Brit. J. Phil. Sci. **58** (2007), 173–205

Newtonian Forces

Jessica Wilson

ABSTRACT

Newtonian forces are pushes and pulls, possessing magnitude and direction, that are exerted (in the first instance) by objects, and which cause (in particular) motions. I defend Newtonian forces against the four best reasons for denying or doubting their existence. A running theme in my defense of forces will be the suggestion that Newtonian Mechanics is a special science, and as such has certain *prima facie* ontological rights and privileges, that may be maintained against various challenges.

> The basic problem of philosophy seems to be to discover the forces of nature from the phenomena of motions and then to demonstrate the other phenomena from these forces. (Newton, *Principia*)

1 Introduction

Newtonian Mechanics (henceforth, NM) is the force-based physics of the motions of material bodies in classical contexts, where quantum and relativistic phenomena may be ignored. NM, as commonly understood, consists of Newton's three laws of mechanics and their associated presuppositions and

doi:10.1093/bjps/axm004

Advance Access published on May 14, 2007

entailments.[1] Among these presuppositions, of course, is that forces—pushes and pulls, possessing magnitude and direction, that are exerted (in the first instance) by objects, and which cause motions—exist. Do they? One might think the reasons for thinking not (or remaining agnostic on this score) are four times overdetermined.

First is a methodological worry, concerning whether NM is worthy of ontological attention. NM has been superseded, for most purposes, by energy-based theories which are more explanatorily elegant, more practically useful, and more broadly applicable (in extending to quantum as well as relativistic contexts). But why look to an unwieldy and restricted theory for ontological insight—into whether forces exist, in particular?

Second is an epistemological worry, of the sort familiar from debates over how to interpret the purely theoretical posits of scientific theories. Supposing one should withhold belief in such posits, does not the unobservability of Newtonian forces indicate that we are justified, at best, in taking these to be useful fictions?

Third is an ontological worry, motivated by Ockham's razor. We shall see that it is easy to construct a theory empirically equivalent to NM, eliminating all reference to forces. Given that what a theory of mechanics needs to do is predict motions within NM's appropriate range of applicability, shouldn't we accept the more parsimonious theory, and reject Newtonian forces accordingly?

Fourth is a metaphysical worry, involving a threat of causal overdetermination.[2] Forces are supposed to be causes of motions, but they are also supposed to be dependent on nonforce entities (e.g., objects and their properties) which we have independent reason to accept, and which also appear to cause these motions. If we posit forces in addition to these nonforce entities, won't every motion purportedly caused by a force be, implausibly, systematically causally overdetermined?

In what follows, I will argue that each of these reasons for denying or doubting that Newtonian forces exist can be answered.[3] A running theme in

[1] The three laws (inspired by those in the *Principia*) are: (1) A body remains at rest, or moves in a straight line (at a constant velocity), unless acted on by a net external force; (2) The acceleration of an object of constant mass is proportional to the net force acting upon it: $\mathbf{F} = m\mathbf{a}$; (3) Whenever one body exerts a force upon a second body, the second body exerts an equal and opposite force upon the first body: $\mathbf{F}_{ab} = -\mathbf{F}_{ba}$. Applications of NM generally supplement these laws with one or more specific force laws (e.g., Coulomb's law). Newton additionally took the existence of absolute space and time as postulates, with the former serving as the fundamental inertial reference frame relative to which other inertial frames were referred. Even prior to the rejection of absolute space and time associated with Special Relativity (SR), however, the posit of absolute space was seen as dispensable (other reference frames—e.g., the heliocentric reference frame—being inertial enough for practical purposes); following usual practice I won't include these postulates as part of NM.

[2] Unlike the other worries, this worry has not been previously raised against forces.

[3] A fifth worry raised against forces is that these induce a vicious regress (for discussion, see Bigelow *et al.* [1988]). The worry gets going via the supposition that Newtonian forces mediate

my defense of forces will be the suggestion that NM is a special science,[4] and as such has certain *prima facie* ontological rights and privileges, that may be maintained against various challenges.[5]

2 Is Newtonian mechanics ontologically irrelevant?

Throughout this section, let us suppose that there is no in-principle problem with adopting a broadly realist interpretation of scientific theories. Even so, we may distinguish three sources of concern with taking NM ontologically seriously. These are (1) that even in classical contexts, NM has been superseded by energy-based theories, (2) that NM has only restricted application (in particular, fails to apply in quantum contexts), and (3) that the posit of Newtonian forces in NM is incompatible with the posits of more fundamental theories.

2.1 . . . because superseded in classical contexts?

NM incorporates a local, 'differential' approach to understanding motions, according to which the trajectory of a dynamical system is stepwise determined

between nonforce entities and motions, and are required for the former to bring about the latter: if nonforce entities require forces in order to produce motions, then won't forces require further forces in order to do so, and so on, *ad infinitum*? This worry can be easily met, so I won't treat it further beyond what I will now say. First, one can respond (as Bigelow *et al.* do) by accepting the supposition, but maintaining that forces are of a different ontological category from nonforce entities, so that there is no reason to suppose that forces are like nonforce entities in requiring forces to bring about motions. Second, one can deny the supposition, as misidentifying the motivation for forces. As I will argue in Section 4, forces are posited not because they are required in order for nonforce entities to produce motions (nonforce entities are perfectly capable of such production) but rather because the characteristic features of forces provide a distinctive unifying basis for explaining and determining these motions. There is nothing in this motivation for forces which requires accepting the supposition, so the regress never gets started.

4 I take the special sciences (e.g., statistical mechanics, chemistry, molecular biology, botany, biology, psychology) to be those sciences treating of entities (gasses, molecules, proteins, plants, animals, persons) composed (as structured or unstructured aggregates) of entities treated by more fundamental sciences (ultimately, fundamental physics), and that exist (or participate in some range of phenomena) only under restricted circumstances which are theoretically salient from the perspective of identifying causal laws and regularities. I say more about the general conditions motivating the introduction of special sciences in Section 2.2.

5 To be sure, some worry that special science entities never have such rights and privileges, most commonly on grounds (of the sort presented in Kim [1993]) that special science entities are causally, hence ontologically, excluded by the entities upon which they depend. The Kim-style worry is a generalization of that directed against forces in Section 5, however; and my response on behalf of forces implements two general strategies of response (associated with nonreductive physicalism and emergentism, respectively) each of which indicate that considerations of causal exclusion pose no in-principle problem for the causal and ontological autonomy of special science entities. For a more detailed defense (on behalf of nonreductive physicalists, in particular) of the causal and ontological autonomy of special science entities against Kim-style and other objections see Wilson ([unpublished]).

by what external forces act (or do not act, in the case of rest or inertial motion) on the system, in accord with Newton's laws.[6] Though NM's force-based approach continues to have explanatory and practical value (as reflected in NM's being the starting point for education in physics, and continuing to play a central role in engineering applications), this approach is often presented as having been superseded, for most explanatory and practical purposes, by the energy-based approach characteristic of, for example, the Lagrangian and Hamiltonian formulations of mechanics. Energy-based formulations incorporate a global, 'integral' approach to determining the trajectory of a dynamical system, relying upon integral principles such as Hamilton's principle, according to which 'of all the possible paths along which a dynamical system may move from one point to another within a specified time interval (consistent with any constraints), the actual path followed is that which minimizes (more generally, extremizes) the action (that is, the time integral of the difference between the kinetic and potential energies)' (Marion and Thornton [1988], p. 193).[7] So, for example, from Hamilton's principle may be derived the Euler–Lagrange equations of motion for a system $\frac{\partial L}{\partial q_i} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_i} = 0$, where L (the Lagrangian) is (in general) the difference between the kinetic and potential energies, where the dot represents the time derivative of the dotted quantity, and where the q_i may be any coordinates (i.e., not just Cartesian coordinates or their definitional variants, as in NM) suitable to specifying the motion of the system (now conceived as evolving in configuration, rather than physical, space).

The view that energy-based formulations have various explanatory and practical advantages, even within the classical domain, has several motivations. Global integral principles are seen as providing a more elegant explanation of a system's motion than NM's piecemeal 'brute force' aggregation of force-driven accelerations: 'Hamilton's principle is a very compact and aesthetic formulation of classical mechanics [...] it is the first great advantage of the Euler–Lagrange approach' (Stevens [1995], p 62). It is easier to work with scalar energies than vector forces, and the flexibility of generalized coordinates allows problems to be set up so as to take advantage of symmetries, relevant degrees of freedom, and the like. Relatedly, generalized coordinates enable energy-based formulations to treat problems NM cannot treat, involving forces of constraint that are not explicitly known, as when a bead slides along a wire (see Butterfield [unpublished] for discussion). This latter advantage also has explanatory value, for in such cases 'the natural statement of the problem is not in terms of forces but rather in equations specifying the constraints that can be used to eliminate some of the variables' (Stevens [1995], p. 63).

6 See Feynman ([1965], Ch. 9).
7 See (Goldstein *et al.* [2002], pp. 34–5) for more detailed discussion.

That energy-based theories have such advantages over NM does not, however, show that NM is ontologically irrelevant. Consider, by way of analogy, two theories of the motion of a system of particles. The first attends to the motion of each individual particle, the second to the motion of the system's center of mass. In reducing the translational motion of a complicated system of particles to that of a single 'particle', the center of mass theory more elegantly explains the phenomenon at issue; for similar reasons, this theory is more easy to apply. But there is not any question of dismissing the ontological relevance of the theory attending to the motion of each individual particle: the less illuminating, harder to apply theory tells the right ontological story, whereas the illuminating, easily applied theory can't be ontologically trusted (after all, the center of mass of a system of particles might be located where nothing is, as when the particles are distributed in a torus).[8] The center of mass particle is, of course, explicitly introduced as a theoretical and calculational convenience, not meant to be taken ontologically seriously. Whatever the ontological status of energy, the point remains that the explanatory and practical advantages of energy-based formulations don't in themselves show that NM is ontologically irrelevant.

