Abstract

The present paper critically examines the main claims of the new mechanist account of explanation defended by Glennan and Machamer, among others. The two major difficulties of the new mechanism, namely the *circularity objection* and the *bottoming out problem* are discussed and addressed. To solve the bottoming out problem, this paper proposes a modification and enlargement of the mechanist account of explanation advocated by Salmon and Dowe. Such extension can then successfully apply to the explanations provided for the global behaviour of complex systems, not only in physics but also in other disciplines such as biology and the social sciences. The proposed enlarged version of Salmon's and Dowe's account provides a monistic account of explanation based on causal generalizations or laws which need not be construed as necessary to fulfil their explanatory role. Such change-relating generalizations or laws are characterized by the presence of a term that refers to the variation in time of some property, which is identified to the effect whereas the other terms refer to the causes. Thus, by enlarging the Salmon and Dowe notion of mechanism, I advocate a nomological theory of causation instead of the mechanistic theory of causation proposed by Glennan *et alii*.

Keywords

New mechanism, mechanist explanation, mechanist causation

Mechanist Explanation: An Extension and Defence

Mechanist explanation has enjoyed a renewal of interest in the past two decades. This is mostly due to the papers by Glennan (1996, 2002), Machamer *et al.* (2000) and Kuhlmann and Glennan (2014) that advocate the merits of what is called the "new mechanism" or the "new mechanical philosophy" in the philosophy of science. The present paper critically evaluates the main tenets of this new mechanism. It also proposes an amendment and extension of the causal mechanism developed by Salmon (1984, 1994) and Dowe (1992, 2000) in the light of the main insights of the new mechanism. It will be argued that by relying on the notion of causal law such extension permits to counter two major objections to the new mechanism, namely the charge of circularity and the bottoming out problem.

1. The new mechanism

The main motivation for developing the new mechanist view about explanation sprang from the dissatisfaction with the accounts of explanation exclusively inspired by the explanatory practices in physics. These accounts, such as Salmon's and Dowe's, do not capture the nature of the explanations offered for the behaviour of the complex systems typically encountered in the biological and social sciences. Moreover, the new mechanists attempt to provide an explanation of the perplexing notion of causality by relying on the notion of mechanism. Stuart Glennan plainly states that he intends his “analysis of mechanisms to explain the nature of causality.” (Glennan 1996, p. 56)

What is a mechanism? According to the new mechanism, a mechanism is a system of parts which interact in accordance with generalizations or laws. These interactions are supposed to explain the way the system behaves:

Definition 1: “A mechanism underlying a behavior is a complex system which produces that behavior by the interaction of a number of parts according to direct causal laws.” (Glennan 1996, p. 52)

Glennan immediately remarks that a mechanism is a “mechanism underlying a behaviour”:

“One cannot even identify a mechanism without saying what it is that the mechanism does. The boundaries of the system, the division of it into parts, and the relevant modes of interactions between these parts depend upon the behavior we seek to explain. (…) A complex system has many mechanisms underlying its different behaviors” (Glennan 1996, p. 52)

The selection of the relevant parts and the relevant interactions in the underlying mechanism is guided by the aim to explain a specific behaviour. Different behaviours of the same complex system will be accounted for by different mechanisms. Later, Glennan modified this definition in the following way:

Definition 2: “A mechanism for a behavior is a complex system that produces that behavior by the interaction of a number of parts, where the interactions between parts can be characterized by direct, invariant, change-relating generalizations. » (Glennan 2002, S344)

Significantly, this new definition does not include the word “law” anymore, let alone the expression “causal law”. The reason is that Glennan wishes to better “capture the kind of localized causal generalizations that characterize interactions between parts of mechanisms”[1]. Indeed, the term “law” often has stronger and wider connotations, such as universality and necessity, whereas the mechanist philosophy advocated by Glennan is neutral with respect to various conceptions of law. Generalizations in his sense only describe interactions between parts, such as scissors cutting paper, wine staining cotton etc. (Glennan 2016, 810). Yet, these generalizations must “capture the relevant counterfactual truth claims” (Glennan 2002, S344), that is, the counterfactuals which are involved in our understanding of an interaction. Later, Glennan abandoned the expression “change-relating” generalisations because he doesn’t want to seem committed to Woodward’s views on causality (2017).

The behaviour of a mechanism occurs in time. The complex system has properties that change. If we focus on a single changing property of the whole system, the behaviour (or the phenomenon (Glennan 2016, 804)) to be explained is the temporal variation of that property by means of an underlying mechanism. What then are the component parts of a mechanism?

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[1] Private communication.

"These parts must be objects, in the most general sense. They must have a relatively high degree of robustness or stability; that is, in the absence of interventions, their properties must remain relatively stable. Generally, these parts can be spatially localized." (Glennan 2002, S344)

Thus, the component parts of a mechanism are *objects*. Objects have properties which remain "relatively stable". There are two ways to understand stability here. Either the *kinds* of properties possessed by the object remain the same, such as volume and pressure for a gas, while allowing for changes of the values of these properties. Or, the *values* of some of the properties of the object remain constant. In what follows, stability will be understood in the first - more permissive - sense.

