Representing Causation: A Dispositional Perspective

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Abstract

Causation is notoriously difficult to analyze notwithstanding its considerable significance for a detailed description of complex phenomena in multifarious domains, including biomedicine. In this paper we conduct a careful ontological investigation into causation with respect to the biomedical discipline. Characteristic of our methodology is to ground causation upon dispositions, which have been extensively utilized in biomedical ontologies for the last few decades. We begin with a dispositional examination of what we call 'canonical causation': a specific kind of relation between processes. This dispositional perspective is then extended to other varieties of causation that biomedical experts usually observe: probabilistic causation, simultaneous causation, and mental causation. We also discuss counterfactuals, which are intimately connected to causation and dispositions; and scientifically relevant epistemic notions such as explanations and hypotheses.

Keywords:
causation; disposition; Basic Formal Ontology

I. Introduction

Causation is of cardinal importance to the biomedical field. For one thing, causation and causal inference play a central role in sciences in general [1], let alone biomedicine [2,3], because scientists typically observe the natural world to search for causes of phenomena therein and provide a causal explanation of them. For another, closer examination of the causal relationships between pathological processes helps to provide a solid foundation for a generic ontological model of disease [4,5] and to enhance an efficient computational extraction of biological data and information [6].

Despite some prior works [4,5], it is an open question how biomedical specialists should conceptualize causation and represent it formally. Rather, causation still remains an enigma to us, although it has been carefully investigated in a number of different domains, ranging from philosophy [7,8] and foundational ontology research [9-12] to artificial intelligence [13], linguistics [14], and cognitive science [15]. It is nonetheless a pressing issue to build an ontology of causation to serve as a common semantic framework which would facilitate the annotation of biomedical datasets.

In this paper we endeavor to carry out an extensive ontological exploration of causation *vis-à-vis* its practical usage in the context of biomedical ontologies. Granted that philosophical ontology proves to be beneficial to a robust construction of scientific ontologies, including biomedical ones [16,17], causation belongs to the notions that are loosely grouped under the heading of 'natural necessity': e.g., necessarily, a glass breaks when it is pressed with a certain force. Other relevant topics of natural necessity include laws of nature, dispositions, and counterfactuals (see [18] for details).

In this general setting, a dispositional approach to causation is arguably most suitable to meet the needs of those who engage actively in biomedical ontologies. Based on this stipulation, our inquiry begins by considering a dispositional interpretation of what we call 'canonical causation': arguably the most typical kind of causal relation that holds between particular processes. We then extend this dispositional understanding to other kinds of causation that are commonplace in the biomedical practice as well as in other situations. We also discuss a dispositional perspective on counterfactuals, namely another notion of natural necessity than causation, and also on scientifically relevant epistemic notions such as (scientific) explanations and hypotheses. Our work will contribute to offering a vivid ontological picture of the biomedical world.

For the sake of the anchoring of a general ontological background, we deploy Basic Formal Ontology (BFO) [19,20] as an upper ontology (aka foundational ontology), namely an ontology to furnish the most general categories (e.g., space and time) and relations (e.g., identity and parthood) to serve as a useful guideline for building domain ontologies of high semantic interoperability. The BFO-based investigation of causation would be valuable for biomedical ontologies because the practical utility of BFO to them is shown by a widespread recognition of the relevance of the BFO methodological principle of ontological realism [21] (which says that the most effective way to ensure well-founded scientific ontologies is to view ontologies as representations of the reality that is described by science) to development of biomedical ontologies [22]; and by the achievement of the Open Biomedical Ontologies (OBO) Foundry [23], i.e., a collaborative project to coordinate ontologies to support biomedical data integration such that BFO can provide a common semantic basis for all the OBO ontologies.

In the most basic BFO framework, entities fall into two kinds: universals (aka types, classes) and particulars (aka tokens, instances). Particulars (e.g., Mary) bear the instance-of relation to universals (e.g., *Human*). Particulars, on which we put a central focus in this paper, fall into two categories: continuants and occurrents. Characteristically, continuants can persist, that is to say, they can exist at one time and also exist at another different time; whereas occurrents (including processes) extend through time. Continuants can be further divided into independent continuants (including objects) and dependent continuants (intuitively: properties). Independent continuants, or especially objects (e.g., stones) can be bearers of dependent continuants (e.g., hardness) and they can also participate in occurrents (e.g., a fall of the stone).