On the other hand, if we were inclined both to take energy-based formulations ontologically seriously and to think that such formulations were incompatible with NM, then we would thereby have some reason for rejecting NM as a source of ontological insight. But we are not in this situation, for these theories are not incompatible. Indeed, Feynman ([1965], p. 53) claims that Newtonian and Lagrangian dynamics are 'exactly equivalent'; and while there is room to dispute this claim (since what notion(s) of equivalence should apply to scientific theories is obscure), it is clear that the two formulations are compatible, in that (expressions for) the posits and operative principles of either theory (as applied to classical contexts) can be derived, under appropriate assumptions, from those of the other.

It is worth expanding this point. Both kinetic and potential energy are initially defined in terms of the work done in moving a system from one location to another (see, e.g., Goldstein *et al.* [2002], §1.1); but of course the work is the work done *by a force*:

$$W_{12} = \int_1^2 \mathbf{F} \cdot d\mathbf{s}$$

[8] Moreover, as Marc Lange pointed out, taking the center of mass particle ontologically seriously appears to commit one to the existence of action at a distance, since a motion of a component of the system over here would instantaneously cause the center of mass of the system over there to move.

Assuming that mass is constant, and using Newton's second law, we have:

$$W_{12} = \int_1^2 \mathbf{F} \cdot d\mathbf{s} = \int_1^2 m\mathbf{a} \cdot d\mathbf{s} = m \int_{t_1}^{t_2} \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} \cdot \mathbf{v}\, \mathrm{d}t$$
$$= \frac{m}{2} \int_{t_1}^{t_2} \frac{\mathrm{d}}{\mathrm{d}t}(v^2)\, \mathrm{d}t = \frac{m}{2}(v_{t_2}^2 - v_{t_1}^2)$$

The last expression defines a system's kinetic energy T: 'The scalar quantity $\frac{1}{2}mv^2$ is called the kinetic energy of the particle and is denoted by T, so that the work done is equal to the change in the kinetic energy: $W_{12} = T_2 - T_1$' (Goldstein *et al.* [2002], §1.1). For conservative forces, the work done is independent of the path taken, and hence can only be a function of the endpoints:

$$\int_1^2 \mathbf{F} \cdot d\mathbf{s} = -(U_2 - U_1)$$

The last expression defines a system's potential energy U.[9]

Working in reverse, force may be defined as the negative space rate of change (the negative gradient ∇) of potential energy U, so long as U is differentiable (as per the usual cases of interest in mechanics):

$$\mathbf{F} = -\nabla U$$

To see that the gradient of potential energy really does correspond to Newtonian force, consider a particle moving in a 1D potential, subject to conservation of energy (which applies to closed systems involving conservative forces):

$$T + U = \frac{1}{2}mv^2 + U(x) = E$$

Take the time derivative:

$$mv\frac{\mathrm{d}v}{\mathrm{d}t} + \frac{\mathrm{d}U(x)}{\mathrm{d}t} = m\frac{\mathrm{d}x}{\mathrm{d}t}\frac{\mathrm{d}v}{\mathrm{d}t} + \frac{\mathrm{d}U(x)}{\mathrm{d}x}\frac{\mathrm{d}x}{\mathrm{d}t} = 0$$

Divide by $\frac{\mathrm{d}x}{\mathrm{d}t}$ and subtract $\frac{\mathrm{d}U(x)}{\mathrm{d}x}$ to get:

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = ma \equiv F = -\frac{\mathrm{d}U(x)}{\mathrm{d}x}$$

So, (potential and kinetic) energy may be derived from force, and force may be derived from potential energy.[10]

9 Since the zero point of potential energy is arbitrary (only changes in potential energy matter for the dynamics) it is usual to take U_1 to be 0, and U_2 to be 'the' potential energy of the system at point 2.

10 It isn't possible to derive force from kinetic energy T, because the squaring of the velocity in T destroys the information needed to determine the direction of the force. But no matter: it suffices to show the compatibility of the posits that at least one posit of each formulation entails (under appropriate circumstances) the target posit(s) of the other.

The laws and operative principles of these theories are also interderivable, under appropriate assumptions. The Euler–Lagrange equations can be derived from Newton's laws, either directly (see Stevens [1995], pp. 60–1) or via D'Alembert's principle (see Goldstein *et al.* [2002], §1.4); and Newton's laws may be derived from the Euler–Lagrange equations, taking the generalized coordinates at issue to be Cartesian position and velocity coordinates (see Marion and Thornton [1988], p. 212). Newton's laws may also be derived from Hamilton's principle (see Hanc *et al.* [2003]), and Hamilton's principle may be derived from Newton's laws using the conservation of energy (see Hanc and Taylor [2004]). From a theoretical point of view, NM and energy-based approaches to mechanics are mutually supporting, compatible perspectives on the phenomena of mechanical motions.

2.2 . . .because only restrictedly applicable?

NM as traditionally formulated does not apply to contexts where either relativistic or quantum phenomena are at issue. Does this restricted application undermine NM's ontological relevance?

We can sidestep the problem for relativistic contexts, since NM may be extended so as to apply to these contexts without harm to its basic ontological posits. It is true that NM does not follow SR in the latter's assumptions that nothing can travel faster than the speed of light in a vacuum, and that this speed is the same in every inertial frame of reference. But no matter, for nothing in the basic theoretical apparatus of NM, according to which motions proceed via force-driven accelerations, requires denying these assumptions. Of course, NM must be tweaked in order to incorporate them (see Goldstein *et al.* [2002], Ch. 7 for details). Most crucially, the Galilean transformations assumed in NM must be replaced by the Lorentz transformations. On one common interpretation, this transition indicates that the Newtonian assumption that a system's mass does not depend on velocity must be dropped, as per

$$m(v) = \frac{m_0}{\sqrt{(1 - \frac{v^2}{c^2})}}$$

(where m_0 is the system's mass when measured in a frame not moving relative to the system). Accordingly, momentum must be understood to involve relativistic mass and velocity, and force (and Newton's second law) must now be generalized to involve a change in relativistic momentum, as opposed to acceleration:

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \frac{\mathrm{d}(m\mathbf{v})}{\mathrm{d}t}$$

Consequently relativistic force is not generally co-directional with the acceleration it produces; thus Newton's third law no longer holds in its original 'for every action there is an equal and opposite reaction' form, and must be replaced by the more general statement of conservation of momentum.[11] These changes, while significant, amount to comprehensible generalizations and refinements of the posits and operative principles of NM. As Jammer ([1957], p. 257) notes,

> All these modifications, important as they are from the mathematical point of view, do not radically affect the conception of force.

Hence our investigation into whether Newtonian forces exist could continue by attending to NM′ (the suitably extended version of NM), rather than NM. For simplicity, I will continue to speak of NM; if you prefer you can substitute 'NM′' accordingly.

A different strategy is required to address concerns about NM's failure to apply to quantum contexts. NM's force-based approach requires that a system have, at a time, determinate position and momentum values: the force is the force on the system at a specific place and time, and the resulting trajectory is a deterministic function of how the force affects the system's velocity (more generally, momentum) at that place and time. But the joint having of determinate position and momentum values is barred by quantum indeterminacy (reflecting the wave nature of quantum systems), and the trajectory of a quantum system is an irreducibly probabilistic function (reflecting the particle nature of quantum systems).[12] It is unclear how NM might be tweaked or extended so as to accommodate these features of quantum phenomena.[13] Supposing NM does not apply in quantum contexts, should we assume it is ontologically irrelevant?

To the extent that people are inclined to answer 'yes' to this question, I think this reflects their seeing NM's restricted application in light of this theory's original status as a candidate for a fundamental physical theory. *Qua* fundamental theory, NM has been replaced by theories that can accommodate

11 On an alternative common interpretation, the only mass a system has is inertial mass, with $\gamma = \frac{m_0}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$ understood as a separate factor impacting the dynamics (which factor is associated with properties of space-time, if anything). The tweakings associated with the 'relativistic mass' interpretation also apply to this one, *mutatis mutandis*.

12 These claims are correct, assuming the incorrectness of a Bohmian interpretation of quantum theory (as per Bohm [1952] and Bohm and Hiley [1993]), on which indeterminacy is given an epistemological spin, and the trajectories of quantum systems are deterministic.

13 Energy-based accounts also face initial difficulties in dealing with quantum phenomena, most notably in that the trajectory of a quantum particle needn't follow the path extremizing the action. But the concept of action provides a basis for calculating probabilistic trajectories: 'all paths have an amplitude related to the action for that particular path [. . .] [T]he total amplitude to end up at the final place (x, t) should be the sum of the amplitudes for all the ways to get there' (Stevens [1995], p. 105).

quantum phenomena; and in the face of this replacement NM is often presented as being a false though useful approximation to the more fundamental theories:

> Classical laws cease to be valid for material bodies [. . .] on an atomic or subatomic scale (quantum domain). However, it is important to note that classical physics [. . .] can be seen as an approximation of the new theories, an approximation which is valid for most phenomena on an everyday scale. (Cohen-Tannoudji *et al.* [1977])

But if NM is merely a false approximation to more fundamental theories, why look to NM, as opposed to these more fundamental theories, for ontological insight?

