Chapter 6
Space and Matter in Early Modern Science: The Impenetrability of Matter

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6.1 The character of early modern science

The most conspicuous characteristic of early modern in contrast to ancient and medieval science is rightly considered the different kind of recourse to experience in the generation and justification of knowledge.[1] Results of observation and experiment were put forward against the authority of the Aristotelian doctrine. It is true that already in medieval times Aristotelian philosophy had undergone fundamental modifications – just recall, for example, how the various forms of the so-called theory of *impetus* complemented Aristotle's doctrine of motion – but such modifications were the result of internal developments within the framework of an Aristotelian consensus. They were rarely understood as radical alternatives to the Aristotelian doctrine. In contrast, what protagonists of the modern science of the sixteenth and seventeenth centuries had in common, beyond their emphasis on experience, was a downright programmatic anti-Aristotelianism. Modern science was not only supposed to open up new spheres for experience, it also aspired to a new kind of theory radically different from Aristotelianism, but with a comparable claim to universal validity.

This meant that during its first phase modern science was confronted with an insurmountable problem arising out of its internal structure. On the one hand, the experiential basis was far too small to construct a general theory of nature that was generally acceptable owing to its substantiation through empirical evidence. On the other hand, the very pretension of being able to compete with the theory of the Aristotelian tradition, which explained everything, made it imperative to come up with comprehensive theoretical systems that harbored comparable explanatory potential.

From this problematic situation, it is understandable why the insistence on observation and experimentation as the ultimate authorities to judge the truth of scientific propositions was not the only characteristic of the early phase of modern science. There was also the nearly desperate hope and expectation that, through philosophical reflection,[2] it would be possible to create an apodictic theoretical framework for the interpretation of empirical experiences, a framework justified solely on the principles of reason. This program was designated by a term going back to Aristotle: metaphysics.

[1] This chapter is based on a lecture given by Peter Damerow in 1994 at the University of Constance. The supervision of the translation from German into English and the inclusion of additional notes left by Peter Damerow were done by MS. The central concept of the chapter, *conceptual models* (*Modellvorstellungen*), is closely related to the *mental models* introduced in Chapter 1. In particular, the concept is used here to illuminate how metaphysical ideas result from the absolutization of experiences. – [MS]

[2] This reflection was actually not all that different in principle from speculative ancient philosophy.

The topic of this chapter concerns an idea typical of this modern metaphysics, an idea which runs as a thread throughout its development: the idea of distinguishing between space and matter by assuming that matter has the property of being impenetrable.

6.2 Ancient atomism

The early modern idea that matter has the essential property of being impenetrable has its origins in ancient philosophy, namely in a thought experiment. If one conceives of the perceptible bodies of everyday experience as being divided into ever smaller parts, the following alternative appears to be inevitable: Either the division can, theoretically, be continued infinitely; or at some point one runs up against a fundamental limit, against the *indivisible*, the *atom*. And if this smallest unit of matter is to be indivisible then matter must be impenetrable by its nature, that is, no matter can reach the place of other matter without pushing it away.[3]

The assumed existence of such impenetrable atoms of matter became the point of departure for the ancient philosophical tradition of atomism. In their speculative endeavor to reduce the coming-into-being and passing-away of reality to a permanent, rationally conceivable explanation, Greek philosophers developed the idea that the world of macroscopic phenomena and occurrences could be explained by processes in a microscopic world which is no longer accessible by our senses but only by reason. According to this explanatory model the founders of ancient atomism, the Greek philosoper Leucippus and his disciple Democritus, promoted the idea that the qualities of things we perceive are not qualities of these things themselves but rather represent the way our senses react to qualities of these things. Aetius the philosopher wrote in his *Opinions of Philosopers* about the Greek atomists:[4]

> The atomists taught that everything is entirely colorless; sensory qualities emerge from (bodies) without qualities, which are perceivable only by reason.

According to the ancient atomists, our senses merely lead us to believe the colorful world of sensory impressions. In fact there are only atoms, their shapes and their movements, which affect our senses.[5]

The postulated atoms are different from the objects of our direct experience in yet another respect. Since they are supposed to be indivisible they must have characteristics principally different from these objects, for otherwise there would be no reason why the process of division could not be continued. According to tradition, Leucippus and Democritus thus characterized atoms using a pair of absolute concepts that cannot be traced back to any other concepts. The atoms are the ‘full’, the ‘solid’, the ‘being’, while the space in which they

[3] Thus, Lucretius writes: “[…] you must yield and confess that there are things which no longer consist of any parts and are of the smallest possible nature. And since these exist, you must also confess that the first-beginnings are solid and everlasting” (*De rerum natura* I, 624–627; translation taken from Lucretius Carus 1992, 51–53).