Classical mechanisms are composed of *spatially* distinct parts. Glennan does not see this as a compulsory requirement, since parts are "generally" spatially localized but they could not be. Here, he has in mind fields, such as the electromagnetic field, which cannot be confined to a small area, but are parts of many mechanisms (Glennan 1996, p. 56). He also keeps an eye on the applicability of his views to quantum mechanical systems whose parts are often not spatially localized (Kuhlmann and Glennan 2014). Fields then can be parts of a mechanism, and therefore objects, although they do not count as objects in the habitual sense. Particles, on the other hand, are usually considered to be objects which can interact with a surrounding field.

The interactions between parts, *i. e.* the inner workings of the mechanism, "produce" or cause the behaviour of the system, that is, the change of the properties of the system in the course of time. This is an ontological claim: the parts of the mechanism are real and the invariant generalizations are supposed to be true descriptions of real interactions. Mechanisms are the "truth makers for causal claims" (Glennan 2016, 808). Moreover, the actual behaviour of the system – the phenomenon of interest - is *causally explained* by the underlying mechanism, *i.e.* by the interactions between the component objects which produce or cause the changes of the global system's properties.

If what causes a specific behaviour of the complex system is the working of a specific mechanism, the latter is ontologically prior. The causal process undergone by the complex system is grounded on the interactions between the objects which make up the mechanism. These interactions are described by generalizations which can be epistemologically *identified* and *ascertained* without resorting to the notion of causality, in a Humean and Russellian way (Russell 1913). Besides, from an ontological perspective, the regularities described by these generalizations do not alone found the global behaviour of the system since its object-parts are also needed. Some (but not all) of the relevant generalizations are called "laws" by scientists of various disciplines (physics, biology, economics etc.) but Glennan does not want to call them "laws". Nomicity is often associated with causality, or even ground it. But, according to the new mechanists' philosophical agenda, causality should not to be based on laws, but on mechanisms, since they rather sceptical about the notion of law or at least belittle its importance. Against them, I sustain that nomicity grounds causality (see § 6 below).

From an epistemological viewpoint, when we know the workings of the underlying mechanism we also know why the complex system exhibits a specific behaviour. A behaviour is the transition of the system from one event or state - which is defined as the occurrence of a property (or properties) - to another state. If it can be said that a preceding state of the system is the cause of a subsequent state, it is because the underlying mechanism makes the system evolve in such a way. Thus, mechanisms provide not only the ontological foundation of causal relations but causal explanation also epistemologically boils down to mechanical explanation.

To clarify the issues at stake, it is useful to distinguish three levels of causation. The first level is the *causal succession* of states of the whole system in a specific behaviour (among possible others), which is a causal process. The second level of causation consists in the workings of the underlying mechanism, namely the *causal interactions* of the relevant objects. This distinction corresponds to what Glennan calls "an important duality in mechanism talk" (Glennan 2016, 801):

"On the one hand, mechanisms can be characterized as processes with various stages connecting initial and termination conditions. On the other hand, mechanisms can be characterized as systems – stable collections of parts or components organized in such a way as to have persistent states and dispositions."

At first sight, there seems to be a third level of causation, namely the *causation of the behaviour* of the complex system by the workings of the underlying mechanism, which causes an effect, *i.e.* the specific behaviour or phenomenon we are interested in. We would then have an inter-level causal relation between the first level (effect) and the second underlying level (cause). Let us try to make all this clearer by looking at some examples of mechanist explanation.

A first example discussed by Glennan (1996) is the float valve. The specific behaviour of the system to be explained is the maintenance (and variation) of the level of water in a tank. The relevant parts (objects) of the underlying mechanism are the tank, the water, the float and the lever, and the valve, which is connected to a pressurized water source. When the water level is low the float and the lever do not block the flow of water. As the water fills the tank the float goes up until the lever is in contact with the valve and stops the flow of water whose level then remains constant. From an epistemological (and ontological) point of view, three levels of causation are involved. The first level is the behaviour of the whole system, that is, more precisely, the variation of a property, namely the height of the water level. The variation of the height of the water is a causal process: a given height h_1 is the cause of a height h_2 which occurs later in time[2]. At a second level of causation, we have the interactions between the relevant objects of the system, namely the underlying machinery. Finally, the workings of the mechanism causally produce the variation of the height of water, that is, the third (inter-)level of causation.

Let us briefly mention some other examples of mechanisms also discussed by Glennan: the voltage switch which is a mechanical device that explains the change and stability of output voltage in function of input voltage; the transmission of information between the members of a group connected by phones; the mechanical system of molecules underlying the behaviour of a

[2] See my definition of a causal process inspired by the Dowe-Salmon mechanicism in §6 below.

gas in accordance with Boyle-Charles-Mariotte law; the mechanism of cell meiosis which explains Mendel's laws.