This paper is organized as follows. Section II argues for a dispositional ontology of causation that would be maximized in the biomedical field and provides a dispositional construal of canonical causation and quasi-causation in our terminology. Section III considers dispositionally other varieties of causation: probabilistic causation, simultaneous causation, and mental causation. Section IV discusses a dispositional view of counterfactuals, explanations, and hypotheses. Section V concludes with some brief remarks on future work.

II. The Dispositional Grounding of Causation

A) Canonical Causation and Quasi-causation

There is broad agreement among prior works [9-12] in foundational ontology research on some basic characteristics of causation, in spite of its complicated character. First, causation is a binary relation between processes. The terms 'causation' and 'causal relation' will be hereafter used interchangeably. When pressing with a certain force caused a glass to be broken, for instance, the process of the pressing the glass with a certain force has the causal relation to the process of the breaking of the glass. Second, there are two types of causation: type-level causation (e.g., smoking causes lung cancer) and token-level causation (e.g., Mary's smoking caused her to get lung cancer). Lehmann et al. [9] call the former and the latter 'causality' and 'causation', respectively; and causality and causation refer to the causal relation between process universals and between process particulars, respectively. (The terms 'type-level causation' and 'token-level causation' are preferred to be employed in this paper to circumvent terminological confusion, though.) In this paper we focus mainly on token-level causation. Third, causation has a significant bearing on scientifically important epistemic notions such as explanation and hypothesis (see Section IV for details).

We begin by focusing on the most paradigmatic kind of causation (which we call 'canonical causation') and then consider other variants of causation in Section III. Although it may defy easy description, canonical causation possesses at least the following four features. First, it is token-level causation that is observed in the macroscopic world in which classical (Newtonian) mechanics holds. Throughout this paper, we postulate this worldview to avoid complications added by a contentious ontological role of causation in non-classical physical theories such as general relativity and quantum mechanics. Second, it is so-called forward causation (where the cause occurs earlier than its effect); and backwards causation [24,25] (where the cause occurs later than its effect) is outside the scope of our investigation. Third, it is so-called physical causation (which is, roughly, entirely explicable purely in physical terms). Fourth and lastly, it is non-probabilistic. For instance, it is always the case that pressing with a certain force caused a glass to be broken, and in this sense, the process of pressing a glass with a certain force bears the canonical causal relation towards the process of the glass being broken. In contrast, when a toss of a coin caused the coin to land on heads, the causal relation between the process of the toss of the coin and the process of the coin landing on heads is probabilistic because the coin could have landed on tails (with the probability 50 percent) [26].

As for the formal properties of the (canonically) causal relation, it is irreflexive and asymmetric. That is to say, no process caused itself, and if a process *x* caused a process *y*, then it was not the case that *y* caused *x*. On the other hand, the transitivity of the causes relation (i.e., whether a process *x* caused a process *z* if *x* caused a process *y*, which in turn caused *z*) is not presupposed because it is a highly debatable subject [8, Chapter 5] [27].

It has been pointed out in the relevant literature [11] that there is a causal-like relation which a *state* bears to serve as a precondition for the causal relation to hold that and which we may call 'quasi-causation'. For instance, the state of oxygen bears the quasi-causal relation towards the causal relation between striking of a match and the lighting of the match. This quasi-causal relation can be labeled as the verb 'allow' [11]: e.g., the state of oxygen allowed the striking of a match to cause the match to light.

Concerning states, Galton [28] identifies their two distinct, albeit related, meanings:

- *States as continuants.* An 'instantaneous state' of some thing or situation, as given by the values assumed at one time by some of its variable properties. E.g., the position and momentum of a particle in physics.
- *States as occurrents*. A 'state situation', described as unchanging with respect to some selected. property or combination of properties. E.g., the state of the water temperature being 50 degrees Celcius.

Note that this general analysis of states is useful in biomedicine, as is indicated by its concordance with Chaudhri and Inclezan's [29] observation of the multiple usages of the term 'state' in a biology textbook.

