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Newtonian Forces and Causation: A Dispositional Account

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Abstract. We present a model of Newtonian forces and the causal relations they are involved in, applying Röhl & Jansen's model of disposition (extended with a relation between dispositions and their existential conditions), and show that this model fits with the intuition that force is the result of an interaction. We formalize forces as dispositions, dissociating field forces (which have local fields as existential conditions) from composite forces (which encompass contact forces). Finally, we hint at how this model could answer some classical philosophical difficulties concerning forces and dispositions.

Keywords. Force, Causality, Disposition, Classical mechanics

Introduction

Causation is a surprisingly little investigated topic in formal ontologies, despite interesting recent progresses [1]. This article will consider the topic from the perspective of classical mechanics: what kinds of causal relations are involved in the interactions between Newtonian forces[2] and related entities? Answering this question will require specifying what kind of entities Newtonian forces could be.

Some practicing scientists using classical (Newtonian) physics may implicitly assume that forces exist and are real entities. Anti-realists about forces like Berkeley, Russell or Mach, by contrast, have argued that forces do not exist (some of them proposing that forces are instead "useful fictions"). The debate has been kept alive recently with [2–4] who argued in favor of realism about force.

Notice first that forces *can* be eliminated from physical theories: it is possible to construct a theory empirically equivalent to (that is, leading to the same predictions as) Newtonian mechanics, but which does not make any reference to forces [2], by relating directly objects and their properties (mass, charge, etc.) to the accelerations they produce. However, Bigelow, Ellis and Pargetter [2] (see also [4]) have argued that physics without forces is less unifying and less explanatory, and therefore that forces should not be eliminated.

Wilson [4] has also argued that Newtonian mechanics is a special science, *i.e.* an approximately true non-fundamental scientific theory. She argues that we have to

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[2] This term will refer in this paper to forces as they appear in the contemporary version of classical physics – not to forces as they were historically conceived by Newton.

accept the physical entities – like forces – posed by such a special science, even if the question of how forces exactly relate to fundamental quantum particle exchanges is still an unanswered ontological question. This view is largely accepted in the community of applied ontologies, which are generally built in a non-reductionist fashion [5].

Before we start our discussion, let us say what we will *not* formalize. First, we will not formalize kinematic notions like speeds or accelerations. It may appear surprising to formalize mechanical notions without them, but our formalization of forces will only require one kinematic category, namely (accelerated) motion processes[3]. Also, we will not investigate the ontological status of related notions like energy and space-time, each of which brings new complex issues.

Second, we will assume that a reference frame is implicitly chosen in the formal ontology. The question of how forces vary between non-inertial reference frames, and the ontological status of so-called "inertial forces" (e.g. centrifugal or Coriolis forces) will not be considered here.

Third, we will stay within the context of classical (Newtonian) mechanics and will not enter into other physical theories like General Relativity or Quantum Mechanics. That is, we formalize the concepts of force and field as understood in contemporary classical mechanics, and the causal relations they are involved in.

In the first part of the paper, a pre-formal discussion will sketch our philosophical framework, present some intuitions about forces, and motivate the development of a dispositional account of Newtonian forces. A second part will show how gravitational, electromagnetic and contact forces can be formalized as dispositions, and explore the important ontological distinction between forces generated by fields and composite forces (which include contact forces). A conclusion will summarize the virtues of this dispositional account and present in which directions it could be pursued in the future.

1. Pre-formal discussion

1.1. Realist methodology

Let us start with a few words concerning the philosophical view on formal ontologies that is here adopted. We will not take any position in the debate between realism and anti-realism about forces; instead, we will adopt the realist methodology (as described in [6]), a methodological stance according to which an effective way to ensure the consistency of ontologies is to view them as representations of reality as described by science. One does not need to be a realist to accept the realist methodology: an anti-realist can also accept references to universals as convenient expressions denoting other entities, such as cognitive concepts or linguistic usages. Given that the ontology of classical mechanics includes forces, the realist methodology would formalize forces as real, physical entities.

Once a particular scientific theory is chosen, a formalization of the ontology can be evaluated (amongst other criteria) in terms of which intuitions it fits concerning the concepts at hand (see [8] for an analogous case about function). Therefore, we

[3] The question of how to formalize the relation between accelerated motion processes and accelerations will be left open. Thus, in the following, all mentions to vector differentials like accelerations will be formulated in a meta-language, not in the ontological language.

investigated how classical mechanics is presented in contemporary physics textbooks to reveal some of these intuitions[4].

1.2. What forces are not

Before investigating what kind of entities forces could be, it will be useful to state what they are not. It is commonly agree that "Forces are vector quantities, having magnitude and direction" [9]. Of course, this does not mean that forces are vectors – it only means that they can be *represented* by vectors. Forces are considered to be physical, not mathematical, entities.