2. *The regress difficulty with the inter-level causation*

Glennan's mechanist account of causal explanation could lead to an unwelcome regress, which to my knowledge has not so far been noticed in the literature[3]. Glennan's main project is to found causality on the workings of a mechanism. If there is a third inter-level of causation, one should resort to a further mechanism in order to ground it. Let us call this further mechanism M_I, distinct from the mechanism M_G which is supposed to *causally produce* the behaviour of the system. Where is such mechanism to be found? And if it could be found, one still would have to explain *mechanistically* its causal action on the inter-level interaction. So, an unwanted regress looms.

Within Glennan's perspective, there cannot be room for a third inter-level interaction. True, in *Definition 2*, Glennan says that "a mechanism for a behaviour is a complex system that *produces* [our underlining] that behaviour by the interaction of a number of parts". Now, the behaviour at stake must be the behaviour of *something*. This "something" can only be the complex system itself. There cannot be two complex systems involved. So, the "something" is the complex system whose specific behaviour is to be explained. Thus, the complex system can only be the mechanism itself, that is, the system's decomposition in parts effectuated in function of the specific behaviour to be explained. In other words, the behaviour of the complex system is the behaviour of the underlying mechanism. If this interpretation is correct, there is no inter-level causation (third level), but only two levels of causation, namely, to repeat, the variation of some properties of the whole system (first level) and the interactions among the objects composing the underlying mechanism (second level). Such interpretation is supported by Glennan's assertion that "a mechanism is a complex system" (Glennan 2002, S344). The evolution in time of the mechanism is identical to the specific causal process undergone by the complex system with respect to the variation of the specific properties that are considered. This "definitional"[4] move permits to avert the danger of a threatening regress.

Have another look at the float valve. The complex thing is the system of the following interacting objects: the tank, the water, the float, the lever and the valve connected to a pressurized water source. The phenomenon we are interested in is the variation of one property of the global system, namely the variation of the water height in the tank. Notice that the water here is *part* of the mechanism. The behaviour we are looking at is the evolution of a property of a part of the mechanism. There is no problem in this case since interactions among parts occur at the second level of causation. The variation of the height of water is then the result of the causal interactions of the component objects of the mechanism.

Think now of the classical example of mechanism cherished by modern times mechanist thinkers such as Descartes, Locke and so on, namely a pendulum clock. The behaviour we are

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[3] I'm grateful to Brigitte Falkenburg to have pointed this to me.
[4] I owe this suggestion of terminology to Peter Verdee.

focusing on is the motion of the needle on a scale (which marks the time), that is, the behaviour of an object-part of the whole clock-system which is clearly causally produced by the internal workings of the clock's mechanism.

Surely, this way of apprehending the behaviour of a whole by considering only the behaviour of one of its parts cannot be applied to all complex systems. If you study the transmission of information among a group of people connected by cell phones, the behaviour of the system is captured by the variation of a property, namely the amount of information globally possessed by the system, that is, the sum of the bits of information possessed by the individuals who are connected, *i. e.* interact with their cell phones. The variation of the total amount of information is a first-level causal process. But at the second level, as the mechanism operates, the global amount of information automatically increases (or can also decrease…). It makes no sense of talking of some relation of causality between the workings of the mechanism and the behaviour of the system, just because the description of the inner workings of the system is just another way to describe the phenomenon we are interested in. This is what Glennan has in mind when he introduces his notion of a "mechanical model":

"(MM) A mechanical model is a description of a mechanism, including (i) a description of the mechanism's behavior (ii) a description of the mechanism which accounts for that behavior" (Glennan 2002, S347)

Thus, the descriptions (i) and (ii) correspond to the first level and the second level of causation, respectively.

3. *The objection of circularity and the bottoming out problem*

The mechanist account of explanation faces two well-known difficulties which are openly recognized – and addressed – by Glennan: the objection of circularity and the bottoming out problem.

Let us start with the *objection of circularity*. The causal explanation of the behaviour of a complex system relies on the interactions between some of its parts, that is, the relevant ones. The notion of interaction is a causal concept. This is granted by all. Therefore, the mechanist account of causality relies on the causal concept of interaction, and we are confronted with a circularity hurdle. However, the explanation of the behaviour does not have to explicitly refer to a further (mechanical) explanation of the relevant interactions. The search for an explanation concentrates in the first place on some behaviour of the whole system, not on an explanation of the inner interactions within the mechanism.

"In describing the mechanism that connects the two events [of the behaviour] I have explained how these events are causally connected. How the parts are connected is a different question. In can try to answer this second question by offering another account of the mechanisms that connect them, but I need not give such an account to explain the connection between the events. Indeed, such an account would only obscure the relevant features of the original explanation." (Glennan 1996, p. 68)

As Glennan observes, spelling out the interactions would *obscure* the mechanist explanation of the sequence of states (events) of the complex system, by making the explanation unnecessarily complicated and thus hampering understanding. So, from the epistemological standpoint, the objection of circularity is easily defeated. Explanations must stop at some point, and there is no risk of circularity or regress here.