Though natural, this line of thought can and should be resisted. While NM's restricted application spells its failure as a fundamental theory, it might nonetheless be that NM is more than just a false approximation. For NM might a true (or true enough, for ontological purposes) *nonfundamental* theory—that is, a special science—with something important to tell us about the nature of nonfundamental reality.

To motivate this understanding of NM, first note that the theories associated with many of the special sciences—including thermodynamics, chemistry, cell biology, geology, botany, neurobiology, psychology, and so on, traversing the ladder of theories of constitutional and biological complexity—also generally fail to apply in quantum contexts, and moreover require, for their appropriate application, that other constraints or boundary conditions be in place (as requisite for, e.g., the occurrence of thermodynamic systems, complex inorganic and organic structures, specific genetic or environmental factors, and so on). Yet such restricted application does not in itself appear to rule out our drawing ontological conclusions from these theories, to the effect that temperatures, cells, proteins, plants, and persons exist, and are profitably understood by the laws expressed in the associated theories of these entities.

The question of when a special science is called for is a complex issue which cannot be fully treated here,[14] but for present purposes it will suffice to note two sorts of circumstances that frequently accompany the introduction of a special science (and associated special science entities). In the first, certain entities enter into composing structurally complex, relatively stable entities (e.g., atoms, molecules, rocks, planets, cells, proteins, plants) which exhibit properties and behaviors that are sufficiently law-governed that we can profitably theorize about them and their interactions with other entities existing under the specified conditions. In the second, certain entities enter into composing aggregates (e.g., gasses, heat baths) which, while not structurally stable, nonetheless manifest certain properties and behaviors (e.g., temperature, evolution towards thermal

[14] See (Wilson [unpublished]) for further discussion.

equilibrium) that are again sufficiently law-governed to be the appropriate targets of scientific theorizing.

Characteristic of both sorts of circumstances is that certain goings-on (more precisely: certain parameters of variation, or 'degrees of freedom') relevant to understanding the occurrence and behaviors of the entities composing such structured or unstructured aggregates cease to be relevant to understanding the occurrence and behaviors of the aggregate. So, for example, when atoms bind into a molecule, certain of the degrees of freedom relevant to characterizing the (position, velocity, etc. of the) unbonded atoms cease to be relevant to characterizing the (position, velocity, etc. of the) molecule. Similarly, when atoms or molecules form a gas, certain of the degrees of freedom relevant to characterizing the (position, velocity, energy, composition, etc.) of the atoms or molecules average or cancel out, so as to become irrelevant to the evolution of the gas. More generally, it appears appropriate to understand the special sciences as tracking important and distinctive levels of ontological grain that are salient only under certain restricted circumstances—circumstances in which some entities compose a structured or unstructured aggregate, and in which certain details relevant to goings-on involving the composing entities (when not so restricted) cease to be relevant to goings-on involving the composed entity. Far from impugning their ontological relevance, the fact that special sciences apply only in such restricted circumstances is core to their *raison d'être*.

I now want to suggest that NM is also a special science, which like other special sciences may well be ontologically revealing, in spite of—indeed, because of—its restricted applicability. In particular, I suggest that NM instantiates the pattern generally instantiated by special sciences, in tracking an important and distinctive level of ontological grain salient in circumstances wherein quantum details are irrelevant to the dynamics of (relatively) large-scale goings-on.

This is just how Feynman ([1965], §19-2) characterizes NM:

> Newton's laws are the "tail end" of the atomic laws, extrapolated to a very large size. The actual laws of motion of particles on a fine scale are very peculiar, but if we take large numbers of them and compound them, they approximate, but *only* approximate, Newton's laws. Newton's laws then permit us to go on to a higher and higher scale, and it still seems to be the same law. In fact, it becomes more and more accurate as the scale gets larger and larger. [. . .] As we apply quantum mechanics to larger and larger things, the laws about the behavior of many atoms together do *not* reproduce themselves, but produce *new laws*, which are Newton's laws, which then continue to reproduce themselves from, say, micro-microgram size, which still is billions and billions of atoms, on up to the size of the earth, and above.

More specifically, both quantum indeterminacy and the probabilistic nature of quantum trajectories become irrelevant in the macroscopic limit.

Indeterminacy ceases to be relevant because the associated variations are so small by macroscopic standards that they are effectively negligible:

> The minimum value of $\Delta x \Delta p$ is of the order of 10^{-27}erg-s. This is extremely small by macroscopic standards, so for laboratory-scale objects there is no practical difficulty in performing simultaneous measurements of position and momentum. [...] Newtonian mechanics [...] is perfectly adequate for describing large-scale phenomena. (Marion and Thornton [1988], p. 90)

So, for example, if $\Delta x = 10^{-13}$cm (about the size of a proton), $\Delta p \simeq \frac{\hbar}{\Delta x} = 10^{-14}$g cm/sec. For a particle of mass 1g, this implies an uncertainty in velocity of 10^{-14}cm/sec, which is experimentally undetectable. That is an epistemological point, of course, but it has metaphysical consequences, in that differences that are not detectable by macroscopic entities (e.g., laboratory-scale objects) generally will not make a difference to macroscopic goings-on. This is not true across the board, for the indeterminacy in, e.g., a proton's position will spread and indeed become macroscopic with time. But this will take hundreds of thousands of years (and much more for larger entities), and hence will be irrelevant to the dynamics of the many macroscopic entities, which are, alas, relatively ephemeral.[15]

The probabilistic nature of quantum trajectories also ceases to be relevant to macroscopic phenomena, because the probabilistic values of quantum mechanical observables average out to their mean values in the large-scale limit. Moreover—and here is where NM comes into its own—they do so in such a way as to conform to the laws of NM (Messiah [1970], p. 215). Forster and Kryukov ([2003], p. 1040) explain:

> It may be surprising that deterministic laws can be deduced from a probabilistic theory such as quantum mechanics. Here, curve-fitting examples provide a useful analogy. Suppose that one is interested in predicting the value of some variable y, which is a deterministic function of x, represented by some curve in the x-y plane. The problem is that the observed values of y fluctuate randomly above and below the curve according to a Gaussian (bell-shaped) distribution. Then for any fixed value of x, the value of y on the curve is well estimated by the mean value of the observed y values, and in the large sample limit, the curve emerges out of the noise by plotting the mean values of y as a function of x.

15 The possibility of indirect macroscopic detection of quantum goings-on does indicate, however, that we should not characterize the purview of NM's applicability as being to any and all macroscopic entities, but rather as being to any contexts in which quantum phenomena are irrelevant.

> To apply the analogy, consider x and y to be position and momentum, respectively, and the deterministic relation between them to be Newton's laws of motion. Then it may be surprising to learn that Newton's laws of motion emerge from QM as relations between the mean values of QM position and QM momentum. These deterministic relations are known as Ehrenfest's equations. In contrast to curve fitting, the Heisenberg uncertainty relations tell us that the QM variances of position and momentum are not controllable and reducible without limit. Nevertheless, it is possible for both variances to become negligibly small relative to the background noise. This is the standard textbook account of how Newton's laws of motion emerge from QM in the macroscopic limit.

Forster and Kryukov are explicit that probabilistic averaging as a generator of macro-laws is a method of 'abstracting away from the messy details' of the underlying microphenomena.

NM thus conforms to the general pattern characterizing the special sciences, in that both quantum indeterminacy and the probabilistic nature of quantum trajectories become irrelevant to the dynamics of entities that are large compared to (and which are ultimately composed of) quantum entities. We might wish for more as regards the metaphysical story about how, in particular, probabilistic quantum values average out so as to conform to NM. But we do not need to know why quantum features become irrelevant in certain circumstances to know that they do. When they do, NM becomes (along with its compatible energy-based cousins) an appropriate theory of mechanical motions; which is just to say that NM is a special science, applicable under the (not very) 'special' circumstances in which quantum phenomena don't matter to the dynamics. Evidently Newton was wrong to think that the *basic* problem of philosophy (or of physics) is to discover the forces of nature. But for present philosophical purposes, it is enough that NM is a special science; for this is enough to render it of ontological interest.

2.3 . . .because incompatible with more fundamental theories?

Of course, for NM to be of ontological interest is not to say that its apparent ontological commitments are all genuine. As with theories generally, one has to assess the apparent commitments of a given special science in light of what else we believe about the world. Of special importance is the question of whether the posit of Newtonian forces conflicts with the posits of more fundamental scientific theories.[16] (Note that establishing this compatibility does not require that forces exist at more fundamental levels—after all, if forces are special

[16] The question of whether forces are compatible with ordinary experience will be addressed in Section 3.

science entities one would not expect them to exist at such levels.) I will take as my test cases the quantum theories associated with the Standard Model (and their nonrelativistic precursors) and General Relativity (GR).

As regards the compatibility of forces with quantum theories and their posits, we seem to be on safe ground. Fully making this case would require investigating more deeply into the metaphysical and theoretical details of quantum theory (including field theory) than I can afford to do here; but in lieu of such an investigation the following considerations seem positively suggestive.