Newton's 2nd law of motion relates the *resultant force* f^R acting on an object (that is, the sum of the *component forces* acting on this object) with the product of its mass and acceleration, the vectors that represents these entities being equal: $\overrightarrow{f^R} = m\vec{a}$. Despite this vector equality, resultant force and mass-acceleration compounds are usually considered as two different kinds of entity: "The vector ma is not a force. Acceleration […] is not a force itself." [10]

There is some kind of dependence between force and acceleration: "If an object of mass m is acted on by a net force […], it will experience an acceleration a that is equal to the net force divided by the mass" [11]; "Acceleration is a result of a nonzero net force" [10]; "the force on a particle determines the rate of change of its momentum." [12]; "a force is measured by the acceleration it produces." [9] This dependence is clearly asymmetric: no one would say that the resultant force acting on an object results from its acceleration. Forces are not accelerations, but there is some sort of causal dependence between forces and accelerated motions – and one of the goals of this article will be to elucidate this dependence.

1.3. What forces could be

Let us now turn to what forces *could* be (from a methodological realist perspective). A common intuition is that a force is an influence acting on a body: "Before Newton…it was thought that some influence, a 'force,' was needed to keep a body moving at constant velocity." [9] Force is still viewed as such: "Any influence that tends to accelerate an object; a push or pull" [13]; "when a force acts on each body due to the other body" [9]; "If an object of mass m is acted on by a net force […], it will experience an acceleration a […]" [11] Such an influence could be understood along different lines.

First, forces have clear connections with interactions, and may be identified as an interaction, or as part of it. For example, one physics resource describes a pair of action-reaction forces as constituting such an interaction: "Every force is part of an interaction between one thing and another. An interaction requires a pair of forces acting on two separate objects." [13] Alternatively, a force may be seen not as (a part of) an interaction itself, but as a result of such an interaction: "A force acting on a body is always the result of its interaction with another body." [10] A formalization of force will presumably have to choose which of these two (or other) intuitions it wants to fit.

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[4] This focus on intuitions does not imply that we aim at formalizing "naïve physics" as Patrick Hayes [37] defined it: what interests us here is the scientific concept of Newtonian force, not common people's intuitions about forces. Arguably, though, part of the scientific concept of forces may be constituted by physicists' intuitions about forces, hence our investigation of these.

1.4. Force as a dependent continuant

Let us now start our first step towards a formalization by explaining why force will be formalized here as a dependent continuant. We adopt a principle of economy that entails reusing as much as possible the categories that are commonly used in upper ontologies. According to this principle, new categories should be introduced only if already accepted categories are not sufficient. Let us accept, in virtue of this principle, the relatively widespread assumption (in the field of formal ontologies) that entities can be divided between occurrents and continuants, and that the latter can be divided between independent continuants and dependent continuants.

A force is here classified as a continuant: it is fully present at each time it exists; it does not have any temporal parts; and it can change with time. A force is either an independent continuant or a dependent continuant. Arguably, it is not an independent continuant. To understand why, consider for example an electrostatic local field e acting on a charged object o. The electrostatic force f exerted by e on o depends ontologically on e – and therefore also on the charge(s) that generate e – and on o: if e or o would suddenly disappear, then f would also disappear (moreover, its magnitude depends on both the magnitude of the field e and the charge of o). Therefore, f does not meet the requirement for being an independent continuant; thus, f is a dependent continuant.

In which entity does a force inhere? The intuitions on this respect are mixed. On one hand, the linguistic expression that a force is "an influence exerted" on an object may suggest that the force is external to this object; on the other hand, the weight (which is a gravitational force) of a massive object is commonly considered a property of the object.

1.5. Force as a disposition

The question now becomes: which kind of dependent continuant is a force? If a force f acts on an object, this object may get an acceleration $\vec{f}/m$, but only if there are no other forces acting on it (or if the vectorial sum of these other forces is $\vec{0}$). Therefore, a force *tends* to confer an acceleration to an object, but this influence can be counteracted, and the acceleration can be prevented (as summarized by Newton's 2nd law). Force has been defined as "Any influence that tends to accelerate an object; a push or pull" [13]; "…a force may be acting on an object, but its capability to produce a change in motion may be balanced, or canceled, by one or more other forces" [14]. Therefore, there seems to be a dispositional aspect about forces – as dispositions are entities that can be realized in certain circumstances, but can be counteracted, and are held to exist in entities regardless of whether they are realized.