The situation is more complicated with the *bottoming out problem*. One could indeed ask how the interactions between the parts of a mechanism work and attempt a mechanical explanation of these interactions, such as the interaction between the water and the float in the above example. To achieve this, we would have to divide some parts of the system into subparts and explain the generalizations ("laws") describing the higher-level interactions in terms of lower-level interactions between these subparts. Going further down, we would eventually reach the microphysical level where interactions are governed by the fundamental laws of physics for which no further mechanist explanation is available, at least at the present stage of scientific knowledge. This is the case for electromagnetic interactions since the electric and magnetic fields cannot be divided into independently manipulable parts. The space-time points, at which there is a value of the electric and magnetic fields, are not objects because objects must be capable of interacting and they also have to be manipulable constituents (Glennan 1996, p. 56).

True, explanation must stop at some point, and there is no threat of an unwelcome regress or circularity there. But as far as the ontological basis of causality is concerned, there are reasons to worry. To causally explain the regularity of a behaviour, which can be described by a universal statement or lawlike sentence, is to appeal to a real mechanism which grounds such regularity. By definition, if a generalization or a law is fundamental, there is no underlying mechanism available, at least for now. At any rate, even if the laws considered to be fundamental at this time turn out to be based on mechanisms, in practice we will always hit a last ground in the hierarchy of groundings and thus a bottom of fundamental laws, which might be provisional or final, but is nevertheless a bottom. Therefore, either fundamental laws are not causal or, if they are, they are not mechanistically founded. In either case, the new mechanism is in trouble. In the first situation, some regularities cannot be causally grounded. In the second situation, we would have cases of causation which are not mechanist and this would contradict the very aim the mechanist approach.

Glennan acknowledges that there is no mechanical explanation of fundamental laws (otherwise, they would not be fundamental…). Thus, at the fundamental level there is no causal explanation of regularities and the problem of distinguishing generalizations which are causal - and would deserve to be called "laws" (again, in the sense of generalizations which ground the truth of relevant counterfactuals) - and which generalizations are not nomological remains acute. Glennan offers no satisfactory solution to this problem. From an epistemological point of view, this is not a serious difficulty, since explanations must end at some point, and we are not required to explicitly formulate the generalizations which describe the interactions between parts to causally explain a specific behaviour of a complex system. Ontologically, however, causation at higher levels is not ultimately grounded on causation at the fundamental level, since the mechanist account of causation is simply unavailable at the level of the fundamental laws of physics. Glennan then is forced to accept that the mechanist construal of regularities is *ontologically dualistic*. On the one hand, we have causal regularities grounded on actual mechanisms; on the other hand, the most basic regularities described by the fundamental laws of physics must be considered to be causal as well, but in a distinct, non-mechanist sense, on pains of becoming incoherent with respect to the mechanist account of causality.

"This explanation of the role of mechanisms is available as long as the generalizations are mechanically explicable, but here we come to what may seem the key *metaphysical*[5] issue. If mechanisms are truly going to explain how one event produces another, all interactions between parts, at all levels of the hierarchy of mechanisms, will need to be genuinely causally productive. If it were to turn out that these interactions at the fundamental level were not truly interactions, then none of the putative causal interactions mediated by mechanisms would be genuine." (Glennan 2011, p. 811)

Glennan needs causality all the way down, simply because causal interactions at all levels are real. Ontologically or metaphysically, causal relationships at one level must be based on real causal relationships at the lower level. His new mechanism is foundationalist in this sense[6]. If Glennan adopts such ontological posture, this is not because he believes that causation is grounded on some kind of necessity. It is sufficient for him that the fundamental laws (conceived as "invariant change-relating generalizations") warrant the reliability of the relevant counterfactual conditionals. He does not elaborate however on the connection between laws and counterfactuals, but it seems that according to him such connection would be sufficient to have causal interactions at the fundamental level. Be it as it may, such construal of causality at the fundamental level would certainly not be mechanical in his sense. This is why Glennan grants that his view on causality is *dualistic*.

Is it possible to avoid this dichotomy between mechanist causality and fundamental causality? I will try to show that a unifying, monistic account of causality can be defended provided we enlarge the causal-mechanist view advocated by Salmon and Dowe, which mostly is applicable to physics.

4. *The Salmon-Dowe mechanism*

As Peter Railton claimed back in 1978:

"The goal of understanding the world is a theoretical goal, and if the world is a machine – a vast arrangement of nomic connections – then our theory ought to give us some insight into the structure and workings of the mechanism." (Railton 1978, p. 208; quoted by Salmon 1984, p. 123)

Wesley Salmon makes Railton's insight more explicit:

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[5] Our underlining.

[6] On this we disagree with Laura Felline who claims that Glennan's "mechanist account of causation might be consistent with a no-causality-at-the-fundamental level view." (2016, pp. 251-262) Glennan's new mechanism is ontologically foundationalist.