First, as just noted, Newton's laws of motion arise from the quantum laws in the macroscopic limit. Assuming (as per the realist commitment operative throughout Section 2) that the holding of Newton's laws involves commitment to Newtonian forces, it would seem to follow that forces are likewise compatible with quantum goings-on, whatever these may be. This much shifts the burden of proof onto those who would argue that forces are incompatible with quantum theory, presumably (if they are not to question the fact of probabilistic averaging) by questioning the realist assumption (as per Section 3). Second, physicists commonly talk as if forces exist at the quantum level (see, e.g., Salam [1990]; Kane [1993]; and Cline [2004]). Such talk, even if only intended analogically,[17] is some evidence that forces are compatible with quantum goings-on. Third, as noted above, energy-based approaches to mechanical motion can be extended to treat quantum systems. Given the intimate connection between forces and energies in classical contexts, this might again be taken to suggest that there is a quantum analog of force; but in any case the compatibility of forces with the 'quantum' posit of energy (in the macroscopic limit) is clear. Fourth and finally, to the extent that we have an operative metaphysical model of quantum interactions these appear to be compatible with forces. Consider Jammer's ([1957], pp. v-vi) remarks:

> In quantum chromodynamics, gauge theories, and the so-called Standard Model the notion of "force" is treated only as an exchange of momentum and therefore replaced by the ontologically less demanding concept of "interaction" between particles, which manifests by the exchange of additional particles that mediate this interaction. [...] For a simple illustration of how such an interchange works, imagine two skaters drifting along on a frozen lake, side by side, on parallel routes. A sudden exchange of balls between them will produce, due to the transfer of momenta, a repulsive interaction; and an exchange of boomerangs, hitting each

[17] At least sometimes the talk seems quite literal, as in this interpretive discussion of how classical and quantum entities respond to force: '[U]nlike the classical particle, which responds only to the force $F = -V'$ at x_o, the quantum particle responds to the force at neighboring points as well. [...] Each of these terms is a product of two factors, one of which measures the size or nonlocality of the wave packet and the other, the variation of the force with x' (Shankar [1994], p. 183).

> of them from the outside (or the exchange of negative momenta), will produce an attractive interaction.

Jammer concludes that 'Clearly, what one calls the "four fundamental forces of nature" are no longer "forces" in the traditional sense'. The skater analogy does not in fact make this clear, but no matter, since compatibility does not require that there be quantum forces. In particular, if quantum interactions are particle-mediated exchanges of momentum, then since Newtonian forces also involve exchanges of momentum (as per Newton's second and third laws), compatibility does not appear to be a problem. Indeed, this shared feature might lead one to speculate that forces are constituted by quantum particle exchanges, as yet another case where some macro-phenomenon (e.g., solidity) is constituted by some micro-phenomenon (e.g., electromagnetic bonds).

The situation is not as encouraging as regards the compatibility of Newtonian forces and GR, for GR is explicit in denying the existence of gravitational forces: geometry plus inertial motion, rather than forces, determine motions due to gravity. Moreover, GR and NM agree that inertial motion does not involve forces; hence there is no way to argue here that an object's inertial motion along a geodesic 'constitutes' the occurrence of gravitational Newtonian forces. It appears that *if* GR is the correct theory of gravity, then the posit of gravitational Newtonian forces cannot be maintained.[18] On the other hand, it remains unclear whether GR is the correct treatment of gravity. First (as I will expand upon in Section 3), we experience gravitational forces, which is just to say that we experience motion under the influence of gravity as noninertial. Second, there are well-known incompatibilities between GR and quantum theories,[19] with the pressure rather more on revising the former than the latter.

Compatibility with other theories aside, might there be some general reason for thinking that special sciences cannot be ontologically informative? It is hard to see how the mere fact of restricted applicability could generate such reason. Perhaps one might suggest that only theories with universal application are ontologically relevant, but why think this, given that (as just noted) even our (presently) most fundamental theories fail to universally apply? Perhaps one might insist that only theories that universally apply can be said to contain

[18] This concession may be too quick. As a referee noted, geodesic motion of a (spinless) test body is a consequence of the Einstein field equations (a fact of which Einstein was unaware in 1915); so while gravity is not a source-based force, there is a sense in which it pushes bodies around. This line of defense of gravitational forces deserves further exploration.

[19] In particular, the assumption in GR that spacetime has a well-defined curvature at every spacetime location is incompatible with quantum indeterminacy: determinacy in temporal location results in indeterminacy in energy (hence in mass; hence in curvature) at that location, and determinacy in spatial location results in indeterminacy in momentum (hence in mass; hence in curvature) at that location.

laws, properly speaking; but this is irrelevant to the question of whether restricted theories (containing 'shmlaws') can have ontological import.

A potentially more worrisome concern would focus on the fact that special science entities are nonfundamental; then press that the existence of nonfundamental entities is problematic. The most compelling instantiation of such a schema (due to Kim and others) attempts to show that special science entities are untenable, in leading to an implausible overdetermination of causes. One might rather accept such overdetermination than reject all those nonfundamental entities one knows and loves, but in any case I will argue in Section 5 that there is no real threat here. In the meantime, the appropriate *prima facie* stance is to maintain that the fact that a theory has restricted applicability of the sort characteristic of special sciences is no proof of its ontological irrelevance. On the contrary, such theories appear to provide us with crucial information about the rich ontological structure of the world.

3 Are forces fictions?

In this section I put aside the realist presupposition, and consider whether Newtonian forces might be subject to the anti-realist objections characteristic of fictionalism, instrumentalism, verificationism, constructive empiricism, and other broadly empiricist views. Proponents of such views typically maintain that we are generally justified in taking observable entities to exist, but are generally unjustified in taking unobservable entities to exist, and in particular are generally unjustified in giving a realistic interpretation to the purely theoretical posits (posits to which we do not have extra-theoretical access) of scientific theories. Couple such a view with the claim that forces are unobservable, purely theoretical posits, and you have what I will call the 'empiricist' objection to the posit of forces.

Berkeley (*De Motu*,) is an early proponent of this objection.[20] He first claims that forces are unobservable (p. 5):

> *Force* likewise is attributed to bodies; and that word is used as if it meant a known quality, and one distinct from motion, figure, and every other sensible thing [. . .]. But examine the matter more carefully and you will agree that such force is nothing but an occult quality.

then goes on to suggest that forces are useful fictions (pp. 17–8):

> *Force*, *gravity*, *attraction*, and terms of this sort are useful for reasonings and reckonings about motion and bodies in motion, but not for

[20] Of course, the status of 'observables' on Berkeley's idealist metaphysics departs from that of the usual empiricist or instrumentalist.

> understanding the simple nature of motion itself or for indicating so many distinct qualities [. . .] They serve the purpose of mechanical science and reckoning; but to be of service to reckoning and mathematical demonstration is one thing, to set forth the nature of things is another.

Jammer ([1957], p. 73) concurs, offering a more detailed instrumentalist reconstruction of the role of force terms in NM:

> The main advantage [. . .] of the concept of force [. . .] is that it enables us to discuss the general laws of motion irrespective of the particular physical situation with which these motions are associated. The concept of force in contemporary physics plays the role of a methodological intermediate [. . .] to show or to predict that a certain body A moves on a certain trajectory B, when surrounded by a given constellation of bodies C, D, . . . which may be gravitating, electrically charged, magnetized, and so forth, we introduce the middle term 'force' and state the two 'premises': (1) the constellation C, D, . . . gives rise to a force F; (2) the force F (according to the laws of motion) makes the body A move in the trajectory B. In our final conclusion, 'Body A, surrounded by C, D, . . . under the given circumstances, moves along trajectory B,' the middle term 'force' again drops out.

More recently, van Fraassen ([1980], p. 118) endorses an empiricist agnosticism about forces: 'All we are entitled to assert by any evidence which supports a hypothesis about the unobservable is that things are as if there were forces or photons, or whatever the unobservable entities in question are'.

Suppose we grant a *prima facie* concern with warranted belief in purely theoretical entities. Must we also grant that belief in Newtonian forces is unjustified, and that we should rather take them (at best) to be useful fictions?

It seems not, on the face of it. The empiricist concern is with purely theoretical posits—posits to which we do not have extra-theoretical access. So the empiricist objection to Newtonian forces will have traction only if we do not have extra-theoretical access to these. But on the face of it, we do have such access.

Newton himself ([1704/1952], Query 31) thought that forces were generally observable:

> It seems to me farther, that these Particles have not only a *Vis inertiae*, accompanied with such passive Laws of Motion as naturally result from that Force, but also that they are moved by certain active Principles, such as is that of Gravity, and that which causes Fermentation, and the Cohesion of Bodies. These Principles I consider, not as occult Qualities, supposed to result from the Specific Forms of Things, but as general Laws of Nature, by which the Things themselves are form'd; their Truth appearing to us by Phenomena, though their Causes be not yet discover'd. For these are manifest Qualities, and their Causes only are occult.

Certainly we seem to experience forces, as anyone who has ever bumped into a table, opened a window, tripped, lifted anything, stood on their head, or been the victim of static cling can attest. We continually seem to experience forces as we come into contact with other entities in the world, and we often seem to feel specific forces, such as gravitational and electromagnetic forces. Whatever the type of force, and throughout the diversity of our experience, we seem to experience these as pushes and pulls, having particular directions and magnitudes; moreover, we experience the features of 'felt forces', as I will call them, as specifically relevant to the production of motions, our own as well as those of other objects.[21]

Might there be some specifically empiricist grounds for denying felt forces?[22] The most plausible suggestion along these lines maintains that we experience certain nonforce effects rather than forces, and the most promising cases for the suggestion are those where the effects at issue are motions. For certainly we do experience motions, and the empiricist might claim (perhaps in an attempt to be cautious about what entities are posited as observables) that we have confused experience of forces with experience of motions.