However, the fact that there is something dispositional about forces does not imply that forces are dispositions themselves. The exact connection between forces and dispositions has been debated, with von Wachter [15] identifying forces with dispositions, whereas Jansen [16] suggests that a force brings about (but is distinct from) a disposition.

Imagine that we follow Jansen's suggestion and consider that there are two entities at play: a force, and the disposition to which it gives rise. This would raise two difficulties. First, there does not seem to be any entity appearing in classical mechanics that could play the role of such a disposition; so if such a disposition would be formalized, it would be an entity added to the ontology of classical mechanics. This is at odds with one applied ontology principle consisting in avoiding the introduction of artificial categories, categories not already recognized by science [17]. The second difficulty is that, by differentiating forces from the dispositions they give rise to, we would still be left with the question of explaining the nature of forces. However, if we identify forces with these dispositions, as suggested by von Wachter [15], no additional artificial category would be introduced, and the ontological status of forces would be clarified. This second picture is arguably more attractive if it can be made logically coherent and shown to fit both classical mechanics and some intuitions about forces.

1.6. Conclusion of the pre-formal discussion

We will present a dispositional account of forces in classical mechanics, by applying Röhl & Jansen's model of dispositions [18][5], that will fit the intuition that force is the result of an interaction. This will enable us to formalize the ontological dependence relations among forces, their underlying fields, and the objects they are exerted upon.

More specifically, we will show that forces can be ontologically described as dispositions inhering in the object exerted upon. However, in agreement with the realist methodology, we will not assert a metaphysical claim to the effect that forces are indeed such dispositions. There may be alternative ontological classifications of forces that fit other set of intuitions about forces. For example, force could be formalized as a dependent continuant inhering in the local field[6]. Also, if one would not accept the principle of economy mentioned above, force could be described as other than a dependent continuant, perhaps reflecting a new type of ontological category. Alternatively, force may be formalized as a relation: Massin [3] argues that force is a symmetrical relation and that we should not distinguish ontologically between forces in an action/reaction pair (see also [2], [19]). Here, we do not claim that such alternative accounts are impossible[7]. Rather, we will expose the virtues of a dispositional account.

2. Formalization of forces and causal-like relations

2.1. Röhl and Jansen's extended dispositional model

Forces will be formalized in this article as dispositions, along the line of Röhl & Jansen's model of dispositions [18], which will be extended with one additional relation (involving what we will call "existential conditions"). Röhl & Jansen developed their model in the context of the Basic Formal Ontology (BFO), and it can presumably be adapted to a large variety of ontologies. In what follows ontological

[5] Thus, we are applying Röhl & Jansen's model of dispositions to von Wachter's conception of force, rather than to Jansen's.

[6] Such an account may fit better the intuition that force is a property of the exerter (the field), not of the object exerted upon. However, a formalization that would take this intuition seriously would have to explain how a force can be ontologically dependent not only on the exerter, but also on the object exerted upon (as explained above in 1.4); and if force is taken as a disposition inhering in the exerter, the precise connections between the realization of this disposition and the accelerated motion of the object exerted upon should also be elucidated.

[7] However, a relational account may have to explain how force as (first-order) relation can be related (through a second-order relation) to the accelerated motion (or the acceleration) it produces. Such an account should also clarify the exact connections between forces and dispositions.

classes, including their relations, will be italicized, and relations involving at least one particular will be written in boldface.

In this model, a disposition is a type of property that *inheres_in* a *Material_entity*, and is realized (*has_realization*) via a process. The realization process has the material entity as a participant, and the disposition is triggered by (*has_trigger$_D$*) some event or process[8]. Finally, some quality (or more generally, some "aggregate of dependent continuants") is the *base_of* the disposition, and the material entity is the *bearer_of* the disposition. For example, salt is soluble: solubility is the disposition of the salt to dissolve (dissolving being the realization) when it is placed in water (a trigger of the realization). The salt is the bearer of this disposition, and the base of this disposition is a particular molecular structure of the salt.

Röhl & Jansen also mention another relation that they do not formalize (because of its intricacies), but that will be relevant here: the relation of "being a background condition of" a disposition. For example, consider the disposition d_0 of a match to combust when a trigger (striking of the match) happens in conjunction with the presence of oxygen; the presence of oxygen is called a "background condition" for this disposition. d_0 exists (inheres in) the match even when there is no oxygen present: a match always[9] has a disposition to combust when it is struck in an environment containing oxygen – the match has this disposition even if not in such an environment.

