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Natural necessity: An introductory guide for ontologists

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Abstract. Natural necessity is the kind of necessity that is supplied by 'nature': e.g., necessarily, a glass is broken when it is pressed with a certain force. Relevant topics of natural necessity include causation, dispositions, laws of nature, and counterfactuals. Those subjects are vital for a proper ontological characterization of various entities of scientific inquiry. They are also intimately connected to some scientifically important epistemic notions such as observation, hypothesis, explanation, and prediction. In the field of formal ontology, different notions of natural necessity have been investigated individually to a differing degree and the close interrelationship between them has been little explored. This paper provides an introductory panoramic study of natural necessity in formal ontology to help ontologists utilize it in their actual practice. As for ontology of natural necessity, fundamental commitments to type-level causation, type-level dispositions, and laws of nature are especially discussed. As for its epistemology, close consideration is given to the link between natural necessity and scientific explanation. The practicality of ontology of natural necessity is also illustrated with a case study of suitable primary choices of natural necessity for upper and domain ontologies and its potential application to some domain-specific tasks.

Keywords: Natural necessity, causation, disposition, law of nature, counterfactual

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1. Introduction

1.1. Background and purpose: Ontology and epistemology of natural necessity

Ontologies are nowadays used in a number of different scientific domains, ranging from physics, chemistry, and biomedicine to linguistics, cognitive science, and social sciences. A deeper understanding of sciences would therefore enhance significantly the robust construction of scientific ontologies. It is not straightforward to discover a common thread running through multifarious scientific fields, however, as is indicated by the considerable difficulty of drawing clear lines of demarcation between sciences and pseudosciences (Pigliucci and Boudry, 2013).

One of the most effective ways to meet this challenge is arguably to think of natural necessity (aka physical necessity). First of all, there are many different types of modality (necessity and possibility). In saying "Necessarily, two plus two equal four," for instance, one is speaking of mathematical necessity; and one may find it logically impossible to claim that grass is green and not green. One would express deontic or moral necessity in saying: "You must wash your hands before lunch." In stating "I must have two hands," one may be talking about epistemic necessity: the sort of necessity regarding agents' knowledge of the world. Natural necessity is roughly the kind of necessity that is supplied by 'nature'. Assuming that dropped stones must fall, for example, the fall of dropped stones is necessitated in virtue of some 'natural feature' of the world. In this paper the focus will be on four major topics of natural necessity: causation, dispositions, laws of nature, and counterfactuals. These subjects may be too complex to be defined explicitly, but they can be illustrated with the example of pressing and (Newtonian) force as follows:

- *Causation*: Pressing with a certain force caused a glass to be broken.
- *Disposition*: A fragile glass is disposed to break if it is pressed with a certain force.
- *Law of nature*: Any object will have an acceleration given by the ratio of the resultant force applied on it divided by its mass (Newton's Second Law of Motion).
- *Counterfactual*: If a glass had been pressed with a certain force, it would have broken.

Natural necessity would have also implications for the epistemic dimension of sciences as well as their ontological dimension. Scientists in general observe a certain phenomenon precisely, formulate and confirm hypotheses about that event typically by experiment, offer an adequate scientific explanation of the fact, and sometimes predict future possible outcomes. Granted that natural necessity is at the core of the understanding of objects of scientific inquiry, an accurate picture of scientific phenomena based on ontology of natural necessity would promote closer examination of some scientifically relevant epistemic concepts: e.g., observation, hypothesis, explanation, and prediction.

Indeed, natural necessity has been explored in the field of formal ontology. As will be seen below, causation and dispositions have been investigated comparatively carefully for the last two decades and, in a meticulous analysis of them, laws of nature and counterfactuals are frequently mentioned and discussed. There is also a growing recognition of the need for research into epistemology of ontology. It would seem nonetheless that those four topics of natural necessity have been individually examined and little detailed study has been provided of the interconnection among them in such a way that they are loosely grouped under the heading of natural necessity. This paper aims to offer an introductory comprehensive study of natural necessity, thereby contributing to more robust construction of scientific ontologies. More precisely, the purpose of this paper is not to propose a universally accepted formal-ontological theory of natural necessity; but to specify conceptually which option for modeling natural necessity is congenial to which domain-specific assumptions and knowledge.

1.2. Methodology: Grounding as a meta-ontological tool

As a conceptual tool for investigating natural necessity, a meta-ontological notion of grounding will be leveraged. In formal ontology, there is an increasing practical interest in meta-ontology (Tahko, 2015) as a second-order inquiry into ontologies. Among meta-ontological concepts is a truthmaker: something that 'makes true' (i.e., bears the 'truthmaking relation' towards) a proposition (Armstrong, 2004a; Beebee and Dodd, 2005). The idea of truthmaker or truthmaking has been employed for the last decade to clarify complex ontological categories and relations. Examples include the formalization of states (of affairs) as truthmakers for propositions (Botti Benevides and Masolo, 2014) and the conceptualization of properties, relations, and events in terms of 'truthmaking patterns' (Guarino and Guizzardi, 2016; Guarino, Sales and Guizzardi, 2018).

Grounding is a sibling notion of truthmaking (Schnieder and Correia, 2012; Trogdon, 2013; Raven, 2015); and it has been only recently used in formal ontology, e.g., to give a foundational analysis of roles (Toyoshima, 2018a, 2019e) and contexts (Toyoshima, 2019f). In this paper the most orthodox version of grounding is deployed which is called 'fact-grounding': a primitive relation between facts (Fine, 2001, 2012b). For instance, the fact (say F) that Japan is an eastern Asian country with a population of nearly

130 million is (partially) grounded in the fact (say G) that Japan is an eastern Asian country; and informally, F holds 'in virtue of' G. The theory of fact-grounding is usually coupled with the claim that the grounding relation at least entails (ontological) explanation; see Raven's (2015) survey of controversy over grounding and explanation. In the Japan example, G grounds, and *ipso facto* explains, F. Grounding is also so analogous with causation that one may sometimes call grounding 'ontological causation' (Wilson, 2018).

One can speak of some formal properties of grounding (Fine, 2012a, 2012b). (a) Irreflexivity: no fact grounds itself. (b) Transitivity: if a fact F_1 grounds a fact F_2, which in turn grounds a fact F_3, then F_1 grounds F_3. From (a) and (b) follows straightforwardly the asymmetricity of grounding: if a fact F_1 grounds a fact F_2, then it is not the case that F_2 grounds F_1. Assuming that G is grounded in the fact (say H) that Japan is an Asian country, for example, F is grounded in H by the transitivity of grounding. To simplify the matter, it is set aside a highly debatable topic of whether grounding is, in some sense, 'well-founded': whether it has no infinite descending chains or not (Dixon, 2018). Note that, unlike grounding, the truthmaking relation fails to preserve the property of chaining (Fine, 2012b).

Fact-grounding presupposes an ontology of facts. To keep things manageable, the problematic character of facts is left aside (Mulligan and Correia, 2017). It is instead stipulated that the term 'fact' can be interpreted either as a true proposition or as a state of affairs. On the one hand, a proposition is standardly taken to play three major roles:

- The semantic content of a (declarative) sentence. E.g., two sentences "Snow is white" and "La neige est blanche" express the same proposition that snow is white.
- The object of various linguistic and cognitive attitudes ('propositional attitudes') including belief, assertion, and denial. E.g., when she sincerely utters "Snow is white," Mary bears the believing attitude towards the proposition that snow is white.
- The truthbearer: the bearer of truth-values (truth and falsehood). E.g., the proposition that snow is white is true.

On the other hand, a state of affairs is a concrete, neither linguistic nor cognitive portion of reality, and with a 'propositional structure': e.g., a state of affairs of snow being white (Armstrong, 1997). A fact can be therefore described as something that 'holds' in reality in virtue of its propositional structure, irrespective of whether it is a true proposition or a state of affairs.