B) Theory of Dispositions

A disposition is a (specifically) dependent continuant that is linked to a realization, namely to a specific *possible* behavior of an independent continuant that is the bearer of the disposition. To be realized in a process, a disposition needs to be triggered by some other process. Classical examples include fragility (the disposition to break when pressed with a certain force) and solubility (the disposition to dissolve when put in a certain solvent). Characteristically, dispositions may exist even if they are not realized or even triggered. A glass is fragile even if it never breaks or even if it never undergoes any shock, for instance. We will also speak of a categorical basis [30] (aka a base [31]) and a background condition [31] of a disposition: a quality (or a sum of qualities) of the disposition bearer and a necessary condition for the realization of the disposition, respectively. For instance, flammability of this match is the disposition to be realized when the match is struck (trigger) against a certain surface in an oxygenated environment (background condition), thereby bringing about the production (realization) of fire; and it is based on a particular molecule structure (categorical basis) of the match.

There are nowadays several accounts of the identity of dispositions available. For instance, Barton, Grenier, Jansen and Ethier [30] criticize Röhl and Jansen's [31] traditional disposition model for being susceptible to 'disposition multiplicativism': the excessive and arbitrary proliferation of dispositions that would nullify their ontological importance. They instead propose an alternative model of dispositions: two dispositions are identical if and only if ('iff' hereafter) they have the same categorical basis, the same universal of minimal triggers, and the same universal of maximal realizations, where the universal of minimal triggers of a disposition *d* is the universal of triggers of *d* for which no proper part is a trigger of *d*, and the universal of maximal realizations of *d* is the universal of realizations of *d* which are not proper parts of another realization of *d*. For instance, a minimal trigger and a maximal realization of the fragility disposition of a glass would be the weakest shock on the glass that is strong enough to enable the glass to break and the whole process of the breaking of the glass, respectively. To keep things manageable, we will employ a practical identity condition [32] of dispositions that is acceptable in both the above-introduced frameworks for dispositions: two dispositions are identical iff they have the same categorical basis, the same universal of triggers and the same universal of realizations.

C) A Dispositional Interpretation of Canonical Causation and Quasi-causation

We contend that a dispositional understanding of causation can be most fully exploited in the biomedical domain as compared to e.g., its primitivism [33] and its lawful interpretation [34]. For a negative reason, even the existence of biological laws is a highly controversial topic [35]. For a positive reason, realizable entities such as tendencies and dispositions are central to medical information sciences [36]; and dispositions serve as such a useful conceptual tool for the analysis of the explanatory practice in the biological sciences [37] that a dispositional theory of causation captures well the dynamicity, continuity, and context-sensitivity of biological phenomena [38]. It has been also argued that a dispositional analysis of causation helps to contribute to evidence-based medical practice [39] than its counterfactual analysis [40,41] (but see [42] for criticism).

Moreover, a dispositional approach to causation has its advantages with regard to OBO ontologies. For one thing, BFO is fundamentally committed to dispositions, as is indicated by its explicit grounding of natural necessity in dispositions: "Incorporation of dispositions into the BFO ontology provides a means to deal with those aspects of reality that involve possibility or potentiality without the need for complicated appeals to modal logics or possible worlds" [20, p. 102]. For another, dispositions have been carefully investigated in ontology research in general ontology research for the last decade. Accordingly, they have been conceptually and logically examined, so that ontology of dispositions has been exploited for formalizing various biomedical entities: e.g., diseases [32,43,44], medical risk [45], and medical Bayesian indicators of performance [46].

The crux of a dispositional approach to causation is that when causation occurs, there is a corresponding realization of some disposition [47]. A glass broke, as the dispositional theory goes, in virtue of the realization of the fragility disposition of the glass triggered by pressing the glass with a certain force. The causal relation between two processes can be thus interpreted as the relation between the triggering and the realization processes of some disposition.