One can define a different but closely related disposition d_0', namely the disposition of a match to combust when the trigger (striking of the match) occurs, period, irrespective of background conditions: this disposition does not include the presence of oxygen as a background condition. Because of that, this disposition exists in the match *only* when there is oxygen around the match: if there is no oxygen around it, this disposition does not exist in the match, because in such a case, the match has no disposition to combust when it is struck. For d_0' to appear in the match, one would have to place the match in an environment with oxygen[10]. To summarize: when the match is in an environment without oxygen, d_0 (but not d_0') inheres in the match; and when the match is in an environment with oxygen, both d_0 and d_0' inhere in the match.

Here, the presence of oxygen is not a background condition for d_0'; we will call it instead an *existential condition* of this disposition (because the existence of d_0' depends on this condition). An existential condition acts, so to speak, as an "external base" of the disposition: both the base and the existential condition have a causal role in the existence of the disposition (and in its realization), but the base inheres in the object, whereas the existential condition does not – it is external to the object[11]. On the other hand, a *background condition* is a condition that must accompany the trigger for the disposition to be realized, but a disposition can exist without its background condition being fulfilled (or without its trigger happening). Thus, the presence of oxygen is a background condition for d_0, and an existential condition for d_0'.

To summarize, a background condition is a necessary condition for the realization of the disposition, and an existential condition is a necessary condition for the existence

[8] A disposition can be triggered without its realization occurring, as illustrated by the example of probabilistic dispositions [20].

[9] Here we idealize the situation and do not take into account that there may be reasons for which the match would actually not combust in such a situation – for example, if it is wet.

[10] Such dispositions are thus subject to so-called "Cambridge changes" (see [35]).

[11] Alternatively, one could formalize d_0' as inhering in the couple formed by the match and the oxygen around; a model of symmetric force along similar lines will be sketched at the end of section 2.4.

of the disposition[12]. This distinction between background and existential conditions will be essential to understand the conception of forces as dispositions. We will not try to clarify here the ontological status of existential conditions in their full generality: this would require considering many examples of dispositions, not only forces - and such an investigation would probably require elucidating the status of background conditions. We will just assume that a gravitational or electromagnetic field (or an aggregate of such fields) can belong to the domain of the relation *existential_condition_of* (of course, other kinds of entities can be the existential condition of a disposition, as illustrated by the match example), with *Disposition* as the range of this relation.

2.2. Field force

Now that this dispositional model has been described, let us apply it to the formalization of forces. We will start with a pre-formal description, in the context of classical mechanics, of a simple scenario S_1 in which there are only two massive objects o_1 (with mass m_1, at location x_1) and o_2 (with mass m_2, at location x_2), each exerting a gravitational force on each other. We will here focus on the force exerted by o_1 on o_2 (of course, the force exerted by o_2 on o_1 can be dealt with on exactly similar lines). The object o_1 – or its mass m_1 – generates a local gravitational field $g_1(x)$ at each point of space[13] x, represented by vector $\overrightarrow{g_1(x)}$. At o_2's position, $g_1(x_2)$ exerts a gravitational force f^g on o_2, represented by the vector $\overrightarrow{f^g} = m_2 \overrightarrow{g_1(x_2)}$, which leads to the motion of o_2 with an acceleration represented by $\overrightarrow{a_2}$, such that $\overrightarrow{f^g} = m_2 \overrightarrow{a_2}$ (this is communicative of Newton's 2nd law). Let us now turn to the ontological formalization (table 1 next page summarizes the taxonomy of relevant entities).

Field is a complicated ontological category, as illustrated by [22]'s discussions. As this present article focuses on forces, we will leave open the question of whether local fields should be formalized as an independent continuant or a dependent entity, and accept a general universal class *Field*[14] (with *Gravitational_field*, *Electrostatic_field*, and *Magnetic_field* as subclasses). Once this accepted, it can be said that m_1 generates a gravitational local field $g_1(x)$ (an instance of *Field*) at every spatial location x - in particular at x_2, where o_2 is located. This relation will be formalized as: m_1 **property_generates_field**[15] $g_1(x_2)$.

The idea is to formalize forces as dispositions whose realizations are accelerated motion processes of the object in which they inhere. Therefore, our taxonomy will include a class *Force* (a subclass of *Disposition*), and a class *Motion_process* (a subclass of *Process*[16]), such that the following necessary condition holds:

[12] These two kinds of conditions reflect two kind of *ceteris paribus* clauses involving dispositions, as explained by Schrenk [21].

[13] We will not take into account here the fact that a field is generated locally around a body and then propagated at finite speed in space, as this would involve non-classical physics.

[14] "Field" will always refer here to a local field – that is, a field at a point of space – in the remainder of this article, we will never refer to the field extended through space; if necessary, the class *Field* that is introduced here can be renamed *Local_field* for clarity. Also, in this model, many local fields can exist at the same spatial position, but this is not surprising: physicists commonly distinguish the fields generated by different objects at the same place, and our model fits with this conception.