Ontology and epistemology of natural necessity can be articulated in terms of fact-grounding: the former (resp. the latter) is about grounding between states of affairs (resp. true propositions) regarding natural necessity. Some cautionary notes need to be made. First, not all the aforementioned four concepts of natural necessity can be construed straightforwardly as facts. Laws of nature and counterfactuals would be intuitively understood as states of affairs, whereas causation and dispositions are not because, as will be seen below, causation is something relational and dispositions are properties. Strictly speaking, states of affairs that have as constituent (in some way) causation or dispositions can be relata of grounding; but for the sake of simplicity, for instance, the statement "Dispositions ground causation" will be employed instead of the one "A fact having as constituent dispositions grounds a fact having as constituent causation". In this respect, this paper may endorse a more moderate view of states of affairs than usually adopted in philosophy and in formal ontology. Second, the terms used in epistemology of natural necessity may be polysemous. When interpreted as an epistemic concept of natural necessity, for example, the term 'explanation' refers not to an act of explaining but to the resulting true explanation (proposition). Third, epistemic notions (propositions) of natural necessity (e.g., hypothesis) can be generally false; but they are postulated to be true when spoken of as relata of grounding.

1.3. Structure of the paper and basic ontological assumptions

The paper is organized as follows. Section 2 presents a general overview of four concepts of natural necessity: causation, dispositions, laws of nature, and counterfactuals. Section 3 explores the question of which is most fundamental among the notions of natural necessity or which grounds all the other concepts of natural necessity. In particular, three possible answers to it are examined there: type-level causation, type-level dispositions, and laws of nature. They are, in other words, arguably three most promising strategies for formalizing natural necessity. Section 4 investigates epistemology of natural necessity, especially the relationship between ontology of natural necessity and relevant epistemic concepts such as explanation, observation, hypothesis, and prediction. Section 5 is devoted to the discussion on the practical usage of natural necessity in ontology building. Section 6 concludes the paper with some brief remarks on future possible directions of research.

For the sake of the anchoring of a general ontological background, some basic categories and relations that are relatively widespread in upper ontologies are posited. Entities fall into two kinds: universals (aka types, classes) and particulars (aka tokens, instances). Note that talk of universals in formal ontology does not *ipso facto* entail philosophical realism about universals (Armstrong, 1989). Particulars (e.g., Mary) bear the instance-of relation to universals (e.g., *Human*); see Smith et al.'s (2005) discussion on and formalization of the type-token distinction. Particulars (resp. universals) fall into two categories: continuants (aka endurants) and occurrents (aka perdurants). Continuants can persist, that is to say, they can exist at one time and also exist at another different time; whereas occurrents (including processes and events) extend through time (typically while having temporal parts). Note that discussion on (the sub-classification of) occurrents in formal ontology is complicated by significantly diverse usages of the terms 'event' and 'process' (and also sometimes the term 'state'). Continuants can be further divided into independent continuants (including objects) and dependent continuants (properties in the broad sense of the term). Independent continuants, or especially objects (e.g., stones) can be bearers of dependent continuants (e.g., hardness) and can participate in occurrents (e.g., a fall of the stone).

2. Four concepts of natural necessity

2.1. Causation

Causation has been carefully investigated in a number of different domains, ranging from philosophy (Collins, Hall and Paul, 2004; Price and Corry, 2006; Paul and Hall, 2013) and artificial intelligence (Pearl, 2009) to linguistics (Bittner, 1999) and cognitive science (Waldmann, 2017). This paper focuses upon several existing formal-ontological studies of causation, partly because they generally accommodate findings on causation from other disciplines to serve as a point of reference or a common ground for comparing and integrating various theories of causation.

There would be broad agreement among those prior works on some basic characteristics of causation. First, causation is (or at least can be represented as) a binary relation between occurrents. The terms 'causation' and 'causal relation' will be hereafter used interchangeably. Certainly, non-occurrent entities are often regarded as a cause or an effect in our everyday discourse. To take Galton's (2012b) example, the fact "The accident was caused by a lorry-driver" would seem to refer to an object (the lorry-driver) as the cause of the accident (effect). As Galton (2012b) says, however, it is natural to think that objects can only cause things by *doing* something; and this fact should be seen e.g., as the causal relation between the occurrent of the lorry-driver's breaking suddenly and the occurrent of the accident. Seen from the perspective of grounding, causal facts such as "The accident was caused by a lorry-driver" are at best 'causal explanations' (to be detailed in Section 4) in the epistemic sphere of causation that are grounded in causal states of affairs in its ontological sphere.

Consequently, different formal-ontological accounts of causation are individuated largely according to different foundational frameworks for occurrents within which they are built. In Lehmann, Borgo, Masolo and Gangemi's (2004) ontology which is developed in compliance with an upper ontology the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE; Masolo, Borgo, Gangemi, Guarino and Oltramari, 2003; Borgo and Masolo, 2010), for instance, causation depends on a specific choice of constraints (structural, causal, and circumstantial) which are in turn to be explicable in terms of dependencies between *quality changes* (which DOLCE characterizes occurrents primarily as). In Michalek's (2009) ontology with an upper ontology General Formal Ontology (GFO; Herre, 2010), the causal relation holds primarily between presentials in GFO, where a presential is "an individual which is entirely present at a time-point" (ibid., p. 309); and secondarily between processes in GFO, which "have a temporal extension thus cannot be wholly present at a timepoint" (ibid., p. 310). In Galton's (2012b) and Toyoshima, Mizoguchi and Ikeda's (2019) ontologies with the 'waterfall view' of the world (Galton and Mizoguchi, 2009; Galton, 2012a), the causal and causal-like relations are investigated based on three kinds of occurrents, namely events as 'completed occurrents', processes as 'ongoing occurrents', and states as 'static occurrents' or 'passive occurrents'; see Stout's (2018) philosophical and Toyoshima's (2019b) formal-ontological discussions on processes in this 'ongoing' sense of the term. In Toyoshima's (2019a) work with an upper ontology Basic Formal Ontology (BFO; Arp, Spear and Smith, 2015; Smith et al., 2015), the causal relation holds between processes in BFO, where a process is 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" (Arp et al., 2015, p. 183).

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 contract lung cancer). Lehmann et al. (2004) call the former and the latter 'causality' and 'causation' respectively; and causality and causation refer to the causal relation between occurrent universals and between occurrent particulars, respectively. (The terms 'type-level causation' and 'token-level causation' are preferred in this paper to prevent terminological confusion, however.) As Galton (2012b) hints, type-level causation may be said to be a 'causal law' that is used for *explaining* token-level causation. To explain why Mary contracted lung cancer, doctors may refer to a clinical general rule (type-level causation) according to which if a person smokes (and some background conditions hold), then she will contract lung cancer. In this way, causation has a significant bearing on epistemic notions such as explanation (see Section 4 for the epistemic aspect of causation). It can be also said that token-level causation is always grounded in type-level causation.

2.2. *Disposition*

Dispositions have been arguably the most carefully investigated of all the four concepts of natural necessity in formal ontology for the last decade. A disposition is a property 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 an occurrent, a disposition needs to be triggered by some other occurrent. Classical examples include fragility (the disposition to break when pressed with a certain force), solubility (the disposition to dissolve when put in a certain solvent), and flammability (the disposition to ignite when met with a certain heat source). 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. As with causation, there are two types of dispositions, namely token-level dispositions (e.g., fragility of this particular glass) and type-level dispositions (e.g., fragility of the glass universal), such that the former is always grounded in the latter.

On the theoretical side, dispositions have been conceptually and logically examined typically in accordance with BFO (which has the category of dispositions as realizable entities) so that different kinds of dispositions can be represented in Web Ontology Language (OWL) (Horrocks, Patel-Schneider, McGuinness and Welty, 2007). Examples of dispositions previously researched include single-track dispositions (Röhl and Jansen, 2011), multi-track dispositions (Barton and Jansen, 2016), probabilistic dispositions (Barton, Burgun and Duvauferrier, 2012), blocking dispositions (Goldfain, Smith and Cowell, 2010), collective dispositions (ibid.), and complementary dispositions (ibid.) or reciprocal dispositions (Toyoshima and Barton, 2019a). Mereology among dispositions (Barton, Jansen and Ethier, 2017a) and the identity of dispositions (Barton, Grenier, Jansen and Ethier, 2018b) have been also recently studied.

