a selection criterion which may interrupt a prediction/observation cycle, and thus eliminate a distinction system representing *B*'s behaviour from A's point of view. We will here not look into the variation process by which *A* generates a new distinction system, potentially representing *B* (this is the “context of discovery”), but restrict ourselves to the selection criteria (“context of justification”). In classical epistemology, only the last condition is considered, with an emphasis on correspondence (internal coherence is usually considered trivial). This means that preparability, detectability and causality are implicitly assumed. However, non-classical models have shown that aspects of physical systems may well be unpreparable, undetectable, and even non-causal.

In general, selection criteria are not a question of all-or-none, but a question of more-or-less, that is to say that the criteria allow us to prefer one representation as being more “adequate” than another one. It is clearly not realistic to assume that a representation which would not completely fulfill one of the criteria, e.g. external coherence, would be "falsified" (Popper, 1959), and hence would have to be eliminated. The idea of "falsification" (or of "verification") presupposes a realist epistemology in which there is an absolute distinction between "true" and "false" representations. In a constructivist epistemology, on the other hand, there is not only no such distinction, there is in general not even an absolute distinction between more and less adequate representations. Indeed, the multidimensionality of the criteria (we have distinguished four main classes, but if we would proceed with the analysis we might find much more different types of invariance or closure) signifies that the ordering of representations according to their adequacy is not complete or linear, but partial. This means that given two representations, it is in general impossible to determine which of the two is the most adequate. The one may be preferable according to a certain criterion (e.g. preparability), but the other one may be more adequate in a different respect (e.g. computability). For example, in physics it does not make much sense to ask which of several representation types, e.g. classical, statistical or quantum mechanical, of a given phenomenon is the "true" one. It is here that the subjectivity of the observer comes into play, making him choose that representation which is most useful in helping to solve his particular problems.

Classical representations

Classical representations, exemplified by the theory of classical mechanics, are based on the paradigm that all change can somehow be reduced to the movement in space of separate, rigid objects, following trajectories completely determined by physical laws. The typical illustration is the movement of planets around the sun, or of billiard balls on a table. The space in which the system is moving is in general an abstract configuration or phase space. The classical evolution of a system is causal, deterministic and reversible, and its representation is supposed to be objective, i.e. independent of the observer.

Let us look at the behaviour of the different types of component distinctions of a classical representation. Objects are supposed to have an invariant identity: during their movement they do not disappear or merge with other objects, and no objects are created out of the void, or by the breaking up of existing objects. In other words, the distinction between object and background is always conserved. An object is supposed either to have a certain property, or not to have it. The attribution of a predicate to an object is objective, and all observers are supposed to agree upon it. Hence the distinction between having a property and not having it is also invariant. The same applies to propositions which are either true or false, independently of the observer, and to the time-ordering of two events, which are either simultaneous, or the one precedes the other one. Hence propositional and temporal distinctions are also invariant. Again the same principle applies to dynamical constraints: a transition is either allowed or not allowed, without any ambiguity. Finally the principle applies to state trajectories: two trajectories starting at distinct states at a certain instant will always remain distinct, and have always been distinct. This is the principle of absolute causality, encompassing reversibility and predictability (Heylighen, 1989b).

In conclusion, all distinctions between objects, between predicates, between different trajectories, between truth and falsity, between past and future, and between possible and impossible, are invariant: they remain the same for all times and for all observers. This absolute distinction conservation can be taken to be the defining characteristic of the classical way of representation. Indeed, as we shall see, each of the non-classical representations can be characterized by the non-conservation of a particular type of distinctions.

If we now apply the concepts from the dynamics of distinctions to the classical representations, we must conclude that all subsystems of the distinction system are closed: the objects, the predicates, the propositions, the state space as a whole, time, trajectories, operators, dynamical constraints, ... If we look at the interaction between subject and object then we must conclude that classical representations are the result of a completely closed observation cycle: the states of the system can be perfectly prepared by the observer, the evolution of prepared states in the system is completely causal, the new states of the system can be perfectly detected, and the observer is supposed to posses all information and knowledge needed to predict or explain the the detected states of the system (this is the assumption of perfect, “unbounded” rationality, see Heylighen, 1990b).

The only thing which can vary is the actual combination of predicates which determines the state, but this variation is completely constrained by the trajectory which is determined by the dynamical constraints. The trajectory is closed in the sense that the system must follow a given trajectory: it cannot leave it and follow another trajectory, or it cannot enter from another trajectory, since the reversibility and predictability of classical evolution precludes any branching of trajectories. Mathematically, the trajectory may be called *linearly closed* (i.e. there is a complete, linear order relation between the points on the trajectory).