"Causal laws *govern* the causal processes and causal interactions, providing the regularities that characterize the evolution of causal processes and the modifications that result from causal interactions. Causal processes, causal interactions, and causal laws provide the mechanisms by which the world works; to understand *why* certain things happen, we need to see *how* they are produced by these mechanisms." (Salmon 1984, p. 132)

It is fair to contend that, according to Salmon, a machine or a mechanism is a system of causal processes and causal interactions at the intersection of processes. A first important difference between Glennan's and Salmon's mechanisms is the following. For Glennan, mechanisms are composed of *stable* things or objects (Glennan 2002, S345), whereas for Salmon, mechanisms are composed of sequences of events or causal processes which intersect, and needn't exhibit the kind of stability that objects have. Yet, for Salmon, processes are worldlines of stable objects, such as particles of bodies. For Salmon, the aim is to explain why certain events ("things", as he says) happen by means of the causal processes and causal interactions which constitute the parts of the mechanism. Thus, for both Glennan and Salmon, the behaviour to be explained would be a sequence of events, that is the temporal occurrences of properties along a space-time line, or the occurrence of a particular event, such as the breaking of a window or the death of the Archduke in Sarajevo. As Glennan says, we attempt to explain the mechanism as a process, namely its trajectory from an initial to a final state, by means of a mechanism as a system of interactions between its inner parts.

However, Salmon does not pay much attention to the global states of some mechanical systems as wholes. Here, we have a second main difference between Glennan's new mechanism and the mechanism promoted by Salmon[7]. For the latter, there is only one level of causality along individual space-time lines and at their intersections. New mechanists, on the other hand, aim at providing causal explanations of what is going on at the level of complex systems (first level) on the basis of the interactions of its parts (second level). My point is that it is possible to unify both approaches by considering the new mechanist' complex systems as mechanisms of causal processes and causal interactions, which underline the behaviour or causal process of the complex system as a whole. Just because the behaviour of an object in Glennan's sense is a causal process in Salmon's view, provided we don't consider physical properties only.

Let us look again at the float valve. Glennan's main concern is to mechanistically explain the behaviour of the complex system *in toto*, whereas Salmon concentrates on the causal processes of the parts and the causal interactions between them. Yet, the two approaches can be reconciled. In this example, the behaviour of the whole system is characterized by a single property, namely the height of the water level in the tank. According to Salmon, there is a mechanism underlying this behaviour, namely the causal processes of the various objects involved and their causal interactions. More generally, the behaviour of a complex system is a temporal sequence of states, each of which is specified by a number of properties. The occurrence of a state at some time is an event. If this is so, the behaviour of a complex system is a sequence of events characterized by the temporal variation of some properties. Such behaviour is explained, both by Salmon and Glennan, by the workings of a mechanism. Glennan

[7] I'm grateful to Brigitte Falkenburg for having drawn my attention to this difference.

speaks about the interactions of the component objects according to invariant change-relating generalizations, whereas Salmon appeals to the notions of causal processes, causal interactions and causal laws. But later on, reacting to objections addressed by Phil Dowe, Salmon attempted to avoid the recourse to causal laws (Salmon 1994), just as Glennan did.

How are the crucial notions of "causal process" and "causal interaction" to be defined? Here is the definition provided by Salmon after he took into account some of Phil Dowe's (1992) critical remarks:

"A causal process is a world-line of an object that *transmits*[8] a non-zero amount of an invariant quantity at each moment of its history (each space-time point of its trajectory)." (Salmon 1998, p. 257)

According to Salmon and Dowe, such definition permits to distinguish processes which are causal form processes which are not and which are called "pseudo-processes", like the worldline of the shadow of a moving car. Since transmission is a causal notion, Salmon proposes an allegedly *non*-causal definition of transmission to avoid the charge of circularity:

"A process transmits an invariant (or conserved) quantity from A to B (A≠B) if it possesses that quantity at A and at B and at every stage of the process between A and B without any interactions in the half-opened interval (A, B] that involve an exchange of that particular invariant (or conserved) quantity." (Salmon 1998, p. 257)

This is Russell's "at-at theory of causal transmission", reformulated by Salmon.

"A causal interaction is an intersection of world-lines which involves the exchange of a conserved quantity." (Dowe 1992, p. 212, and also Salmon 1998, p. 253)

In virtue of these definitions, an event is explained when it is shown that it is inserted in a nexus of causal processes and interactions. The component parts of a mechanism are the objects which manifest causal processes and interact when their worldlines cross together with an exchange of a conserved physical quantity. This way of explaining is called an "ontic account of explanation" in the literature since it relies on the existence of a causal network in the world. A sequence of events, which can be a regularity, is thus explained by an underlying mechanism.

The examples discussed by Salmon and Dowe are exclusively drawn from physics, such as the collision of two billiard balls and atomic decay. According to them, if you consider the system of two billiard balls, there are two causal processes along which the linear momentum (quantity of motion) is conserved. When the balls collide, an exchange of linear momentum takes place at the intersection of the worldlines of the balls (Dowe 2000, p. 102). No attention is paid to the properties of the global system of the balls. Glennan and the new mechanists rightly complains about this. They also criticize the narrow physicalist strategy implemented by Salmon and Dowe. But these defects can be eliminated by drawing attention to the properties (which needn't be physical) of whole systems whose internal workings are captured by mechanisms as

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[8] Underlining is mine.

understood by means of an extension of the Salmon and Dowe account of explanation, as will be shown below.