On the practical side, ontology of dispositions has been exploited for a formal modeling of a wide variety of entities. Examples of entities that are analyzed along dispositional lines include disease (Scheuermann, Ceusters and Smith, 2009; Goldfain et al., 2010; Barton, Grenier and Ethier, 2018a; Toyoshima, 2019c) and risk (Barton, Jansen, Rosier and Ethier, 2017b) in biomedicine; Newtonian force (Barton, Rovetto and Mizoguchi, 2014) and velocity (Barton and Ethier, 2016) in physics; simulation modeling (Guizzardi and Wagner, 2013) in engineering; capability (Miranda, Almeida, Azevedo and Guizzardi, 2016; Merrell, Limbaugh, Anderson and Smith, 2019); and belief (Barton, Duncan, Toyoshima and Ethier, 2018), desire (Toyoshima, 2019a), affordances (Toyoshima, 2018b; Toyoshima and Barton, 2019a), and image schemas (Toyoshima and Barton, 2019b) in cognitive science.

A cloud of suspicion hangs over dispositions in formal ontology notwithstanding a vast amount of research on them. For instance, Guarino (2016, p. 14) criticizes the BFO category of dispositions as follows: "The connection between a particular kind of crystalline structure [of a fragile object] and the corresponding conditional behavior is given by a law of nature, whose ontological presuppositions do not require the existence of other specifically dependent continuants [dispositions in BFO] besides the crystalline structure itself. Of course, it may be important, for scientific reasons, to be able to *represent* such laws of nature, but this is not a good reason to introduce an ad hoc ontological category."

Guarino's worry may derive from the polysemy of the term 'disposition'. To clarify this point, it would be useful to introduce Bird's (2016) distinction between *dispositions* as 'predicatory properties' and (*causal*) *powers* as 'ontic properties'. Predicatory properties are properties that are defined by almost any predicate (e.g., "This apple *is green or not green*"). The predicatory usage of the term 'property' is an ontologically uncommitted, mere *façon de parler*: e.g., the property of being green or not green. Ontic properties are, by contrast, properties with a distinctive ontological role such as the property of being negative charged (which is vital in physics and chemistry); and powers are ontic properties with dispositional *essence*. Interpreted from this point of view, Guarino would seem to criticize BFO for accepting the ontic construal of the term 'disposition' (hence an ontological commitment to powers) since BFO has the distinctive ontological category of dispositions, and also to espouse its predicatory view because he suggests indirectly that dispositions be grounded in laws of nature.

As will be argued in Section 5, BFO would be indeed fundamentally committed to dispositions, as Guarino rightly points out. He may be wrong in saying however that the BFO category of dispositions is 'an ad hoc ontological category' because BFO could coherently endorse the dispositional grounding of laws of nature, which is completely different from Guarino's strategy for grounding dispositions in laws of nature. In philosophy of natural necessity, the question of which is the primary notion of natural necessity has been usually addressed in a 'monarchical' attempt to seek a single privileged answer to it. What is desirable for formal ontology of natural necessity is, however, the 'republican' task of figuring out accurately which fundamental commitment to natural necessity (that could be found in upper ontologies) meshes with which domain-specific needs and assumptions. In the latter approach embraced by this paper, dispositions (in the predicatory sense of the term) should not be neglected because they are ontologically relevant regardless of which is the most basic concept of natural necessity.

2.3. *Law of nature*

Laws of nature (e.g., Newton's Second Law of Motion) are, roughly, general facts that do not merely happen to be the case. On the other hand, it is a mere accidental generalization, but not a law of nature, that every solid lump of gold is less than ten cubic meters in volume (assuming that this is true). In previous formal ontology research (Lehmann et al., 2004; Galton, 2012b), laws of nature are referred to most often in analyzing causation, or especially in explaining the law-like character of type-level causation. They are also sometimes (if not as frequently) mentioned in discussions on dispositions (Röhl and Jansen, 2011). Rarely has careful formal-ontological consideration been given to laws of nature as such, however. To take the first step towards an ontology of laws of nature, some of the main philosophical views of them are presented:

- *The regularity theory*. Laws of nature are true regularities. More precisely, a regularity of the sentential form "All Fs are Gs" (where F and G are suitable predicates) is a law of nature if and only if all Fs are Gs. At the price of its extreme simplicity, the regularity theory has been subject to harsh criticism (Armstrong, 1983). For instance, it is fairly obscure whether and how the meaning of the regularity theorist's term 'suitable' can be restricted to exclude from the realm of lawhood the fact that every solid lump of gold is less than ten cubic meters in volume.
- *The best-system theory* (aka the Ramsey–Lewis theory) (Ramsey, 1928; Lewis, 1973b, pp. 72–77). The basic idea is that a sentence S is a law of nature if and only if S features as an axiom or a theorem in the best deductive theory of the world, or more specifically, in the deductive system of true sentences that achieves the best balance between simplicity and strength. In other words, a sentence counts as a law of nature when it is part of the best axiomatization of our (scientific) knowledge of the world. Despite its elegant simplicity ("$F = ma$"), for example, Newton's Second Law of Motion is strong enough to account for various physical phenomena, thus contributing to the overall set of laws of nature (Beebee, 2000; Hall, 2015).
- *Primitivism*. Laws of nature are primitive: they are insusceptible to further analysis. For instance, Maudlin (2007) argues that laws of nature ought to be accepted as ontologically primitive and elaborates a law-based account of physical possibilities, counterfactuals, and explanations. Primitivism is sometimes coupled with the 'sentential operator view' of lawhood: e.g., $\Box p$ where $\Box$ and p are semantically read as "it is a law of nature that" and "any object has an acceleration given by the ratio of the resultant force applied on it divided by its mass", respectively.
- *The Dretske–Tooley–Armstrong (DTA) theory* (Dretske, 1977; Tooley, 1977; Armstrong, 1983). Armstrong (1983, p. 85) concisely describes the core idea: "Suppose it to be a law that Fs are Gs. F-ness and G-ness are taken to be universals. A certain relation, a relation of non-logical or contingent necessitation, holds between F-ness and G-ness. This state of affairs may be symbolized as '$N(F, G)$'." It is a law of nature that all humans are mortal (assuming that this is the case), for instance, in virtue of the fact that the universal *being human* (F) bears the primitive 'contingent necessitation' relation (N) toward the universal *being mortal* (G). Note that N is *contingent* necessitation because it is contingent *which* universals are related by N.

While the regularity theory is off the table since it is generally thought to be conceptually seriously flawed, the other three theories of laws of nature would be equally plausible candidates for a formal-ontological treatment of laws because each of them has both its advantages and disadvantages. Although it may be nowadays one of the most popular accounts, the best-system theory would leave laws of nature problematically anthropocentric: laws are explanatorily dependent on people's actual and current preferences as to simplicity and strength. It would be also rather hard to model formally owing to its dependence on the complex notions of simplicity, strength, and the best combination of them. Despite its apparent formal merit, primitivism would be available only for those who take laws of nature to be most fundamental in ontology of natural necessity (see Section 3). Finally, the DTA theory may mesh well with the law-like view of type-level causation in formal ontology, whereas it may lack the virtue of generality owing to its realist commitment to universals (Armstrong, 1989), which is a traditional subject for debate in formal ontology; see the exchange of views between Smith and Ceusters (2010) and Merrill (2010a, 2010b). A worry would also arise as to the extensibility of an ontology of laws of nature aligned with the DTA theory because not all laws can have the simple form $N(F, G)$ and it is unclear how the quantitative aspect of laws of nature (e.g., physical laws) can be formalized in this direction.

2.4. Counterfactual

Counterfactuals are facts that represent what did not happen or what is not the case: e.g., if a glass had been pressed with a certain force, it would have broken. 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." Seldom have counterfactuals as such been examined closely in formal ontology. For one thing, counterfactuals, or especially logics of counterfactual conditionals, have been already researched extensively in other domains such as philosophy (Stalnaker, 1968; Lewis, 1973b; Kvart, 1986), modal logic (Meyer and Veltman, 2007), and artificial intelligence (Costello and McCarthy, 1999).

