Chapter 10
Scientific Laws

Nature and Nature's laws lay hid in night
God said 'Let Newton be!' and there was light

A Pope

10.1 Introduction

The goal of the sciences is to discover scientific laws, many say and according to Hempel's model of explanation we need laws for scientific explanations. Some examples of such laws are Kepler's three laws of planetary motion and Newton's law of gravitation.

Within the natural sciences it is largely uncontroversial to claim that the goal is to discover the laws of nature. Thus one might similarly think that the goal of the social sciences is to discover the laws of society. However, many have claimed, for various reasons, that there are no social laws to be discovered. Presently, I will not take a stance in regards to this issue. Instead, I shall focus on the discussion of the concept of a scientific law, taking its use in the natural sciences, in particular physics, as my starting point. As we will see, there are many deep controversies about the concept of scientific (or natural) law and e.g. van Fraassen claim that there are no laws, neither in the social nor in natural science.

But the term 'law of nature' and its associates are often used both by scientists and laymen and it is an important task for philosophy of science is to give an analysis of this concept. The questions to be answered include: What is a law? What conditions must be met for something to be called a law? Why do we sort out *some* parts of scientific theories and attribute to these a special status?

It has proven astonishingly difficult to give generally acceptable answers to these questions. John Earman has characterized the debate as follows:

> It is hard to imagine how there could be more disagreement about the fundamentals of the concept of law of nature – or any other concept so basic to the philosophy of science – than currently exists. A cursory survey of the recent literature reveal the following oppositions (among others): there are no laws of nature vs. there are/must be laws; laws express relations between universals vs. laws do not express such relations; laws are not/cannot be Humean supervenient vs. laws are/must be Humean supervenient; law do not/cannot contain ceteris paribus clauses vs. laws do/must contain ceteris paribus clauses.

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> One might shrug of this situation with the remark that in philosophy disagreement is par for the course. But the correct characterisation of this situation seems to me to be 'disarray' rather than 'disagreement'. Moreover, much of the philosophical discussion of laws seems disconnected from the practice and substance of science; scientists overhearing typical philosophical debates about laws would take away the impression of scholasticism – and they would be right! (Earman 2002)

In particular I agree with Earman's last remarks, that the debate is disconnected from the practice of science and that it has an air of scholasticism. I will try to avoid these defects in what follows.

10.2 Empirical Generalizations: Fundamental Laws

In the discussion about laws one may first distinguish between *empirical generalizations* and *fundamental laws*. An example of an empirical generalization could be

All grass is green, if it is alive.

An example of a fundamental law is

Energy is constant in any closed system (Principle of Energy Conservation).

Empirical generalizations are direct generalizations of singular, observable facts of the form 'the grass on my lawn is green', 'the grass on my neighbour's lawn is green', etc. Once we have collected a sufficient number of instances, and no counter-instances, we are inclined to infer empirical generality and the result is sometimes called a law. Conversely, a single counter-instance forces us to reject the empirical generalization.

Fundamental laws, on the other hand, are not bound in the same way to one type of observed phenomena. The energy principle, to take the most obvious example, is so generally applicable that it holds for the most disparate systems. Whether studying a cell, an atom, an aquarium or even our own solar system, the principle of energy conservation is valid for all. Furthermore, energy is an abstract property that cannot be measured directly, although it manifests itself in many different forms such as potential energy, kinetic energy, mass, electricity, etc. Therefore, if we were to observe an event in conflict with this principle, there are several possibilities for saving the principle from refutation. For example, one could claim that the measuring device was faulty, or that the system was in fact not closed. Summarizing, one could say that even if the distinction is not entirely clear, it is intuitive that there is a significant difference between empirical generalizations and fundamental laws.

A large number of empirical generalizations have proven to be logical consequences of more fundamental laws. A good example is the ideal gas law

$$pv = nRT, \tag{10.1}$$

which states that for any quantity of gas, the product of its pressure (p) and volume (V) is proportional to the product of its number of moles (n) and temperature (T) (R is the general gas constant.). It is a well-known fact that this law is a consequence of the energy principle, given certain simplifying assumptions concerning gas particles. But the general law of gases was discovered before the molecular theory of gases was in place; it's status was first that of an observed empirical regularity, and much later was it discovered to be a consequence of energy conservation.