But it seems wrong to say that we experience motions, not forces, for two reasons. First, appeal to (experience of) forces seems to provide a natural account of why we experience different *kinds* of motions. There is an important distinction between motion of the sort astronauts experience when freely floating in space, and that of the sort we experience when bumping around Earth's surface, which is naturally characterized as a distinction in whether or not forces are involved in the motion. And there is an important distinction between motions where we are pulled and motions where we are pushed, which again is naturally characterized by reference to the characteristic features of forces, as pushes or pulls. Perhaps the empiricist has some account of these different types of motions that does not involve forces, but it is not clear what this would be or why we should not just accept felt forces as providing a

[21] A referee noted that a similar argument might be used to establish that we directly observe centrifugal forces (and other 'forces of inertia' associated with accelerating reference frames), despite such forces being usually characterized as 'fictitious'. One way to respond would be to note that even if our experiences of forces are illusory in certain identifiable contexts (i.e., noninertial reference frames), this does not in itself undermine the claim that we genuinely experience forces in other contexts—after all, that our experiences of external objects are illusory in certain identifiable contexts (e.g., after taking hallucinogens), does not in itself undermine the claim that, in other contexts, our experiences of external objects are genuine. Alternatively, one might resist the characterization of inertial forces as fictitious—after all, that we seem to experience such forces (and that these have effects, such as the tides, and as when grass on a rotating plane grows in opposition to centrifugal as well as gravitation force) provides evidence of their reality. Along these lines it's worth noting that such forces are usually deemed 'fictitious' on grounds that there is no obvious entity that can be identified as exerting the force; but one might wonder whether an unobvious entity might be so identified or whether any such identification is required (c.f. fn. 18).

[22] Alternative grounds for this denial, based in Ockham's razor, will be considered in Section 4.

natural account of these experienced differences. Second, the suggestion that our seeming experience of felt forces is really experience of nonforce effects is particularly implausible for cases where what is experienced is not motions, but rather what might be called tensions or pressures. In such cases, the experienced effects seem to *just be* experienced forces. I conclude that there are no plausible distinctively empiricist grounds for denying felt forces.

Supposing (modulo the outcome of Section 4) that felt forces exist, is it appropriate to take felt forces to be instances of Newtonian forces? Again, physicists commonly suppose so:

> Why then should we not admit that the familiar mode of communicating motion by pushing and pulling with our hands is the type and exemplification of all action between bodies . . .? (Maxwell [1890], p. 312)

> As a rough approximation we think of force as a kind of push or pull that we make with our muscles, but we can define it more accurately now that we have [Newton's second] law of motion. (Feynman [1963])

What barrier could there be to taking felt forces to be Newtonian forces? Perhaps one might wonder whether the theoretical connections of forces in NM to the notions of mass and acceleration undermines doing so, since these connections are not obvious for felt forces. Of course, the theoretical features of an experienced phenomenon need not be obvious (witness the case of perceptual experience). But as it happens our experience of forces does involve the notions of mass (as manifested in weight) and acceleration, for we find that heavier (that is, massier) objects are harder to move, and that forces are associated with changes of motion (that is, accelerations). It is plausible to take felt forces to be instances of Newtonian forces, even taking certain theoretical connections of the latter into account.

It is useful here to compare the case involving forces with one where there are acknowledged difficulties in identifying an experienced entity with a presumed theoretical counterpart; namely, the case of colors. We have experience of colors, and there are various physical theories of colors. But it is not obvious how to map experienced onto theoretical colors, since there does not appear to be any physical or theoretical property that all entities experienced as red have in common: objects may be red by reflecting light, by emitting light, by absorbing light, etc. (see Hardin [1988] for discussion). By way of contrast, felt forces and Newtonian forces face no failure of experiential or theoretical isomorphism, and there is no associated barrier to taking the former to be instances of the latter.

Since we have experience of felt forces, and since felt forces are warrantedly taken to be instances of Newtonian forces, we have extra-theoretical access to Newtonian forces. The presupposition in NM that forces exist is thus not a claim about a purely theoretical posit, and the empiricist objection is misdirected.

This would be enough to warrant taking at least some of the forces appearing in NM (namely, felt forces) to be more than useful fictions. But we can say more; for it is simplest and most natural to suppose that, just as forces and their characteristic features enter into producing our motions and the motions of other entities with which we interact, so too do forces and their characteristic features enter into producing the motions of the inanimate objects whose behaviors are among the subject matter of NM. A perverse empiricist is free to resist the supposition by distinguishing between felt and nonfelt forces as they appear in NM. But empiricism (nor its variations) does not require taking this silly stance, which is moreover at odds with the general desideratum of scientific theories to give unified accounts of diverse phenomena. Given that a theory posits entities all of a given type, some of which happen to be experienced, and given that the theory itself makes no distinction between experienced and unexperienced entities of the type in question, the empiricist is free to maintain, as entirely compatible with their concerns, that belief in all is justified.

4 Are forces ontologically redundant?

The most frequently cited objection to Newtonian forces is the redundancy argument, according to which forces are not needed to account for or explain (in the sense of: make metaphysical sense of) motions, since the entities standardly taken to enter into causal interactions—e.g., objects, properties, events—are already sufficient unto the task.

There are several forms of the objection. An early version is found in Mill ([1843], p. 254, emphasis in original):

> To grind corn, there must be a certain collocation of the parts composing a mill, relatively to one another and to the corn; but there must also be the gravitation of water, or the motion of wind, to supply a force. But as the Force in these cases was regarded as a property of the objects in which it is embodied, it seemed a tautology to say that there must be the collocation *and* the force. As the collocation must be a collection of objects possessing the force-giving property, the collocation, so understood, included the force.

Another version (related to the previously discussed objection against felt forces) is that Newtonian forces are not needed to explain our felt experience of pushes, pulls, and so on. As Bigelow *et al.* ([1988], p. 615) characterize the argument prior to giving their own defense of forces, '[I]t seems just as satisfactory to explain the experiences as being not the "sensation" or direct experiences of the forces themselves [but rather] the properties we experience [...] *without any mediation*'. Talk of mediation aside (which talk reflects Bigelow, Ellis, and Pargetter's specific understanding of forces as causal intermediaries) the concern here is that, for example, the experience I have upon bumping into a table can be explained by reference to specific nonforce properties of me and of the table (my velocity and mass, the table's mass, etc.). Given that nonforce entities we already accept are sufficient for explaining our experience, it would be redundant to additionally posit forces as doing so. Finally, Jammer's suggestion that Newtonian forces are mere methodological intermediates may also be seen as a version of the redundancy argument, if we see his suggestion as motivated not so much by concerns about unobservables as by the the fact that the 'gravitating, electrically charged, magnetized' bodies already on the scene are sufficient to explain the motions.

Developing the redundancy concern, Bigelow *et al.* (pp. 617–8) provide a blueprint for eliminating forces from NM:

> For each kind of force postulated in physics, there is a law of *distribution* which regulates the way in which various situations give rise to forces. For example, there is Newton's law of universal gravitation. In addition, there is a set of *action* laws which determine the outcome or effect of the action of a force or forces on a system. Such laws include Newton's second law, linking force to mass and acceleration; and the law of composition of forces. Now laws of these two kinds can always be combined to eliminate forces and give us a law or laws relating the properties that cause the forces to the effects those forces have. So, for instance, we can combine the law of universal gravitation with the law of composition of forces and Newton's second law, and have a law relating distribution of massive objects to the 'natural acceleration' experienced by those massive objects.

Using this blueprint, we can construct a theory empirically equivalent to NM (understood as flexibly supplemented by any relevant force laws), but which does not contain forces. Hence even if—as Jammer and other proponents of the redundancy argument may agree—there are good pragmatic reasons for using NM instead of a force-free theory, Ockham's razor counsels the rejection of forces:

> [T]he fundamental eliminativist argument [...] rests on Ockham's Razor [...] A force cannot exist unless there is something that exerts that force. And a force cannot exist unless it is being exerted on something. [...] The force exists if and only if things are being related as required by [the] laws. [...] Forces can be eliminated; hence they should be eliminated. (Bigelow *et al.* [1988], p. 616)[23]

[23] A referee wondered whether allowing that forces need not act instantaneously at a distance might undermine the redundancy argument, since then it might be (and in fact sometimes is) that a given force exists though its source no longer exists. Such a possibility does not undermine the

Bigelow *et al.* agree that forces can be eliminated, but disagree that it follows that forces should be eliminated. They correctly maintain that appropriate application of Ockham's razor depends on whether the tacit *ceteris paribus* clause is satisfied: other things being equal, if we can eliminate forces, we should do so. But other things are not equal, they claim, for physics without forces is less unifying than physics with forces (that is, NM). It is worth considering their argument for this claim, for though its spirit is correct, its letter needs revision.

On the usual theory, Bigelow *et al.* note,

> [A]ll accelerations are explained in terms of forces—albeit forces of different kinds. There is a unity, or connectivity in this theory, in that different phenomena of the one kind are linked together, and explained in terms of a single unifying concept. (pp. 619–20)

Moreover, theories which partially reject forces lack said unity, they argue, as follows. On a theory eliminating some forces (e.g., gravitational forces), but retaining others (e.g., those associated with exchange particles), some accelerations are due to forces, and others not; and a resultant force need not give rise to an acceleration. Hence, plausibly, 'the usual theory is [. . .] tidier and has greater explanatory power' (p. 620).

