ISSN 2045-5577

ORDER: GOD'S, MAN'S AND NATURE'S

'Maxwell's Scientific Metaphysics and Natural Philosophy of Action: Agency, Determinacy and Necessity from Theology, Moral Philosophy and History to Mathematics, Theory and Experiment'

Jordi Cat*

'In the beginning was the Action' Goethe, *Faust*, Part I, Scene 3.

Abstract

Maxwell's writings exhibit an enduring preoccupation with the role of metaphysics in the advancement of science, especially the progress of physics. I examine the question of the distinction and the proper relation between physics and metaphysics and the way in which the question relies on key notions that bring together much of Maxwell's natural philosophy, theoretical and experimental. Previous discussions of his attention to metaphysics have been confined to specific issues and polemics such as conceptions of matter and the problem of free will. I suggest a unifying pattern based on a generalized philosophical perspective and varying expressions, although never a systematic or articulated philosophical doctrine, but at least a theme of action and active powers, natural and human, intellectual and material, with sources and grounds in theology, moral philosophy and historical argument. While science was developing in the direction of professional specialization and alongside the rise of materialism, Maxwell held on to conservative intellectual outlook, but one that included a rich scientific life and held science as part of a rich intellectual, cultural and material life. His philosophical outlook integrated his science with and captured the new Victorian culture of construction and work, political, economic, artistic and engineering.

1. Physics vs metaphysics

Maxwell deplored the absence of metaphysical inquiry in contemporaneous scientific works and chastised repeatedly his colleague and old friend Peter Guthrie

* Department of History and Philosophy of Science, Goodbody Hall 130, Indiana University, Bloomington, IN 47405, USA. Email: drjordicat@yahoo.com

Tait for duplicity, never missing ‘an opportunity to denounce metaphysical reasoning’ in science, except when engaging in theological speculation. Tait’s inconsistency and ‘betrayal’ of his Edinburgh intellectual school friend echoed the developments and tensions of his time, with the rise of science and technology in power and prestige, embodied in the science, engineering and business successes of Tait’s collaborator William Thomson, Lord Kelvin,[1] and the debates over their conflict with religion. But he also added praise when Tait adopted an intermediate position, in a treatise on thermodynamics, employing metaphysical notions to inform, ground and stimulate physical thought:

‘in the very first page of the book, he denounces all metaphysical methods of constructing physical science, and especially any a priori decisions as to what may have been or ought to have been. In the second page he does not indeed give us Aristotle's ten categories, but he lays down four of his own:—matter, force, position, and motion, to one of which he tells us, "it is evident that every distinct physical conception must be referred," and then before we have finished the page we are assured that heat does not belong to any of these four categories, but to a fifth, called energy.
This sort of writing, however unlike what we might expect from the conventional man of science, is the very thing to rouse the placid reader, and startle his thinking powers into action.’ (in Niven 1890 vol 2, heretofore SP2, 661).

Maxwell’s writings exhibit an enduring preoccupation with the role of metaphysics in the advancement of science, especially the progress of physics. I want to examine the question of the distinction and the proper relation between physics and metaphysics and the way in which the question relies on key notions that bring together much of Maxwell’s natural philosophy, theoretical and experimental. Previous discussions of his attention to metaphysics have been confined to specific issues and polemics such as conceptions of matter and the problem of free will.[2] I suggest a unifying pattern based on a generalized philosophical perspective and varying expressions, although never a systematic or articulated philosophical doctrine, but at least a theme of action and active powers,

[1] Thomson was at the center of developments in electro-technology, especially telegraphic cables and precision measurement instruments, amassing wealth from his designs and patents. See Smith and Wise 1989 and Hunt 1991.
[2] See, especially, Harman 1995.

natural and human, intellectual and material, with sources and grounds in theology, moral philosophy and historical argument. While science was developing in the direction of professional specialization and alongside the rise of materialism, Maxwell held on to conservative intellectual outlook, but one that included a rich scientific life and held science as part of a rich intellectual, cultural and material life. His philosophical outlook integrated his science with and captured the new Victorian culture of construction and work, political, economic, artistic and engineering.

What is physics? Maxwell made recurring methodological remarks in the discussion of new and old results, his own and of others. Physics aims at understanding through precision and generality of symbolic representation, with simplicity, unity (particularly interconnection), objectivity and truth. It involves the formation of hypotheses, calculation of predictions and the interrogation of nature in material interaction with it.[3] The minimal form of interaction is exact measurement (see below). Understanding seeks ultimately true explanation, dynamical explanation, in terms of the arrangements of constituents of matter, their masses, velocities, acting forces, and transforming but conserved energy.[4]

An example that helps illustrate the distinction of physics from metaphysics is molecular theory, 'a branch of physics which not very long ago would have been considered rather a branch of metaphysics.' (SP2, 221) So, what has come to differentiate molecular physical theory from metaphysical atomism? It is the

[3] 'I hope to attain generality and precision, and to avoid the dangers arising from a premature theory professing to explain the cause of the phenomena. (…) those who by interrogating Nature herself can obtain the only true solution of the questions which the mathematical theory suggests.' (SP1, 159)

[4] 'in a physical point of view all matter must in itself be the same, and can be modified only by differences of arrangement and motion and by being actuated by different systems of force.' (Harman 1992-2000, vol 1, heretofore LP 1, 423) and 'there are certain general laws, regulating the amount of Energy arising from given conditions, and determining the total effect of the forces called into play, which are among the most important conclusions of physical science. The science founded on these laws is called Energetics.' (LP1, 666) Understanding includes both illustration, which requires concrete construction in imaginary conception, and explanation, which assumes believe in the truth of a causal model; see my Cat 2001.

application of standards and methods of representation, explanation and belief:

'The molecules have laws of their own, some of which we select as most intelligible to us and most amenable to our calculation. We form a theory from these partial data, and we ascribe any deviation of the actual phenomena from this theory to disturbing causes.'[5] (SP2, 228-29)

Alternatively, beyond a certain established limit, deviations might be considered inconsistency: 'If experiments on gases are inconsistent with the hypothesis of these propositions, then our theory, though consistent with itself, is proved to be incapable of explaining the phenomena of gases' (SP1, 378) Although Maxwell does not provide a specific criterion for deciding when deviation is large enough to declare the result inconsistent with the prediction. Precision does not help set the criterion, only to apply it.

In general, Maxwell writes,

'The first part of the growth of a physical science consists in the discovery of a system of quantities on which its phenomena may be conceived to depend. The next stage is the discovery of the mathematical form of the relations between these quantities. After this, the science may be treated as a mathematical science, and the verification of the laws is effected by a theoretical investigation of the conditions under which certain quantities can be most accurately measured, followed by an experimental realisation of these conditions, and actual measurement of the quantities.'[6] (SP2, 257)

The aim is explanation, which aims at laying out the causes of phenomena; the latter, in the most general case, are causes of changes in configuration or motion, and then are forces:

---

[5] 'At the same time we confess that what we call disturbing causes are simply those parts of the true circumstances which we do not know or have neglected, and we endeavour in future to take account of them.' (ibid.)

[6] 'all the mathematical sciences are founded on relations between physical laws and laws of numbers, so that the aim of exact science is to reduce the problems of nature to the determination of quantities by operations with numbers.' (SP1, 156) Moreover, the application to nature involves measurement and experiment:
'the human mind, in order to conceive of different kinds of quantities, must have them presented to it by nature.' (SP2, 218)
'mature theory, in which physical facts will be physically explained, will be formed by those who by interrogating Nature herself can obtain the only true solution of the questions which the mathematical theory suggests.' (SP1, 159)

‘When any phenomenon can be described as an example of some general principle which is applicable to other phenomena, that phenomenon is said to be explained. Explanations, however, are of very various orders, according to the degree of generality of the principle which is made use of.
(…)when a physical phenomenon can be completely described as a change in the configuration and motion of a material system, the dynamical explanation of that phenomenon is said to be complete. We cannot conceive any further explanation to be either necessary, desirable, or possible, for as soon as we know what is meant by the words configuration, motion, mass, and force, we see that the ideas which they represent are so elementary that they cannot be explained by means of anything else.’ (SP2, 418)

Explanation also aims at further generalization, which provides a measure of scientific progress:

‘If it should then appear that these laws, originally devised to include one set of phenomena, may be generalized so as to extend to phenomena of a different class, these mathematical connexions may suggest to physicists the means of establishing physical connexions; and thus mere speculation may be turned to account in experimental science.’ (SP1, 188)

Cambridge science, especially mathematics, emphasized the virtue of generality, which also enjoyed a Newtonian credential, as the goal of the third and fourth rules for reasoning in natural philosophy.[7]

Now, what is metaphysics? Maxwell’s scattered remarks (see below) appear as early as those on physics and associate metaphysics with speculation at a time when the term ‘speculation’ was also associated with morally questionable financial practices unrestrained by the exchanged of material goods or transactions involving services. He associated metaphysics with depth (rather than generality), abstract foundations, first principles, reasoning from language (from meanings or concepts), and concern with necessary truth. Maxwell argues for a particular relation between physics and metaphysics. Metaphysics is for him historically inseparable from scientific progress. But the relation is also a reflection of the educational and cultural place of science in Scotland and Cambridge, with a natural regime of humanities and religion of integrating the new natural philosophy in the traditional models of knowledge and also keeping it under control anxious about being left

[7] See *Principia*, Book Three. On the scientific culture of generality, see Cat 2011.

behind or being superseded. Both the relation and the argument Maxwell provides are historical. This consistency allows him to incorporate and defend his personal rich intellectual life, formation and speculative inclinations and to justify the metaphysical dimensions of his own natural philosophy, to be taken, indeed, in his own historical context as relevant to the latest stage of physical progress. The historical argument is also consistent with his interest in history as the consequence of the actions of individuals, especially in the history of science, and not just the determinism of blind forces and crowds, in the manner suggested by Henry Buckle, which he came to associate with the statistical approach. To this effect he distinguishes the science of history from the history of science.[8] Maxwell emphasizes both the development of physics out of metaphysics, and the philosophical influence of physics:

'I would have you remember that the men to whom we owe the greatest discoveries in mathematics and physics were metaphysicians. They thought it a very important thing to determine the *evidence* on which they built any law…'

and he adds,

'the greatest and most original metaphysicians have been *nourished* as it were on physical truth.' (LP1, 424-5, orig, emph.) In other words, metaphysics strengthened attention to formal rigor in reasoning and physics provided content. Independently, with Descartes and Leibniz in mind, metaphysics sought necessary truths, truths of

---

[8] 'It is true that the history of science is very different from the science of history. We are not studying or attempting to study the working of those blind forces which, we are told, are operating on crowds of obscure people, shaking principalities and powers, and compelling reasonable men to bring events to pass in an order laid down by philosophers.
The men whose names are found in the history of science are not mere hypothetical constituents of a crowd, to be reasoned upon only in masses. We recognise them as men like ourselves, and their actions and thoughts, being more free from the influence of passion, and recorded more accurately than those of other men, are all the better materials for the study of the calmer parts of human nature.' (SP2, 251)
History of science is historical, not statistical in the sense of following and valuing individual action: 'The study of human nature by parents and schoolmasters, by historians and statesmen, is therefore to be distinguished from that carried on by registrars and tabulators, and by those statesmen who put their faith in figures. The one may be called the historical, and the other the statistical method.' (SP2, 374)

reason which are the outcome of necessary relations established by laws of reasoning:

‘there is a science which treats of necessary truth, and which carefully distinguishes that which must be from that which only happens to be. The science of Metaphysics is not of modern growth. Philosophers of the greatest eminence have attacked these very questions from the earliest times, and yet it would appear that the one party could never wholly convince the other. One reason was that up to the sixteenth century both parties were wrong, for the laws they contended about were neither necessary truths nor the results of experience, being contrary both to fact and to reason, and after the sixteenth century both parties were on a different ground for now the laws they admitted were at least true if not necessary.’ (LP1, 424)

Metaphysical influence is also a sign of physical value and success. Maxwell’s key historical example, now professor at Cambridge, is Newton:

‘The influence of the physical ideas of Newton on philosophical thought deserves a careful study. It may be traced in a very direct way through Maclaurin and the Stewarts [the mathematician Matthew and his son Dugald] to the Scotch School, the members of which had all listened to the popular expositions of the Newtonian Philosophy in their respective colleges. In England, Boyle and Locke reflect Newtonian ideas with tolerable distinctness, though both have ideas of their own. Berkeley, on the other hand, though he is a master of the language of his time, is quite impervious to its ideas. Samuel Clarke is perhaps one of the best examples of the influence of Newton; while Roger Cotes, in spite of his clever exposition of Newton's doctrines, must be condemned as one of the earliest heretics bred in the bosom of Newtonianism.’ (1873, LP2, 816-17)

Using history as a source of empirical data and inductive evidence, in the manner of, or simply following, his College Master, William Whewell, he also notes negative instances:

‘The whole course of history is full of examples showing how the neglect of scientific principles produces, in the first place, the certain failure of every enterprise, secondly, how the unscientific mind has been led from one error to another up to the very pinnacle of absurdity, and thirdly how the want of observation, wrongheadedness, and superstition thus produced have generated systems of philosophy which, by beginning with the contradiction of physical facts, guarantee the thorough unreality of the whole superstructure.’ (LP1, 673)

After all, '[The metaphysician] is nothing but a physicist disarmed of all his weapons.'[9]

However, metaphysical occasions provided by contemporaneous physics still abound, for instance, on the nature of the individuality of atoms:

'If a theory of this kind is true, or even if it is conceivable, our idea of matter may have been introduced into our minds through our experience of those systems of vortices which we call bodies, but which are not substances, but motions of a substance; and yet the idea which we have thus acquired of matter, as a substance possessing inertia, may be truly applicable to that fluid of which the vortices are the motion, but of whose existence, apart from the vortical motion of some of its parts, our experience gives us no evidence whatever.
It has been asserted that metaphysical speculation is a thing of the past, and that physical science has extirpated it. The discussion of the categories of existence, however, does not appear to be in danger of coming to an end in our time, and the exercise of speculation continues as fascinating to every fresh' (SP2, 255)

Or the case of action at a distance:

'These are some of the already discovered properties of that which has often been called vacuum, or nothing at all. They enable us to resolve several kinds of action at a distance into actions between contiguous parts of a continuous substance. Whether this resolution is of the nature of explication or complication, I must leave to the metaphysicians.' (SP2, 323)

These metaphysical considerations of the ether are contrasted with the too 'highly metaphysical' uses of the idea of an ether made by Descartes and others:

'The hypothesis of an aether has been maintained by different speculators for very

---

[9] 'a disembodied spirit trying to measure distances in terms of his own cubit, to form a chronology in which intervals of time are measured by the number of thoughts which they include, and to evolve a standard pound out of his own self-consciousness. Taking metaphysicians singly, we find again that as is their physics, so is their metaphysics. Descartes, with his perfect insight into geometrical truth, and his wonderful ingenuity in the imagination of mechanical contrivances, was far behind the other great men of his time with respect to the conception of matter as a receptacle of momentum and energy. His doctrine of the collision of bodies is ludicrously absurd. He admits, indeed, that the facts are against him, but explains them as the result either of the want of perfect hardness in the bodies, or of the action of the surrounding air. His inability to form that notion which we now call force is exemplified in his explanation of the hardness of bodies as the result of the quiescence of their parts.'

different reasons. To those who maintained the existence of a plenum as a philosophical principle, nature's abhorrence of a vacuum was a sufficient reason for imagining an all-surrounding aether, even though every other argument should be against it. To Descartes, who made extension the sole essential property of matter, and matter a necessary condition of extension, the bare existence of bodies apparently at a distance was a proof of the existence of a continuous medium between them.
But besides these high metaphysical necessities for a medium, there were more mundane uses to be fulfilled by aethers.' (SP2, 763)

Metaphysics also appears more formally, as the conceptual order of theory, for instance, reviewing Thomson and Tait's foundational project:

'Hence kinematics, as involving the smallest number of fundamental ideas, has a metaphysical precedence over statics, which involves the idea of force, which in its turn implies the idea of matter as well as that of motion.' (SP2, 327)

In general, then,

'It is absolutely manifest from these and other instances that any development of physical science is likely to produce some modification of the methods and ideas of philosophers, provided that the physical ideas are expounded in such a way that the philosophers can understand them.' (LP2, 817)

The relationship between physics and metaphysics is not just historically, but conceptually intimate. Metaphysics concerns more abstract versions of physical ideas and practices:

'The intimate connexion between physical and metaphysical science is indicated even by their names. What are the chief requisites of a physical laboratory? Facilities for measuring space, time, and mass. What is the occupation of a metaphysician? Speculating on the modes of difference of co-existent things, on invariable sequences, and on the existence of matter.' (1873, LP2, 815; Bio 436)

Physics has philosophical value: 'the chief philosophical value of physics is that it gives the mind something distinct to lay hold of.'[10]

But what about the other direction, metaphysics stimulating physics? Maxwell is least explicit on this relation, especially in his public scientific and methodological works, because in a period of ascendency and institutional and

---

[10] Letter to his undergraduate friend Richard Buckley Litchfield of March 1858, LP1, 588.

professional consolidation of scientific authority, it is not physics-first. He declared that 'the practical relation of metaphysics to physics is most intimate' (1868, LP2, 361) But, what makes it practical? History has shown the dependency of one upon the other: 'Metaphysicians differ from age to age according to the physical doctrines of the age and their personal knowledge of them', and now the time has come for his own physics enabling metaphysics. As he wrote to Litchfield in July 1856, at the end of his first Cambridge period: 'I find I get fonder of metaphysics and less of calculation continually and my metaphysics are fast settling into the rigid high style, that is about ten times as far *above* Whewell as Mill is *below* him or Comte or Macaulay *below* Mill using above and below conventionally like *up* & *down* in Bradshaw.' (LP1, 411) and 'I happen to be interested in speculations standing on experimental & mathematical data and reaching beyond the sphere of the senses without passing into that of words and nothing more.' (LP2, 361; comp. LP1, 425).

Maxwell integrates the speculative tradition with the new scientific attitude not as an act of modernism but as an outcome of historical argument. He is interested in metaphysical speculation grounded on physical theory. But the grounding establishes physics firmly on metaphysical foundations. These are the physics and metaphysics of his own historical situation. He calls it a science of metaphysics. Again, discussing Tait as an immediate historical precedent of selective metaphysical thinking:

'We are glad to find, however, that in spite of the contempt which Prof. Tait pours upon the *a priori* physics of non-experimental philosophers, he admits that there is a true science of metaphysics which discusses the fundamental ideas of all science and knowledge, not by shutting out all the facts of experience, but by calling in all the evidence obtainable from the whole circle of the science' (LP3, 309)

Even to other members of the Mathematical and Physical Section of the BAAS, he reminds that

'we are met as cultivators of mathematics and physics. In our daily work we are led up to questions the same in kind with those of metaphysics; and we approach them, not trusting to the native penetrating power of our own minds, but trained by a long-continued adjustment of our modes of thought to the facts of external nature.' (SP2, 216)

He considers the conceptual foundations of mechanics (see below), for instance, in the case of molecules:

'That matter, as such, should have certain fundamental properties,-that it should exist in space and be capable of motion,-that its motion should be persistent, and so on,-are truths which may, for anything we know, be of the kind which metaphysicians call necessary. We may use our knowledge of such truths for purposes of deduction, but we have no data for speculating as to their origin. But that there should be exactly so much matter and no more in every molecule of hydrogen is a fact of a very different order.' (SP2, 376-77)

The relation of metaphysics to physics is practical also in a metaphysical, or as Kant put it, transcendental, sense. Active metaphysics provides the possibility of physical theory. And physical theory is a theory of action. The practical relation between physics and metaphysics goes both ways. This is the metaphysics of power and agency, natural and human, material and mental, of the active and constructive aspects of the mind in scientific cognition, a position common to Scottish Philosophy reinforced by the foundational projects and metaphysical systems of German Idealism. Understanding the world and understanding and constructing, ideas are inseparable conditions of knowledge, generally and scientific.