[4] Aetios 1,15,11, see Diels 1951-1952, Vo. 2, 112; for a German translation, see Jürß, Müller, and Schmidt 1988, 175 (Fragment 209).

[5] Thus, Aristotle writes: “Democritus […] and Leucippus postulate the ‘figures’ and make ‘alteration’ and coming-to-be result from these, attributing coming-to-be and passing-away to their dissociation and association, and ‘alteration’ to their arrangement and position; […].” Aristotle *On Coming-to-be and Passing-Away* 315b, 7–9, translation taken from Aristotle 1992, 173.

move is the 'void', the 'nothing', the 'infinite'. According to Simplicius, Leucippus and Democritus[6]

> thought them [i.e. the atoms] to be uncuttable, indivisible, and unaffectible on account of their being compact and having no share of void. For they said that division occurred because of the void in bodies, and that these atoms are separated from one another in the infinite void, and, differing in shape and magnitude and position and order, they move through the void and meet with and collide with one another, and that some bounce off in whatever way they will, while others become intertwined with one another because of the congruity of their shapes, magnitudes, positions, and orders, and it so happens that the generation of composite things is accomplished.

This speculative structure describing the microscopically small contains tacit assumptions about the relationship between space and matter, which were later to constitute the core of the problem to be discussed here. Apparently it is presumed as a matter of course that atoms cannot penetrate each other. Matter is granted the property that, wherever it is located, no other matter can get there without displacing it from its location. Matter, the solid, thus differs from the space in which it is located, the void, through a fundamental impenetrability. This property presents a constitutive prerequisite for the assumption of the indivisibility of atoms and thus for the atomistic explanation of creation, decay and change. The space of the atomists is an absolute void. It does not provide any resistance against matter and thus cannot exert any causal effects. Matter, by contrast, is absolutely impenetrable, such that collisions of atoms bring forth causal effects, which appear as creation and decay or as change on the macroscopic level.

Wherein lies the persuasiveness of such assumptions about the structure of the microscopically small? Doubtlessly in the fact that the structures attributed to the microscopically small appear to have such obvious validity in the macroscopic world. Thus Lucretius, for instance, justifies the basic assumptions of atomism as follows:[7]

> But now to resume my task begun of weaving the web of the discourse: the nature of the universe, therefore, as it is in itself, is made up of two things; for there are bodies, and there is void, in which these bodies are and through which they move this way and that. For sensation common to men declares that body has its separate existence; and unless our belief in sensation is first firmly established, there will be no principle of appeal in hidden matters, according to which we may establish anything by the reason. Then further, if there was no place and space which we call void, bodies could not be situated anywhere nor could they move anywhere at all in different directions […].

Atoms thus were assigned properties resembling those of the objects in the macroscopic space that surrounds us. But there is a decisive difference between the world of macroscopic things and the world of atoms. In contrast to the properties of macroscopic things, properties in the world of atoms are absolute properties. The thought experiment's step of declaring

[6]Simplicius *On Aristotle On the Heavens*, 242, 17–27; translation taken from Simplicius 2004, 64.
[7]Lucretius *De rerum natura*, I, 418–428; translation taken from Lucretius Carus 1992, 35–37.

atoms to be absolutely indivisible entails further absolutizations. The matter of the ancient atomists is absolutely impenetrable and space is absolutely empty.[8]

6.3 The revival of atomism in the renaissance

Ancient atomism experienced a renaissance in the corpuscular theories of the sixteenth and seventeenth centuries. It was attractive to the representatives of modern science not only as an alternative to Aristotelianism, but above all because it corresponded to the metaphysical goal of explaining the world immanently from principles of reason. Atomism depicted the world as the result of an interplay among its smallest parts, an interplay that is complex and yet determined by laws, and about whose nature one could apparently gain insight through reasoning.