Another way of expressing this feature of classical representations is by remarking that in classical evolution the phases of variation (= distinction creation) and selection (=distinction destruction) are simultaneous, and that they counterbalance each other's influence. For each new variant created, another variant is eliminated, so that at each instant there is only one possible variant present. In such case the conceptual separation of variation and selection leads of course only to trivial results and no dynamics of distinctions is needed, unless one tries to understand classical distinction conserving evolution as a limit case of non-classical distinction-changing evolution.

This can be seen more clearly in a formulation where classical dynamics is based on a variation principle, like in the Hamilton formulation. Here the trajectory is determined as that path between two points for which the action is minimal. We might see this as a “virtual” variation where all different paths between two points are explored, followed by a “virtual” selection where the one optimal path is retained and where all other paths are eliminated. If we go to quantum mechanics, on the other hand, the variation of paths is no longer virtual: in the path integral formulation of quantum mechanics, the quantum wave function is supposed to simultaneously follow all the possible paths between two points. The path with minimum action is privileged only insofar that along that path there is minimal destructive interference. In this representation the selection occurs when the position of the quantum system is observed: the collapse of the wave function then singles out one intermediate position out of the variety of possible paths.

A classification scheme of representation structures

We have shown that classicality of a representation implies conservation of distinctions. However, it can also be argued that conservation implies classicality. To prove this inverse implication, we will consider its contraposition: non-classicality implies non-conservation of distinctions. It suffices to show that each of the standard “non-classical” representations (quantum mechanics, relativity theory, non-equilibrium thermodynamics or complex dynamics) is characterized by the variation of certain distinctions. The conservation of distinctions then becomes a real *demarcationcriterion* distinguishing classical from non-classical representations Heylighen, 1990b). The generality of this criterion allows us to use it outside the physical domain, so that we might distinguish between classical and non-classical representations in domains such as economics, computer science, cognition, systems theory, ...

We may refine the classification and distinguish different non-classical representations by the type of distinction they do not conserve, and by the type of distinction processes, like in Fig. 1. Combining the four process types with four distinction types (distinctions between trajectories, between predicates or propositions and their negation, between past, present and future, and

	conservation of all distinctions	destruction of distinctions	creation of distinctions	creation and destruction ...
trajectories	*classical mechanics*	*thermodynamics*		*stochastic processes*
predicates propositions				*quantum mechanics*
time simultaneity				*relativity theory*
objects				*quantum field theory*

Table 1: a 4 × 4 classification scheme of classical and non-classical representations.

between objects and their environment) leads to a 4 × 4 matrix, depicted in Table 1. Let us discuss the most important components of this matrix.

For each distinction category (vertical axis) there is just one corresponding process category (horizontal axis). Since most distinctions in physical representations are conserved anyway, we have placed specific representation types in that square of the matrix where there is no complete conservation, assuming by default that for the other distinction categories there is conservation. An exception is classical mechanics, where all 4 distinction types are conserved, and which hence has been placed in the first vertical column.

We encounter the first non-classical representation in row 1, column 2: thermodynamics. The non-classicality is here rather limited since there is only a destruction of distinctions (corresponding to irreversibility), but no creation (corresponding to unpredictability). This destruction takes place at the level of trajectories: thermodynamical systems with initially distinct states may evolve towards the same attractor or equilibrium (maximum entropy) state, so that their trajectories in state space merge. In order to find also creation of trajectory distinctions (i.e. the branching of possible trajectories) we must go to the theory of stochastic processes (e.g. Markov processes) in column 4, where a given initial state may have several outcomes with different probabilities. In principle we could also imagine a representation with only creation of distinctions and no destruction, but it does not seem very useful to have a specific theory for processes which are unpredictable, yet remain reversible. Therefore column 3 is empty.

The second row describes the behaviour of predicate distinctions. If the objects are considered to be invariant, a proposition, made by attributing a predicate to an object will behave in the same way as a predicate. The only representation where predicate distinctions are variable is quantum mechanics. A predicate or property is assigned to an object after an observation process. In quantum mechanics the result of such an observation is in general indeterminate, given the state of the object. It is in general impossible to distinguish objects which will appear to have a certain property after a measurement from objects which will appear to lack that property. On the level of propositions, this indeterminacy of predicate distinctions leads to a non-Boolean logic of propositions.