[15] This relation is called **property_generates_field** to avoid confusing it with another relation that will be introduced later and that relate objects to the field they generate, namely **object_generates_field**.

[16] *Process* might be taken here e.g. in the sense defined by Galton & Mizoguchi [23], as this may enable to formalize accelerations as entities dependent on motion processes.

f **instance_of** *Force* ⇒ f **instance_of** *Disposition* ∧ ∃ o o **instance_of** *Material_entity* ∧
f **inheres_in** o ∧ ∀ r [f **has_realization** r → (r **instance_of** *Motion_process* ∧ o **enacts**[17] r)]

The gravitational force f^g undergone by o_2 is formalized as a particular disposition (o_2 is the bearer of f^g, and f^g **inheres_in** o_2). f^g exists because o_2 has a mass (m_2) and because of the field $g_1(x_2)$. Since m_2 inheres in o_2, it can be considered as the physical base of f^g: m_2 **base_of** f^g. On the other hand, $g_1(x_2)$ is external to o_2, and therefore cannot belong to its base. It is also not a background condition of f^g: f^g exists only when $g_1(x_2)$ exists – whereas a disposition can exist even when its background condition does not exist. Therefore, $g_1(x_2)$ is formalized as the existential condition of f^g: $g_1(x_2)$ **existential_condition_of** f^g. This reflects the fact that if $g_1(x_2)$ ceases to exist, then f^g would also. Finally, if f^g is realized in a process $r_2{}^g$ (that is, if f^g **has_realization** $r_2{}^g$), then $r_2{}^g$ is an accelerated motion of o_2 with acceleration $\frac{\overrightarrow{f^g}}{m_2} = \overrightarrow{g_1(x_2)}$, instance of a *Motion_process*.

- *Occurrent*
    - *Process*
        - *Motion_process*
- *Continuant*
    - *Independent_continuant*
        - *Material_entity*
    - *Dependent_continuant*
        - *Quality*
            - *Mass*
            - *Charge*
        - *Disposition*
            - *Force*
                - *Field_force*
                    - *Gravitational_force*
                    - *Electrostatic_force*
                    - *Magnetic_force*
                - *Composite_force*
                    - *Contact_force*
    - *Field*
        - *Gravitational_field*
        - *Electrostatic_field*
        - *Magnetic_field*

Table 1. Taxonomy of the relevant entities

f^g is as a force generated by a field, instance of a class *Field_force* that we define as:

f **instance_of** *Field_force* := f **instance_of** *Force* ∧ ∃ g g **instance_of** *Field* ∧
g **existential_condition_of** f

This class has several subclasses including *Gravitational_force, Electrostatic_force, Magnetic_force*; for example, a gravitational force is a force that has a gravitational field as its existential condition:

[17] Cf. [23]; the relation of enactment means that o is the maximal object that moves in the process r. If r is the motion process of a ball, then o is the ball – rather than, say, a part of it.

f **instance_of** *Gravitational_force*:= f **instance_of** *Field_force* ∧
∃ g g **instance_of** *Gravitational_field* ∧ g **existential_condition_of** f

The relations **existential_condition_of, has_realization** and **inheres_in** may be slightly unusual for the physicist: in physics texts, forces are commonly described as being *exerted* and as *acting on* objects, and motions as being *produced*[18] by forces. For more user-friendly labels (without changing any of the underlying ontological dispositional semantics), one could define the following sub-relations of these dispositional relations:

g **field_exerts_force** f :=
g **instance_of** *Field* ∧ f **instance_of** *Field_Force* ∧ g **existential_condition_of** f

f **force_produces_motion** r :=
f **instance_of** *Force* ∧ r **instance_of** *Motion_process* ∧ f **has_realization** r

f **force_acts_on_object** o :=
f **instance_of** *Force* ∧ o **instance_of** *Material_entity* ∧ f **inheres_in** o

Shortcut relations can also be introduced to formalize the fact that an object can generate a field, exert a field force or produce a motion. An object generates a field if it has a quality that generates this field:

o **object_generates_field** g := o **instance_of** *Material_entity* ∧ g **instance_of** *Field* ∧
∃q q **instance_of** *Quality* ∧ q **inheres_in** o ∧ q **property_generates_field** g

An object exerts a field force if it generates a field which exerts (*i.e.* which is an existential condition of) this field force (this relation will be generalized later for non-field forces, so it is presently formalized as a sufficient condition only):

o **instance_of** *Material_entity* ∧ f **instance_of** *Field_force* ∧ ∃g g **instance_of** *Field* ∧
o **object_generates_field** g ∧ g **field_exerts_force** f ⇒ o **object_exerts_force** f

An object produces a motion if it exerts a force that produces (*i.e.* which is realized by) this motion:

o **object_produces_motion** r := o **instance_of** *Material_entity* ∧ r **instance_of** *Motion_process* ∧
∃f f **instance_of** *Force* ∧ o **object_exerts_force** f ∧ f **force_produces_motion** r

Of course, other shortcut relations can be introduced and straightforwardly defined (such as **property_exerts_force**, **field_produces_motion** or **object_produces_motion_of_object**). We will not take any position here on which of these relations are the true causal relations; we will only claim that there is something causal about them – that is, that they are "causal-like" [1].