Before we do that, it is appropriate to point out two main difficulties encountered by Salmon's ontic account of explanation. As we observed, Salmon and Dowe strive to avoid the notion of law. However, conservation of an invariant quantity without interaction along a worldline is a nomological feature of the world described by conservation laws. Moreover, interactions are ruled by laws. To capture the nature of a particular interaction it is not enough to say that an interaction is by definition the exchange of a conserved quantity at the intersection of worldlines. One must also formulate the precise law that governs this exchange when we offer an explanation in a specific case. What is more, laws governing interactions are causal laws and the threat of circularity looms again…

A second difficulty arises from the fact that a worldline is always the worldline *of an object*, such as a billiard ball. How do we define the identity of an object through time? Averting circularity forbids any recourse to causal notions. Biting the bullet, Dowe claims that the notion of identity of an object is a "primitive concept" (Dowe 2000, p. 107). But, as Psillos remarks, this is "deeply unsatisfactory" because then "which processes count as causal will also be a primitive concept of his theory." (Psillos 2002, pp. 123-124)

Before proposing a modified and enlarged version of the Salmon-Dowe causal mechanist explanation which addresses these two difficulties, it will be profitable to make a brief historical detour to early modern science and the origins of mechanical explanation.

5. *Cartesian intermezzo*

The classical early modern science mechanism aimed at explaining phenomena, *i.e.* "sequences of observed events", by means of mechanisms. Typically, the behaviour of a clock is explained by the internal motions and interactions of wheels, weights, chains etc. which produce the regular motion of a needle on a scale. Surely, these ancient mechanists intended to mechanistically explain the behaviour of whole complex systems, just as the new mechanists do.

For the founding fathers of modern science such as Galileo Galilei, René Descartes and Robert Boyle among others, a mechanism is a spatially organized ensemble of bodies in relative motions. Bodies possess the properties of extension (volume) and geometrical shape. Besides, they are hard (impenetrable) and interact by contact or collision. Thus, a mechanism is a complex system the behaviour of which is characterized by sequence of states (events), that is, the occurrence of properties along a worldline. The relevant properties, the celebrated "primary" properties, are distinguished by two main features: they are objective and they have a quantity which is measurable in principle. The "secondary" qualities on the other hand, are deemed to be subjective and supposed to be explainable by the behaviour of corpuscles endowed with primary qualities only.

The laws of nature, which originally were limited to the laws of motion, are relations between the primary properties of bodies such as position, velocity, extension, shape etc. As history of science unfolded, the scope of primary properties, *i. e.* the scientifically relevant properties, has been considerably extended to include temperature, mass, electromagnetic field, amount of information, DNA splitting and so on. For our present purpose, it is important to stress that laws state relations between *properties*. I'm happy to grant that properties are properties of objects (or corpuscles according to the early modern science mechanists). But we do not have to enter an ontological analysis of objects to understand what a scientific law is. Within a scientific context, it is plausible to maintain, as Hume and many others do, that an object is only a bundle of properties. This is not the way I take objects to be[9]. But for a discussion of mechanical explanation we can safely concentrate on properties and leave aside an analysis of the concept of object.

Within the objectifying approach specific to science, an entity is reduced to an object, *i.e.* a bundle of properties which can sometimes be organized according to a mathematical law. Thus, a (perfect) gas is reduced to a collection of properties such as volume, pressure and temperature related in accordance with the Boyle-Charles-Mariotte law. The behaviour of a clock is reduced to the circular motion of a needle on a scale that can be described by a general statement. Properties are judged to be objective when their measurements by different individuals and apparatuses at different spatiotemporal locations deliver the same results. In scientific activity, we can rest satisfied with objectivity in the weak sense of intersubjective agreement. In science, an object is a collection of objective and measurable properties. The relations between those properties might be governed by a scientific law[10].

Surely, the behaviour of a clock, as well as the behaviour of a gas, can be explained by the interactions between their component parts that are bundles of primary qualities, which interact only by contact.

6. The Salmon-Dowe mechanism amended and expanded

Our historical detour to the birth of modern science taught us that mechanist explanation eventually relies on properties and laws construed as relations between properties. The concept of object is no longer primitive since an object can be considered as nothing else than a collection of properties (which needn't be physical only). Furthermore, we cannot avoid appealing to laws to accurately describe the interactions involved in particular cases. Given this, we are now in a position to propose the following definition of a mechanism.

A mechanism is a complex system of causal processes and causal interactions – described by causal laws - which explain its behaviour, i. e. the changes of some of its global properties with time.

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[9] I do not defend myself that an object is a bundle of properties. An object is an entity that has properties and can stand in relations with other objects. My position is close to the one advocated by John Heil (Heil 2003, chapter 15).