Similarly, they argue, for a theory in which all forces are eliminated, as illustrated by the following case (p. 620):

> Consider two particles, each of mass 1 unit and charge 1 unit. One is in an electrostatic field and has an acceleration of 1 unit, the other is in a gravitational field and has an acceleration of 1 unit. These two phenomena display a significant similarity. On the usual theory, we should say that this similarity is due to another similarity. The phenomena are connected in that the particles experience forces of the same magnitude, and this is what accounts for their having the same acceleration.[24]

redundancy argument, for two reasons. First, the redundancy argument (which points to some nonforce entity upon which a given force depends as already capable of explaining whatever effects the force is supposed to account for) does not hinge on the assumption that force and nonforce entity exist at the same time. Even supposing not, and rejecting instantaneous action at a distance, time-retarded action at a distance remains a live option (see Lange [2002]). Second, even granting that the threat of redundancy is most compelling in cases where force and nonforce entity are cotemporaneous, this is compatible with the *original* source of the force (say, a particle) ceasing to exist, while the still-existing force cotemporaneously depends on some *other* nonforce entity (e.g., a field or particle via which the force propagates) that also accounts for whatever effects the force causes. (To prefigure the discussion of the ontology of forces in Section 5: this second point also shows that the denial of either instantaneous or retarded action at a distance does not undermine taking forces to be dependent aspects of nonforce entities; insofar as forces may be transmitted, the proponent of the aspect view may maintain that whenever a force exists, there is *some* nonforce particular upon which it cotemporaneously depends.)

24 In considering this case, I will be ignoring the question of whether Newtonian gravitational forces are incompatible with the gravitational interaction as understood in GR. For present

Call this Case (*). Here Bigelow *et al.* tacitly appeal to a 'similar effect, similar cause' principle (SESC) as an important means to unity: 'where possible, similar phenomena should be granted similar causes'.[25] If we admit forces, we can satisfy this principle: 'the phenomena are connected in that the particles experience forces of the same magnitude'. But the eliminativist, they claim, must say either that the accelerations are uncaused (an untenable view) or else that 'the causes must be circumstances and not forces'. Since 'the circumstances are, *ex hypothesi*, extremely different', the eliminativist's account is less unifying than a force-based account: 'Only with the acceptance of mediating forces between the circumstances and the effects [...] do we get this most desirable connectivity and unification' (p. 621). Other things are not equal, then, for while the formal program of elimination of forces can go through, the resulting physical theory does not match the theory containing forces (NM) with respect to providing a unified account of phenomena.

Though I agree that the posit of forces enhances the unity and connectivity of physics, broadly understood, the argument just given does not establish this conclusion, for it contains a false premise. Here is the argument:

1. A scientific theory with more unity is preferable to one with less.
2. A posit P increases the unity of a scientific theory containing it if it explains a given collection of similar effects in terms of similar causes. (SESC)
3. Forces satisfy SESC as directed at Case (*), and hence increase the unity of physics.
4. Without forces, SESC cannot be satisfied, as directed at Case (*).

∴ Physics with forces has more unity than physics without forces.

∴ We should admit forces.

One problem with this argument is that SESC (as stated) is suspect, from the perspective of motivating ontological posits. So, for example, a paradigmatic case of a posit that in some sense accounts for similar effects, but which is not genuinely unifying, is the first-order property of 'dormative virtue'. It would similarly fail to be genuinely unifying to posit, as explaining some effects of kind K, the second-order property of 'being such as to cause effects of kind K'. At a minimum, SESC needs to be qualified so as require that the posited similar causes of similar effects are not trivially defined in terms of these effects.

purposes, nothing turns on this issue, both because the case might rather have been cast in terms involving diverse nongravitational forces, and because the redundancy argument is directed at the seeming ontological competition between Newtonian forces and other nonfundamental phenomena.

[25] C.f. Newton's second Rule of Reasoning in Philosophy: 'Therefore to the same natural effects we must, as far as possible, assign the same causes'.

Another problem with the argument is that it is invalid, for it is compatible with the premises that there be other ways for a theory to unify phenomena (besides satisfying SESC), which would trump the unification at issue in the argument and so falsify the conclusion. For present purposes, however, the main problem is that premise (4) is false.

It is true that the usual relata are, in Case (*), assumed to be in 'diverse' circumstances—one particle is in a gravitational field, the other in an electrostatic field; and we might even up the diversity ante by supposing (contra the specification of Case (*)) that only the former is massy and only the latter is charged. Even so, nothing in the above argument rules out these relata having similar nonforce parts or properties, or entering into similar nonforce-involving events, which parts, properties or events unify the similar effects at issue, without reference to forces. In the case at issue, at least two such alternatives suggest themselves.

First, each particle plausibly has the second-order property of having a first-order property (mass or charge) that interacts, in accordance with an inverse-square law, with a field whose values are determined by the presence of other entities having the first-order property. (Note that this property does not fall afoul of the aforementioned qualification of SESC, in that the effects in question do not enter into the specification of the property.) The accelerations may each be causally explained by reference to the having of this second-order property; and that each particle has this property evidently unifies the similar effects in question. Reference to such a second-order property also explains the similar forms of Newton's law of gravitation and Coulomb's law, and so explains diverse as well as similar effects involving electricity and gravity. A second, yet more general means of unifying effects might appeal to Hamilton's principle, and the associated Euler–Lagrange equations, which involve (scalar) energies. These energies are plausibly properties of the usual causal relata ('quantities associated with the body') which unify the similar effects in Case (*), as well as other effects involving trajectories: 'Hamilton's principle has not provided us with any new physical theories, but it has allowed a satisfying unification of many individual theories by a single basic postulate' (Marion and Thornton [1988], p. 215).[26]

Various accounts exist via which similar (not to mention diverse) effects of the sort Bigelow *et al.* discuss may be unified without apparent appeal to forces. Hence premise (4) is false, and a different argument is required to establish that acceptance of forces is advised on grounds of unity.

[26] As previously noted, Newton's laws and the existence of forces may be derived (under appropriate assumptions) from energy-based formulations of mechanics, so the latter are ultimately not 'force-free' theories. But the point remains that unifying accounts of situations such as Case (*) may be given that do not explicitly appeal to forces.

The primary thing to note as regards identifying the needed argument is that resisting the claim that forces are redundant does not require that forces be the *only* entities available to unify the phenomena at issue—here, motions. It is enough to resist Ockham's razor that forces mark *a distinctive way* of doing this. Making out this possibility does not require denying that there are or may be alternative unifying accounts (involving entities besides forces) of seemingly diverse causes of motions. Of course, it might turn out that positing multiple entities as unifying the same effects is somehow problematic (I will consider the main threat along these lines in Section 5). But that is a different issue. For purposes of responding to the redundancy argument, all that is required is to show that forces unify phenomena, in a way that appeals, in a nontrivial fashion, to the characteristics distinctive of forces (as pushes or pulls, having a magnitude and direction).

But of course, we have such good reason; for as the success of NM in classical (indeed, nonquantum) contexts indicates, the characteristics distinctive of forces are relevant to accounting for motions across a very wide range of circumstances. Contra Mill, to say that there are forces, having admitted the usual causal relata, is not to utter a 'tautology', for to say there are forces is to say what is common to and relevant to motions involving these relata. Similarly, it is the characteristics distinctive of forces that are common to and relevant to our diverse experiences of contact with nonforce entities, as when e.g., our experience of the weight of a gold brick differs from our experience of its color, but is the same as our experience of the weight of a lead brick of equal mass. Contra the redundancy argument against felt forces, it is not 'just as satisfactory' to suppose that we do not experience forces, but rather just nonforce entities (e.g., nonforce properties of objects).

That Newtonian forces represent a distinctive level of explanatory unity also turns Jammer's redundancy argument on its head. Recall Jammer's claim that 'The main advantage [...] of the concept of force [...] is that it enables us to discuss the general laws of motion irrespective of the particular physical situation with which these motions are associated'. As just noted, however, the source of this advantage is that motions can be understood by reference to the characteristic features of forces alone. Contra Jammer, that motions can be so determined is evidence not that forces are mere methodological intermediates, but rather that forces mark a category cutting nature at a crucial metaphysical joint.

We can now give a (sound and valid) argument against the supposed redundancy of forces:

1. A scientific theory with more unity is preferable to one with less.
2. A posit P increases the unity of a scientific theory containing it if it unifies phenomena in a distinctive way.

3. Forces unify phenomena in a distinctive way, and hence increase the unity of physics.

∴ Other things being equal, physics with forces has more unity than one without forces.

∴ Other things being equal, we should admit forces.

(The ‘other things being equal’ qualifiers on the conclusions are intended to accommodate the earlier observation that there might be more than one way for a theory to be unifying. Assuming that the unity associated with the posit of forces is not trumped by some alternative route to unity that only a nonforce theory can travel, then we may endorse the conclusions.)

5 Do forces induce causal overdetermination?

We have good reason to posit Newtonian forces, even if other causes of motions (unifying or not) are on the scene. But now a new problem arises concerning whether forces, understood as producing effects that nonforce entities also appear to cause, induce an unsatisfactory overdetermination of effects.

The threat of overdetermination here is relevantly similar to that arising in the problem of mental causation. The latter problem gets going, most crucially, in cases where a brain event in a subject necessitates (with at least nomological necessity) a mental event in that subject (e.g., an event of feeling thirsty). If it is assumed that the mental and physical events are distinct, then the threat arises that every physical effect seemingly caused by the mental state (e.g., a reaching for a glass of water) is also caused by the brain state, so that such effects are systematically causally overdetermined.[27]

Like mental events, Newtonian forces appear to be ontologically dependent, in some way that involves at least nomological necessitation, on other entities (e.g., objects, properties, events).[28] And like mental events, the effects produced by forces (in particular, changes in motion) appear also to be caused by the entities necessitating the forces—indeed, this was what motivated the

[27] That the brain state (or some related physically acceptable state) is a cause of the physical effect is usually motivated by appeal to the *Causal closure of the physical*, according to which any physical (physically acceptable) effect has a purely physical (physically acceptable) cause. But the more general problem of ‘higher-order’ causation gets going any time a necessitated entity appears capable of causing certain effects that the necessitating entity appears capable of causing, as when *being fragile* competes with *having such-and-such specific crystal lattice structure* for causing the shattering of the glass.