In philosophy of natural necessity, grounding of counterfactuals has two general features. First, counterfactuals are used to ground causation and dispositions, but it is widely recognized to be highly problematic. A counterfactual theory of causation has been fairly popular and its most basic version says that c was a cause of e if and only if e counterfactually depends on c: that is to say, if and only if c and e occurred, and if c had not occurred, then e would not have occurred (Lewis, 1973a, 2000). This approach has been however severely criticized for many counterexamples (Collins, Hall and Paul, 2004; Paul and Hall, 2013); but see Beckers and Vennekens's (2018) recent work. Likewise, 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 if and only if the object would realize r if s were the case (Lewis, 1997). This view has been also subject to numerous critical appraisals (Martin, 1994; Bird, 1998); but see Gundersen's (2017) and Schlosser's (2018) recent works.

Second, counterfactuals are usually grounded in laws of nature when they are supposed to ground causation and/or dispositions. For example, Lewis (1973a, 1997, 2000) can be seen as a staunch advocate for the counterfactual grounding of causation and dispositions, but Lewis (1973b) builds his theory of counterfactuals upon the 'similarity relation' between possible worlds that can be measured by laws of nature of each world. This would mean the grounding of counterfactuals in laws of nature.

In formal ontology, counterfactuals are discussed when the topic is causation or dispositions, but quite differently in different contexts. For instance, Michalek's (2009) formal-ontological theory of causation involves only partially the counterfactual grounding of causation. Contrarily, Röhl and Jansen (2011) maintain that disposition ascriptions entail counterfactual conditionals, which would mean the dispositional grounding of counterfactuals. In another direction, Galton (2012b) implies an intimate connection between counterfactuals and causal explanation (rather than causation). There would be, overall, no general consensus on a formal-ontological treatment of counterfactuals *vis-à-vis* causation and dispositions. In addition, unlike in philosophy of natural necessity, there is no explicit argument for the lawful grounding of counterfactuals; see e.g., Michalek's (2009) work.

3. Fundamental choices as to natural necessity

Ontology of natural necessity is, at bottom, characterized by which is the most fundamental concept among causation, dispositions, laws of nature, and counterfactuals. It is proposed in this paper that there are three possible primary notions of natural necessity: type-level causation, type-level dispositions, and laws of nature. After preliminaries on causation, how the most basic concept of natural necessity could ground some other ones in each case will be scrutinized below. It is reasonable to acknowledge fundamental commitments to laws of nature and dispositions because they constitute the two prominent theories in philosophy of natural necessity (Koons and Pickavance, 2014). Although it may occupy a minor position in philosophy (Tooley, 1987), the primacy of type-level causation is also well worth considering in formal ontology, partly because type-level causation is close to laws of nature in the sense of being conceived as 'causal *laws*' (Galton, 2012b), partly because some upper ontologies would seem to take type-level causation to be most basic (see Section 5). On the contrary, the counterfactual grounding of natural necessity will not be discussed here, as is witnessed by the fact that neither in philosophy of natural necessity nor in formal ontology has this view been regarded as tenable. For instance, it is hardly intelligible how laws of nature can be grounded in counterfactuals.

3.1. Canonical causation and quasi-causation

A more detailed description of causation is required to consider carefully the grounding of natural necessity. A primary focus will be upon the paradigmatic kind of causation around which formal ontology of causation generally centers and which may be called 'canonical causation' (Toyoshima, 2019a). Although it may defy easy description, canonical causation has at least four characteristics. First, it is observed in the macroscopic world in which classical (Newtonian) mechanics (Bittner, 2018) holds (see Section 6 for some thoughts on causation in non-classical physics). Second, it is so-called forward causation (where the cause occurs earlier than its effect); and simultaneous causation (where the cause occurs at the same time as its effect) (Taylor, 1966) and backward causation (where the cause occurs later than its effect) (Dummett, 1954; Flew, 1954) are left aside. Third, it is so-called physical causation (roughly, the causal relation which is entirely explicable in physical terms); and mental causation (Heil and Mele, 1993; Walter and Heckmann, 2003) and agent causation (O'Connor, 2000) are set aside. Fourth, it is non-probabilistic as compared to probabilistic causation (Hitchcock, 2016). For instance, it is always the case that pressing with a certain force causes a glass to be broken; and in this sense, the occurrent of pressing a glass with a certain force bears the canonical causal relation towards the occurrent 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 occurrent of the toss of the coin and the occurrent of the coin landing on heads is probabilistic because the coin could have landed on tails (with the probability 50 percent).

To ensure generality, it is postulated that the (canonically) causal relation holds between occurrents, their more specific characterization being open to interpretation (Kim, 1976; Davidson, 1980; Botti Benevides, Bourguet, Guizzardi, Peñaloza and Almeida, 2019; Rodrigues and Abel, 2019). The causal relation is generally acknowledged to be irreflexive and asymmetric. That is to say, no occurrent caused itself; and if an occurrent x caused an occurrent y, then it was not the case that y caused x. On the other hand, the transitivity of the causal relation (i.e., whether an occurrent x caused an occurrent z if x caused an occurrent y, which in turn caused z) is not presupposed because it is a highly controversial topic (Hall, 2000; Paul and Hall, 2013).

Interesting enough, there is also a causal-like relation which a state bears to serve as a precondition for the causal relation to hold (Galton, 2012b) and which may be called ‘quasi-causation’ (Toyoshima, 2019a). For example, the state of the presence of oxygen in this room bears the quasi-causal relation towards the causal relation between the striking of a match and the lighting of the match. The quasi-causal relation can be labeled as the verb ‘allow’ (Galton, 2012b): e.g., the presence of oxygen *allowed* the striking of a match to cause the match to light. As for states, Galton (2018a) identifies their two distinct, albeit related, meanings (which would be concordant with e.g., Chaudhri and Inclezan’s (2015) analysis of the multiple usages of the term ‘state’ in a biology textbook):

- *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 Celsius.

It is undecided in this paper whether a state is fundamentally a continuant (Jansen, 2015) or an occurrent (Galton and Mizoguchi, 2009; Galton, 2012a) because it depends on some general ontological assumptions. For instance, states would be classified *primarily* as subtypes of continuants in BFO (Toyoshima, 2019a) and subtypes of occurrents in DOLCE (Galton, 2018a). In addition, the notion of precondition used has been formally studied with regard to situation calculus (McCarthy and Hayes, 1969) and event calculus (Kowalski and Sergot, 1986) in knowledge representation.

3.2. Fundamental choice (i): Type-level causation

The primary commitment to type-level causation is naturally paired with the claim that causal and quasi-causal relations between occurrent universals are primitive. Further elucidation of this claim would need a robust ontology of relations (Marmodoro and Yates, 2016; Guarino and Guizzardi, 2016) which is beyond the scope of this paper. One possible understanding may be however that occurrents are as such, in some sense, causally efficacious (Galton, 2012b; Toyoshima et al., 2019); and since this implies the ontological significance of occurrent universals, laws of nature would be reasonably conceptualized in the DTA theorist’s fashion. As for the type-level causal grounding of counterfactuals, for instance, the truth of the counterfactual conditional “If this glass had been pressed with a certain force, it would have broken” is determined by type-level causation to the effect that pressing with a certain force causes a glass to be broken.

When grounded in type-level causation, dispositions are to be interpreted functionally (Mumford, 1998) in the sense that the functionalist about dispositions takes dispositions to be ‘second-order’ functional properties such that they have some first-order property that plays a causal role with respect to their inputs (triggers) and their outputs (realizations); see Barton, Grenier, Jansen and Ethier's (2018b) functional direction of research into dispositions. In this point, the functionalist reduces the alleged causal role of dispositions to the one of properties to which they are functionally related. On the functionalist view, for example, the causal feature of fragility of a glass is explicable in terms of the one that some specific molecular structure of the glass has in relation with the shock on the glass and the breaking of the glass. To put it in another way, the type-level relation between the trigger and the realization of a disposition is grounded in some type-level causal relation.

Furthermore, the type-level causal grounding of dispositions applies to quasi-causation as well. To explain this, the notion of background condition of a disposition is introduced: roughly, a necessary condition for the realization of the disposition (Röhl and Jansen, 2011; Barton et al., 2014). The presence of oxygen is a background condition of the flammability disposition of a match, for instance. Given the fundamentality of type-level causation, the type-level background condition of a disposition can be grounded in some type-level quasi-causal state for the corresponding causal relation. For one thing, the trigger and a background condition of a certain disposition are largely pragmatically distinguished causal factors (Röhl and Jansen, 2011) 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 preconditional states for the causal relation failed to. For another, background conditions can comprise categorially diverse kinds of entities (ibid.) and this conforms to the aforementioned observation that preconditional states of quasi-causation can be construed as either continuants or occurrents (see Section 3.1).