Furthermore, quasi-causation would be explicable in terms of a background condition of a disposition. For one thing, the trigger and a background condition of a certain disposition are largely pragmatically distinguished causal factors [31] and this coheres well with the idea that quasi-causation is so relevant to ontology of causation that a certain causal relation would cease to hold if any one of preconditionsl states for the causal relation failed to. For another, background conditions can comprise categorially diverse kinds of entities [31] and this conforms to the aforementioned observation that preconditional states of quasi-causation can be construed as either continuants or occurrents. The state that brings about quasi-causation can be therefore explicated in terms of a background condition of some disposition.

Against the BFO background, a 'continuant-state' can be construed as a subtype of quality (see e.g., [48]): "A specifically dependent continuant that, if it inheres in an entity at all, is fully exhibited, manifested, or realized in that entity. In order for a quality to exist, one or more independent continuants must also exist. Examples include the mass of a kidney, the color of this portion of blood, and the shape of a hand" [20, p. 183]. In contrast, an 'occurrent-state' would be as a subtype of process: "An occurrent entity that exists in time by occurring or happening, has temporal parts, and always depends on at least one independent continuant as participant" [ibid.]. Since it essentially needs some participant, an occurrent-state (process) of a participant occurs in virtue of the fact that the participant bears some relevant continuant-state (quality).

III. Other Varities of Causation

A) Probabilistic Causation

The exemplary dispositions (e.g., fragility and flammability) that we have so far discussed are all 'sure-fire dispositions': "such dispositions that will necessarily be realized given the respective realization conditions" [31, p. 5]. Put more perspicuously, sure-fire dispositions follow the 'realization principle': if a trigger of a disposition occurs, then does its realization [31]. Canonical causation can be thus recast as the causal relation that is grounded in some sure-fire disposition.

Not only canonical causation but also probabilistic causation [26] is part and parcel of the biomedical practice, as is observed by the ubiquity of probabilistic and statistical notions in the medical domain: e.g., the probability of a person to contract a disease within a given time frame. A straightforward dispositional interpretation of probabilistic causation would depend on probabilistic dispositions such as the disposition of a coin to lands on heads when it is tossed up. Barton, Burgun and Duvauferrier [49] elaborate upon probabilistic dispositions and maintain that they fail to obey the realization principle because the triggering process of a probabilistic disposition can occur without its realization occurring.

All those findings show that probabilistic causation would be explainable in terms of a direct extension of a dispositional understanding of canonical causation based on probabilistic dispositions. Consider the aforementioned paradigmatic example of probabilistic causation: a flip of a coin caused the coin to land on heads. In dispositional parlance, this was the case in virtue of the fact that the process of the flip of the coin triggered the probabilistic disposition of the coin to land on heads, which was in turn realized in the process of the coin landing on heads. Note that the probabilistic disposition of the coin to land on tails was triggered at the same time, but it was not realized.

B) Simultaneous Causation

As frequent in and as important for biomedicine as probabilistic causation is simultaneous causation, where the cause occurs at the same time as its effect [50]. Typical examples include a key and a lock such that the former opens the latter. A certain lock (say $Lock_1$) becomes open only when it is unlocked by some key (Key_2) and *vice versa*. It may be tempting to speculate that the Key_2-pivoting-in-$Lock_1$ process caused the $Lock_1$-opened-by-Key_2 process and *vice versa*. This would seem to go beyond canonical causation because it fails to preserve the property of asymmetricity. One may be also inclined to use the term 'process' with an emphasis on its dynamic connotation to describe this apparently simultaneously causal scenario (see e.g., [11,12]).

We suggest that alleged simultaneous causation be explicable in terms of the idea of reciprocal disposition [51], which can date back to complementary dispositions [43] and the reciprocal dependence among dispositions [19,20]. For instance, $Lock_1$ has the disposition d_1 to be opened by Key_2 and Key_2 has the disposition d_2 to open this particular $Lock_1$. Then d_1 and d_2 are said to be reciprocal dispositions in that they can be triggered by the same process universal and they can be realized in the same process universal; and d_1 bears the has_reciprocal_disposition_of relation [51] towards d_2. This relation is irreflexive and symmetric. For instance, d_1 (resp. d_2) is not reciprocal of itself and the has_reciprocal_disposition_of relation holds between d_2 and d_1.