A typical example of recourse to the ancient theoretical tradition is presented by the corpuscular theory of Robert Boyle, with which he attempted to explain chemical reactions in particular.[9] As for the atomists of antiquity, for Boyle, too, the macroscopic properties of matter were secondary qualities, that is, ways of perceiving the primary qualities of size, shape and motion of the microscopically small particles of which matter actually consists. The program he pursued aimed to trace the secondary qualities back to two principles:[10]

> I should likewise, after all this, explain to you how, although matter, motion and rest, seemed to me to be the catholick principles of the universe, I thought the principles of particular bodies might be commodiously enough reduced to two, namely *matter*, and (what comprehends the two other, and their effects) the result, or aggregate, or complex of those accidents, which are the motion or rest, (for in some bodies both are not to be found) the bigness, figure, texture, and the thence resulting qualities of the small parts, which are necessary to intitle the body whereto they belong to this or that peculiar denomination; and discriminating it from others to appropriate it to a determinate kind of things, (as yellowness, fixtness, such a degree of weight, and of ductility, do make the portion of matter wherein they concur, to be reckoned among perfect metals, and obtain the name of gold) this aggregate or result of accidents you may if you please, call either *structure*, or texture (though indeed, that do not so properly comprehend the motion of the constituent parts especially in case some of them be fluid) or what other appellation shall appear most expressive.

Yet there are two essential differences between Boyle's corpuscular theory and ancient atomism. For one, Boyle was convinced that he did not only have to *postulate* the microscopic corpuscles hypothetically, he believed that they could actually be *proven* using empirical methods. Second, Boyle believed that the movements of the corpuscles were subject to the laws of mechanics formulated in the modern era. Through Boyle's 'mechanical explanations' the macroscopic properties of matter were thus supposed to be traced back to the mechanical laws, which were obtained macroscopically, but now applied to microscopic corpuscles.

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[8] Cf. the quote from Lucretius in note 3.
[9] Cf. Boyle 1666.
[10] Boyle 1937, 201.

For this immanent explanation of the world based on mechanical laws, Boyle selected a metaphor common in his day: The world functions like a mechanical clock composed of innumerable small parts, which, once set in motion by its creator, continues moving in accordance with strict laws without any further intervention.

6.4 Consequences of mechanical models

Modern corpuscular theories like that of Boyle were thus, like ancient atomism, associated with constitutive assumptions about the relation between space and matter. Such assumptions drew their persuasiveness from being based on conceptual models that were transferred from the macroscopic sphere, in which they appeared evident, to the microscopically small.

In ancient atomism these conceptual models represented the absolutized elementary structures of experiencing objects.[11] By contrast, in the corpuscular theories of early modernity conceptual models became more varied and differentiated, because the results of modern empirical evidence were transferred to the corpuscles as well, especially results from the science most highly developed at the time: mechanics. Thus the modern mechanical world view emerged from ancient atomism through mechanical conceptual models.

The variety of such conceptual models entailed a corresponding variety of metaphysical foundations for natural science.[12] Among the controversial points was particularly the question as to whether there actually were in fact absolutely empty spaces. This question had always been negated in the Aristotelian tradition, as opposed to ancient atomism, for according to Aristotle's law of motion, the speed of a moving body would become infinitely great in a space without resistance.

A number of modern corpuscular theorists also found the atomistic assumption that atoms move in absolutely empty space problematic, albeit for different reasons. Giordano Bruno, for instance, explicitly drew on Democritus and Leucippus but did not follow the ancient atomists in the question as to the existence of a vacuum, because to him the cohesion of bodies did not appear certain if they consisted only of atoms in motion. According to his view, matter would disperse into infinity if there were not another kind of matter, which he designated the *ether*. This "glued together and encompassed"[13] the atoms, as water did for the particles of the Earth.

The ancient atomists absolutized elementary experiences that can be gained in the handling of corporeal objects and had thus arrived at the opposition of impenetrable matter and empty space. Referring to Epicurus's atomistic theory, but criticizing its dualism of full and empty, Bruno, in his *On the Infinite Universe and Worlds*, lets his protagonist Filoteo explain his alternative to the Aristotelian Elpino as follows:[14]

> We do not call aught Void as being mere nullity, but rather accept the view whereby that which is not corporeal nor doth offer sensible resistance is wont,

[11] 'Absolutization' is here to be understood as elevating cognitive structures such as properties attributed to everyday objects (e.g. the hardness of a billiard ball) to fundamental principles (e.g. the indestructibility of atoms). – [MS]
[12] Owing to the simplicity of its basic assumptions about the relationship between absolutely impenetrable matter and space as an absolute void, ancient atomism constituted little more than a general background for the modern corpuscular theories. After all, these multifarious theories were based on complex, often mutually incompatible assumptions about processes on the microscopically small level.
[13] Cited after Lasswitz 1984, 378.
[14] Singer 1968, 273.