[28] As in the case of mental causation, the terminology of necessitation is useful in being largely neutral as regards how, specifically, forces are related to the entities upon which they depend. As we will shortly see, different responses to the threats of overdetermination under discussion reflect different ways of filling in the dependency relation at issue.

redundancy argument. Hence it is unsurprising that we can formulate what I will call 'the problem of force-based causation':

1. Changes in motion are caused by forces.
2. Every such change in motion is caused by an entity necessitating (with at least nomological necessity) the force.
3. Forces and their necessitating entities are distinct.

∴ Every change in motion is causally overdetermined.

If avoiding the conclusion requires rejecting either (1) or (3), then we have a positive argument for eliminating forces. (1) might be rejected by claiming either that there are no forces, or else by claiming that forces exist, but do not cause motions; but since forces are presumed to be essentially efficacious *vis-á-vis* motions, the latter option doesn't make sense. So rejecting (1) entails rejecting forces. Rejecting (3) by maintaining that forces are identical with their necessitating entities also amounts to rejecting forces, insofar as we have independent good reason to accept the entities (objects, properties, events, etc.) necessitating forces, and since maintaining the existence of forces in the face of the redundancy argument requires (as per the previous section) that forces mark a level of unifying grain distinct from that marked by these independently accepted entities.

There are, however, ways of maintaining (1) and (3) (hence commitment to forces) while resisting overdetermination. Here I will take advantage of certain responses to the problem of mental causation, that can be brought to bear on the problem of force-based causation. Each requires getting somewhat more specific about the relation between forces and the entities upon which they depend.

5.1 Response: Newtonian forces as aspects

The first option, which I favor for forces, is relevantly similar to a promising nonreductive physicalist approach to the problem of mental causation. The strategy turns on showing that there are ways of understanding the relation between the causally competing mental and physical (physically acceptable) states on which these are ontologically distinct, but are so intimately related that causal overdetermination is nonetheless avoided. So, for example, nonreductive physicalists have suggested that mental states are parts (Shoemaker [1999]) or determinables (Yablo [1992]) of their necessitating physically acceptable (e.g., brain) states, with the underlying idea being that the part/whole and determinable/determinate relations plausibly guarantee that the causal powers (here and throughout, understood as tokens) had by a given mental state (to produce the effect in question) are a proper subset of those had by its necessitating physically acceptable state. In effect, the following condition is imposed:

> *Proper subset condition on the causal powers of mental states*: The causal powers had by any given mental state m are a proper subset of the causal powers had by the physically acceptable state necessitating m.[29]

where what it is to have a causal power is as follows:

> *Causal power possession*: S has a causal power $C(E, K)$ just in case an entity of type S, in circumstances of type K, causes an effect of type E.

and where the account of what it is for an entity to cause an effect is left open.

The nonreductivist's strategy plausibly avoids causal overdetermination: since each causal power of a given mental state is identical with a causal power of its necessitating (e.g., brain) state, there will be only one production of any effect supposed to be caused by the mental state (only one manifestation of the causal power). It also plausibly preserves the ontological autonomy of the mental state, since (as per the proper subset condition) the set of causal powers of this state will be different from that of its necessitating state.[30] Finally, the strategy plausibly preserves the causal efficacy of the mental state, for sometimes it will be the specific set of causal powers associated with the mental state, as opposed to the set associated with the physically acceptable state, that is most relevant to the production of the effect.[31]

We may bring a similar strategy to bear on the problem of force-based causation. The relevant condition in this case is:

> *Proper subset condition on the causal powers of forces*: The causal powers of any given force are a proper subset of the causal powers of the entity necessitating the force.[32]

[29] If more than one physically acceptable state necessitates m, then the condition applies to each. I assume here and throughout that mental states have causal powers—i.e., are not epiphenomenal—so that the condition, if satisfied, is satisfied nonvacuously.

[30] It is common to appeal to multiple realizability as grounds for supposing that the mental (more generally: higher-order) state has only a proper subset of the causal powers of any of its realizing states (see Shoemaker [1999]), with the general idea being that a realized entity has the causal powers in the intersection of its realizers (hence, under certain plausible assumptions, a proper subset of the causal powers had by each realizer). Appeal to multiple realizability is not, however, necessary to establish that the proper subset relation is in place (see Wilson [unpublished]).

[31] For example, since I would have reached for the glass even if my thirst had been realized by a $B2$ rather than a $B1$ state, it was the causal powers associated specifically with my thirst, as opposed to all those associated with $B1$, that were most relevant to my reaching for the glass.

[32] If more than one entity necessitates the force, the condition must apply to each.

Here too, various relations might be taken to hold between forces and their necessitating entities, that would guarantee the satisfaction of this proper subset condition. Indeed, given that the necessitating entities might be of different types, there might be several such relations. So, for example, if the necessitating entity is an event, then perhaps the force is a part of this event. Or if the necessitating entity is a property or property instance (trope), then perhaps the force is a determinable of the property or trope. No doubt there are other options. To signal this ontological neutrality, call the present view the 'aspect view' of mediating forces:

> *The aspect view*: Forces are aspects (characterized as having magnitude and direction of push-pull influence) of the nonforce entities necessitating them, whose causal powers satisfy the *Proper subset condition on the causal powers of forces*.[33]

One need not decide between the ontological options to see that understanding forces as per the aspect view is both plausible, and provides a basis for a feasible solution to the problem of force-based causation.

First, the view is plausible, in appropriately preserving the intuition motivating the redundancy argument; namely, that there is a sense in which forces are 'nothing over and above' their necessitating entities. In particular, this intuition is given a precise metaphysical ground in the identification of causal powers required by the proper subset condition. This ground also dismantles the threat of causal overdetermination of the effects of forces, since the identity of causal powers at issue indicates that when a force produces an effect (when a causal power of a force is manifested) this production is identical with the production of the effect by (a manifested causal power of) the nonforce cause necessitating the force. There is only one 'causing' of the effect, not two.

Second, the aspect view preserves the intuition of nothing over and aboveness without undermining either the existence or causal relevance of forces, hence avoids overdetermination in a particularly feasible fashion. First note that it is plausible to suppose that forces satisfy the proper subset condition, for reasons analogous to those typically appealed to in the case of mental states; namely, that forces are 'multiply realizable': forces of the same type may be necessitated by very different types of entities (as in variants on Case (*), in which particles with different properties and in different circumstances experience similar forces).[34] But if forces satisfy the proper

[33] I assume that we are concerned with causes and effects that are spatiotemporally proximal, so it makes sense to think of a force as involved in their causal interaction.

[34] Here again I do not think the appeal to multiple realizability is required in order to establish satisfaction of the proper subset condition; however, such appeal will do.

subset condition, then they may be reasonably claimed to be ontologically distinct from their necessitating entities, for entities with different sets of causal powers are different entities. Moreover, the causal autonomy of forces is assured, for as above the main motivation for positing forces is precisely that the characteristic features of forces (direction and magnitude of push-pull influence) and associated causal powers (to produce motions, tensions, etc.) mark a distinctive level of (in particular, causal) unity. Just as the distinctive unity achieved by the features of forces supports taking them to exist, even if other unifying entities are on the scene, so does this unity support taking forces to be causally relevant to the production of various effects, even if other causes of these effects are on the scene.

5.2 Response: forces as intermediaries

Another approach to the problem of force-based causation is roughly analogous to a broadly 'emergentist' strategy for resolving the problem of mental causation. It is again useful to present the strategy in terms of a proper subset condition on causal powers—in this case, to the rejection of such a condition.

With respect to the problem of mental causation, there are two ways the denial might proceed. First, one might deny that the necessitating (e.g., brain) state has a causal power (manifested on the occasion in question) to produce the effect in question, in which case overdetermination is avoided by denying that the brain state causes the effect. Second and more plausibly, one might allow that the brain state has a causal power to produce the effect, but maintain that this power is different from the causal power had by the mental state, in that the brain state has the causal power only in virtue of being, in the circumstances, a necessary precondition for the mental state. So, for example, the brain state might cause the mental state, which then causes the effect in question, with overdetermination avoided by noting that links in causal chains do not overdetermine their effects.[35]

On either approach, the *Proper subset condition on the causal powers of mental states* is rejected, in that mental states are assumed to have at least one causal power not identical to one had by their necessitating states. Supposing

[35] A different filling in of the 'necessary precondition' suggestion is required if it is denied that causation can be synchronic (as the mental and physical states at issue are often supposed to be). See (Wilson [2002]) for a suggestion as to how such filling in might proceed. This issue would not affect the present discussion, since in the case of the problem of force-based causation, there is no presupposition that forces are synchronic with the entities (the usual causes) necessitating them. Of course, on the aspect view, it is natural to take forces and the entities necessitating them to be synchronic. But since the causal powers of effects are usually not a proper subset of the causal powers of their causes, the proponent of the aspect view is unlikely to take the relation between forces and their necessitating entities to be causal.

this assumption is correct, there appears to be no in-principle problem with maintaining the ontological and causal autonomy of mental states from these necessitating states: a given mental state has at least one causal power that its necessitating brain state does not have, which is specifically implicated in causing the effect in question.[36]

One could similarly respond to the problem of force-based causation. First, one might deny that the nonforce entities necessitating forces cause the effects attributed to forces. Second and more plausibly, one might allow that these necessitating entities also cause the effects in question, but in a way different from forces—say, by causing forces, which go on to cause the usual effects. Either way, a given force is assumed to have at least one causal power not identical with a causal power of the nonforce entity that necessitates it; hence the *Proper subset condition on the causal powers of forces* is denied. Again, there might be various ontological accounts of forces compatible with the denial of this condition. But reflecting that this denial indicates that forces are not appropriately seen as aspects of the entities necessitating them, and given the continuing supposition that forces cause the effects in question, forces on this view are plausibly taken to be intermediaries between the usual causes and the usual effects. So (again allowing for some ontological flexibility) call this the 'intermediary' view of mediating forces:

> *The intermediary view*: Forces are intermediaries (characterized as having magnitude and direction of push-pull influence) between the nonforce entities necessitating them and the nonforce entities that they cause, having at least one causal power not identical with a causal power of their necessitating entities.