The notion of reciprocal disposition can be employed to capture supposed simultaneous causation. In the case of lock-opening, the $Lock_1$-opened-by-Key_2 process should be elucidated in such a way that it refers to either the whole Key_2-opening-$Lock_1$ process or the $Lock_1$-components-moving process. In virtue of the causal efficacy of d_1 and d_2, the Key_2-pivoting-in-$Lock_1$ process indeed caused the $Lock_1$-components-moving process but not *vice versa*; and they are temporal parts of the same Key_2-opening-$Lock_1$ process. Generally speaking, simultaneous causation is explicable in terms of the 'causal dependence' [19, p. 5] between two reciprocal dispositions.

C) Mental Causation

Mental and behavioral disorders constitute an acute problem for the public health all over the world [52]; and biomedical ontologies must take seriously mental functionings. An ontology of mentality would facilitate an interdisciplinary research on mental disease, thereby contributing to the improvement of psychiatric diagnostics and treatment [53]. In particular, it would help to fill a semantic gap between affective science and psychiatry, which have been historically separate notwithstanding their common goal to explore human mental phenomena [54]. Several ontologies of mentality have been built, including an OBO ontology the Mental Functioning Ontology (MF) [55].

Mental causation [56,57] nonetheless remains elusive from an ontological viewpoint despite its centrality to mentality. For instance, it is fairly difficult to figure out what it is supposed to mean to say: "I ate a cake because I was hungry." To simplify the matter, we assume the so-called belief-desire principle according to which an agent's action is basically a causal consequence of her beliefs and desires. Inspired by Bratman [58], the Belief-Desire-Intention (BDI) model of agency [59] indeed recognizes the primacy of intentions (as well as beliefs and desires) in practical reasoning and rational actions, and it is widely used in applied ontology in virtue of its implementational and logical benefits [60,61]. We omit to posit intention as a fundamental mental entity, however, partly owing to considerable controversy as to the (ir)reducibility of intention to desire-belief pairs [62,63].

Seen dispositionally, mental causation would be most straightforwardly explained in terms of dispositionality of both belief and desire. As for belief, Barton, Duncan, Toyoshima and Ethier [64] sketch out an ontology of belief in alignment with MF and argue for two ontological meanings of the term 'belief': a *dispositional belief* as a disposition that can be realized in an occurrent belief and an *occurrent belief* as a MF-*mental process* of taking something to be the case. A mental process is a bodily process which brings into being, sustains or modifies a cognitive representation or a behavior inducing state, where a behavior inducing state is a bodily quality inhering in a mental functioning related anatomical structure which leads to a behavior of some specifi sort [55]. They say: "A dispositional belief exists even when we are not actively thinking it, and when we are actively thinking about a belief, we engage in an occurrent belief process during which we take something to be the case" [64, p. 4]. For the sake of our own terminology, we will use the terms 'belief disposition' and 'belief process' to refer to a dispositional belief and an occurrent belief, respectively.

This Janus-faced view of belief can be extended to desire, although its ontological nature has been little studied carefully in applied ontology. Intuitively, desire is intimately linked with motivation, which is in turn with behavioral dispositions. In wanting to eat a cake, for instance, Mary is plausibly taken to be disposed to act (e.g., to go towards a refrigerator) to satisfy her hunger desire. As the most orthodox, motivational theory of desire goes [65], for an agent to desire *p* is for the agent to be disposed to take whichever action she believes will satisfy *p* (see [66] for criticism). Based on this intuition and along Barton et al.'s [64] line of argument, we can identify two ontological interpretations of the term 'desire' and call them 'desire disposition' and 'desire process'. At first approximation, a desire disposition is a disposition that can be realized in a desire process; and a desire process is a mental process which modifies a behavior inducing state so that the behavior inducing state will lead to a behavior to satisfy the agent's desire. Additionally, our assumption of the belief-desire principle would imply that, to realize itself, a desire disposition needs to be triggered (or 'co-triggered' if it is preferable) paradigmatically by multiple belief processes.