The structure of time is based on the distinction between events which happen in the past, simultaneously, or in the future, with respect to another event. The only representations for which those distinctions become variable are relativistic theories (row 3, column 4). Here the relationship of simultaneity becomes relative, i.e. dependent upon the reference frame of the observer (Heylighen, 1990b).

The concept of field allows us to represent physical phenomena so that there is no longer a clear separation between objects and predicates. A field is expressed by a function $Q(x)$ which assigns a value Q (e.g. charge, electric field, or gravitational potential) to each point x of space.

Q(x) can be interpreted as well in the sense of "*the point x [object] has field strength Q [predicate]*" as in the sense of "*the field Q [object] has position x [predicate]*". The quantization of field theory, with the fields taken as predicates, signifies that the field becomes indeterminate, in the case of a superposition of states with different field values. On the other hand, the field can be interpreted as denoting potential objects (e.g. photons or electrons) to be found in a certain region of space, and then the indeterminacy of the field strength induced by quantization means that the number of objects or particles becomes variable. Quantum field theories, such as quantum electrodynamics, can hence be characterized by the destruction and creation of object distinctions. This may be exemplified by processes in which a particle and its anti-particle annihilate, resulting in a photon. In practice quantum field theories are also relativistic so that in fact they can be characterized by both [row 4, column 4] and [row 3, column 4], and if we keep the predicate interpretation of fields, we could also add [row 2, column 4]. In that sense relativistic quantum field theories are the "least classical" representations used in physics. No one will be surprised if we add that they are also the most complex, both conceptually and computationally.

Non-classical representations

Multiplicity of subrepresentations

Suppose that you have a representation where certain distinctions vary, but that you want nevertheless to understand it in a classical way. In that case you will need several classical subrepresentations (in generally an infinite number) in order to represent the different states of your system. Indeed, for each variant of a distinction, you will have to define a new classical subrepresentation, since no classical representation can encompass different variants of one distinction. It seems as though the same system is represented in multiple, mutually incompatible ways, and that it is impossible to single out one of those subrepresentations as being the true one. We will call this phenomenon the multiplicity of subrepresentations. By a classical subrepresentation we do not mean a representation limited to just a part of the system, leaving out certain components or properties, but a representation of the complete system, which is "frozen" in the sense that it fixes certain distinctions and hence is incapable of representing a change in the relation between system and observer in which these distinctions vary. In order to represent that change the subrepresentation itself must be transformed.

In quantum mechanics, subrepresentations are determined by a particular set of compatible predicates or "observables" (e.g. position, energy or momentum) whose eigenvectors form a basis for the Hilbert space of all quantum states (see Heylighen, 1990b). For a state belonging to that basis, the observables (e.g. position) establishing the subrepresentation have determined, "classical" results. However, there are always incompatible observables (e.g. momentum) whose results are not determined for states in that basis. In order to represent the latter properties in a way which is determined, the basis must be changed by a unitary transformation, leading to a different subrepresentation. This feature of subrepresentations is called *complementarity*: you need different subrepresentations which are mutually exclusive, yet jointly necessary for an exhaustive description of the system (Jammer, 1974).

In relativity theory, a subrepresentation corresponds to what is called a *reference frame*: a set of coordinate axes forming a basis for the 4-dimensional space-time continuum. The phenomenon of multiplicity is here called the *relativity* of a reference frame: the relations of simultaneity and precedence (defining the order of time) are different for different frames (see Heylighen, 1990b). The different subrepresentations (frames) can be transformed one into the other by Lorentz transformations.

In statistical mechanics and thermodynamics, there is as yet no detailed theory about multiple subrepresentations, but one basic problem encountered here is called *granularity* (Hobbs, 1985): the same phenomenon can be represented with different “grain sizes” (i.e. amount of detail or discrimination). A fine-grained subrepresentation can be transformed into a more coarse-grained one by a partitioning of the state space. A process which appears deterministic or reversible at one grain size may appear indeterministic or irreversible at another one (Prigogine, 1979).

To a classically trained mind such a variety of incompatible representations appears truly paradoxical. Classical epistemology indeed presupposes that there is only one complete and truthful representation of a given physical system, and that this representation is isomorphic to the system itself. In a constructivist epistemology, on the other hand, it is clear that different incompatible models can be constructed which are all adequate in solving the problems the observers has in mind. Yet it seems very difficult to relinquish this classical way of viewing things. Even Bohr who introduced the concept of complementarity in quantum mechanics, started from the postulate that “it lies in the nature of physical observation that all experience must ultimately be expressed in terms of classical concepts” (Bohr, as quoted by Jammer, 1974).