Sometimes we make empirical generalizations that later prove to be false. Many would perhaps be willing to accept the proposition 'All adult swans are white' as an empirical generalization. Yet, this proposition is false, since there exists black adult swans. Thus 'All adult swans are white' is not a law.

An interesting question here is whether all true empirical generalizations are logical consequences of some fundamental laws. The answer is unknown.

10.3 Deterministic and Statistical Laws

Some laws are deterministic, and some are not. Coulomb's Law – which says that the electric force between two charged bodies is proportional to the product of the two charges and inversely proportional to the square of the distance between them– stands as a good example of a deterministic law. If we know the state of a system consisting of two charges (and nothing else) at one point of time, we can determine its state at any other time, using Coloumb's law, provided the system is not influenced by other charges. An example of a statistical law is that which concerns the radioactive decay of the Carbon-14 isotope. The probability of decay of a single C-14 nucleus during a time interval of 5730 years is 50 %. Even if we know the precise state of such a nucleus at some point in time we cannot determine its state at other times with certainty; at any point of time it may have decayed or it may not.

However, if we consider a sufficiently large number of such nuclei, more than 10^{20} or so, then we can treat this decay as the following deterministic law: after 5730 years, 50 % of them will remain. Hence we do not have to give a probability distribution given the degree of precision in such cases. However, in the case of individual atoms, we cannot know which atom will decay, or when. All we can say is that the probability that a given atom will decay within 5730 years is 50 %. Thus at the microscopic level, we can only describe radioactive decay using a statistical law.

It may seem reasonable to assume that if we had a better theory, we would be able to predict when, and under which conditions, the decay of an individual nucleus occurs. But why does it seem plausible that our present theory is incomplete? Is it not just as plausible that nature is inherently probabilistic?

Among present day atomic and nuclear physicists, the general opinion is that there is genuine randomness in nature and that the statistical character of radioactive decay does not depend on our having failed to describe all of the relevant factors. On the contrary, many believe quantum mechanics, which is the theoretical foundation for radioactive decay, to be a complete theory in this sense. However, some people are seriously convinced that nature must be deterministic. For example, Einstein is reported as once saying 'Der liebe Gott würfelt nicht' ('The good Lord does not play with dice') (One should not infer that Einstein was religious in any usual sense; it is quite clear from his writings that for Einstein this was a metaphorical way of saying that there is no randomness in nature.).

Further examples of statistical laws are some heredity laws. For example, we know that having brown eyes is a dominant trait, whereas having blue eyes is recessive. Thus if a child has inherited the gene for brown eyes from one parent, then that child will also have brown eyes. Conversely, for a child to get blue eyes it must inherit genes for blue eyes from both of the parents. If one of the child's parents, e.g. the father, has brown eyes, but one of the child's grandparents on the father's side has blue eyes, one can conclude that the father only has one gene for brown eyes. If the other parent of this child has blue eyes, then the child has a 50 % chance of getting brown eyes. This can be formulated into a heredity law in the following way:

For all x, if x is human, the probability for x having blue eyes, conditional on x having one blue-eyed and one brown-eyed parent, and one of the brown-eyed parent's parents being blue-eyed, is 50 %, i.e.,

$$\forall x P(Bx|Ax) = 50\% \tag{10.2}$$

where Bx stands for 'x has brown eyes' and Ax stands for 'one of x's parents is brown-eyed, the other is blue-eyed, and one of x's grandparents is blue-eyed'.

10.4 The Extension of the Concept of a Natural Law

By the term 'natural law' we usually intend not only things so called, such as Newton's laws, but various principles, postulates, and fundamental equations, such as the principle of energy conservation, Einstein's postulate that the velocity of light is a constant upper limit for all velocities and Maxwelll's equations. Why are these superficially quite different things grouped under the term 'natural law'?