Finally, forces are dispositions that do not need any special trigger to be realized. In terms of Röhl & Jansen's [18] formalization, this means that any kind of process in which the object participates will be a trigger: *Force has_trigger*$_D$ *Process*. Therefore, a force is a disposition that is always triggered (contrarily to e.g. the fragility of an object which is active only when this object receives a shock). However, this does not imply that it will always be realized (in the sense of this disposition having a realization): a fundamental characteristic of forces is that they can be masked by other

[18] There is no strict regularity however in the way these terms are used in physics, so the naming conventions that will follow are arbitrary to some extent.

forces – that is, their realization may not occur because of other forces, as we are now going to explain.

2.3. Composite force

Let us now consider a scenario S_2 of two massive charged bodies o_1 (with a charge q_1) and o_2 (with a charge q_2), each exerting a gravitational force and an electrostatic force on each other. In usual physical terms, o_1 generates both a gravitational field $g_1(x_2)$ and an electrostatic field $e_1(x_2)$ at x_2. Thus, o_2 undergoes two forces: a gravitational force f^g such that $\overrightarrow{f^g} = m_2\, \overrightarrow{g_1(x_2)}$ and an electrostatic force f^e such that $\overrightarrow{f^e} = q_2\, \overrightarrow{e_1(x_2)}$. These two forces lead to a composite[19] force f^C such that $\overrightarrow{f^C} = \overrightarrow{f^g} + \overrightarrow{f^e}$, which produces an acceleration of o_2 that can be represented by a vector $\overrightarrow{a_2}$, such that $\overrightarrow{f^C} = m_2\, \overrightarrow{a_2}$ (this is Newton's 2nd law). Now turn to the ontological formalization of this scenario.

The formalization of the gravitational force f^g is identical as before. In addition, q_1 generates an electrostatic field $e_1(x_2)$ at position x_2 (that is, q_1 **property_generates_field** $e_1(x_2)$), which gives rise to an electrostatic field force f^e (a disposition): with the user-friendly renaming of the dispositional relations presented in the former part, one can say that $e_1(x_2)$ **field_exerts_force** f^e, and f^e **force_acts_on_object** o_2. A realization of f^e would be an accelerated motion process of o_2 named r_2^e, with acceleration $\frac{\overrightarrow{f^e}}{m_2} = \frac{\overrightarrow{q_2 e_1(x_2)}}{m_2}$: f^e **force_produces_motion** r_2^e.

In this physical scenario, the dispositions f^g and f^e are not realized, as they mask each other[20]; therefore o_2 does not have a motion r_2^g or r_2^e. However, Newton's 2nd law can be interpreted as stating that the combination of f^g and f^e constitutes the composite force f^C, which is also formalized as a disposition (f^C **instance_of** *Composite_force*, where the class *Composite_force* is the complementary class of *Field_force* inside the class *Force*). A realization r_2^C of f^C is an accelerated motion process r_2^C of o_2 with acceleration $\frac{\overrightarrow{f^g}+\overrightarrow{f^e}}{m_2}$ (f^C **has_realization** r_2^C). The bearer of f^C is o_2, its basis is constituted by both m_2 and q_2 (we write $\{m_2,q_2\}$ **base_of** f^C) and its existential condition is constituted by both $g_1(x_2)$ and $e_1(x_2)$ (we write $\{g_1(x_2),e_1(x_2)\}$ **existential_condition_of** f^C).

The relation between each field force and the composite force can be formalized by a new relation **contributes_to**, such that f^g **contributes_to** f^C and f^e **contributes_to** f^C. This relation expresses the intuitive idea that even when f^g

[19] We call this force a "composite force" rather than a "resultant force", as the term "resultant force", represented by f^R, generally refers to the sum of all forces acting on an object; here, it happens that $\overrightarrow{f^R} = \overrightarrow{f^C}$, but if an additional force f' would act on the object, we would then have $\overrightarrow{f^R} = \overrightarrow{f^C} + \overrightarrow{f'}$ and thus $\overrightarrow{f^R} \neq \overrightarrow{f^C}$. We will not address here the question of whether, in scenario S_2, the resultant force f^R is a different physical entity on top of the composite force f^C (rather than, say, an information entity); this question is akin, to some extent, to the question of whether the statue and the amount of matter that constitutes it should be formalized as two different entities or only one [24].