Maxwell's own historical and philosophical vantage point are the basis of an argument for the role of philosophy in science, his experienced philosophy and science. Among the philosophical sources stand out Aristotle, Kant, Dugald Stewart, Adam Smith, William Hamilton, John Wilson and William Whewell. Metaphysics was part and parcel of his education, Scottish and English: First in Edinburgh, where general philosophy was the basis of the Scottish system of general education, with John Wilson and William Hamilton; and next in Cambridge, especially at Trinity, where metaphysics was not only a distinctive aspect of German culture and the Master Whewell's interest, but also topic of examination for fellowships, alongside classics and mathematics.[11] By contrast, Kelvin's education in Glasgow and at

[11] This consistent idealist aspect of Maxwell education has been noted in Everitt 1983 and Harman 1995.

Peterhouse College in Cambridge took him to an interest in a more purely French education, in Cambridge and Paris, in mathematical and experimental precision.[12]

The new metaphysics was a metaphysics of necessary thought, often of scientific thought and, not surprisingly, especially mathematics. Idealism echoed but had replaced rationalism. For Hamilton space was 'one of our necessary notions, -in fact, a fundamental condition of thought itself', part of our 'acts of knowledge…contributed by the knowing subject', 'is a necessary notion…native to the mind', as established by the 'analysis of Kant…beyond the possibility of doubt', while spatial extension is a material property of reality.[13] Maxwell wrote in his class essay for Hamilton that geometric figures are 'forms of thought and not of matter' (LP1, 111). And next at Cambridge, at the secret conversation society of the Apostles that further encouraged his speculative philosophical and literary interests, he told his companions that fundamental ideas of space and time, prior to those of matter and force, are for him, as are for Hamilton and Whewell, products of acts of intellection: 'As for space and time, any man will tell you that 'it is now known and ascertained that they are merely modifications of our own minds'' (LP1, 377) Similarly, for Hamilton 'comparison is supposed in every, the simplest act of knowledge' and Maxwell adopted the doctrines that knowledge is relational, and the perception of relations 'implies an exercise of reason,'[14] and mathematical knowledge is knowledge of 'relations of quantities to each other', ideas of relations, although imperfect, being 'clearer and more distinct' than ideas of 'inward essences.'[15] Also for Whewell, as was for Kant, knowledge is of connections, and 'without thoughts, there could be no connection', but 'without things, there could be no reality', such is the 'fundamental antithesis of philosophy'. Of connecting

---

[12] I note and explore the contrast in Cat forthcoming a.
[13] Hamilton 1859, *Lectures on Metaphysics* 1: 160, and 2: 113-14; cited in Harman, LP1, 111, n. 5.
[14] Hamilton 1859, *Lectures on Metaphysics* 2: 279, cited in Harman, LP1, 112, n. 9; see also Stewart 1818, *Philosophy of the Human Mind*, 2: 386.
[15] After MacLaurin 1742, *A Treatise of Fluxions* 1: 51-2.

thoughts stand out the fundamental ideas, these 'entirely shape and circumscribe our knowledge' and 'regulate the active operations of our minds.'[16]

Maxwell, effectively, adopted the relational a priori standpoint with an emphasis on quantitative relations and specific fundamental ideas for the constitution of different theories of natural phenomena:

'Every science must have its fundamental ideas —modes of thought by which the process of our minds is brought into the most complete harmony with the process of nature—and these ideas have not attained their most perfect form as long as they are clothed with the imagery, not of the phenomena of the science itself, but of the machinery with which mathematicians have been accustomed to work problems about pure quantities.' (SP 2: 325)

And 'in the scientific point of view the *relation* is the most important thing to know' (LP1: 382, orig. itals.).[17] He gives, among others, the examples of space and force. The concept of three-dimensional space is a fundamental idea, a necessary one, signifying 'a real analogy between the constitution of the intellect and that of the external world', bridging the gap between thoughts and things (LP 2, 378). Another example is force, following the example of the concepts of Euclidean geometry: 'If a man understands what Force means, I have only to secure his attention, and I can prove to him as many propositions as I please, but if he has not the fundamental idea, no amount of demonstration will give it him. He must think for himself till he gets it.' (LP1, 668)

Following Whewell, and the example of Euclidean geometry, he also defends the a priori nature of the fundamental laws of motion, which describe different roles of force: 'the mechanical sciences treat of the motion of matter considered simply as matter, and are built upon the fundamental ideas of force and mass without any appeal to experimental measurements.' (LP1, 421) In *Matter and Motion* (1876), he still holds the same position and specifically notes the non-experimental basis for

[16] Whewell 1847, *Philosophy of the Inductive Sciences* 1: 16, 18, 59.
[17] 'The student who wishes to master any particular science must make himself familiar with the various kinds of quantities which belong to that science. When he understands all the relations between these quantities, he regards them as forming a connected system, and he classes the whole system of quantities together as belonging to that particular science.' (SP2, 218)

each law, mostly, what he calls 'the contradiction of an absurdity', which is effectively the notion of a priori he borrows from Whewell (see below). Similar considerations apply to absolute space, which contradicts what he considers the relational, relative, nature of our knowledge, especially empirical knowledge (see Appendix).

It is in mathematics where, as in reasoning more generally, we encounter key conceptual coordinates of Maxwell's natural philosophy: fundamental ideas, generality, determinacy and necessity. I will focus mainly on the much neglected notion of determinacy, or determination, determinateness, definiteness or fixity, and the corresponding *relations* and *acts* of determining, defining and fixing. Determination is a legacy of the scholastic and later rationalist concern with conceptual individuation and differentiation, also the empiricists' concern fixity and distinctness of ideas and beliefs, including matters of relations and inference. In the early Victorian period the concern with fixing took also the form of a pursuit of stability and permanence in material practices from photography (fixing images) to mechanical engineering (stability of fixing parts of machines or machines to a base). In mathematics and logic the determinacy of these relations implies univocality, precision of boundaries, unique applicability of concepts and criteria, unique determinability of outcomes of calculation and unique decidability, without ambiguity, or underdetermination, arbitrariness or uncertainty, even lack of connectedness itself, all recurring concerns in Maxwell's discussion of physical representation and calculation.

Maxwell paid attention to the value of the quantitative nature of mathematical representation rather early. An expression of this appears first in his Inaugural Lecture at Marischal College, Aberdeen, in 1856, his first professorial teaching post. Mathematical knowledge applied to nature is of phenomena based on 'determinate physical arrangements of pure matter and forces', which are of a 'determinate nature' (SP1, 423) and principles with 'distinct ideas' (SP1, 428). Metaphysical speculation may lead the intellect, as a hiker lost in Scotland, to meteorological altitudes of 'mist and storm', characterized by darkness and vagueness, indistinctness of form, unfixed from precision in physical fact, especially

incontrovertible, unfalsifiable physical fact. The precondition for such distinction is quantitative representation:

'There is nothing more essential to the right understanding of things than a perception of the relations of *number.* Now the very first notion of number implies a previous act of intelligence. Before we can count any number of things, we must pick them out of the universe, and give each of them a fictitious unity by definition. Until we have done this, the universe of sense is neither one nor many, but indefinite.' (LP1, 377, orig. emph.)

And this extends, in particular, to physics:

'in *physical* speculation there must be nothing vague or indistinct. The truths with which we deal are far above the region of mist and storm which conceals them from the popular mind and yet they are solidly built upon the foundations of the world and were established of old, according to number, and measure, and weight. Nothing that we can say or think here can escape from the ordeal of the measuring rod and the balance. All quantities must be exact quantities, and all laws must be expressed with reference to exact quantities, so that we have a most effectual means of discovering error, and an absolute security against vagueness and ambiguity.' (SP1, 425)

Quantitative relations have virtues of intellectual comprehension that also allow for empirical representation and testing. This relates to the value of precision in manipulation of symbols and calculation and in measurement.

Part and parcel of the mathematical knowledge of determinate or distinct quantitative relations is necessity. Metaphysics and the mathematical representation of nature, especially empirical nature, are related; Kant had taught that. More circumscribed than metaphysics, mathematics, says Maxwell, concerns 'necessary truth with regard to measurable quantity' according to 'the principles of accurate reasoning', while metaphysics 'extends its authority over all other species of necessary truth.' (SP1, 428-29)

What is the necessity of quantitative relations? For Whewell and Maxwell, the standard is cognitive, intelligibility, as set by fundamental ideas. Necessity takes the form of a cognitive kind of determinacy. Inconceivability of alternatives, like Kant's impossibility of intuition, is the measure of necessity. It is a radically cognitive notion, different from logical contradiction that characterizes the analytic.

To those who simply ‘cannot distinctly conceive the contrary,’[18] the necessity and fundamentality in the idea of three-dimensionality of space is rooted in a failure of our powers of conception –including the imagination?-, the ‘impossibility to conceive a fourth dimension’ (LP1, 378). Mathematical and, by application, physical necessity are rooted in a cognitive a priori.