3.3. Fundamental choice (ii): Type-level disposition

Not surprisingly, the fundamental choice of type-level dispositions leads to powerism (Mumford and Anjum, 2011b): the doctrine that is committed to ontology of powers, i.e., ontic properties that have their own causal potency, to the manifestation of which the powerist attributes causation. On this powerist account, dispositions play a substantial causal role in the world. (Note that, unless considerable confusion arises, the term 'disposition' will be preferred over the term 'power' even within the powerist's worldview, partly because the latter currently receives little recognition in formal ontology.) More perspicuously, the crux of a dispositional approach to causation is that causation occurs only when some disposition is realized (Mumford and Anjum, 2010, 2011a, 2011b). For instance, a glass broke in virtue of the realization of the fragility disposition of the glass triggered by pressing the glass with a certain force. As the dispositional view goes, therefore, the type-level causal relation is grounded in some type-level relation between the trigger and the realization of a disposition; and the type-level quasi-causal state for a given causal relation is grounded in some type-level background condition of the relevant disposition.

Concerning laws of nature, there are two main dispositional accounts of them in philosophy of natural necessity. One is Bird's (2007) *dispositional reductionism*, according to which "The laws of a domain are the fundamental, general explanatory relationships between kinds, quantities, and qualities of that domain, that supervene upon the essential natures of those things" (ibid., p. 201) where, by the standard definition, A-properties *supervene upon* B-properties if and only if no two entities can differ with respect to the A-properties without differing with respect to the B-properties. The other is Mumford's (2004, 2005) *dispositional eliminativism*, which justifies the non-existence of laws of nature on the grounds that the role that they are supposed to fulfill is completely performed by powers; see Bird's (2007) criticism. Those two theories, despite some non-trivial differences between them, share the conviction that laws of nature are mere reflections of which dispositions exist and how they work together. Because of its endorsement of primitively dispositional properties, the dispositional grounding of laws of nature would fit well with their DTA-theoretic treatment, primitivism being clearly off the table; but it can be plausibly consistent with the best-system theory (Demarest, 2017).

Lastly, the dispositional grounding of counterfactuals is shown by the entailment of counterfactual conditionals by disposition ascriptions (Röhl and Jansen, 2011). For instance, the truth of the counterfactual conditional "If this glass had been pressed with a certain force, the glass would have broken" is given by the 'disposition fact' that a (fragile) glass is disposed to break if it is pressed with a certain force. As for formalization, Jacobs (2010) develops a dispositional semantics for counterfactuals; see Yates's (2015) criticism. Jacob's purpose is to generate a dispositional semantics for modal logic (as an alternative to traditional possible world semantics; Braüner and Ghilardi, 2007) which is motivated by the dispositionalist's standard actualist account of modality (Borghini and Williams, 2008) according to which modality is grounded in dispositions within the (only existing) actual world, as compared to the possibilist view (Lewis, 1986) that modality is grounded in the (possible) entities in possible worlds. To achieve the same goal, Vetter (2015) builds a dispositional semantics for modal operators based on her original concept of potentiality. See Warmke's (2016) general survey of dispositional semantics for modal logic, which are presently generally underdeveloped, though.

3.4. Fundamental choice (iii): Law of nature

The third option for modeling natural necessity is its grounding in laws of nature. When they are taken to be most fundamental, laws of nature can be interpreted along with either the best-system theory or primitivism or the DTA theory; and their choice should be made on a case-by-case basis. For instance, one may adopt either of the former two accounts if the nominalist treatment of properties (Rodriguez-Pereyra, 2002) is preferable, including the trope theory (Simons, 1994; Maurin, 2002; Ehring, 2011). More specifically, one may employ primitivism in seeking a rigorous (modal) formalization of laws of nature (Bittner, 2018). As was said in Section 2.4, the lawful grounding of counterfactuals has been carefully investigated in philosophy of natural necessity (Lewis, 1973b).

There are several ways in which causation can be grounded in laws of nature depending on how they are conceptualized. The best-system theorist can make an (albeit hardly promising) attempt to ground causation in laws of nature by way of counterfactuals (Lewis, 1973a, 2000). The primitivist may think that causation depends on laws of nature which govern a situation and intuitions about causation are based on 'lawlike generalizations' rather than on laws as such: "generalizations which resemble laws at least insofar as being regarded as supporting counterfactual claims and being confirmed by positive instances" (Maudlin, 2007, p. 158). The DTA theorist would think that causation is, in some sense, an 'instantiation' of laws of nature (Armstrong, 1983, pp. 93–96; Armstrong, 2004b). In any case, the lawful grounding of causation is such that laws of nature as the most general laws (e.g., Newton's Second Law of Motion) ground type-level causation as more specific 'causal laws' (e.g., pressing a *given* glass with a certain force *causes* the glass to be broken), which grounds in turn token-level causation as particular causal phenomena (e.g., pressing *this* glass with a certain force *caused* the glass to be broken).

Finally, to explain the grounding of dispositions in laws of nature, the notion of categorical basis of a disposition is introduced: a categorical property or the sum of categorical properties of the disposition (Röhl and Jansen, 2011; Barton, Grenier, Jansen and Ethier, 2018b) where a categorical property is, roughly, a non-dispositional, causally inert property. Paradigmatic examples of categorical properties include the property of being square and the property of having some molecular structure. For instance, the fragility disposition and the electrical sensitivity disposition of a glass should be grounded in different (sums of) categorical properties of the glass, even though they have as their material basis the same, whole glass. The lawful grounding of dispositions typically involves categoricalism about dispositions, which says that dispositions are mere reflections of their categorical bases that act in accordance with laws of nature (Lewis, 1986). In other words, the purported causal role of dispositions would be eliminable for the categoricalist because it boils down to lawful dynamics of their categorical bases. Despite its apparent causal potency, for instance, fragility of a glass represents nothing more than possible (physically) lawful movements of some specific molecular structure of the glass.

4. Epistemology of natural necessity

4.1. *Scientific explanation*

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 concepts of natural necessity. First of all, scientific explanation will be carefully investigated among the scientific epistemic notions because it is of central importance to sciences, 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.

4.1.1. *Related work*

In formal ontology, the notion of explanation has been considered especially in connection with observations (Masolo, 2016; Masolo, Botti Benevides and Porello, 2018), but it has been scarcely ever studied from the perspective of natural necessity. A brief summary will be given of some leading philosophical models of scientific explanation (Salmon, 1989; Woodward, 2017):

- *The Deductive-Nomological* (*DN*) *model* (aka the covering law model). The basic idea is that a scientific explanation consists of an explanans and an explanandum such that there is a sound deductive argument whose premises are the explanans and whose conclusion is the explanandum; and the explanans contains at least one 'law of nature', where laws of nature were initially conceived in the regularity theorist's fashion (Hempel, 1965). Although it is the most influential view of scientific explanation, the DN model has been susceptible to a number of counterexamples (Salmon, 1989, Chapter 2.3).
- *The Statistical Relevance* (*SR*) *model*. The underlying intuition that a scientific explanation is an assembly of information that is statistically relevant to its explanandum; in other words, the explanans is determined by its statistical relevance relationship with the explanandum (Salmon, 1971). One consequence of this is that the same explanans may explain both a certain explanandum and explananda that are inconsistent with that explanandum. A fundamental problem with the SR model is the well-known underdetermination of causal relationships (which scientific explanations are plausibly taken to cite typically) by statistical relevance relationships.
- *The Causal Mechanical* (*CM*) *model*. The CM model introduces two central causal notions: *causal processes* and *causal interactions*. A causal process is an occurrent (e.g., the moving of an automobile) that is characterized by the ability to transmit a *mark* (e.g., a dent on the automobile fender) in a (spatio-temporally) continuous way, where a mark roughly means some local modification to the structure of the occurrent. A causal interaction involves a spatio-temporal intersection between two causal processes which modifies the structure of both: e.g., a collision between two cars that dents both. The main claim is that a scientific explanation of an occurrent O is to trace (at least some

portions of) the causal processes and interactions leading to O (Salmon, 1984). A worry arises as to the gap between causal and explanatory relevance in the CM model and its applicability to complex systems, thereby resulting in repeated restatements of the CM model (Salmon, 1994, 1997).