[20] For an introduction to the notion of masking, see [25]. The fact that forces can be masked by other forces could be formalized by axioms stating that a necessary background condition for the realization of a force is that the vector sum of all other forces acting on this object is $\vec{0}$. However, this would require first a unified formalization of masking for dispositions in general (as well as a formalization of the relation of being a background condition), and thus would exceed the present work. Note that here, the notion of masking is taken in a very general sense: even if f^g and f^e both 'push' the object in the same direction, they will be said to mask each other, as the object has neither a motion r_2^g nor r_2^e; this view may be closer to McKitrick's view of dispositions [26] than to Mumford [27] and Molnar's [28] view (see also [29]).

(resp. f^e) is not realized because f^e (resp. f^g) masks its realization, it still contributes to the composite force f^C that is realized in the accelerated motion r_2^C of o_2.[21]

Here again, various causal-like shortcut relations can be introduced: we will adopt the linguistic convention that a motion is "influenced" by a partial causal factor[22] (by opposition to being "produced" by a full causal factor); for example, one can say that a force influence motion (here, f^g **force_influences_motion** r_2^C) if it contributes to a force which produces this motion:

f **force_influences_motion** r := f **instance_of** *Force* ∧ r **instance_of** *Motion_process* ∧
∃f' f' **instance_of** *Force* ∧ f **contributes_to** f' ∧ f' **force_produces_motion** r

Other shortcut relations can be straightforwardly defined, on the model of the former relations of production, like **field_influences_motion**, **object_influences_motion** and **object_influences_motion_of_object**.

We have formalized the relation **object_exerts_force** for a field force only. In order to define this relation for any kind of force (field force or composite force) and be able to state that o_1 **object_exerts_force** f^C, we can formalize the idea that o exerts a force f iff every field force that contributes to f is exerted by o; that is:

o **object_exerts_force** f := o **instance_of** *Material_entity* ∧ f **instance_of** *Force* ∧
∀ f^f (f^f **instance_of** *Field_force* ∧ f^f **contributes_to** f) →
(∃g g **instance_of** *Field* ∧ o **object_generates_field** g ∧ g **field_exerts_force** f^f)

2.4. Extension of the model

Formalization of the magnetic force could be straightforwardly adapted from the above formalization of electrostatic force (the base of the force would then be the aggregate $\{q_2,v_2\}$, where q_2 is the charge of the body upon which the force is exerted, and v_2 is its speed[23]; and the existential condition would be a magnetic field $b(x_2)$).

Any combination of gravitational and electromagnetic forces between any given number of objects can be formalized along the lines presented above. In particular, the intuitive idea that a body can partially cause, alter or contribute to the motion of another body (when more than two bodies are interacting) can be captured by the relation **object_influences_motion**.

There is another important family of forces that appear in classical mechanics, namely contact forces. A contact force can also be formalized as a disposition that can be masked by other forces, and should be reducible to a composite of small-scale underlying fundamental forces, each categorized as a disposition contributing to this force; thus, *Contact_force is_a Composite_force*.

Finally, let us hint at how to deal with Newton's law of action and reacton in this framework. In scenario S_1, o_1 exerts a gravitational force f_2^g on o_2 (that we wrote "f^g" until now) and o_2 exerts a gravitational force f_1^g on o_1 such that $\overrightarrow{f_1^g} = -\overrightarrow{f_2^g}$. In our account, both forces are dispositions. But they could be seen as aspects of a more

[21] Intuitively, a force contributes to another force if it composes the latter force, as defined by classical physics. This could be formalized by stating that f contributes to f' iff the base of f is included in the base of f', and the existential condition of f is included in the existential condition of f'.

[22] Here also, we will not take any position on which of the following relations are authentic relations of partial causation.

[23] At least, if the speed of an object is formalized as a quality.

general disposition $f_{1\text{-}2}^g$ inhering in the pair $\{o_1,o_2\}$, whose base is $\{m_1,m_2\}$ (and no existential conditions would need to be involved for the existence of $f_{1\text{-}2}^g$, as the fields $g_1(x_2)$ and $g_2(x_1)$ are respectively generated by m_1 and m_2[24]); the realization of $f_{1\text{-}2}^g$ would be o_1 and o_2 accelerating towards each other, each with a specific acceleration (respectively $\overrightarrow{f_2^g}/m_2$ for o_2 and $\overrightarrow{f_1^g}/m_1$ for o_1). In such a framework, the force f_1^g and f_2^g (formalized as dispositions of o_1 and o_2) are simply two aspects of the same "symmetrical force" $f_{1\text{-}2}^g$ – as suggested by Massin [3][25].