Though Bigelow *et al.* do not identify or discuss the problem of force-based causation, it appears that they would endorse the intermediary view in responding to this problem. For in giving an additional response to the redundancy argument (what might be called 'the argument from causation'), they say the following:

> After the elimination of forces, our physics relates the properties of objects: the properties of the 'exerter' and the properties of the 'exerted upon.' But this physics is remarkably Humean. There is no causation left in the story. Yet good science is incomplete without causation. ([1988], p. 619)

[36] I say that there is no in-principle problem, with a caveat. The emergentist's 'new causal power' approach to the problem of mental causation faces a difficulty discussed in (Kim [2000]) and (Wilson [2002]), that I think can be resolved without much trouble, and which is related to the alternative strategy noted in the previous footnote. Again, this issue would not affect the present discussion.

The claim that 'after the elimination of forces [...] there is no causation left in the story' is compatible with either version of the intermediary view, according to which the entities necessitating forces are merely necessary preconditions (causal or noncausal) for forces, and where the latter are the key locus of causal efficacy as regards the effects in question.[37]

6 Conclusion

Notwithstanding the advantages of energy-based formulations of mechanics and the apparent failure of NM to apply in quantum contexts, NM is not an ontologically obsolete theory. For in classical contexts, forces and energies are compatible, mutually supporting posits; and in being only restrictedly applicable NM is no different from any special science. I have suggested here that NM is also a special science, with the concomitant potential to deliver insight into the nonfundamental ontology of the world—as including Newtonian forces, in particular. And I have argued that this potential is realized, both because Newtonian forces are compatible with more fundamental theories (with the exception of GR, but on which the jury is still out) and with ordinary experience; and because neither traditional (empiricist, redundancy) nor new (causal overdetermination) arguments against forces go through.

This defense of Newtonian forces brings several metaphysical questions in its wake. Are forces aspects of the nonforce entities upon which they depend (as I maintain) or independent intermediaries between these (as Bigelow *et al.* [1988] maintain)—or is the order of dependence reversed (as Faraday evidently thought), with nonforce entities being constituted by forces? More generally, what is the ontological status of Newtonian forces—are they manifested dispositions, causal relations, sui generis? Forces and energies are theoretically compatible, but what is the metaphysical story to be told concerning this compatibility? And how exactly are Newtonian forces related to more fundamental goings-on, such as quantum particle exchanges? These questions stand unanswered; Newton stands largely vindicated.

Acknowledgements

[37] Bigelow *et al.*'s 'argument from causation' would not strike many as providing an adequate response to the redundancy argument. Those (e.g., Shoemaker) who think that the usual causal relata are essentially individuated by the causal relations they may enter into will not accept the 'no forces, no causation' claim; nor will those (e.g., Lewis) who, while denying that the usual causal relata are so essentially individuated, think they have ways of accounting for causal interactions between these entities by means of more or less regular associations. Neither essentialists nor Humeans, then, will agree that forces are needed for causal efficacy. But as per Section 4, this does not matter for purposes of responding to the redundancy argument.

Many thanks to David Baker, Richard Boyd, Benj Hellie, Eric Hiddleston, Andrew Janiak, Jim Joyce, Gordy Kane, Marc Lange, Brian McLaughlin, Jonathan McCoy, Peter Railton, Sydney Shoemaker, Larry Sklar, Jason Stanley, and Daniel Steel for helpful comments on (sometimes distant and very different) ancestors of this article.

Department of Philosophy
University of Toronto
jessica.m.wilson@utoronto.ca

References

Berkeley, G. [1948–1957]: 'De Motu', in A. A. Luce and T. E. Jessop (*eds*), *The Works of George Berkeley*, London: Nelson.

Bigelow, J., Ellis, J. and Pargetter, R. [1988]: 'Forces', *Philosophy of Science*, **55**, pp. 614–30.

Bohm, D. [1952]: 'A Suggested Interpretation of Quantum Theory in Terms of "Hidden Variables", Parts I and II', *Physical Review*, **85**, pp. 166–79, 180–93.

Bohm, D. and Hiley, B. J. [1993]: *The Undivided Universe: An Ontological Interpretation of Quantum Theory*, London: Routledge.

Butterfield, J. [unpublished]: 'Between Laws and Models: Some Philosophical Morals of Lagrangian Mechanics', <philsci-archive.pitt.edu/archive/00001937/>.

Cline, D. [2004]: *Weak Neutral Currents: The Discovery of the Electro-Weak Force*, Boulder, CO: Westview Press.

Cohen-Tannoudji, C., Diu, B. and Laloë, F. [1977]: *Quantum Mechanics*, 2nd edn, vol. 1, Chichester: John Wiley and Sons.

Feynman, R. [1963]: *The Feynman Lectures on Physics*, vol. i, Reading, MA: Addison Wesley.

Feynman, R. [1965]: *The Character of Physical Law*, Cambridge, MA: MIT Press.

Forster, M. and Kryukov, A. [2003]: 'The Emergence of the Macroworld: A Study of Intertheory Relations in Classical and Quantum Mechanics', *Philosophy of Science*, **70**, pp. 1039–51.

Goldstein, H., Poole, C. and Safko, J. [2002]: *Classical Mechanics*, 3rd edn, San Francisco, CA: Addison Wesley.

Hanc, J. and Taylor, E. F. [2004]: 'From Conservation of Energy to the Principle of Least Action: A Story Line', *American Journal of Physics*, **72**, pp. 514–21.

Hanc, J., Tulega, S. and Hancova, M. [2003]: 'Simple Derivation of Newtonian Mechanics from the Principle of Least Action', *American Journal of Physics*, **71**, pp. 386–91.

Hardin, C. L. [1988]: *Color for Philosophers*, Indianapolis: Hackett Publishing Co.

Jammer, M. [1957]: *Concepts of Force*, Cambridge, MA: Harvard University Press.

Kane, G. [1993]: *Modern Elementary Particle Physics: the Fundamental Particles and Forces*, Boulder, CO: Westview Press.

Kim, J. [1993]: 'The Non-reductivist's Troubles with Mental Causation', in J. Heil and A. Mele (*eds*), *Mental Causation*, Oxford: Oxford University Press, pp. 189–210, Reprinted in Kim, J. 1993, *Supervenience and Mind: Selected Philosophical Essays*, Cambridge: Cambridge University Press.

Kim, J. [2000]: 'Making Sense of Emergence', *Philosophical Studies*, **95**, pp. 3–36.

Lange, M. [2002]: *An Introduction to the Philosophy of Physics: Locality, Fields, Energy, and Mass*, Oxford: Blackwell Publishing.

Marion, J. B. and Thornton, S. T. [1988]: *Classical Dynamics of Particles and Systems*, New York: Harcourt Brace Jovanovich.

Maxwell, J. C. [1890]: 'On Action at a Distance', in W. D. Niven (*ed.*), *The Scientific Papers of James Clerk Maxwell*, London: Cambridge University Press, pp. 311–23. Reprinted by Dover Publications.

Messiah, A. [1970]: *Quantum Mechanics*, Amsterdam: North-Holland.

Mill, J. S. [1843]: *A System of Logic*, London: Longmans, Green, Reader, and Dyer.

Newton, I. [1687/1999]: *The Principia: Mathematical Principles of Natural Philosophy*, Berkeley: University of California Press, I. B. Cohen and A. Whitman, translators. Originally published in 1687.

Newton, I. [1704/1952]: *Opticks: Or a Treatise of the Reflections, Refractions, Inflections & Colours of Light*, New York: Dover.

Salam, A. [1990]: *Unification of Fundamental Forces*, Cambridge: Cambridge University Press.

Shankar, R. [1994]: *Principles of Quantum Mechanics*, 2nd edn, New York: Kluwer Publishers.

Shoemaker, S. [1999]: 'Realization and Mental Causation', in Elevich (*ed.*), *Proceedings of the 20th World Congress, Vol. 9: Philosophy of Mind*, B. Green: Philosophy Documentation Center, pp. 23–31. A revised version appears in C. Gillett and B. Loewer (*eds*), 2001, *Physicalism and Its Discontents*, Cambridge: Cambridge University Press.

Stevens, C. F. [1995]: *The Six Core Theories of Modern Physics*, Cambridge, MA: MIT Press.

van Fraassen, B. [1980]: *The Scientific Image*, Oxford: Oxford University Press.

Wilson, J. [2002]: 'Causal Powers, Forces, and Superdupervenience', *Grazer Philosophische-Studien*, **63**, pp. 53–78.

Wilson, J. [unpublished]: 'Non-reductive Physicalism and Degrees of Freedom', In preparation.

Yablo, S. [1992]: 'Mental Causation', *Philosophical Review*, **101**, pp. 245–80.