- *The unificationist model*. The primary thought is that scientific explanation is a matter of providing a unified account of a range of different phenomena. Kitcher (1989, p. 432, de-italicized for readability) encapsulates this theory as follows: "Science advances our understanding of nature by showing us how to derive descriptions of many phenomena, using the same patterns of derivation again and again, and, in demonstrating this, it teaches us how to reduce the number of types of facts we have to accept as ultimate (or brute)." On this view, the causal knowledge of phenomena derives from the efforts at unification of them. There is considerable doubt about whether and how the notion of unification involved in this model can be precisified well enough to capture causal and explanatory relevance. It is well worth noting that Salmon (1989) pursues harmonization between the CM model and the unificationist model because he thinks: "Kitcher is firmly committed to the general thesis (with which I am strongly inclined to agree) that unification is a fundamental goal of explanation – that unification yields genuine scientific understanding" (ibid., p. 101).

4.1.2. Causation, counterfactual, and causal explanation

The previous four models listed above provide some insights into an inextricable connection between natural necessity and scientific explanation. 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, causation plays the most important role in characterizing scientific explanation of all the four ontological concepts of natural necessity. Each model of scientific explanation is evaluated crucially with respect to its ability to accommodate causal relevance. The DN model undoubtedly depends on laws of nature; still, it is convincingly taken to approach causation through its lawful grounding. All this would vindicate the grounding relations between the ontological fact (state of affairs) of causation and the epistemic facts (true propositions) of causal and scientific explanations: causation grounds causal explanation, which in turn grounds scientific explanation. This claim can be represented in the following diagram, where boldface, italics, and arrows ('→') mean ontological facts (states of affairs), epistemic facts (true propositions), and grounding relations between them, respectively:

causation → *causal explanation* → *scientific explanation*

To elucidate the grounding relation between causation and causal explanation, consider the issue of negative causation (Schaffer, 2004) which is also known as causation by disconnection (Schaffer, 2000) and absence causation (Schaffer, 2005). In particular, two cases of negative causation will be discussed: causation by absence (aka causation by omission) and causation by double prevention (aka causation by omission of prevention). First, causation by absence is the causal phenomenon where the cause is allegedly the absence: e.g., the absence of Vitamin C caused scurvy (Schaffer, 2000). On arguably the most persuasive interpretation, no absence can enter into causation regardless of whether it is canonical or quasi-causal because one would be otherwise problematically committed to the arbitrary reification of absence such as a continuant (or an occurrent, especially a state) of the absence of Vitamin C. Therefore, causation by absence must find itself in the epistemic sphere of causal explanation, but not in the ontological sphere of causation. For instance, the fact that the absence of Vitamin C caused scurvy is not a causal state of affairs but a causal explanation that is grounded in causation. Thus, the following grounding relation holds:

The ontological fact (state of affairs) that scurvy was caused (causation)

→ *The epistemic fact (proposition) that the absence of Vitamin C caused scurvy*

(causal explanation)

More concrete approaches to causation by absence depend on which is the most basic concept of natural necessity; see Mumford and Anjum's (2011b) dispositional understanding of causation by absence.

Second, causation by double prevention is illustrated by Hall (2004) as follows. Suppose that Suzy's plane will bomb an enemy target if she is not shot down by an enemy pilot; and, piloting another plane, Billy shot down the enemy; and finally, Suzy bombed the enemy target. Intuitively, Billy's shooting the enemy caused Suzy's bombing the enemy target in the sense that Billy's shooting the enemy pilot *prevented* the enemy pilot's shooting Suzy, which had it occurred would have *prevented* Suzy's bombing the enemy target. This case should not be taken ontologically at face value either because, as Mumford and Anjum (2009) argue, causation by double prevention entails causation by absence. Different foundational choices as to natural necessity would yield different accounts of causation by double prevention; see Mumford and Anjum's (2009) dispositional view of causation by double prevention.

Moreover, the expansion of ontology of natural necessity to scientific explanation would bring the theoretical value of counterfactuals into sharp focus. It is broadly acknowledged that a counterfactual analysis of causation claims to treat negative causation better than other competing (e.g., dispositional) theories (Schaffer, 2000, 2004). Given that counterfactuals are highly unlikely to ground causation (see Section 2.4) and that negative causation resides in the epistemic realm of causal explanation, it would be plausible to think that counterfactuals act as an intermediary between the ontological notion of causation and the epistemic notion of causal explanation in the sense that causation grounds counterfactuals, which in turn ground causal explanation. It can be further submitted that counterfactuals thereby aid in elucidating the relationship between causation and causal explanation. This argument can be depicted in the following diagram based on the notation introduced above:

causation → **counterfactual** → *causal explanation* → *scientific explanation*

E.g., **The ontological fact (state of affairs) that scurvy was caused** (causation)

→ **The ontological fact (state of affairs) that if this patient had taken more vitamin C,**

she would not have contracted scurvy (counterfactual) → *The epistemic fact (proposition) that*

the absence of Vitamin C caused scurvy (causal explanation)

4.2. *Observation, hypothesis, and prediction*

Three other epistemic notions than (scientific) explanation will be briefly discussed: observation, hypothesis, and prediction. The first thing to note is that they can be broadly characterized according to the temporal dimension of scientific practice, although a full-fledged ontology of time is outside the scope of this paper (see Section 6). For scientists in general formulate hypotheses to extract explanations of the *present* world from observations that they *made in the past*; and they also predict *future* possible outcomes based on their explanations and/or hypotheses. At first approximation, observations, hypotheses, and predictions are propositions that are about the past, the present, and the future, respectively.

In formal ontology, observations have been investigated mainly from an epistemological standpoint (Masolo, 2016; Masolo et al., 2018) from which they can be conceptualized as "empirical or cognitive classifications of objects under (qualitative or quantitative) *concepts* (. . .) that result from measurement, testing, perceptive, cognitive, or analytical processes" (ibid., p. 43). Seen from the perspective of natural necessity, observations are propositions that are about the past and that are grounded in some explanation when they are true, which is diagrammatically representable as follows:

causation → **counterfactual** → *causal explanation* → *scientific explanation* → *observation*

For instance, a 18th-century chemist Lavoisier offered an explanation of his (true) observation of combustion saying that a substance which he termed 'oxygen' is incorporated into objects when they burn, hence the following grounding relation:

The epistemic fact (proposition) that oxygen is incorporated into objects when they burn

(scientific explanation)

→ *The epistemic fact (proposition) that combustion occurred* (observation)

It is an interesting line of inquiry to compare (and integrate) the present view of explanation as a proposition that grounds observations with an epistemological, observational interpretation of explanation as "a cognitive process that induces a *simple* observation to emerge from a (possibly) complex one" (Masolo, 2016, p. 203).

In contrast with observation (and explanation), hypotheses have been little considered explicitly in formal ontology, arguably much less prediction. As the simplest account goes, confirmed hypotheses (i.e., those which turn to be true) would be ontologically equivalent to explanations; and confirmed predictions are grounded in explanations or true hypotheses. For example, physicists' true prediction of the discovery of black holes can be grounded in the theory of general relativity, namely a specific explanation of spacetime. Those contentions can be together described in the following diagram:

causation → **counterfactual** → *causal explanation* → *hypothesis* → *prediction*

E.g., *The epistemic fact (proposition) that the theory of general relativity holds*

(hypothesis, confirmed)

→ *The epistemic fact (proposition) that black holes will be discovered* (prediction)

Questions arise, by contrast, as to the ontological nature of *unconfirmed* hypotheses and predictions. For instance, Soldatova and Rzhetsky (2011) maintain that, despite their importance in (biomedical) ontology research, unconfirmed hypotheses can be hardly represented in the BFO realist framework (Smith and Ceusters, 2010) because it remains to be seen whether they are truly part of the world. Further investigation is evidently warranted into general epistemology of natural necessity.