Furthermore, there are laws, which appear to be no more than definitions of quantities. One such example is Ohm's law, $U = RI$, which states that the voltage (U) across a resistor is equal to the product of the resistance R and the electric current (I). Looking at the quantities that make up the SI-system–the international standard system of quantities and units–we can easily convince ourselves that Ohm's law is used to define one quantity in terms of the other two. For a long time, resistance was defined in terms of voltage and current. However, some years ago one reversed the order; with the help of the quantized Hall effect one was able to give a very accurate and operational determination of resistance. Thereafter, Ohm's law became a definition of current in terms of resistance and voltage.

The philosophical debate about laws has not addressed the question whether a definition could be a law, so I will postpone this question aside for the time being and return to this issue in Sect. 10.7. For now, lets focussing on some uncontroversial examples of laws, since it is an astonishing fact that there is deep disagreement about the concept of natural law, but common agreement about quite a number of concrete examples, such as Newton's laws, the principle of energy conservation and Maxwell's equations. But if so, do these quite different kinds of propositions really have anything in common deserving philosophical interest?

10.5 Laws and Accidental Generalisations

One might assume that, since all parties in the debate agree on a number of prime examples of natural laws, they agree on the criteria. And in fact they do to *some* extent. A formal property of all laws is generally accepted viz., they are universally generalized conditionals. This applies even to such laws as the ideal gas law or Coulomb's law, i.e. laws usually expressed as equations. The latter is given by the equation:

$$F = k\frac{q_1 q_2}{r^2}. \tag{10.3}$$

This formula is to be interpreted as 'for all pairs of bodies with charges q_1 and q_2 respectively, there is a force F proportional to their product, and inversely proportional to the square of the distance r between them'. It is implicit that this law holds only if no other forces act upon the charged bodies. Likewise, it is implicit that this law generally applies. If we were to make these implicit conditions explicit, then the complete interpretation of the above formula would be the following:

> For all pairs of bodies with charges q_1 and q_2, with a distance r between them, the force between them is
>
> $$F = k\frac{q_1 q_2}{r^2}, \tag{10.4}$$
>
> given that no other forces act upon them.

Examining the statement above, we see that (1) it is a general statement, (2) that it is of the form 'if p, then q', and (3) that it contains a version of the so-called *ceteris paribus* clause, viz., 'given that no other forces act upon them' and (4) it is true. Ceteris paribus conditions are always contained in the application of scientific laws to concrete situations, and are often implicit. However, everyone agrees that (1) and (2) are necessary conditions for all scientific laws, whereas ceteris paribus conditions are not considered constitutive of the concept of a law, even though they are often implicitly assumed.

Have we now given the necessary and sufficient formal conditions for a proposition to count as a law? No! There are many statements that fulfil these requirements and yet are not laws. One example is

All the coins in my wallet are made of copper.

(Let's suppose it is true.) This is a general statement that can easily be reformulated into 'for all x, if x is a coin in my pocket, then it is made of copper'. Thus it fulfils criteria (1) and (2); yet it is obvious that this statement is not a scientific law, even though it is true. Such statements are called *accidental generalizations*.

How does one distinguish between laws and accidental generalizations? This is the core question concerning the concept of a law, and a number of ideas for solving this problem have been proposed. We shall discuss three of those ideas here.

(i) A true law supports a so-called *counterfactual conditional*, whereas an accidental generalization does not. A counterfactual conditional is a sentence of the form 'if x, then y' in which both the antecedent and the consequent are false. Often they are expressed in subjunctive mode: 'if x were the case, then y would be the case.' For example, the sentence 'if Bill Clinton had told the truth when under oath, then he would not have been impeached' is a counterfactual, since the antecedent is false. Clinton did lie under oath about his relations with Monica Lewinsky, and he was impeached.[1]

Now compare the following two statements

1. All spheres made of gold are less than 1 km in diameter.
2. All spheres made of U-235 are less than 1 km in diameter.

U-235 is radioactive and fissible; its cricital mass is 52 kg (a sphere with diameter of 17 cm) which means that a sphere with a diameter bigger than 17 cm will start a chain reaction and explode. (This is the principle for constructing an atomic bomb.) So it is impossible to have a solid sphere of U-235 of any size. Hence (2) *must* be true and we consider it a law, since it can be derived from basic principles of nuclear physics that it is impossible to collect a sufficiently large amount of U-235 without it exploding. In contrast, (1) is not a law, even if it is true, but an accidental generalisation. It just so happens that gold is not that concentrated (And if we would find an enormous

[1] Clinton was US president 1993–2000. He had an affair with Monica Lewinsky, who had an internship at the White House.

solid body of gold somewhere in the universe, we could easily increase the limit and still get the contrast.).