> if it hath dimension, to be named Void, since we do not usually understand as corporeal that which hath not the property of offering resistance; whence they say that just as that is not flesh which is not vulnerable, so that which doth not offer resistance is not corporeal. In the same way we name infinite that which is an immense ethereal region in which are innumerable and infinite [numbers of] bodies such as the earth, the moon, and the sun, and these are called by us worlds, composed of Plenum and of Void: for this spirit, this air, this ether not only surroundeth these bodies but also penetrateth within them and becometh inherent in everything.

Bruno, like the ancient atomists, transferred experiences from the world of macroscopic things to the world of the microscopic, but his assumptions about the relation between matter and space were oriented on the conceptual model of an all-pervading fluid.[15]

Clearly, the question as to whether there can be a vacuum, an absolutely empty space, is not only a theoretical question but also an empirical one. In fact, even back in Scholastic natural philosophy observations of phenomena that were caused by air pressure, such as the way a clepsydra or siphon works, had been related to this question. The fact that a fluid does not flow out of a closed vessel or a narrow tube as long as no air can flow into it, was explained through a *horror vacui*, which prevented the occurrence of an absolutely empty space.

Galileo Galilei also referred to such observations to explain his corpuscular theory, the basic assumptions of which also deviated from those of ancient atomism regarding the existence of an empty space. In contrast to Bruno, Galileo already used his deliberations on the relation of matter and space in the microscopically small to elucidate many kinds of macroscopic, physical and technical issues. According to Galileo, while matter is certainly impenetrable, space is generally not empty, as this is prevented by the horror vacui, for which he mentions numerous empirical observations.

Galileo was already aware, however, that the horror vacui has only a limited magnitude. From the observation that water can only be pumped up to a certain height, which Galileo gave fairly accurately as 18 cubits,[16] and from the correct theoretical explanation that at this height the horror vacui, i.e. air pressure, is surpassed by the weight of the water column, he drew the conclusion that the horror vacui represented only a limited force, which cannot absolutely prevent the occurrence of an empty space. Galileo further assumed that for solids the horror vacui prevents atoms from separating from each other, and derived from this an explanation for the relative solidity of macroscopic bodies. Only if the fine particles of fire in lively motion push themselves between the atoms, as for example when metals melt, can they be separated without a void occurring between them.[17]

The assumption that space is not empty, but rather completely filled with matter, represented a profound change in atomism, one which inevitably led to further modifications to its basic assumptions. For instance, ancient atomism had a plausible explanation for the fact

[15]Once it has been introduced, the ether takes on further explanatory functions, which are not rooted in the metaphysical system and cannot be substantiated directly with the original conceptual model. For Bruno this is, above all, the relation between spirit and matter, which is identified with the differentiation between ether and all other matter.

[16]Galilei 1974, 24–25.

[17]Galilei 1974, 27.

that matter can change its volume,[18] which could no longer be valid, since it was based on the assumption that material bodies contained empty spaces in the form of pores that grew larger in the process of rarefaction and smaller in the process of condensation.

Galileo solved the problem as to how "condensation and rarefaction […] can be understood to take place without assuming interpenetration of bodies and [at the same time] without introducing void spaces […]"[19] through yet another drastic change to the basic assumptions of atomism, which he oriented on a model from geometry: Galileo's atoms are indeed impenetrable and indivisible but, like the equally indivisible points of a line, they are also infinitely small, and their number, like those of points on a line, infinitely large; between them are infinitely many infinitely small empty spaces.[20] On the basis of this assumption Galileo explained the possibility of condensing or rarefying matter, analogous to the possibility of projecting a small line onto a large one, that is, by uniquely assigning the points of the two lines to each other.[21]

6.5 The rationalist program

The examples outlined above may already be sufficient to show how the structural problem of modern science presented itself to its proponents. Common to these theories was that they were anti-Aristotelian and drew orientation from ancient atomism. The perceptible properties of objects and the changes in these properties were traced back to movements of a matter that obeys absolute mechanical laws on the microscopic level, and these laws were deduced from experiences with macroscopic objects. But owing to the alteration of the experiential basis in early modern times, this approach inevitably resulted in deviations from the traditional, canonical ideas of ancient atomism; and owing to the multiplicity of possible conceptual models it resulted in theories that could hardly be reconciled with each other. The diversity of such theories stood in blatant contradiction to the claim to apodictic certainty raised by metaphysical foundations.