5. Discussion

5.1. Natural necessity for ontology development

It is broadly acknowledged that philosophically inspired principles play a crucial role in practical ontology design, as is most clearly shown by an increasing importance of building domain-specific ontologies upon upper ontologies (aka foundational ontologies): "while a top-level ontology is a classification system that deals with general domain-independent categories only, a foundational ontology is a top-level (formal) ontology that has been built and motivated by *the upfront and explicit choice of its core principles*" (Borgo and Hitzler, 2018, p. 3, our italicization added). Examples of choices of upper ontologies include ontological choices (Borgo and Masolo, 2010), i.e., choices as to whether a certain ontological category (e.g., abstract objects such as sets and numbers) or relation (e.g., functional parthood; Keet, 2017) is adopted; and meta-ontological choices (de Cesare et al., 2016), i.e., choices (e.g., as to whether the realist approach to ontology is taken; Smith and Ceusters, 2010) that are foundational enough to determine ontological choices.

As was argued in Section 3, there are three possible fundamental commitments to natural necessity: type-level causation, type-level dispositions, and laws of nature. This choice among them can be seen as a meta-ontological choice of upper ontologies. As will be seen below, for instance, the primary view of type-level dispositions embraced by an upper ontology would result reasonably in an ontological choice of the category of dispositions made by the upper ontology. A deeper understanding of natural necessity will thus enable practitioners in information systems and formal ontology to assess the consequences of selecting one upper ontology over another in their fields and to figure out accurately which upper ontology would satisfy their domain-specific needs most fully (de Cesare et al., 2016). To provide some indications as to this, a case study will be given about which most basic commitment to natural necessity would accord with which upper ontology and with which application domain.

5.1.1. Natural necessity in upper ontologies

It is not hard to judge which is the most basic concept of natural necessity in some upper ontologies. For instance, BFO is fundamentally committed to type-level 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" (Arp et al., 2015, p. 102, our italicization added). Furthermore, a dispositional treatment of causation has been suggested regarding the future direction of BFO (Smith et al., 2015, p. 5); see Toyoshima's (2019a) development of the BFO-based dispositional view of causation. Because the relevance of ontology of dispositions to scientific practice has been argued for (Chakravartty, 2017), the BFO primary choice of type-level dispositions may stem from its meta-ontological choice of the methodology of ontological realism (Smith and Ceusters, 2010): "The realist methodology is based on the idea that the most effective way to ensure mutual consistency of ontologies over time and to ensure that ontologies are maintained in such a way as to keep pace with advances in empirical research is to view ontologies as representations of the reality that is described by science. This is the *fundamental principle* of ontological realism" (ibid., p. 139).

For another example, DOLCE seems to take type-level causation to be most basic. For one thing, Lehmann et al. (2004) provide a DOLCE-based conceptualization and formalization of causation, by characterizing type-level causation in terms of dependencies between types of quality changes and then specifying some particular constraints on token-level causation by dint of type-level causation. This would imply the DOLCE fundamental choice of type-level causation, because a sophisticated theory of qualities in DOLCE (roughly, properties in the terminology of this paper) is a distinguishing feature of DOLCE (Borgo and Masolo, 2010). Certainly, Guarino (2016) favors the grounding of dispositions in laws of nature when he examines critically BFO (or especially BFO-dispositions) as compared to DOLCE (see Section 2.2); but his reference to laws of nature can be interpreted more generally as some sort of law-like relations, including type-level causation as 'causal laws'. Moreover, since causation is closely entwined with epistemology of natural necessity (see Section 4.1.2), the DOLCE primary commitment to type-level causation may be a consequence of its meta-ontological objective to represent the categories with a clear cognitive bias that are associated with, e.g., human cognition and socio-cultural artifacts: "the aim of DOLCE is to capture the intuitive and cognitive bias underlying common-sense while recognizing standard considerations and examples of linguistic nature. (...) it [DOLCE] looks at reality from the mesoscopic and conceptual level aiming at a formal description of a particular, yet fairly natural, conceptualization of the world" (Borgo and Masolo, 2010, pp. 279–280).

However, other upper ontologies need to come under close scrutiny in order for their basic choices as to natural necessity to be correctly understood. Consider for instance the Unified Foundational Ontology (UFO; Guizzardi and Wagner, 2010): "a philosophically and cognitively well-founded reference ontology" (ibid., p. 175) that is tailored mainly for evaluating conceptual modeling languages. Apparently, UFO regards dispositions to be foundational because it includes the category of dispositions as a subtype of intrinsic moments. UFO may nevertheless take a moderate stance on dispositions. For instance, Porello and Guizzardi (2017) offer a first-order modal formalization of UFO based on the possibilist account of modality. As was explained in Section 3.3, the fundamental view of type-level dispositions is orthodoxly coupled with actualism (accepted e.g., by BFO), and this stance is sharply opposed to possibilism, which is assumed e.g., by the DOLCE axiomatization (Masolo et al., 2003). One possible interpretation is that UFO is primarily committed to either type-level causation or laws of nature, but not type-level dispositions. Another, more complex explanation is that UFO takes type-level dispositions to be most basic; and possibilism, on which the UFO modal formalization seemingly depends, is a mere logical way of speaking of actualism embraced genuinely by UFO.

5.1.2. Natural necessity in domain ontologies

As was alluded to in Section 2.2, in philosophy, which aims at the underlying structure of reality, the problem of which is the primary concept of natural necessity has been usually dealt with on the assumption that there is a single privileged solution to it. This attitude would nevertheless lead to an improper ontological modeling in formal ontology because it is generally recognized that different granular levels of reality must be fully appreciated to have an accurate formal-ontological representation of different domains (Bittner and Smith, 2008; Keet, 2008; Masolo, 2010). The relevance of granularity to ontology of causation has been also pointed out (Galton, 2012b; Toyoshima et al., 2019). A focus will be upon fundamental commitments to natural necessity in two domains that have been relatively intensively researched in formal ontology: (classical) physics and biomedicine (see Section 6 for some brief considerations on natural necessity especially in non-classical physics).

One of the most plausible criteria for this determination is arguably that a concept of natural necessity c_1 is preferable to another concept c_2 with respect to a domain d if, all other things being equal, c_1 contributes more significantly to knowledge and assumptions in d than c_2 does. By this standard, laws of nature would fit with ontology of physics better than type-level causation and dispositions. For one thing, laws of nature are of paramount importance in physical theories in general (Bittner, 2018), whereas causation and dispositions are so infrequently discussed that e.g., Russell (1913) argues that the notion of causation is useless in physical theories and eliminable from physics; but see Price and Corry's (2006) criticism and discussion. For another, it is sometimes claimed that contemporary physics lends credence to ontology of dispositions (Mumford, 2006); but preceding arguments for this are nonetheless far from decisively convincing (Williams, 2009, 2011).

On the other hand, type-level dispositions would suit ontology of biomedicine better than laws of nature and type-level causation. For a negative reason, even the existence of biological laws is a highly controversial topic (Hamilton, 2007). For a positive reason, the disposition concept is central to medical information sciences, as is observed by the widespread usage of the terms 'disposition' and 'tendency' in the medical literature (Jansen, 2007); and dispositions serve as such a useful conceptual tool for the analysis of the explanatory practice in the biological sciences (Hüttemann and Kaiser, 2018) that a dispositional theory of causation captures well the dynamicity, continuity, and context-sensitivity of biological phenomena (Anjum and Mumford, 2018). It has been also argued that a dispositional analysis of causation helps to contribute to evidence-based medical practice (Sackett, Straus, Richardson, Rosenberg and Haynes, 2003) better than its counterfactual analysis (Kerry, Eriksen, Lie, Mumford and Anjum, 2012; Anjum, Kerry and Mumford, 2015); but see Strand and Parkkinen's (2014) criticism. The fundamental commitment to type-level dispositions in biomedicine might be practically supported by the success of the Open Biomedical Ontologies (OBO) Foundry (Smith et al., 2007): a collaborative project to coordinate ontologies to support biomedical data integration that tends to adopt BFO as its standard upper ontology.