2. Theological conditions of scientific practice and knowledge: divine order and power.

The determinate character of natural phenomena, or nature, and the necessity we find in the mathematical and causal relations Maxwell calls laws have a larger and deeper metaphysical foundation, regarding both form and formation. They are brought together by a theological unity and foundation. They are part and consequence of divine order. In Maxwell ‘s case, we can find such connections rooted in the intellectual teachings of natural theology, in popular versions and Paley and the Bridgewater Treatises at Cambridge, his broadly ecumenical theological knowledge, with a marked preference for teachings of evangelical divines in the tradition of Browne, Baxter, Edwards and Owen, and the Presbyterian context of his personalist approach to religious life, which informed and gave meaning to his personal commitment to scientific inquiry, explaining equally its successes and limitations, its grounds and bounds.[19] Scottish education committed to Presbyterian learning and teaching, just as the English did for less radical Anglicanism.[20] So Maxwell found the opportunity in public addresses to discharge his duty at University, and otherwise among his workers, tenants and neighbors as

---

[18] Whewell 1847 1, 90.

[19] Maxwell developed a general faith, scholarly informed and deeply felt, brought up both Presbyterian by his father and Episcopalian by his aunt before an evangelical turn at Cambridge and involvement with the theologian F.D. Maurice’s Christian socialist project of Working Men’s Colleges, as did several other Trinity fellow undergraduates, including R.B. Litchfield, who would become director of the College in London. See Everitt 1983 and Theerman 1986 and on the Working Men’s College, Cat 2001 and forthcoming. Joan Richards has distinguished between the evidentiary and the personalist attitude to religion especially among Victorian mathematics in Richards 1992.

[20] Craik 2008.

paternalist landowner, or laird, and elder of his Scottish kirk, or preaching to his wife in correspondence. The introduction to natural philosophy required expounding on the place of natural philosophy, its metaphysical and methodology, within the theological framework:

'And is not that one thing to learn something of the first principles of the works of nature, the rudiments of the creation so that we may no longer be oppressed with the multitude of wonders, but rather confident that as we have recognized the operation of general principles in some instances, so in due time we shall discover more and more that the whole system of nature is disposed according to a wonderful *order.*
Indeed the very fact that these general principles are to be found shows that it is needless to bewilder our minds with an accumulation of detached facts for in the light of the great laws of nature these facts are no longer detached and bewildering, but necessary consequences of principles which they illustrate.
When we have once made our minds familiar with one or two great physical laws we begin to look upon the Universe as a realization of the highest principles of Order & Beauty and we are prepared to see in Nature not a mere assemblage of wonders to excite our curiosity but a systematic museum designed to introduce us step by step into the fundamental principles which are displayed in the works of Creation.'[21] (Inaugural Lecture, Aberdeen, 1856, LP1, 420, orig. emph.)

In this sense, laws of nature are, he writes, 'in other words that portion of the Divine Order which relates to things without life.' (LP1, 429) They represent the relation of determination arising from the action of causal powers in nature. The necessary connection they reveal to us, however partially or imperfectly, is the necessity of the highest form of determination, that of divine order, the relations

[21] In 1876 still, writing to the Bishop of Gloucester, he added 'I think that each individual man should do all he can to impress his own mind with the extent, the order, and the unity of the universe, and should carry these ideas with him as he reads such passages as the 1st Chap. of the Ep. to Colossians!' ['For by him were all things created ... *I* And he is before all things, and by him all things consist.'](see Lightfoot on Colossians, p. 182), just as enlarged conceptions of the extent and unity of the world of life may be of service to us in reading Psalm viii. ['0 Lord Our God, how excellent *is* thy name in all the earth! who hast set thy glory above the heavens./... When I consider thy heavens, and the work of thy fingers, the moon and the stars, which thou hast ordained; What is man, that thou art mindful of him? and the son of man, that thou visitest him?'.]; Heb. ii. 6 ['But one in a certain place testified, saying, What is man, that thou art mindful of him? or the son of man, that thou visitest him?'], etc.' (letter to John Ellicott, 14 nov 1876, LP3, 418, see n. 9, 11 and 12)

determined by the divine plan, intellectually and also metaphysically, unfolding through the action of His powers:[22]

'as Physical Science advances we see more and more that the laws of nature are *not* mere arbitrary and unconnected decisions of Omnipotence, but that they are essential parts of one universal system in which infinite Power serves only to reveal unsearchable Wisdom and eternal Truth.
When we examine the truths of science and find that we can not only say 'This *is* so' but 'This *must* be so, for otherwise it would not be consistent with the first principles of truth ' - or even when we can only say 'This *ought* to be so according to the analogy of nature' we should think what a great thing we are saying, when we pronounce a sentence on the laws of creation, and say they are true, or right, when judged by the principles of reason. Is it not wonderful that man's reason should be made a judge over Gods works, and should measure, and weigh, and calculate, and say at last 'I understand I have discovered - It is right and true'.' (LP1, 426-27, orig. emph.)

This metaphysical layout has epistemic consequences, with methodological virtues reflecting religious Calvinist ethics. Scientific progress is progress into the mystery of creation, limited knowledge is part of knowledge of the totality of creation:

'Man has indeed but little knowledge of the *simplest* of God's creatures, the nature of a drop of water has in it mysteries within mysteries utterly unknown to us at present, but what we do know we know *distinctly;* and we see before us distinct physical truths to be discovered and we are confident that these mysteries are an inheritance of knowledge, not revealed at once, lest we should become proud in knowledge, and despise patient inquiry, but so arranged that, as each new truth is unravelled it becomes a clear, well- established addition to science, quite free from the mystery which must still remain, to show that every atom of creation is *unfathomable* in its perfection. While we look down with awe into these unsearchable depths and treasure up with care what with our little line and plummet we can reach, we ought to admire the wisdom of Him who has so arranged these mysteries that we find first that which we can *understand* at first and the rest in order so that it is possible for us to have an ever increasing stock of *known* truth concerning things whose nature is absolutely incomprehensible.
(…) I have also thought it unnecessary to tell you that the study of the world in which we live is our obvious duty as a condition of our fulfilling the original command' *to subdue the earth and have dominion over the creatures'.*' (LP1, 426-27, orig. emph.)

[22] God's infinity makes his intellection and creation, thinking and doing, inseparable.

And five years later, delivering the Inaugural lecture at King's College, London, he repeated almost verbatim the same words and added:

'We shall find that it is the peculiar function of physical science to lead us, by the steps of rigid demonstration, to the confines of the incomprehensible, and to encourage us to apply our minds to that which we do not yet understand, since it is only to those who labour patiently and think steadily, that such mysteries are ever opened.' (Inaugural Lecture London 1860, LP1, 670)

In both addresses and other remarks from both periods, the theological framework provides the precondition for the possibility of scientific knowledge, metaphysically and cognitively, materially and intellectually. The interplay of powers and actions involved are but a consequence of the powers of creation:

'all the skill and knowledge we lay up will round itself to a perfect whole of Wisdom when all the elements of Science, from the matter which exhibits its modes of action, to the mind which perceives them, are felt to be mutually related parts of one great whole.' (LP1, 673)

And,

'though the world we live in, being made by God, displays His power and goodness even to the careless observer, yet that it conceals far more than it displays, and yields its deepest meaning only to patient thought.

They will learn that the human mind cannot rest satisfied with the mere *phenomena* which it contemplates, but is constrained to seek for the principles embodied in the phenomena, and that these elementary principles compel us to admit that the laws of matter and the laws of mind are derived from the same source, the source of all wisdom and truth.' (LP1, 430)

This common source at the heart of mystery of creation yields a pre-established harmony of thought and fact, and is therefore a precondition of objective knowledge. Maxwell made a not so veiled reference in his address to the BAAS: 'But who will lead me into that still more hidden and dimmer region where Thought weds Fact,-where the mental operation of the mathematician and the physical action of the molecules are seen in their true relation?'(SP2, 216)

One of Maxwell's expressions of his enduring concern with the value of determination is his corresponding concern with the limits of determination. Examples of failures of determinacy in mathematical representation (pure and

applied) include the conventionalism of standards, the unfixity of ideas vis a vis principles and sensible intuitions, analogical approximation to explanatory truth, approximations by expansion series of exact functions, the problem of uniqueness of solutions of differential equations (potential theory, boundary problems, singularities),[23] the generality of representation as an expression of ignoration (Thomson and Tait's 'method of ignoration' of cyclic variables) and underdetermination of specific representation of possible fundamental primary colors, electric and magnetic potential values, microscopic connecting mechanism of the ether, disturbing causes in experimental field, indefinite number and evolution of molecular and historical individuals in statistical populations, especially the historical individuals' freedom of the will. Part of his a priori conception of mathematical representation in terms of relations of number and fundamental ideas of space and geometry, is to acknowledge the need and value of standards of units that are not determined or fixed intellectually, as a spontaneous or otherwise grounded modification of the mind, or else by experience.

The discussion of conventions is part of his more philosophical account of measurement as numerical determination of experience and part of the Victorian context of metrological activities. Maxwell was not alien to such activities, from the issuing of the British Imperial system of units of weight and measures, and other earlier contributions by his family in Scotland,[24] to his own work in the mid-1850s in color research with material standards provided by his acquaintance the interior decorator and art theorist D.R. Hay and since the early1860s for the BAAS committee on the system of electrical units. He was also brought up in a social arena of scientific and technological public institutions devoted to the communication and discussion of members' findings and material constructs. His scientific and

[23] The problem of uniqueness in potential theory is part of Maxwell's class notes on the calculus from Hopkins, an issue which led Thomson to work on boundary problem while in Paris with the French specialists in analysis such as Cauchy and Liouville. On Maxwell's application to the problem to electric and magnetic potential functions and their physical interpretation, see Cat 2001.