Many of the assumptions of the classical frame, such as the existence of invariant objects, the rules of classical logic and causality, the absoluteness of space and time, the absoluteness of truth, seem intuitively so evident that it appears difficult to imagine a world where these conceptions would not apply. This may be explained by remarking that invariant distinctions are indeed much more easy to work with as far as problem-solving and thought in general is concerned (cf. Heylighen, 1989a). Yet the natural simplicity deriving from invariance does not imply that variable distinctions cannot be modeled in a consistent way.

Limitation principles

In order to explain or motivate the particular violations of classical invariance, different types of *limitationprinciples* have been formulated. These principles typically express the impossibility to establish a certain classical distinction in an absolute way. An example of such a principle in mathematics would be the theorem of Gödel, stating that in each formal system (containing the axioms of number theory) there exist propositions such that it is impossible to distinguish between the truth (provability) and falsity of the proposition within the system itself. However, we will restrict ourselves here to principles in physics.

In quantum mechanics we have the Heisenberg *indeterminacyprinciple*, stating that it is impossible to simultaneously distinguish the position and momentum (or in generally incompatible observables) of a quantum system. In relativity theory we have the *principle of relativity* together with the principle of the invariant limit speed *c* for causal propagation, which entail the impossibility to distinguish simultaneous from non-simultaneous events that are spatially separated. In thermodynamics we have the *second law*, which entails the impossibility to distinguish which different initial states of a system lead to the same maximum entropy final state (i.e. the impossibility to reconstruct or to reverse the transition).

Although these principles appear to be purely negative affirmations, excluding the closure of certain distinctions within a representation, they can also be interpreted in a positive way, by moving to a higher level of representation, where they express certain higher-order closures. For example, the theorem of Gödel is proven by means of a construction allowing the formal system to represent propositions of the system by numbers, so that it is possible to interpret propositions about numbers to be propositions about propositions of the same system. This self-reference is an example of cyclical closure. The incompleteness result can be understood as an application of the more general principle of the impossibility of complete self-reference (Löfgren, 1990). Also the limitation principles in physics can be analysed as specifications of such a principle of the necessary incompleteness of self-observation or self-knowledge (Heylighen, 1990b; Finkelstein, 1979). This can be understood intuitively by remarking that the observation cycle depicted in Fig. 2, can be interpreted as a “self-observation” of the observer *A* mediated by the object *B*. If self-observation is assumed to be partial, then the transmission of distinctions through the observation cycle must be partial too, and hence there cannot be a complete conservation of distinctions.

Structures entailed by non-trivial closure

Our purpose here, however, is not to motivate why there is no conservation of distinctions (this is in fact an automatic assumption of the concept of “distinction dynamics”), but to understand how this mechanism of distinction change is embodied in the formal and conceptual structure of non-classical theories. The incomplete conservation of distinction means that closure is no longer a universal feature of all representation components, like in classical mechanics. There still is closure, but now its consequences are non-trivial, since they are differentiated, allowing the variation of certain distinctions while precluding the variation of other ones. One of the defining characteristics of closure is that the invariance of the (external) distinction defining the globally closed system is linked with the reduced invariance of the internal distinctions of the system, leading to a connectedness between previously separate components.

In quantum mechanics, there is a “closure” requirement on the state space, called the superposition principle, which is absent in classical mechanics. Although this principle entails the variability of predicate distinctions (the general indeterminacy of observations on a state), it also imposes an additional coherency or redundancy on the state space, so that quantum states are less independent than classical states. An analogous constraint determines relativity theory: the causal structure of space-time, determined by the requirement that causal processes be “enclosed” by the light cone, introduces an additional redundancy (determining a.o. a topology on space-time), and a higher-order distinction between processes inside, outside, or on the light cone (Heylighen, 1990b), while at the same time relativizing the invariance of the lower order distinctions defining simultaneity. The transformations of subrepresentations are defined such that they conserve this closure (e.g. unitary transformations conserve the superposition and product of quantum state vectors, and Lorentz transformations conserve the causal structure of space-time). Even the principle of irreversibility, and the emergence of complex structures in self-organizing processes can be understood as the result of non-trivial closure, by means of the concept of an “attractor” as region of state space closed under the dynamics of the system.