5.2. *Illustrative application examples*

Some domain-specific examples will be presented to exemplify the potential of ontology of natural necessity to ameliorate practical ontology design. It is typically expected that the above-given arguments over natural necessity will be used to compare and integrate previous fragmentary works on a given domain and to provide further development of formal ontology of the domain at issue:

- *Ontology of* (*classical*) *physics*. There are nowadays multiple avenues towards ontology of physics. To be applied in artificial intelligence (e.g., qualitative reasoning), a traditional approach explores naive physics (Smith and Casati, 1994) which emphasizes the importance of causation in the common-sense world. There has been recently a growing interest in dispositional ontologies of physical entities (Barton et al., 2014; Barton and Ethier, 2016) which would be lightly committed to the dispositional grounding of causation. In another direction, Bittner (2018) develops a modal logical axiomatization of physical possibilities with a focus on physical laws. Given the foundationality of laws of nature for ontology of physics (see Section 5.1.2), those prior works are to be unified along with the chain of grounding relations that is describable in the following diagram:

  law of nature → **disposition** → **causation** (→ **counterfactual**; see Section 4.1.2)

- *Ontology of product models*. In the manufacturing and engineering domains, ontologies are expected to enhance product development by making information communication semantically transparent (Borgo and Leitão, 2007); and ontology of products (Vignolo, 2010) is closely intertwined with a foundational issue of how to formalize the relationship between composite objects and their parts (Sanfilippo, Masolo, Borgo and Porello, 2016). Although a key to solving this problem may be the notion of structure (Koslicki, 2008) or pattern (Petersen, 2019), its ontological nature remains notoriously elusive (Johansson, 1998; Hastings, Batchelor, Steinbeck and Schulz, 2010; Röhl, 2012; Ochiai, 2017; Galton, 2018a). Interpreted from the viewpoint of natural necessity, the compositional structure or pattern of products may be well elucidated in terms of dispositionally grounded causation. For one thing, it has been generally argued that only the right kind of causal connection is sufficient to combine parts together into a new whole (Williams, 2017). For another, Guizzardi and Wagner (2013) offer an ontological foundation for simulation modeling by defining dispositionally what they call 'causal laws', which in turn explicate causation of state changes in simulation models. The following diagrammatically representable grounding relations used in their work would provide some considerations in favor of the dispositional grounding of causation in ontology of engineering:

disposition → **type-level causation** ('causal laws') → **token-level causation** (state changes)

- *Ontology of disease*. Disease is so vital to biomedicine that its proper understanding can help to provide a general conceptual framework for the integration of biological and biomedical data. There are currently two major ontological models of disease: a dispositional model of disease provided by the Ontology for General Medical Science (OGMS) (Scheuermann et al., 2009) constructed in alignment with BFO and the River Flow Model (RFM) of diseases (Mizoguchi et al., 2011) with the 'waterfall view' of reality. The harmonization between the OGMS and the RFM remains an unresolved issue in (foundational) biomedical ontology research (Rovetto and Mizoguchi, 2015). Seen from the standpoint of natural necessity, the OGMS is primarily committed to type-level dispositions since it is based on BFO (see Section 5.1.1), whilst the RFM would be to type-level causation because a previous attempt (Toyoshima, Mizoguchi and Ikeda, 2017) to elucidate the causal character of the RFM conception of disease in light of a functional formal-ontological account of causation (Toyoshima et al., 2019) can be construed as a variant of the functional view of dispositions (see Section 3.2). Granted the fundamentality of type-level dispositions to ontology of biomedicine (see Section 5.1.2), the OGMS-RFM orchestration is to be sought through further clarification of the grounding relation that can be depicted in the following diagram:

  type-level disposition (OGMS) → **type-level causation** (RFM)

  See Toyoshima's (2019c) formalization of a general disease module along with the OGMS-RFM harmonization; and see also Toyoshima's (2019d) application of the dispositional grounding of causation to processual biological ontology.

6. Conclusion

This paper aimed at an introductory comprehensive study of natural necessity in formal ontology. To achieve this purpose, a meta-ontological conceptual tool of fact-grounding was exploited to analyze four major concepts of natural necessity and their interrelationships: causation, dispositions, laws of nature, and counterfactuals. In particular, three plausible candidates for the most fundamental notion of natural necessity were proposed and explained: type-level causation, type-level dispositions, and laws of nature. Additionally, epistemology of natural necessity was examined, especially scientific explanation as well as observation, hypothesis, and prediction. Finally, the practicality of natural necessity for ontology development was illustrated by a case study of suitable primary choices of natural necessity in upper and domain ontologies and its potential application to some domain-specific (e.g., unificatory) tasks.

There are a number of different directions in which ontology and epistemology of natural necessity can proceed: e.g., to validate the current grounding approach to natural necessity in compliance with some established upper ontology. Other concrete tasks to be dealt with down the road have been already mentioned separately. In the end a few problems will be listed below which are to be tackled in a long term because their solutions need coping with other (more) foundational issues:

- *Formalizing natural necessity*. A logical characterization of natural necessity remains largely untouched in this paper (but see Section 3.3). Since natural necessity is a modal notion, it may be natural to employ a modal logical system for representing natural necessity (Bittner, 2018). The modal logical inquiry would also have implementational virtue, partly because some first-order modal logics are translatable into first-order logics (Braüner and Ghilardi, 2007) and the latter are normally employed to formalize ontologies. However, it has been a core subject in formal ontology to spell out implicit ontological assumptions that are embedded in logical representation languages (Guarino, 2009); and other logical systems than (modal) first-order logic and OWL should be generally pursued for the sake of better ontological modeling (Borgo, Porello and Troquard, 2014). For instance, the utility of the usage of higher-order logics for ontology development and verification has been recently argued for (Bittner, 2019). Logical specification of natural necessity is to be investigated from diverse perspectives.
- *Natural necessity in non-classical physics*. Discussions have so far taken for granted the mesoscopic world in which classical (Newtonian) mechanics holds, but it is not obvious how ontology of natural necessity works in other physical theories such as general relativity and quantum mechanics. It is a highly contentious topic, for instance, what kind of ontological role the concept of causation plays in those non-classical spheres of reality (Healey, 2009; Hoefer, 2009; Riggs, 2009). For another example, Dorato and Esfeld (2015) offer some considerations in favor of the dispositional grounding of laws of nature over primitivism about them in quantum mechanics; and Kistler (2018) contends that dispositions (powers, precisely) can be useful in the context of the ontological interpretation of both classical and quantum physics. A formal ontology of non-classical physics is strictly required (Bittner, 2018; Galton, 2018b)
- *Natural necessity and ontology of time*. Connectedly, it is well worth investigating the relationship between natural necessity and ontology of time. For instance, Friebe (2018) argues that the fundamental commitment to laws of nature requires eternalism (roughly, the view that the past and the future are as real as the present; Mellor, 1998), but the dispositional grounding of them must not presuppose it. Backmann (2018) even insists that there is no ontology of time that is compatible with ontology of dispositions (powers). Notwithstanding some formal-ontological studies on time (Baumann, Loebe and Herre, 2014; Bittner, 2018), many fundamental issues with the nature of time are yet to be addressed directly even in existing major upper ontologies (Galton, 2018b), and ontology of time merits careful treatment.
- *Natural necessity and ontology of persistence*. Persistence is highly relevant to an ontological modeling of objects (Verdonck, Sales and Gailly, 2018), and ontology of persistence pivots on the debate between endurantism (aka three-dimensionalism) and perdurantism (aka four-dimensionalism). As for the linkage between natural necessity and persistence, for instance, Mumford (2009) says that ontology of dispositions (powers) has some good reasons to favor endurantism. In contrast, Williams (2017) advocates its consistency with perdurantism (as well as endurantism). This issue is further complicated by the recent active re-framing of the endurantism/perdurantism dispute in philosophy of persistence (Wasserman, 2016). For instance, temporal parts are traditionally taken to be the crux of the matter of persistence (Lewis, 1986, pp. 202–204). There is however a growing

consensus that the endurantist and perdurantist accounts of persistence should be primarily characterized in light of spatiotemporal location (i.e., how objects are located in spacetime) and it serves at best as an auxiliary assumption whether objects have or lack (proper) temporal parts (Sattig, 2006; Balashov, 2010; Donnelly, 2011). It is imperative to examine the nature of persistence from a foundational viewpoint because it remains considerably unexplored in formal ontology.

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