From (1) and (2) we can formulate the following two counterfactuals:

3. If an object were a sphere of gold, then it would be less than 1 km in diameter.
4. If an object were a sphere of U-235, then it would be less than 1 km in diameter.

In comparing these two, we are inclined to say that (3) is false, whereas (4) is true. Thus we may state the following criterion for distinguishing between laws and accidental generalizations: If one reformulates a law into a counterfactual conditional, then the resulting sentence is true, whereas, if one reformulates an accidental generalization into a counterfactual conditional, then the resulting sentence is false.

But what grounds do we have for saying that (3) is false? If we interpret (3) as a material conditional (see Appendix), then it follows that since the antecedent is false, the whole sentence is true (See the discussion regarding conditionals in the Appendix). This shows that counterfactual conditionals cannot be interpreted as material conditionals. Thus the question regarding the conditions under which a counterfactual is true cannot be answered by investigating the truth-values of the antecedent and the consequent separately. There must be something in the connection between the antecedent and the consequent that is relevant to the truth of a counterfactual. But how shall we express this connection?

The general idea is to analyse counterfactuals in terms of possible worlds. A counterfactual is true if there exists a possible world in which both antecedent and consequent are true, otherwise false. So when we declare (3) false we mean that there is a possible world in which there is a sphere of gold bigger than 1 km in diameter.

But, then, one may ask, how do we distinguish possible from impossible worlds? A natural way do this is to say that possible worlds are those in which the natural laws are valid, but then we are back were we started. Other alternatives have been proposed, but, as Earman pointed out in the quoted passage, no idea has won general acceptance.

(ii) The second idea for a criterion to distinguish between laws and accidental generalizations is the observation that accidental generalizations refer, though perhaps only implicitly, to a particular location in time and/or space, whereas laws do not make such specifications. The American philosopher Nelson Goodman has criticized this idea by arguing that every law-like generalization is logically equivalent to a formulation that contains such a reference to space and time. The example Goodman gives is the law-like generalization 'all grass is green', which obviously is equivalent to 'all grass in London and everywhere else is green'. The difference between law-like and accidental generalizations, therefore, cannot be that the latter contains a spatial reference, since all law-like generalizations are equivalent to statements containing such references. One is now tempted to propose the following improvement: spatial reference in a law-like generalization is always redundant, whereas in accidental generalization it is not. Another way of formulating this criterion is to say that in accidental generalization, the spatial or temporal reference is necessary, whereas this is not the case as regards laws. However, this formulation immediately raises the question as to what one means by the concept of necessity as it is used in this context.

Regardless of whether this attempted solution bypasses Goodman's critique, there seems to be accidental generalizations that do not make any spatial or temporal references, as in the case of (1) above. Hence (redundant) spatio-temporal specification is not a characteristic by which one can distinguish laws from accidental generalizations in all cases.

(iii) A third alternative in the analysis of a law, which has been quite popular over the last two decades, is to claim that laws express *physical necessity*. It seems reasonable to say that it is necessarily true that bodies with mass gravitate toward each other, and that it is necessarily true that charged bodies act on one another with electrical forces. It is necessarily true that there cannot exist large concentrations of U-235, but it is not necessarily true that there exist large concentrations of gold. Thus a law has three significant traits: a law is general, it has the form 'if x, then y', and it is necessarily true.

How should one analyse the concept of *physical necessity*? It is obvious that 'necessity', as it is used here, means something other than logical necessity: there are no *logical* reasons for why charged bodies act on one another with electrical forces.