[24] Maxwell's uncle, Sir George Clerk, was Lord of the Admiralty and in charge of the Parliamentary commission on weights and measures when the Imperial units were issued in 1824. See Cat forthcoming a.

speculative exercises are always linked to an imagined or an actual community –of relatives, friends or colleagues. Since a teenager, for instance, he attended routinely and contributed to meetings of the Scottish Royal Society of Arts, where his father and maternal uncle John Cay were members. He even redacted early in his Edinburgh college period a 'Memorandum on a Physico-Mathematical Society', for a collaborative project of learning and research.[25] Standards or units of measurement are neither naturally and intellectually determined and necessary nor entirely arbitrary. They are necessary, like scientific definitions and axioms as demonstrated by Euclid, but artificial, like scientific language itself as proven by Whewell and Faraday's coining of new terms; and they are the outcome of material and intellectual construction as well as social convention; they require will and work, decision, cooperation and enforcement by a system of unnatural laws, a human standard of justice of action:

'In order to compare things measured by different persons it is necessary to assume a standard of measure. Some one must indicate a particular specimen of the thing to be measured as the standard of that quantity and everyone else must agree to measure by that standard or by copies of it. This method introduces experiment into mathematics, and greatly disturbs the easy elegance of the adherents of proportions who are not accustomed to the apparatus of the market place; but those who make up their minds to study Nature with measuring rod time-piece and weights will find that these arbitrary and perhaps inaccurate standards are intended to represent something uniform and independent of any individual man, which depends on an ancient decree and is preserved by the power of Nature but which neither a new decree nor new actions of Nature could restore if it were destroyed.' (LP1, 520)

And,

'the existence of many well-adjusted material standards of weight and measure in any country furnishes evidence of the existence of a system of law regulating the transactions of the inhabitants, and enjoining in all professed measures a conformity to the national standard.' (1873 SP2, 483-84)

Social conventions in national metrological standards also find expression in natural theology through an argument by metrical design:

'Atoms have been compared by Sir J. Herschel to manufactured articles, on account of their uniformity. The uniformity of manufactured articles may be traced to very

[25] LP1, 114-115.

different motives on the part of the manufacturer. (…)In another class of cases the uniformity is intentional, and is designed to make the manufactured article more valuable. (…)
[Herschel] used the phrase "manufactured article" to suggest the idea of their being made in great numbers.' (1873 SP2, 483-84)

C.J. Monro noted perceptively in *Nature* in October 1874 that the analogy amounted to a new argument from design, and that the traditional argument from design 'owes much of its virtue to complexity and variety', while the new argument exemplified 'uniformity for the sake of uniformity', but uniformity might indicate imperfection of manufacture, inability to vary the articles to adjust them to different interests (echoing Darwin?).[26] Maxwell sought to defend and clarify the comparison to Piazzi-Smyth and to the Bishop of Gloucester, also professor of New Testament at King's College, London, form the claim that uniformity indicated 'want of power in the manufacturer to adapt each article to its special use.'[27] Instead, Maxwell replied, he had in mind, a more divinity-worthy notion for this unnatural theology, indicator not of specific design but more fundamental action and creation,

'a uniformity intended and accomplished by the same wisdom and power of which uniformity, accuracy, symmetry, consistency, and continuity of plan are as important attributes as the contrivance of the special utility of each individual thing.' (ibid. 417)

And,

'[molecules] continue this day as they were created—perfect in number and measure and weight, and from the ineffaceable characters impressed on them we may learn that those aspirations after accuracy in measurement, truth in statement, and justice in action, which we reckon among our noblest attributes as men, are ours because they are' essential constituents of the image of Him who in the beginning created, not only the heaven and the earth, but the materials of which heaven aid earth consist.' (SP2, 377)

In summary, Maxwell repeatedly appeals to a theological framework of powers, action and determination, including the joint creation of mind and matter, as precondition of scientific knowledge. Besides the natural theology and 'unnatural

---

[26] Monro 1874; cit. in LP3, 416 n.6. On the originality and place in natural theology of Maxwell's uniformity argument, following Monro, see also Stanley 2011.
[27] Letter to John Ellicott, 22 November 1876, LP3, 417.

theology' contexts, one should mention the Presbyterian personal context of scientific inquiry. Maxwell made explicit, general statements, almost two decades after the first ones in Aberdeen, emphasizing the personal and historical nature of the attempts to harmonize a man's science and religion, which 'ought not to be regarded as having any significance except for the man himself and only for a time, and should not receive the stamp of a society. For it is of the nature of science, especially of those branches of science which are spreading into unknown regions to be continually [changing].'[28]

Divine agency is then the source of worldly agency: powers and action in both things and humans. This is the metaphysical precondition of representing and intervening, of ethical and epistemological quest pushing the boundaries of progress between knowledge and mystery. The scientific knowledge of this agency in Nature we call laws is imperfect knowledge of the natural part of the divine powers in creation, determined according to their intellectual place in the divine order and plan.

3. Moral philosophy of nature and natural philosophy of action

Part of this theological picture of divine power and determination is a picture the natural world of human mind, body and matter and its laws. Again, it is a picture of action, agency and powers in man and matter in interplay in the scientific practices of representation and intervention. It is a picture of action in which philosophical inspiration informing natural philosophy extends from metaphysics to moral philosophy.

Scientific cognition rests on the interplay of causal powers and actions specific to mental faculties, scientific disciplines and scientific practices, both theoretical and experimental.

Physics is concerned with material agency: 'In Physics we accept certain great natural agencies and study their effects on all kinds of matter' and 'not till we

[28] Draft letter of March 1875, in Bio, 405; comp. letter to Bishop Ellicott, LP3, 416.

have measured the energies of all known agents, can we hope to make any progress towards a mechanical explanation of their mode of action.'[29]

Maxwell's metaphysical image of matter repudiates what he calls 'metaphysically passive' notions, based on ideas of perceivability, inertia and resistance, he attributes to Newton, Thomson and Tait. Instead, he advocates a metaphysically active dynamical notion, in which matter is the site of storage, transformation and communication of energy, power to do work.[30] In an Edinburgh-style combination of Aristotelian Scottish metaphysics and Scottish engineering, Maxwell's acquaintance and fellow Edinburgh University alumnus, the Glasgow engineer W.J.M. Rankine first distinguished between active and potential energy before his mechanistic colleague Thomson settled for the terms 'kinetic' and 'potential'. Maxwell's picture of matter is not reduced to force, as was Faraday's or Kant's, but tries to preserve some Newtonian mechanics, is aims at finding the adequate relation between matter and force; and the fields of force and energy across space are associated with a medium that contains them. Energy, finally, is the capacity to do work.

Mechanics and engineering alike, especially theory of elasticity and strength of materials is a mathematical and empirical investigation of material powers represented by constants such as moduli of elasticity. The material part of humans is bodily power, especially muscular, and mid-Victorian engineering and political economy gradually incorporated it in the economy of work and waste, energy and fatigue. Bodily exertions are especially engaged in experimental activities.

Experiments, Faraday explained in a famous chemistry manual, involved the active manipulation of material substances and their powers and agencies.[31] Maxwell wrote about experiments in similar terms:

'This [course of Experimental Physics], while it requires us to maintain in action all those powers of attention and analysis which have been so long cultivated in the University, calls on us to exercise our senses in observation, and our hands in manipulation.' (SP2, 241)

[29] LP1, 664 and 666.
[30] See Harman 1995, ch. IX.
[31] Faraday 1827.

And,

'Some of us, on the other hand, may have had some experience of the routine of experimental work. As soon as we can read scales, observe times, focus telescopes, and so on, this kind of work ceases to require any great mental effort. We may perhaps tire our eyes and weary our backs, but we do not greatly fatigue our minds.' (SP2, 247)

And,

'In designing an Experiment the agents and phenomena to be studied are marked off from all others and regarded as the Field of Investigation. All agents and phenomena not included within this field are called Disturbing Agents, and their effects Disturbances; and the experiment must be so arranged that the effects of these disturbing agents on the phenomena to be investigated shall be as small as possible.' (SP2, 505)

Disciplinary powers mental activities part of an action-centered image of mathematics, embedded in the economy of work, energy expense and fatigue:

'We take possession of the field in which the mathematician is first trained in the exercise of his powers, the field of space with all the apparatus of geometry.' (SP1, 664-65).

And,

'Many of us have already overcome the initial difficulties of mathematical training. When we now go on with our study, we feel that it requires exertion and involves fatigue, but we are confident that if we only work hard our progress will be certain.' (SP2, 247)

The image of active mental life in terms of mental powers goes hand in hand with the psychology of faculties that is gradually being replaced around the mid-nineteenth century while retaining much talk of laws of mental activity in, for instance, reasoning as the exercise of reason and morality of action as an exercise of the will: from Kant to Bain and Boole and their new attempts to naturalize and formalize mental life.[32] The traditional scheme divides and explains the mind, in God's image, in terms of the limited powers of understanding/ reasoning,

[32] On the tradition of faculty psychology see Rylance 2000.

conation/will and construction/imagination.

In an essay for John Wilson's Moral Philosophy class in Edinburgh ca. 1850, Maxwell reproduces the class teachings: 'The Faculties of the Human Mind are arranged in three classes, the faculties of Cognition, Feeling and Conation or Will. This division of the faculties was made by Kant and it is adopted by Sir William Hamilton and it seems to me to be more perfect than that into Will and Understanding.' (LP3, 861) With Hamilton Maxwell had dealt with Aristotle and Kant and would read Kant's first Critique at Trinity. To the faculties correspond disciplines researching their operations: 'It may be traced through all the branches of the science of Man, Anatomy and Physiology Metaphysics and Moral Philosophy; for the faculties are the same though their operations are of a higher order as we ascend in the scale of sciences, from life to mind and from mind to soul.' (ibid.) He subsequently distinguishes between corresponding disciplines studying the regulation of the faculties: 'the discussion of the laws of thought which is Logic', 'the first principles of human knowledge or Metaphysics' and 'the consideration of human action regarded as right or wrong, which is Moral Philosophy.' (Inaugural lecture 1857, LP, 543)

Maxwell had read Aristotle, Smith and Hobbes in connection with John Wilson's moral philosophy course. Wilson, essayist and poet under the penname of Christopher North, made the will central to an integrated image of man, 'the Will is the Man!'[33] The will is inseparable from the intellect and rooted in the body: 'The roots of the Will are in the body -and the roots of the Intellect in the Will.'[34] The will nourishes the imagination, which in turn also nourished the intellect.