Our dispositional picture of belief, desire, and action would be still incomplete unless we incorporate into it an ontology of plan(-making) because it is integral to practical rationality. Following Barton et al.'s [64] recommendation, we extract from an OBO ontology the Ontology for Biomedical Investigations [67] the category of *plan specification*, which we here reinterpret more broadly as a generically dependent continuant which directs an agent (e.g., an experimenter) to perform a certain action (e.g., an experiment). A generically dependent continuant is a BFO-category: "A continuant that is dependent on one or other independent continuants and can migrate from one bearer to another through a process of copying. We can think of generically dependent continuants as complex continuant patterns either of the sort created by authors or designers or (in the case of DNA sequences) brought into being through the processes of evolution" [20, p. 179]. Examples include the pdf file on Mary's laptop and the pdf file that is a copy thereof on John's laptop. Characteristically, a generically dependent continuants exists only if it is *concretized* in some counterpart specifically dependent continuant. To take one example, a paragraph of a novel in concretized in each pattern (quality) of ink on the pages of the printed novel.

Mental causation is to be understood in terms of the application of belief and desire dispositions (and their processes and related plan specifications) to the schema of canonical causation. To illustrate this point, imagine that a hungry girl Mary went towards a refrigerator to eat a cake inside it. Our rough dispositionally causal analysis of this scenario proceeds as follows. First of all, Mary's hungry physical process triggered one (say d_B) of Mary's belief dispositions, which realized itself in her belief process of taking to be the case that there is a cake in the refrigerator. Next, this belief process triggered one (say d_D) of Mary's desire dispositions, which was realized in her desire process of wanting a cake. Most importantly, there is a plan specification which is concretized in both d_B and d_D and which induces Mary to approach the refrigerator to have a cake. To satisfy her hunger, Mary might have taken another action (e.g., to go to buy a cake) if she had believed otherwise: e.g., "There is no cake left in the refrigerator and a nearby cake shop is still open." It is interesting to remark that one may sometimes use the term 'intention' to refer to a plan specification that is concretized in belief and desire dispositions, and intention could be therefore classified in our present framework as a subtype of plan specification. Finally, Mary's desire process under discussion modified her behavior inducing state to make it lead to her behavior of going towards the refrigerator to eat a cake, hence the satisfaction of her hunger desire.

IV. Discussion

A) Counterfactual

Let us consider briefly counterfactuals from the BFO viewpoint. Counterfactuals are, broadly speaking, statements that represent what did not happen or what is not the case: e.g., if a glass were pressed with a certain force, the glass would break. It is typically expressed by dint of a counterfactual conditional, i.e., a special case of the subjunctive conditional, which uses what is known in grammar as the 'subjunctive mood'. A counterfactual conditional has the form "If P had been the case, then Q would have been the case" or "If P were the case, then Q would be the case." It is not hard to see the significance of counterfactuals for biologists' and medical professionals' practice because scientific procedures (e.g., experiments and clinical trials) generally take on a crucial counterfactual aspect [10]. Clinicians would ordinarily think, for instance: "If this patient had taken more vitamin C, she would not have contracted scurvy." Moreover, a counterfactual analysis of dispositions is a well-known traditional understanding of them and its core idea is that an object is disposed to a realization r as a response to a stimulus s iff the object would realize r if s were the case [68]. This view has been subject to numerous critical appraisals, though [69,70].

We submit that, when grounded dispositionally, counterfactuals are to be interpreted in terms of a generically dependent continuant that is concretized in some disposition. For one thing, counterfactuals are a kind of statements, which accord arguably most suitably with the category of generically dependent continuants (e.g., information). For another, the crux of the dispositional grounding of counterfactuals is that counterfactual conditionals are made true by dispositional ascriptions (but not *vice versa*) [31] and this entailment would be ontologically well explicable in terms of the concretization-in relation (which we could reinterpret as one of the BFO family of grounding relations) between a counterfactual (which we construe as a generically dependent continuant) and some disposition.

B) Explanation and Hypothesis

Ontology of natural necessity will exert a downstream effect on epistemology of sciences, since scientific knowledge is about scientific phenomena that are to be foundationally captured by the notions of natural necessity. We will focus on scientific explanation because it is of central importance to sciences (including biomedicine), which consist in providing an adequate explanation of the world. One paradigmatic example of scientific explanation is that sky is blue because the molecules in the atmosphere of the earth will scatter more blue light towards the ground than other colors. In applied ontology, the notion of explanation has been considered especially in connection with observations [71,72], but it has been scarcely ever studied from the perspective of natural necessity.