There are presently several ideas for analysing physical necessity, but none of them have succeeded in overcoming the scepticism of empirically minded philosophers. These philosophers affirm that a theory is either true or false, and the only possibility we have of determining which is the case is to compare the theory with our observations. An observation must be formulated into a statement, thus enabling us to compare the theory's empirical consequences with that observational statement. The most we can say is that the empirical consequences are true or false. However, a theory's empirical consequences are independent of whether or not we view an individual statement of that theory as a law or not. In other words, we cannot empirically determine whether a theory is comprised of laws or true accidental generalizations. But if we assume the empirical principle that there must be some empirical basis for distinguishing between physically necessary and accidental statements, then we must discard the concept of physical necessity as inessential metaphysics.

Metaphysically inclined philosophers disagree; they hold that laws are metaphysical relations between universals and we need such things in order to explain regularities in nature. Let us illustrate with Maxwell's first equation, which says that the divergence of the electric field is proportional to the enclosed electric charge. The metaphysical explanation of this would be something like: the two universals *electric charge* and *electric field* are such that in all possible worlds they are so related to each other that it makes every instance of Maxwell's first equation true (This is an application of the general idea that relations between universals are truth-makers for true sentences.). In other words, it impossible that Maxwell's equation could be false. This is, of course, a very rough description of one metaphysical explanation of the necessity of laws, but even more elaborate ones are, in my view, hardly convincing or explanatory. Do there really exist any universals, and why are they related so as to make our laws true? And more important, it is certainly not an analysis of what physicists intend when they say that Maxwell's first equation is a law.

10.6 van Fraassen's Alternative

Bas van Fraassen, who is arguably the leading empiricist of our time, has discussed, in detail, all of the main attempts at analysing the concept of a scientific law in terms of necessity and has concluded that they are all unsuccessful (see van Fraassen (1989)). He has subsequently proposed that we give up the concept of a scientific law as a metaphysical relic. He first argues that this concept is not needed in science, since all conclusions that are made can be motivated without assuming the existence of some special category of statements, *scientific laws*, which has some characteristic properties beyond truth and universality.

van Fraassen's second argument for this point is that laws can be replaced by certain symmetry principles. These symmetry principles are *conditions for our descriptions of nature*, and not conditions for nature itself. The following example may help clarify this point. When we describe the motion of a body, we must use a coordinate system and a clock. It is obvious that our choice of origin and directions in our coordinate system, as well as the choice of the starting point of the clock, is purely conventional; a question of what is the most practical. Hence it is also obvious that these purely conventional choices must not have any consequences as regards the content of our descriptions of nature. The statements we make about nature should be independent of such conventions. Another way of expressing this point is to say that our theories should be invariant, or symmetric, under a transformation from one conventional choice to another. These requirements of symmetry can be either global or local. The global symmetries are

- Symmetry under translations along the time axis,
- Symmetry under translations in space,
- Symmetry under rotations in space.

There are also a number of local symmetry principles, the best known of which is

- Phase transformation invariance of the electromagnetic potential.

These requirements may appear rather trivial, but it is interesting to notice that each such requirement of invariance under continuous transformations yields a conservation principle according to a famous theorem by Emmy Noether

(1882–1935). The well-known principle of energy conservation is one such law, as are the conservation laws for momentum, angular momentum and charge. Noether showed that each such conservation law could be derived from a symmetry principle. Thus we get the following:

(i) Symmetry under time translations entails energy conservation,
(ii) Symmetry under space translations entails momentum conservation,
(iii) Symmetry under rotations entails angular momentum conservation.
(iv) Symmetry under phase transformations of the electromagnetic phase entails charge conservation.

There are more symmetry transformations and laws of conservation, but these are the most central. It follows that these conservation laws are really just consequences of certain conditions for our descriptions of nature. These conditions are motivated by the requirement of objectivity; our descriptions of nature should be independent of the observer's frame of reference. This is hardly a principal restriction on how nature is constructed, but merely on how it should be described. It seems quite reasonable to require that our descriptions of nature be as objective as possible; that we purge all subjectivity from the universe, including how we construct our measuring devices and frames of reference. If so, we may say that conservation laws are necessary, in the sense that they are necessary consequences of objectivity demands. And general statements derivable from these conservation laws (using some definitions as auxiliaries) may also be said to be necessary and thus laws.