Maxwell's more speculative or philosophical preoccupation with man's nature focused on the practical and moral dimensions of man's power to act. Like for Wilson, a voluntarist image of man and a partly voluntarist image of cognition follows, and a consistent image of man and nature based on determination through

---

[33] Wilson 1856, 211. The emphasis on the will and its relation to the intellect appear also in Alexander Bain's *The Senses and the Intellect* (1855) and *The Emotions and the Will* (1859). Bain introduces scientific methodology, mechanical and energy models and advocates psychophysical parallelism.
[34] Ibid., 211.

agency:

‘The three principles concerning the nature of man are continually changing their shape, so that it is not easy to catch them in their best shape. Nevertheless :
Lemma: Metaphysics.-A man thinks, feels, and wills, and therefore Metaphysicians give him the three faculties of cognition, feeling, and conation.
Cognition is what is called Understanding, and is most thought of generally.
Feelings are pleasures, pains, appetites; desires, aversions, approval and disapproval, love, hate, and all affections.
Conations are acts of will, whatever they be.
Now to move a man's will it is necessary to move his affections. (How? Wait !) For no convictions of the understanding will do, for a man does what he likes to do, not what he believes to be best for himself or others. The feelings can only be moved by notions coming through the understanding, for cognition is the only inlet of thoughts. Therefore, although it can be proved that self-love leads to all goodness, or, in other words, that goodness is happiness, and self loves happiness, yet it can also be proved that men are not able to act rightly from pure self-love; so that though self-love is a very fine theoretical principle, yet no man can keep it always in view, or act reasonably upon it.’

Here Maxwell examines Hobbes and Smith:

‘[Hobbes] deduces the obligation of obeying the powers that be from the necessity of Power to prevent universal war. Adam Smith's theory of Moral Sentiments (which is the most systematic next to Hobbes) is that men desire others to sympathise with them, and therefore do those things which may be sympathised with; that is, as Smith's opponents say, men ought to be guided by the desire of esteem and sympathy. Not so. Smith does not leave us there’
‘I was thinking today of the duties of [the] cognitive faculty. It is universally admitted that duties are voluntary, and that the will governs understanding by giving or with- holding Attention.’[35] (letter to Lewis Campbell, ca. July 1850, LP1, 195-6)

Inevitably, Maxwell maps out different forms of determination, logical, moral and metaphysical, causal, with material instantiation; and the different forms of

[35] ‘They say that Understanding ought to work by the rules of right reason. These rules are, or ought to be, contained in Logic; but the actual science of Logic is conversant at present only with things either certain, impossible, or *entirely* doubtful, none of which (fortunately) we have to reason on. Therefore the true Logic for this world is the Calculus of Probabilities, which takes account of the magnitude of the probability (which is, or which ought to be in a reasonable man's mind). This branch of Math., which is generally thought to favour gambling, dicing, and wagering, and therefore highly immoral, is the only" Mathematics for Practical Men," as we ought to be.’ (ibid.)

determined action come together in man's activities. But they might also result in a conflict between the different orders of necessity and determination in the form of laws of thought, laws of morality and laws of nature:

'A reason or argument is a conductor by which the mind is led from a proposition to a necessary consequence of that proposition. In pure logic reasons must all tend in the same direction. There can be no conflict of reasons. We may lose sight of them or abandon them, but cannot pit them against one another. If our faculties were indefinitely intensified, so that we could see all the consequences of any admission, then all reasons would resolve themselves into one reason, and all demonstrative truth would be one proposition. There would be no room for plurality of reasons, still less for conflict.' (LP1, 379)

And,

'The mind of the mathematician is subject to many disturbing causes, such as fatigue, loss of memory, and hasty conclusions; and it is found that, from these and other causes, mathematicians make mistakes.
I am not prepared to deny that, to some mind of a higher order than ours, each of these errors might be traced to the regular operation of the laws of actual thinking; in fact we ourselves often do detect, not only errors of calculation, but the causes of these errors. This, however, by no means alters our conviction that they are errors, and that one process of thought is right and another process wrong.
One of the most profound mathematicians and thinkers of our time, the late George Boole, when reflecting on the precise and almost mathematical character of the laws of right thinking as compared with the exceedingly perplexing though perhaps equally determinate laws of actual and fallible thinking, was led to another of those points of view from which Science seems to look out into a region beyond her own domain.' (SP2, 229)

More generally, in our initial considerations man occupies, for Maxwell, 'regions of physical and metaphysical chaos', where moral action and physical event might conflict, as part of conflicting systems of determination he calls the moral order of things and mechanical order of things. The philosophical resolution of the conflict comes from adopting partial points of view, as all human knowledge is partial. What remains is establishing correspondences or analogies. For instance, Maxwell writes about reciprocity of action, moral and mechanical (LP1, 383). Smith meets Newton, moral philosophy meets natural philosophy.

Soon after the application to physics from geometry and in physics from within in 'On Faraday's Lines of Force', the dual nature of reciprocity and analogy

appeared in a more general discussion paper for a meeting the Apostles Society, 'Are There Real Analogies in Nature?': 'Now, as in a pun two truths lie hid under one expression, so in an analogy one truth is discovered under two expressions. Every question concerning analogies is therefore the *reciprocal* of a question concerning puns, and the solutions can be transposed by *reciprocation*.' (SLP, vol. 1, 376, my emphasis)

Besides the different distinctions and hierarchies of logical abstraction in the use of the term, it is quite likely that the terms 'reciprocity' and 'reciprocation' held for Maxwell deep moral and religious connotation -free from theological or metaphysical baggage- well entrenched in sources familiar to Maxwell: in Scottish moral philosophy and political economy, especially in Adam Smith, and in Victorian Christianity, even Scottish Presbyterianism, centered on principled behavior (ordinary, professional, artistic and scientific). For instance, Thomas Chalmers spoke of a 'reciprocal action' between the will and the understanding in the constitution of 'human machinery', of a 'reciprocal affinity' between souls, and law moral reciprocity, with mechanical connotations, in connection with his views on charity and gratitude: 'It is this pure action and reaction of soul with soul –it is this law of moral reciprocity which obtains between one human bosom and another- it is the radiance of good will from the first, calling back the reflection of gratitude from the second…'[36] The mechanical natural analogies are recurrent in his sermons: 'The law of love begetting love, will obtain in eternity. Like the law of reciprocal attraction in the material world, it will cement the immutable and everlasting order of the moral system, which is to emerge with the new heavens and the new earth, wherein dwelleth righteousness.'[37]

In Maxwell's overall picture, one might note that to the three laws of motion correspond in moral philosophy three metaphysical and moral laws he calls laws of liberty, equality and fraternity. We might call them the analogies of action, by analogy with the three analogies of experience that Kant, and Whewell, use as the metaphysical foundation of the three laws of mechanics:

[36] Chalmers 1840, 49, 202 and 361, resp.
[37] Chalmers 1850, 70.

‘my Collection of the Metaphysical principles of Moral Philosophy founded on the three laws of Liberty, Equality, Fraternity, thus expressed:
1. That which can be done is that which has been done; that is, that the possibility (with respect to the agent) of an action (as simple) depends on the agent having had the sensation of having done it.
2. That which ought to be done is that which (under the given conditions) produces, implies, or tends to the greatest amount of good (an excess or defect in the variables will lessen the good and make evil).
3. Moral actions can be judged of only by the principle of exchange; that is (I), our own actions must be judged by the laws we have made for others; (2),
others must be judged by putting ourselves in their place.’ (letter to Lewis Campbell 14 March 1850, LP1, 187-88)

Moral philosophy, social preoccupations and the principles of action were inseparable from the life and dimensions of cognition. His speculations continued at Cambridge fueled by diverse intellectual company and intense conversation:

‘T. senr. described the inducement to hard work among engineers at Manchester; the reward is not profit, but situation.
There are advantages in subordination, besides good direction, for it supplies an *end* to each man, external to himself. Activity requires Objectivity.
Objectivity alone is favourable to the free circulation of the soul. But let the Object be real and not an Image of the mind's own creating, for Idolatry is Subjectivity with respect to gods. Let a man feel that he is wide awake,-that he has something to do, which he has authority, power, and will to do, and is doing; but let him not cherish a consciousness of these things as if he had them at his command, but receive them thankfully and use them strenuously, and exchange them freely for other objects. He has then a happiness which may be increased in degree, but cannot be altered in kind.’ (letter to Lewis Campbell, 10 February 1852, Bio 177)

What we are offered is a voluntarist, active, constructive image of cognitive life, intellectual and material: ‘As mathematicians, we perform certain mental operations on the symbols of number or of quantity’ (SP2, 216)

And,

‘the success of any physical investigation depends on the judicious selection of what is to be observed as of primary importance, combined with a voluntary abstraction of the mind from those features which, however attractive they appear, we are not yet sufficiently advanced in science to investigate with profit.’ (SP2, 217)

Modeling itself is for Maxwell a form of construction, whether in the mind by the constructive faculty of the imagination or in material form, as exhibited in the

fine and mechanical arts. He himself characterized his own mind by his constructive imagination in reply to Galton's questionnaire.[38] Scientific life is an active life of construction of a priori fundamentals, mental and material, and other actions.

4. The conflict of physical and metaphysical necessities: the problem of indeterminacy in freedom of the will.

In *Matter and Motion*, Maxwell adds a metaphysical-sounding statement in causal terms, which he calls, in a Leibnizian fashion, 'Statement of the General Maxim of Physical Science': 'that the same causes produce the same effects'.[39] But elsewhere around the same time he distinguishes between similar metaphysical and physical axioms: 'It is a metaphysical doctrine that from the same antecedents follow the same consequents. No one can gainsay this.' The proper application of the metaphysical axiom to antecedents is to precisely defined events-token, its application implies identity and precision and its scope of application is limited to singular cases, so its empirical and practical value is null. By contrast, he points out, the 'physical axiom which has a somewhat similar aspect is 'That from like antecedents follow like consequents.'' And he notes, 'here we have passed from sameness to likeness, from absolute accuracy to a more or less rough approximation.' (LP2, 821) Empirically applicable and practically valuable general claims concern types, and sameness of type is based on likeness. Likeness is a matter of degrees. Physical thinking is relational and fundamentally analogical thinking, and analogical thinking is approximate thinking.