[10] This is not necessary however: the charge and spin of the electron are not related by a law…

The parts of a mechanism are objects, *i. e.* bundle of properties, which remain constant or vary along worldlines and at their intersections in accordance with causal laws. The central explanatory role evidently rests on causal laws. We must then say what is a causal law. Moreover, we must define the notions of process, causal process and causal interaction[11].

A process is a continuous worldline (space-time line or tube) along which some property is conserved and other properties may vary according to a process law.

The properties at stake are not just physical properties but can also be properties referred to in scientific disciplines such as biology, economics, demography etc. However, the recourse to a law is necessary to distinguish between worldlines which are processes and which are not. A process is not just any line drawn in space-time along which some properties vary. There must be a *connection* between the events in a process and such connection is achieved by a law. We thus avoid the problem of the identification of objects. But what about the identification of properties? Properties are identified in the first place in perception, which permits us to distinguish different properties and to attest that a property remains constant along a worldline. A detailed discussion of the identity of properties would take us to far afield. On this issue, I follow Heil for whom the identity and similarity of properties is a primitive relation (Heil 2003, chapter 14), although I include in the list of relevant properties all scientific properties, whereas Heil doesn't.

The word "tube" occurs in the definition to allow for regions of space-time endowed with some properties. (In what follows we will use the word "worldline" to refer to tubes as well as lines). For example, the worldline of the water in a tank is characterized by the permanence of the property of being water. (It is a law that molecules keep their structure unchanged in the absence of chemical reactions.) Along this worldline, the height of the water varies in a regular fashion. Such regularity holds for *all* tanks equipped with a float valve, a water source etc. which are organized in a certain structure. A universal statement describing this regular behaviour of water (given some initial conditions) could then be considered as a (non-natural) phenomenological law related to the relevant counterfactual conditionals. At any rate, this regularity is governed by several process laws, namely the laws that describe the internal processes of the underlying mechanism.

A process law is a mathematical law which contains time as one of its variables.

The restriction to mathematical laws is not compulsory however. Process laws could be formulated in natural language by means of universal sentences that make reference to time. This is the case for some change-relating generalizations used in biological and social sciences. A conservation law is a law which asserts that some property does not vary in time.

Some processes are causal, whereas some are not. For a process to be causal, an additional condition is required: a *causal process* is a process governed by a causal law. What then is a *causal law*?

A law is causal if and only it contains a time derivative.

[11] For further discussion of these concepts, see Blondeau and Ghins (2012).

Such definition was originally proposed in physics by Philipp Frank in 1932 (Frank 1997). (Again, a causal generalization can be formulated in natural language. It is causal if and only if it contains words that refer to some change.) This criterion is formal and intrinsic (see Blondeau and Ghins 2012). The effect corresponds to the time derivative of a quantity (property) in the mathematical expression of the law; the other term(s) designate the cause(s). Such definition conforms our intuition: a cause is what produces a change, namely the variation of properties in time, that is, an effect.

A causal interaction is an interaction between distinct processes, which is described by a causal law and which results in changes of properties along the involved processes.[12]

Such definition does not require that interactions be local[13]. In a causal law, an instantaneous change in time is mathematically expressed by a time derivative.

$$E = \frac{\partial x}{\partial t} = C_1 + ... + C_n$$

E denotes the effect: the variation of the quantity *x* in time. C_i refer to the causes - forces, fluxes, sources etc. – the sum of which is equal to the effect. C_i do not denote variations in time, but they may be functions of time. If C_1, C_2,…. are all equal to zero, or if their sum is zero, *x* does not change, and we have a conservation law. Examples of causal laws include Newton’s second law, the law of chemical kinetics, the Schrödinger equation, some laws of demography, the Lotka-Volterra laws of evolution of predators and prey, the Kermack-McKendrick equations in epidemiology, the Vidale-Wolf equation in marketing etc. (Ghins and Blondeau 2012). The proposed criterion of causal nomicity is not limited to physics but applies to other scientific disciplines as well. The proposed extended mechanism can be applied to mechanisms which are biological, social etc. all the more that change-relating generalizations or causal laws could be formulated in natural language in which some terms or expressions refer to effects and others to causes[14].

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[12] There is causation along a causal process, without interaction. In an inertial process for example: the variation of position is caused by the constant velocity (see Blondeau and Ghins 2012, p. 398). Thus, causality is not restricted to causal interactions.

[13] This account leaves open the possibility of non-local interactions.

[14] Glennan objects [private communication] that our criterion of lawhood could be applied to correlations due to common causes, such as the correlation between the fall of a barometer and the occurrence of a storm. But there is no process connecting these two events, and a fortiori no causal process connecting them. The correct explanation of the storm is of course the occurrence of a depression. There is a causal process connecting the depression and the fall of the barometer, and another causal process connecting the depression and the occurrence of the storm. These causal processes are described by causal laws according to our criterion. Empirical inquiry allows us to detect genuine processes and causal processes from apparent ones. Glennan appears to agree with this kind of strategy since he believes that we can distinguish between genuine activities from other happenings by relying on empirical investigation (Glennan 2016, 810).