Conservation laws are fundamental laws, but all fundamental laws are not conservation laws (e.g. the law of gravity, Coulomb's law, and Schrödinger's equation). Thus we cannot claim that we have solved the problem of the nature of a scientific law through this analysis of conservation laws. Van Fraassen maintains that one cannot go any further if one wants to stick to empiricist principles. However, many philosophers disagree with van Fraassen on this point, even those which are not metaphysicians in the first place. In my view they have not been able to offer a more appealing analysis. In the next section I will propose an explanation of the nature of some laws, which I think would be acceptable to all empiricists, including van Fraassen.

10.7 A Proposal: Some Laws Are Implicit Definitions of Quantities

Many laws state relations between quantities. Some of these are explicit definitions, such as Ohms law, U = RI, (the voltage over a resistor equals its resistance times the current through it), and some are derivable form other more fundamental laws. But what about fundamental laws expressing relations between quantities? I will here suggest an analysis of why such fundamental laws have a special character in our theories and why we say that they are necessary. My example consists of two laws of classical mechanics.

The basic idea is that some laws at the same time are implicit definitions of new quantities and empirical generalisations of observed regularities. Their being empirical generalisations give them empirical content, and their being a kind of definition is the reason we say that they are necessarily true.

Classical mechanics is commonly divided into kinematics and dynamics. Kinematics describes the motion of physical bodies, usually called 'particles' in the theoretical exposition, since their inner structure is irrelevant, while dynamics is the theory about interactions between particles (We may treat the earth as a particle if we don't care about its volume or inner structure!). Galilei discovered some simple regularities in kinematics, for example that all bodies have the same acceleration when falling to the ground and that the distance travelled is proportional to the square of the elapsed time.

When describing particles' positions, velocities and accelerations and the relations between these we only need two fundamental quantities, *time* and *distance*. Velocity and acceleration are also needed, but they are not fundamental, they are defined as the first and second time derivative of distance. That we have two fundamental quantities in kinematics is a consequence of the fact that we need two measuring instruments, a meter stick and a clock, to measure and observe the values of the kinematic quantities. One also needs some geometry and arithmetic, of course, but these disciplines belong to mathematics; no measuring instruments are needed in pure mathematics.

How, then, do we proceed to dynamics, i.e., a theory about interactions between physical bodies? The actual history is illuminating. According to Rothman (1989, p. 85) it was John Wallis who took the first step in advancing a successful dynamics. In a report to Royal Society 1663 Wallis described his measurements of collisions of pendulums. Huygens and Wren then performed similar experiments and Newton used their results in his *Principia*. He described their experiments and findings in the section *Scholium* following corollary VI in the first section of the first book of *Principia*.

In modernized notation the result of these collision experiments is that there is a constant proportion, an observed regularity, between the velocity changes of two colliding bodies:

$$\frac{\Delta v_1}{\Delta v_2} = constant, \tag{10.5}$$

which can be written

$$k_1 \Delta v_1 = -k_2 \Delta v_2 \tag{10.6}$$

The minus sign is introduced so as to have both k_1 and k_2 positive. By testing with different bodies (which was done by Huygens) we will find that the constants really are constants following the bodies, i.e., they are permanent attributes of the bodies.

These constant attributes are their *masses*, and we may chose a mass prototype giving us the unit. So we have the following law:

$$m_1 \Delta v_1 = -m_2 \Delta v_2 \tag{10.7}$$

This is the law of momentum conservation, a fundamental law in physics. It is at the same time an observed regularity and an implicit definition of a new theoretical quantity, *mass*.

People have objected to this, saying that a proposition cannot at the same time be a definition and a generalisation of empirical observations. They are wrong. The fundamental point is that, in order to be able to formulate the generality that all bodies are such that their collisions satisfy Eq. (10.7), we need the concept of mass and this concept was not available earlier, nor is it defined by any other quantitative relation. It was invented precisely for the purpose of expressing the regularity that Wallis, Huygens and Wren found. Equation (10.7) function as implicit definition of mass (An explicit definition of mass in terms of other quantities is impossible, since it is one of the fundamental quantities in physics.).

Moreover, as Quine forcefully argued, the distinction between analytic and synthetic sentences cannot be upheld (see his *Two Dogmas of Empiricism*.[2]), and those who criticizes the idea that one and the same proposition can both be an implicit definition and an observed regularity presumably would motivate their criticism by saying that a definition is analytically true and an empirical generalisation is synthetically true.