For instance, he also provides the empirical conditions of validity of mechanical determinacy, or determinism, and also its limits:

'There is another maxim which must not be confounded with that quoted at the beginning of this article, which asserts "That like causes produce like effects." This is only true when small variations in the initial circumstances produce only small variations in the final state of the system. In a great many physical phenomena this condition is satisfied; but there are other cases in which a small initial variation may produce a very great change in the final state of the system, as when the displacement of the "points" causes a railway train to run into another instead of

---

[38] Hilts 1975, 59.
[39] Maxwell 1876, *Matter and Motion*, art 19.

keeping its proper course.' (art. 19)

This is the metaphysical setting for the problem of compatibility between the idea of general mechanical determinacy or determinism, indeterminacy of action by reason and nature, the problem of freedom of the will. From this perspective, the problem and solution to the problem are part of the larger framework of thought in terms of action and determination, their limits and higher grounds.

The essay delivered to the Eranus Club in February 1873 bears the title '*Does the progress of Physical Science tend to give any advantage to the opinion of Necessity* (or *determinism) over that of the Contingency of Events and the freedom of the Will?*' Maxwell makes clear is a problem of the relation between physics and metaphysics:

'At a certain epoch of our adolescence those of us who are good for anything begin to get anxious about these questions, and unless the cares of this world utterly choke our metaphysical anxieties, we become developed into advocates of necessity or of free-will. What it is which determines for us which side we shall take must for the purpose of this essay be regarded as contingent.' (LP2, 815)

The physical science scenario distinguishes between the Statistical and the Dynamical or Historical method:

'If we betake ourselves to the statistical method, we do so confessing that we are unable to follow the details of each individual case, and expecting that the effects of widespread causes, though very different in each individual, will produce an average result on the whole nation, from a study of which we may estimate the character and propensities of an imaginary being called the Mean Man.' (LP2, 818)

From the individual standpoint, this is a situation of change and chance. For the individual case, the idea is the historical or dynamical method, associated with absolute precision, immutability and certainty (SP2, 374), and 'that prejudice in favour of determinism [or mechanical necessity] which seems to arise from assuming that the physical science of the future is a mere magnified image of that of the past.' (LP2, 823). Accordingly, he writes,

'We may observe the conduct of individual men and compare it with that conduct which their previous character and their present circumstances, according to the best existing theory, would lead us to expect. Those who practise this method endeavour to improve their knowledge of the elements of human nature in much the same way as an astronomer corrects the elements of a planet by comparing its actual position with that deduced from the received elements. The study of human

nature by parents and schoolmasters, by historians and statesmen, is therefore to be distinguished from that carried on by registrars and tabulators, and by those statesmen who put their faith in figures. The one may be called the historical, and the other the statistical method.
The equations of dynamics completely express the laws of the historical method as applied to matter, but the application of these equations implies a perfect knowledge of all the data.' (SP2, 373-74)

And,
'when an infinitely small variation in the present state may bring about a finite difference in the state of the system in a finite time, the condition of the system is said to be unstable.
It is manifest that the existence of unstable conditions renders impossible the prediction of future events, if our knowledge of the present state is only approximate, and not accurate.' (LP2, 819)

The causality of agency sheds the 'prejudice' of determinism –and with it stability and predictability. But it does so within the margins left by natural order itself:

'if the direction of the ray within a biaxal crystal is nearly but not exactly coincident with that of the ray-axis of the crystal, a small change in direction will produce a great change in the direction of the emergent ray. Of course, this arises from a singularity in the properties of the ray-axis, and there are only two ray-axes among the infinite number of possible directions of lines in the crystal; but it is to be expected that in phenomena of higher complexity there will be a far greater number of singularities, near which the axiom about like causes producing like effects ceases to be true.' (LP2, 821-22)

'It appears then that in our own nature there are more singular points- where prediction, except from absolutely perfect data, and guided by the omniscience of contingency, becomes impossible - than there are in any lower organisation. But singular points are by their very nature isolated, and form no appreciable fraction of the continuous course of our existence. Hence predictions of human conduct may be made in many cases.' (LP2, 822)

'Is the soul like the engine-driver, who does not draw the train himself, but, by means of certain valves, directs the course of the steam so as to drive the engine forward or backward, or to stop it?
The dynamical theory of a conservative material system shews us, however, that in general the present configuration and motion determine the whole course of the system, exceptions to this rule occurring only at the instants when the system passes through certain isolated and singular phases, at which a strictly infinitesimal force may determine the course of the system to any one of a finite number of equally possible paths, as the pointsman at a railway junction directs the train to one set of rails or another. Prof B. Stewart has expounded a theory of this kind in his

book on The Conservation of Energy, and MM. de St Venant and Boussinesq have examined the corresponding phase of some purely mathematical problems.' (SP, 760)

Boussinesq in 1878 would take up the same problem and work out the notion of singular solutions of differential equations of motion; Maxwell referred Galton to this work in 1879, with mentions to Cournot 1875 and St Venant 1877, who had addressed the conflict between materialism and freedom.[40] The notion of singularity in the behavior of differentiable functions was topic of research in Cambridge mathematics since the 1820s, especially Archibald Smith co-funder of the *Cambridge Mathematical Journal* (whose editorship was taken up by Kelvin).

What is the new power of free will? What sort of indeterminacy is freedom? Maxwell insists on making it compatible with the other orders of determination:

'I do not say that caprice and disorder are not the result of free will (so called) only I say that there is a liberty which is not disorder and that this is by no means less free than the other, but more. (…) by means of a great development of will whereby instead of being consciously free and really in subjection to unknown laws, it becomes consciously acting by law, and really free from the interference of unrecognised laws.' (1858, LP1, 588-89)

'There is action and reaction between body and soul, but it is not of a kind in which energy passes from the one to the other, - as when a man pulls a trigger it is the gunpowder that projects the bullet, or when a pointsman shunts a train it is the rails that bear the thrust.'[41] (Letter to Lewis Campbell, 21 April 1862, LP1, 712)

The pointsman has now joined the non-working molecular being, the so-called demon, reversing entropic direction of macroscopic thermodynamical processes.[42] Reversibility played a dual philosophical role; as a challenge to thermodynamical necessity, it made room for agency, the operation of the will; thermodynamical

---

40 LP3, Letter to Galton 26 February 1879, LP3, 756.

41 'We see also that the soul is not the direct moving force of the body. If it were, it would only last till it had done a certain amount of work, like the spring of a watch, which works till it is rundown. The soul is not the mere mover. Food is the mover, and perishes in the using, which the soul does not.(…) But the constitution of our nature is not explained by finding out what it is not. It is well that it will go, and that we remain in possession, though we do not understand it.' (Letter to Lewis Campbell, 21 April 1862, LP1, 712)

42 For a discussion of the pointsman see Stanley 2008.

irreversibility implied the idea of a beginning and an end, contrary to the eternalism associated with materialism (SP 2, 226). The metaphysical dimension of his anti-materialist critique of the fundamental nature of irreversible thermodynamical law, metaphysical molecular reductionism and of physical -and social, or historical-determinism. Maxwell was standing against 'the materialist spirit of the age' (SP2, 251) represented by Tyndall's 'scientific materialism' (1868), a naturalist worldview of reduction to molecular physics (including, much like Leibniz, energy conservation and deterministic, causal continuity of nature).[43] Maxwell, then, avoids framing the conflict in terms of an inconsistency between mechanical determinism and Calvinist doctrines of theological predestination.

The freedom of individual agents in history applies to the active, constructive life of science itself, and makes it possible: 'All great results produced by human endeavour depend on taking advantage of these singular states when they occur.' (LP2, 822)

And,

'The men whose names are found in the history of science are not mere hypothetical constituents of a crowd, to be reasoned upon only in masses. We recognise them as men like ourselves, and their actions and thoughts, being more free from the influence of passion, and recorded more accurately than those of other men, are all the better materials for the study of the calmer parts of human nature.'[44] (SP2, 251)

Human agency introduces a form of determination that plays the key role in the creative and conventionalist moments of science, when those of the laws of nature, the laws of reasoning and laws of morality fail to determine.

Conclusion

---

[43] On the metaphysical motivation to counter social and statistical analyses as fundamental in history and physics, see Porter 1976 and Cat forthcoming.

[44] 'It is true that the history of science is very different from the science of history. We are not studying or attempting to study the working of those blind forces which, we are told, are operating on crowds of obscure people, shaking principalities and powers, and compelling reasonable men to bring events to pass in an order laid down by philosophers.' (ibid.)

Will as condition of agency and agency itself are required for construction and convention, for scientific practice in representation and intervention, explanation and experimentation. Conative determinacy operates to fill the gaps opened by the cognitive limits of internal mathematical determinacy. Human agency interact with the agency of the world as we encounter and control. It reflects a metaphysical framework of agency and determination, material and rational, and thereby the determination of the higher orders of moral law and divine law. But this philosophical picture, although not a detailed system or doctrine, invites a broader perspective, and suggests a higher degree of consistency, complexity and integration in Maxwell's natural philosophy and philosophical thinking. Ironically, rather than a vestige of earlier intellectual periods and traditions, it fits well with the new Victorian culture of construction and materialism. In an age of materialism, Maxwell presented a life of construction and the age of construction –cognitive, methodological, artistic, engineering, etc.- metaphysically reconstructed. This is his free contribution to the advancement of science from his place of history, and history is the possibility of influential individual action.