2.5. Philosophical considerations

It is sometimes [2] claimed that whenever the realization of a disposition occurs, the complete causal story explaining this occurrence can be given without mentioning this disposition, which would thus be causally inert[26]. For example, in order to explain why a fragile glass broke after a shock, one can simply mention the molecular structure of the glass and the shock that it has undergone: it is not necessary to mention its "fragility". This peculiar feature of dispositions fits well with forces: as stated in the introduction, the mechanical interactions between physical objects can also be given without any reference to force – by only mentioning the objects, their properties, the generated fields, and the accelerated motions they give rise to. In a nutshell, forces supervene [31] on properties of the objects and local fields, and dispositions likewise supervene on their base and their existential conditions. This common feature between forces and dispositions should therefore be seen as an argument in favor of the dispositional model.

Also, a common worry in philosophy of Newtonian forces is the problem of causal over-determination [4]. For example, in a scenario S_2, there is an intuitive sense in which f^C caused r_2^C; but there is also a sense in which f^g and f^e caused r_2^C together. In order to solve this problem, Cartwright [32] has argued that only f^C exists, not f^g and f^e; Creary [33], on the opposite, argued that f^g and f^e both exist, but not f^C. From the perspective of our methodological realist framework, these three forces all exist. Although a full philosophical discussion would exceed the scope of this article, one could develop an argument (along the line of [4]; see also [34]) to the effect that this formalization does not constitute a case of causal over-determination: the base of f^C (namely $\{m_2,q_2\}$) is constituted by the union of the base of f^g (the quality m_2) and f^e (the quality q_2); and similarly the existential conditions of f^C (namely, $\{g_1(x_2),e_1(x_2)\}$) is constituted by the union of the existential conditions of f^g (the field $g_1(x_2)$) and f^e (the field $e_1(x_2)$). Thus, in our formalization, the underlying entities (base and generating conditions) on which the dispositions are based are the same whether one considers f^g and f^e together on one hand, or f^C on the other hand, which may solve the problem of causal over-determination.

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[24] $\left\|\overrightarrow{f_1^g}\right\| = \left\|\overrightarrow{f_2^g}\right\| = Gm_1m_2/d^2$ with d the distance between o_1 and o_2 and G the gravitational constant.

[25] But contrarily to Massin's views, f_1^g and f_2^g and $f_{1\text{-}2}^g$ are here viewed as dispositions (inhering in respectively o_1, o_2 and $\{o_1,o_2\}$), rather than as relations.

[26] However, Kistler [30] objects against this view.

3. Conclusion

Let us now relate this formalization to the pre-formal discussion of part 1. First, in Röhl & Jansen's extended model, a disposition borne by an object can include a double ontological dependence: dependence upon its base (which is internal to the object), and upon its existential condition (which is external to the object). This is what enables us to formalize force as a disposition that is an *extrinsic*[27] property of the object exerted upon (as it depends not only on this object, but also on an external entity, namely the field exerting the force).

We have thus provided a dispositional account of forces and the causal dependencies relating them to local fields and accelerated motions. This account presents two additional virtues. First, it fits with at least two intuitions about forces (namely, the ideas that there is something dispositional involved in Newtonian laws of motion, and that force is the result of an interaction between its base and its existential condition). And second, it satisfies a principle of economy by re-using already formalized entities (occurrent, independent continuant, dependent continuant, disposition, etc.).

Several ontological models may be compatible with our scientific theories. There may be other models fitting different sets of intuitions about forces (for example, the idea that force is an interaction, rather than the result of an interaction) and categorizing forces as other than dispositions, such as a relational model. In any case, it seems that the intuitions concerning the notion of force are too diverse to find a single model that would fit all of them.

This account of force also shows the usefulness of Röhl & Jansen's dispositional model, and points to three directions in which it could be extended, namely in formalizing, for general dispositions (not only forces): 1) the relation between a disposition and its existential conditions (not only the background conditions introduced by Röhl & Jansen); 2) the circumstances under which a disposition can be masked; and 3) the relation of contribution between dispositions.

Finally, a next step in this work would be to categorize the variety of ways in which objects can interact via contact forces (via elastic or inelastic collisions, involving elastic or plastic solids, taking into account fluid mechanics, etc.). Such an investigation could enable the formalization of a variety of mechanical causal interactions appearing in biomedicine, in particular in Mizoguchi et al.'s River-Flow model of disease [36], according to which diseases are constituted by causal chains of disorders.

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