There are two important points which prior philosophical models of scientific explanation have in common, although we omit to delve into them owing to spatial limitations (see [73,74] for a general survey). First, a strong link between scientific explanation and causal explanation is generally agreed upon. It is certainly debatable whether all scientific explanations involve causal statements, but it can be safely said that scientific explanation is paradigmatically underpinned by causal explanation, as is implied by the ubiquity of the terms 'causes' and 'because' in the scientific literature. Second, and not surprisingly, causation plays the most important role in characterizing scientific explanation in the realm of natural necessity. Each model is evaluated crucially with respect to its ability to accommodate causal relevance. All this would vindicate the extension of the grounding relations between the ontological notions of natural necessity to the epistemic notion of explanation: causation grounds causal explanation, which in turn grounds scientific explanation, hence the causal grounding of scientific explanation. For the sake of simplicity, we will henceforth employ the term 'explanation' to refer to causal and scientific explanation.

In our BFO framework, explanation is plausibly taken to a subtype of Information Content Entity (ICE) from an OBO ontology the Information Artifact Ontology [75]: a generically dependent continuant of which that some material entity is a bearer and that *is about* a 'portion of reality', which covers not only BFO categories but also universals, relations, other ICEs and configurations. An ICE is concretized by some information quality entity as a subtype of quality. For instance, an ICE to the effect that Donald Trump is the President of the U.S. is about the configuration of Trump having the role of the U.S. President and it is concretized in a string of alphabetical characters on this paper. Given the dispositional grounding of causation, explanation may well be seen as an ICE that is about some disposition and that is generally recognized to be true in a given scientific community. When biologists agree that an egg is fertilized when it meets a sperm, for instance, an ICE to that effect is about the disposition of the egg to welcome the sperm (as well as the disposition of the sperm to enter the egg) and this ICE is concretized in their *mental qualities* [75]. Along this line of argument, we could ontologize (scientific) hypotheses, although their accurate representation necessitates so careful treatment within the BFO realist framework as to go beyond the scope of our investigation (see e.g., [76]). Here we just say that a hypothesis may be interpreted as an ICE that is about some disposition and whose veracity has not yet been definitively established within a given scientific group.

V. Conclusion

In summary, we pondered over an ontology of causation in relation with the biomedical domain, thereby arguing for the dispositional grounding of causation and illustrating it with canonical causation (and quasi-causation) in our terminology. We then expanded our dispositional view of canonical causation into other sorts of causation that are relevant to biomedical practice: probabilistic causation, simultaneous causation, and mental causation. We finally discussed a dispositional approach to counterfactuals as well as scientifically important epistemic notions such as explanations and hypotheses. Our findings can be succinctly summarized in Table 1.

Future work includes the extension of our dispositional theory of causation to type-level causation (i.e., the causal relation between process universals) because ontological realism compels ontologies to represent, *inter alia*, universals [21]. It will serve as a useful starting point for our discussion to construe type-level causation as a 'causal law' to be used for explaining token-level causation [9,11]. Further investigation is also warranted into our deeper dispositionally causal understanding of other notions of natural necessity such as laws of nature and epistemology of (biomedical) sciences, e.g., with respect to observation and prediction.

Table 1 – Entities and Their Dispositional Representations

Entity	How to represent it dispositionally
canonical causation	Use the relation between the trigger and the realization of a disposition.
quasi-causation	Use a background condition of a disposition.
probabilistic causation	Apply probabilistic dispositions to canonical causation.
simultaneous causation	Do not take it at face value and focus on reciprocal dispositions.
mental causation	Apply mental dispositions (e.g., belief and desire) to canonical causation.
counterfactual	Use a generically dependent continuant that is concretized in some disposition.
explanation (causal and scientific)	Use an information content entity that is about some disposition and that is scientifically verified.
hypothesis	Use an information content entity that is about some disposition and that is yet to be scientifically verified.

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