References

-Campbell, L. and W. Garnett 1882, *The Life of James Clerk Maxwell*, London: Macmillan.
-Cat 2001, 'On Understanding: Maxwell on the Methods of Illustration and Scientific Metaphor', *Stud. Hist. Phil. Phys.* 32, 3, 395-441.
-Cat 2011, 'Maxwell, Matter and Method: Maxwellian Methodology, Methodological Maxwellianism, and Methods of Historical and Philosophical Speculation', in G. Morgan, ed., *Philosophy of science Matters, Essays in Honor of Peter Achinstein*, New York: Oxford University Press, 29-43.
-Cat forthcoming a, 'Maxwell's Color Statistics: From Reduction of Visible Errors to Reduction to Invisible Molecules'
-Cat forthcoming b, *Master and Designer of Fields: James Clerk Maxwell and Constructive, Connective and Natural Philosophy*, Oxford: Oxford University Press.

-Chalmers, T., 1840, *The Works of Thomas Chalmers*, vol. 5, *Sketches of Moral and Mental Philosophy*, vol. 5, Glasgow: William Collins.
-Chalmers, T., 1850, 'Sermons on the Depravity of Human Nature. Sermon X. Gratitude, Not a Sordid Affection', *The Selected Works of Thomas Chalmers*, vol. IV, Edinburgh: Thomas Constable, 65-74.
-Craik, A.D.D., 2008, *Mr. Hopkins' Men: Cambridge Reform and British Mathematics in the 19th Century*, London: Springer Verlag.
-Everitt, C.W.F., 1983, 'Maxwell's Scientific Creativity', in R. Aris et al., eds., *Springs of Scientific Creativity*, Minneapolis: University of Minnesota Press, 71-141.
-Faraday, M., 1827, *Chemical Manipulation*, London: W. Phillips.
-Harman, P.M., 1990-2002 (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, 3 vols, Cambridge: Cambridge University Press.
-Harman. P.M., 1995*, The Natural Philosophy of James Clerk Maxwell*, Cambridge: Cambridge University Press.
-Hilts, V.L., 1975, 'A Guide to Francis Galton's English Men of Science', Transactions of the American Philosophical Society, 65 Part 5, 59.
-Hunt, B., 1991, *The Maxwellians*, Ithaca: Cornell University Press.
-Monro, C.J., 1874, 'Manufactured Articles', *Nature* 10, 15 October 1874, 481.
-Niven, W.D. 1890,(ed.), *The Scientific Papers of James Clerk Maxwell*, 2 vols., Cambridge: Cambridge University Press,
-Porter, T.M., 1986, *The Rise of Statistical Thinking, 1820-1900*, Princeton: Princeton University Press.
-Richards, J.L. 1992, 'God, Truth and mathematics in Nineteen-Century England', *Boston Studies in the Philosophy of Science* 139, 51-78.
-Rylance, R., 2000, *Victorian Psychology and British Culture 1850-1880*, Oxford: Oxford University Press.
-Smith, C. and M.N. Wise, 1989, *Energy and Empire: A Biographical Study of Lord Kelvin*, Cambridge: Cambridge University Press.
-Stanley, M., 2008, 'The pointsman: Maxwell's demon, Victorian free will, and the boundaries of science', *Journal of the History of Ideas* 69, 467–491.
-Stanley, M., 2011, 'By Design: James Clerk Maxwell and the Evangelical Unification of Science', Brit. J. Hist. Sci. ?
-Theerman, J., 1986, 'James Clerk Maxwell and Religion', *American Journal of Physics*, 54 (4), 312–317.
-Whewell, W., 1847, *Philosophy of the Inductive Sciences*, 2 vols., London: Parker.
-Wilson, J., 1856, *The Works of Professor Wilson*, J.F. Ferrier, ed., vol III, *Noctes Ambrosianae*, Edinburgh and London: William Blackwood and Sons.

Appendix- Metaphysics of space and matter and a priori status of Newton's laws of motion.

In the essay 'On Absolute Space' (ca. 1857), Maxwell aims in the mind of the reader 'to render distinct the idea of space as independent of matter' (LP1, 515). In *Matter and Method* (1876) he adopts the Newtonian concept of an entity 'remaining always similar to itself and immovable', with its parts only distinguishable by their 'relation to the place of material bodies' (art. 18). In the Scholium of the Definitions in the Principia, Newton had written that 'Absolute space, in its own nature, without relation to anything external, remains always similar and immovable' Its measure, relative space, is determined by our senses 'by its position to bodies.' Recall that Cambridge friends and University of Glasgow colleagues Hugh Blackburn and William Thomson edited a new reprint of Roger Cotes' 1726 Latin edition of Principia in 1871. Thomson and Tait had formulated a new systematization of natural philosophy resting on energy principles and Newton was their chief precedent and foil. Thomson must have used the Principia in his teachings as he and Blackburn complain that all editions were out of print. But this conceptual foundation absolute space provides yields what he calls the doctrine of relativity of dynamical knowledge (art. 102): 'All our knowledge, both of time and place, is essentially relative.' (art. 18) He also refers to it as the relativity of all physical phenomena. All spatio-temporal and dynamical descriptions are relational. But unlike his conceptual relationalism, his physical relativism is epistemological, concerning measured (observed) quantities.

Harman's focus on concepts of matter as metaphysical/conceptual foundations of dynamics: Maxwell's concept (quantitative and dynamical concept of mass, medium in which energy exists, is stored and communicated) against Thomson and Tait's (object of empirical perception that can also exert or be acted upon by force, has the power of resistance and perseverance, 'as that which can be perceived by the senses or as that which can be acted upon by, or can exert, force' (Thomson and Tait 1879, Treatise on Natural Philosophy, 1, 219), Newtonian inertial view of matter, 'matter has an innate power of resisting external influences, so that every body, so far as it can, remains at rest or moves uniformly in a straight line'), and Newton's *vis inertiae*,

Definition III of Principia. Intelligibility of mass vs mystery of material substratum (SP2, 778-81) and Faraday's monistic reduction to centers of force and Clifford's geometric reduction to curvature of space (Clifford 1870 'On the space-time theory of matter'). Maxwell calls Thomson and Tait's statement of their conception of matter pusillanimous because Tait, he remarks with sarcasm, who 'never misses an opportunity of denouncing metaphysical reasoning, except when he has occasion to expound the peculiarities of the Unconditioned,' here qualifies the statement as one that cannot be given to satisfy the metaphysician but is meant to content the naturalist (SP 2, 778-89). Unlike Tait, Maxwell sought to find the appropriate relation between physics and metaphysics, and between force and matter. In the case of Tait and Thomson, and many other since Newton, Maxwell objects to an inertial conception of matter based on 'metaphysical passivity' (LP2, 364). Maxwell in this particular case objects to the mystery of a metaphysical substratum, substance, and to it opposes physical quantification, mass over matter. But the larger scope and the recurring remarks paint a picture of physical and metaphysical emphasis on activity: 'In Physics we accept certain great natural agencies and study their effects on all kinds of matter.' (LP1, 664) And,
'Whether our work is to form a science by the colligation of known facts, or to seek for an explanation of obscure phenomena by devising a course of experiments, the principle of the conservation of energy is our unfailing guide. It gives us a scheme by which we may arrange the facts of any physical science as instances of the transformation of energy from one form to another. It also indicates that in the study of any new phenomenon our first inquiry must be. How can this phenomenon be explained as a transformation of energy ?' (SP2, 594)

Whewell follows Kant in the MFNS using the three analogies of experience, rules of schematization of categories in the intuition, to found on three metaphysical axioms of causality Newton's three mechanical laws of motion (Whewell 1847 1, 215-245). Hopkins, and his three pupils, Thomson, Tait and Maxwell, adopted in their notes and works Whewell's formulation of Newton's second law in terms of the relation between changes of momentum during a time interval and the impulse of external

forces during the same (Harman 1995, 25). As fundamental ideas, the rejection of their truth cannot be conceived intelligibly, and 'once fairly set before the mind [are] apprehended by it as strictly true' (Maxwell's review of Whewell's writings in 1876, SP2, 530, cit. Harman 1995, 34). In *Matter and Motion* Maxwell emphasizes the superior source of evidence for the laws of motion from non-experimental proof, effectively a *reductio* based on their denial, similar in form with the necessity criterion: 'But our conviction of the truth of this law may be greatly strengthened by considering what is involved in a denial of it.' So Maxwell claims that 'the denial of Newton's first law of motion would be in contradiction to the only system of consistent doctrine of space and time which the human mind has been able to form' (Maxwell 1876, Matter and Motion, art. 41). The second law is based on a definition, namely, of equal masses and of equal forces (art. 45). Similarly, the third law, of action and reaction, he claims, despite Newton's experimental illustrations, is given a non-experimental proof: 'We cannot, therefore, regard Newton's statement as an appeal to experience and observation, but rather as a deduction of the third law of motion from the first.' (art.58) This is not surprising given what he claims the putative content of the laws is:

'The first law tells us under what conditions there is no external force.
The second shows us how to measure the force when it exists.
The third compares the two aspects of the action between two bodies, as it affects the one body or the other.' (art. 40)

More basically, from the clear intellectual understanding of the ideas of motion and force 'we are able to prove all the law relating to force' (LP1, 426). To Litchfield, he wrote: 'Experiment furnishes us with the values of our arbitrary constants, but only suggests the form of the functions. Afterwards, when the form is not only recognised but understood scientifically, we find that it rests on precisely the same foundation as Euclid does, that is, it is simply the contradiction of an absurdity, out of which may we all get our legs at last!' (4 july 1856, Bio 261). The a priori mathematical form on what counts as relevant experience allows for the prediction of mechanical states and the testing and correction in the formulation of exact mathematical laws.

He reminded the audience at Marischal College that ‘we build upon facts of observation which we cannot completely explain but which we can mathematically define.’ (LP1, 421) Measurement and experiment establish the bounds of the intellectual construction of the system of physics (LP1, 425-6),