Conclusion

We have analysed the dynamical representations used in physics as distinction systems, constructed by an observer in interaction with an object. The creation, conservation and destruction of distinctions can be understood on the basis of a distinction dynamics. The fundamental mechanism is the variation through recombination and selective retention of closed combinations. The conservation of all distinctions was shown to provide a demarcation criterion, distinguishing classical from non-classical representations. Different non-classical representations could be distinguished on the basis of which distinctions they do not conserve. It was argued that the specific structures of these non-classical representations can be derived by studying the properties of non-trivial closure.

What must be done now is to study each of these non-classical representation (quantum mechanics, relativity theory and thermodynamics or complex dynamics) in more detail, and to analyse in which way their structures can be understood on the basis of the principles of the dynamics of distinctions. This problem will be tackled in the subsequent papers of this series, of which the present paper has laid down the conceptual framework.

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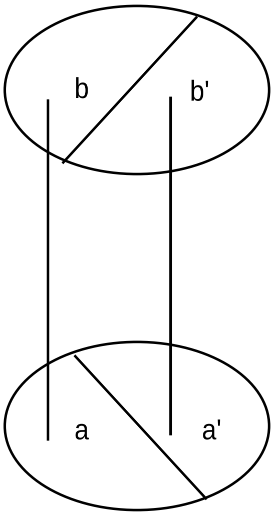

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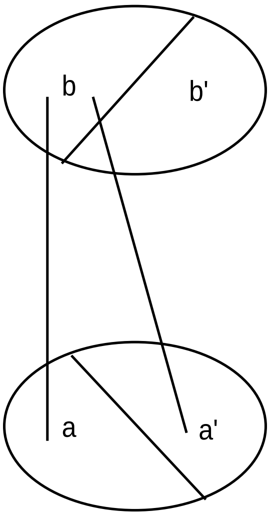

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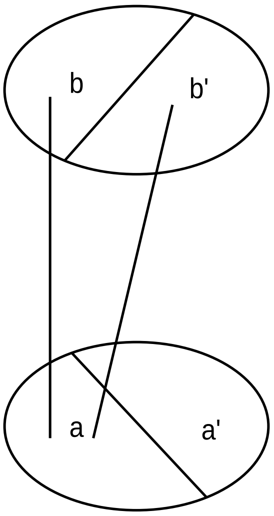

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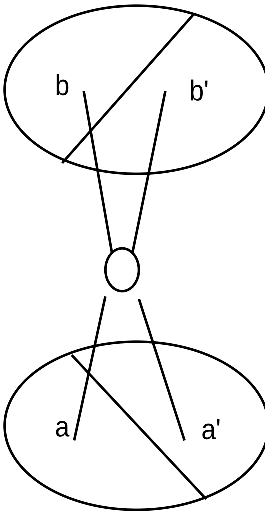

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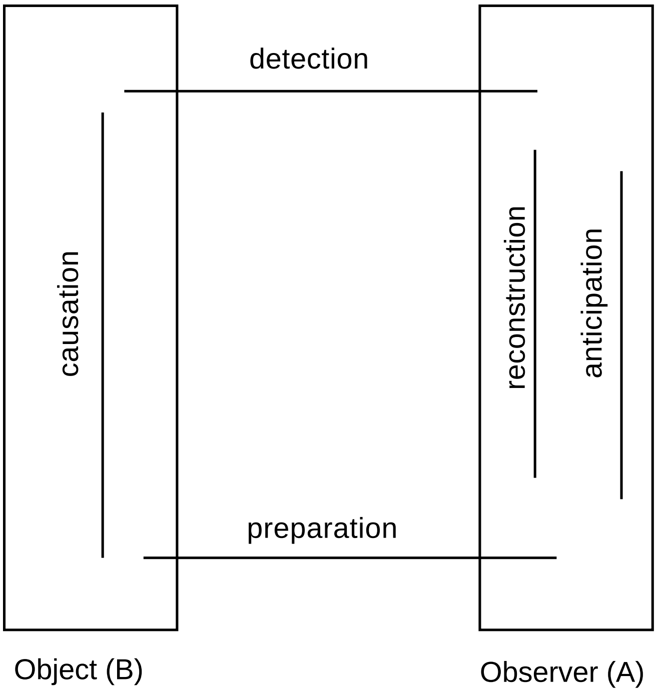

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	conservation of all distinctions	destruction of distinctions	creation of distinctions	creation and destruction ...
trajectories	*classical mechanics*	*thermodynamics*		*stochastic processes*
predicates propositions				*quantum mechanics*
time simultaneity				*relativity theory*
objects				*quantum field theory*