Newton published *Principia* 23 years after Wallis reported his findings to Royal Society. He begins *Principia* by defining mass as 'quantity of matter', (on page one in the main text), but this definition only gives us an intuitive meaning of the word 'mass', it does not tell us how to measure it. Wallis, Huygens and Wren had long before the publication of *Principia* provided that without using the word 'mass'; they in effect introduced this quantitative predicate in physics.

If we now divide both sides of Eq. (10.7) with the collision time, we get (neglecting the difference between differentials and derivatives since this is of no relevance for the present argument):

$$m_1 a_1 = -m_2 a_2 \tag{10.8}$$

Let us further introduce the term 'force', labelled 'f', as shorthand for the product of mass and acceleration. This gives us Newton's second and third laws:

$$\mathrm{N2 : f = ma} \tag{10.9}$$

[2] In his (1953), pp. 20–46. See also his (2004).

$$N3 : f_1 = -f_2 \tag{10.10}$$

Thus we have got Newton's second and third laws based on an observed regularity, viz., momentum conservation during collisions between bodies.

Many readers would, I guess, oppose my saying that Newton's second law is an explicit definition of force, since forces usually are thought of as causes, viz., the causes of bodies' accelerations, which conflicts with saying that the term 'force' simply is shorthand for 'mass times acceleration'. But if so, what is here cause and what is effect? Newton's third law tells us that we can either focus attention on the motion of body 1 and ask about the force on it from body 2, or the converse), no cause-effect distinction can be made. This is also the modern view in physics, instead of talking about causes, one talks about interactions. So I reject the common interpretation of Newton's second law as a causal law; this interpretation is in fact inconsistent with Newton's third law.

Newton himself appears to have thought of forces as causes. But that cannot be correct and perhaps a remnant from Aristotelian thinking about motion.

It is thus a bit misleading to say that Newton *discovered* his second law; it is more correct to say that he changed the meaning of the word 'force', which was used in ordinary language long before Newton, when he established his second law.

What he discovered was that, contrary to the Aristotelian view that matter and quantity are distinct ontological categories, to every body he could attribute a *quantity of matter*, i.e. mass. We may carefully observe that mass is not a directly observable quantity and it is not the same as weight! This is the core idea, which entailed a radical change of our entire thinking about motion.

In this example we have talked about mechanical forces. This is no real restriction; it is well known that there is, as far as we know, four fundamental kinds of interactions in nature, gravitation, electromagnetism, the weak and the strong nuclear force, and the same reasoning applies in all these kinds of interactions. Mechanical interactions, by the way, are electromagnetic interactions.

It seems to me correct to say about science that inventing and defining new and precise concepts and establishing laws are two sides of the same coin. This is very clearly the case in classical mechanics. Neither the concept of mass, nor the modern concept of force, was used or known before Galilei and Newton; The introduction of these concepts and the establishment of the law of momentum conservation and of Newton's laws cannot be separated either historically or conceptually.

Let us now proceed to the law of gravitation:

$$F = G\frac{m_1 m_2}{r^2} \tag{10.11}$$

Since (i) we earlier have introduced the concept of mass in the law of momentum conservation, (ii) force is shorthand for mass times acceleration and (iii) distance is a kinematical quantity, it appears that this must be a purely empirical law; all concepts are earlier defined. But that is really astonishing: how could it be that four quantities, defined by other relations, always and exactly relate to each other according to Eq. 10.11? It seems to be a truly cosmic coincidence!

I don't believe in cosmic coincidences, and in fact neither do we have any such here. As Newton himself realised, the mass concept utilized in this law express another property than the mass concept occurring in our descriptions of collision experiments. The law of gravitation describes how physical bodies interact at distance, whereas the law of momentum conservation describes how bodies interact when they collide. We have two distinct mass concepts, *gravitational mass* and *inertial mass*. And we may say, just as with the law of momentum conservation, that the law of gravitation at the same time is an implicit definition of gravitational mass and an empirical generalisation found by observing e.g., how planets move around the sun and Jupiter's moons move around Jupiter.