In reply to Glennan's concern about the explanation of the behaviour of whole systems, this *Enlarged version of the Salmon-Dowe causal Mechanism* (hereafter ESDM) conforms to the explanations given for the global behaviour of complex systems, whether stable or not. This is clear enough for the variation of the level of a tank, where the interaction between the worldline of the water and of the flow is governed by the laws of fluids. The behaviour of a gas is classically explained by the causal processes and interactions of its component molecules. Each molecule is associated to a worldline which is a causal process governed by Newton's laws. When a collision occurs, the interaction obeys Newton's second law. For gases, their macroscopic properties are related to the average properties of the molecules by means of mathematical equations.

For more complex systems, such as biological or social systems, a complete causal mechanist explanation in terms of fundamental laws is not articulated in most cases, nor is it always feasible or even necessary. Such complete explanation is not needed to understand how the underlying mechanism explains the behaviour of the system. It would even make the explanation unnecessarily obscure or convoluted. A main virtue heralded by the proponents of the mechanist explanation is precisely that intelligibility and understanding of the production of some behaviour is achieved without the formulation of laws (Machamer *et al.* 2000, p. 4). Nevertheless, some change-relating generalizations which describe the relevant causal processes and the interactions that take place between the parts of mechanisms must be indicated, otherwise we would not understand how the mechanism functions. For example, the mechanist explanation of protein synthesis resorts to the following change-relating (causal) generalization: in appropriate triggering circumstances the DNA double helix splits. Splitting is a causal process whose end point is the separation of the two complementary sequences of bases. Besides, going further down, there is every reason to believe that laws play a crucial role at the fundamental level. In the mechanisms of chemical neurotransmission and protein synthesis examined by Machamer *et al.* (2000), it would be hard to deny that laws play a crucial role for an illuminating explanation of the relevant behaviour. At bottom, quantum mechanical processes certainly are involved.

7. *The circularity objection and the bottoming out problem*

Does this expanded version of the Salmon-Dowe causal mechanist approach solve the difficulties faced by the new mechanist approach, namely the circularity objection and the bottoming out problem?

As we saw above, the circularity objection is easily defeated by Glennan, who points out that we can causally explain the behaviour of a whole system by resorting to causal relations between the component parts of the mechanism. Thus, two levels of causation are kept carefully distinct: the level of the global behaviour and the level at which the interactions between the relevant parts operate. Once we have described the inner workings of the mechanism which produce the global behaviour, the explanation comes to an end. Analogously, for our ESDM approach, the explanation for a behaviour relies on causal processes and causal interactions. The explanation is achieved when the causal processes and causal interactions, which are responsible for the behaviour, have been described. Instead of referring to objects and interactions between them, the ESDM view involves properties, causal processes and interactions between these processes.

Within the approach I propose, the bottoming out problem is solved thanks to the concept of causal law. A complete explanation of the behaviour of a mechanism ultimately rests on fundamental causal laws[15]. Causal laws are identified by an intrinsic, formal criterion, as suggested above. The effect is identified as the variation of some property in time. The behaviour of a mechanism is also characterized by such temporal variation of properties. The cause of such behaviour is to be found in the inner workings of the mechanism, which according to ESDM boil down to causal processes and causal interactions described by causal laws. If this approach is correct, our enlarged approach provides a unified, monistic account of causality, unlike Glennan's dualistic view.

At the fundamental level, the concept of causality is captured by causal laws, as defined by the proposed intrinsic criterion. At higher levels, the workings of mechanism are also described by causal laws, *i. e.* change-relating generalizations, which describe the behaviour of mechanisms. It must be stressed that no metaphysics of laws is needed to articulate the ESDM conception of explanation. Laws can only be considered to be general statements which describe regularities related to counterfactual conditionals. In such explanatory context, we can refrain from attributing any kind of necessity to laws. The explanatory role of laws does not rest on any kind of necessity[16].

8. Conclusion

The new mechanism has two main merits. First, it has drawn our attention on the explanation of the global behaviour of complex systems. Second, according to the new mechanism, mechanical explanation is not limited to simple physical systems and interactions but can in principle be applied to the complex systems investigated in all scientific disciplines. We have attempted to show that the Salmon-Dowe causal mechanist account of explanation can be amended and extended in such a way to generally comprehend the nature of the causal explanations offered in practice for the global behaviour of complex systems in all scientific fields. Moreover, we have proposed a unifying solution of the so-called "bottoming out problem" by resorting to the notion of causal law, understood as a universal statement which mentions the variation in time of some properties of the system in function of other properties. For the purpose of explanation, those laws can be construed as mere "invariant change-relating generalizations" which do not involve any kind of necessity.

Acknowledgements

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[15] Even in explanations of an emergent behaviour, we cannot do without causal laws.
[16] This position does not prevent to defend the necessity of laws on the basis of some metaphysics for reasons which are distinct from their explanatory capacity. In my view, only necessary laws can ground the truth of counterfactual conditionals since the latter involve modalities (see Ghins 2007, 2014)

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