The remarkable thing is that inertial and gravitational mass, although conceptually distinct properties, always are exactly equal! This is truly astonishing! Newton realised that gravitational and inertial mass was different properties, but had no explanation of their equality. This conundrum was not explained until the advent of general theory of relativity; and the explanation is the most natural one, viz., that gravitational and inertial mass really *is the same property*, because gravitation and inertia at bottom is the same phenomenon.

Summarising my account of classical mechanics: we have two fundamental laws, momentum conservation and the law of gravitation, which each have a double function; they are each an implicit definition of a new quantitative predicate and at the same time expresses an inductive generalisation of observations. Newton's second law is an explicit definition of force and Newton's third law is a direct consequence of momentum conservation, given the definition of force.

What, then, about the necessity of laws? First, definitions, both implicit of explicit, are *necessary conditions* for the use of the defined terms in our theories. Second, logical consequences of definitions are necessary consequences of these definitions, since necessity distributes over logical consequence. So we have an account of why we think of laws as necessary.

Medieval philosophers distinguished between necessity *de dicto* and necessity *de re*; necessity de dicto is a necessity in what is said, whereas necessity *de re* is necessity in the object, viz., that the object talked about has a property, or stands in a relation, by necessity. Applying this distinction, we see that the necessity of both the fundamental laws and of those laws derived from them, are species of necessity *de dicto*. It is the *statements* that are said to be necessary. It does not follow that the objects talked about have any properties by necessity and independently of how we characterize them. So empiricist scruples about metaphysical necessity are satisfied.[3]

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[3] If we formalise a sentence claiming the necessity of a law as 'N "L"', i.e., treating 'necessary' as an abbreviation for 'necessarily true', i.e. a second order predicate and the sentence 'L' as an argument) one blocks the distribution of necessity into the law sentence since one cannot distribute inside quotation marks, and hence the attribution of necessary properties to things.) Cf. Quine: 'Three grades of modal involvement', pp. 158–176 in his Quine (1976).

There are, for sure, several laws that are not definitions of quantitative concepts, or consequences thereof, and this account obviously doesn't apply to these. But some progress is made, or so I hope.

10.8 Summary

Scientists and others often use phrases such as 'natural laws', physical postulates', 'fundamental principles' 'NN's law', 'NN's equation' etc. The things denoted by these phrases are often referred to as 'laws of nature' in the philosophical debate.

Philosophers disagree sharply about the concept of natural law. Some say that it is obvious that there is a certain category of propositions, *laws*, which differ from other true propositions of the same logical form, *accidental generalisations*. Many of these philosophers think that the property of being a law is based on a kind of metaphysical necessity. Other philosophers of a more empiricist bent disagree and point out that the predictive power of a theory does not depend on whether some of its propositions are called laws or not; calling some true propositions 'laws' is unnecessary metaphysics. This empiricist argument is convincing, but why, then, is the concept of natural law, used not only by philosophers but also by laymen and scientists? Surely, this concept serves *some* purpose, although perhaps not a philosophical one.

For four types of laws it is possible to give an explanation of our propensity to call them 'laws' and treat them as having a special status of being *physically necessary*, without assuming any kind of metaphysical necessity. The first type comprises conservation laws, each of which can be shown to be a consequence of a certain objectivity demand on our descriptions of the events in nature. The second type comprises some equations, each of which may be viewed as an implicit definition and at the same time an empirical generalisation of observations. The third type consists of explicit definitions of one of the quantities used in the respective equation. Finally, those true generalised conditionals that can be derived from the three types above are also labelled laws.

Further Reading

Armstrong, D. (1983). *What is a law of nature*. Cambridge: Cambridge University Press.
Bird, A. (2007). *Nature's metaphysics, laws and properties*. Oxford: Oxford University Press.
Carroll, J. (1994). *Laws of nature*. Cambridge: Cambridge University Press.
Cartwright, N. (1983). *How the laws of physics lie*. Oxford: Clarendon.
Lange, M. (2009). *Laws and lawmakers*. Oxford: Oxford University Press.
Mumford, S. (2004). *Laws of nature*. London: Routledge.
van Fraassen, B. (1989). *Laws and symmetry*. Oxford: Clarendon.