It seemed obvious to blame this unfortunate situation on the fact that the claim to a rational justification was not sufficiently fulfilled, and to aspire to a more methodologically controlled approach as a way out of the situation. This was the goal of rationalism, and in particular of its outstanding representative René Descartes.

Descartes' attempt to determine the relationship between matter and space strictly, without resorting to empirical experiences, led him to a radical solution. He assumed "that the nature of matter […] consists not in its being something which is hard or heavy or coloured, or which affects the senses in any way, but simply in its being something which is extended in length, breadth and depth."[22] Descartes attempted to explain that there was no difference at all between matter and space. Through this the foundations of natural science were to be traced back entirely to mathematical considerations, which at the time still appeared to be indisputably independent from experience.

[18] Galileo offers as an extreme example "the boundless rarefaction of a small amount of gunpowder, when it is resolved into a vast bulk of fire" (Galilei 1974, 64).
[19] Galilei 1974, 64.
[20] Galilei 1974, 33.
[21] He writes: "In this way there would be no contradiction in expanding, for instance, a little globe of gold into a very great space without introducing quantifiable void spaces – provided, however, that gold is assumed to be composed of infinitely many indivisibles" (Galilei 1974, 33–34).
[22] Descartes *Principles of Philosophy*, II, 4; Descartes 1998, 224.

Descartes' identification of space and matter had a number of drastic consequences for all of the problems connected with the relation between space and matter. Thus, for instance, the question as to the existence of empty spaces became senseless, since Descartes' space was, by definition, filled with matter.[23] Nor could there be any indivisible atoms for Descartes. Like space, Descartes' matter was infinitely divisible.[24] Further, he had to conceive of material bodies as purely kinematic phenomena, as matter with a homogeneous state of motion.[25] Consequently, he thus formulated the following definition:[26]

> By 'one body' or 'one piece of matter' I mean whatever is transferred at a given time, even though this may in fact consist of many parts which have different motions relative to each other.

Finally, the impenetrability of matter became a tautology for Descartes, for if space and matter are identical, then it is a logical contradiction to assume that two different bodies could be located in the same place, that is, penetrate each other.

Descartes meticulously justified his metaphysical principles, proceeding from a theory of human cognition. Thus he emphasized that the matter-space structure he described follows strictly from the postulates of reason. Yet his rationalistic system was certainly not a deductive theory in the modern sense. In particular it is obvious that he, too, was able to make his identification of space and matter plausible only through conceptual models. So, for instance, in order to elucidate that motion was possible even in a space completely filled with matter, he compared the structure of matter with the pool of a fountain, in which fish move as freely as if they were in an empty space.[27] Just as the water moves in a circular motion around the fish, so that no empty space emerges in the place the fish just left, so he assumed "that no motion ever takes place which is not circular."[28]

In a similar manner Descartes explained why the possibility of condensing or rarefying matter did not contradict his theory, which eliminated the possibility of empty pores: he compared matter with a sponge soaked with liquid. According to this idea, a body can, depending on the conditions, absorb a greater or smaller amount of a finer kind of matter and thus increase or reduce its volume.[29]

Here, too, we thus encounter a plausible conceptual model which is absolutized for the sphere of the microscopically small. While in ancient atomism the assumption of impenetrable and indivisible atoms moving in a void was based on the absolutized conception of

[23]"The impossibility of a vacuum, in the philosophical sense of that in which there is no substance whatsoever, is clear from the fact that there is no difference between the extension of a space, or internal place, and the extension of a body" (Descartes *Principles of Philosophy*, II, 16; Descartes 1998, 229–230).

[24]"We also know that it is impossible that there should exist atoms, that is, pieces of matter that are by their very nature indivisible [...]. For if there were any atoms, then no matter how small we imagined them to be, they would necessarily have to be extended; and hence we could in our thought divide each of them into two or more smaller parts, and hence recognize their divisibility. For anything we can divide in our thought must, for that very reason, be known to be divisible; so if we were to judge it to be indivisible, our judgement would conflict with our knowledge" (Descartes *Principles of Philosophy*, II, 20; Descartes 1998, 231).

[25]"All the variety in matter, all the diversity of its forms, depends on motion" (Descartes *Principles of Philosophy*, II, 23; Descartes 1998, 232).

[26]Descartes *Principles of Philosophy*, II, 25; Descartes 1998, 233.

[27]Descartes *The World*, Chapter 4; Descartes 1998, 86–87. Cf. Descartes *Principles of Philosophy*, II, 17; Descartes 1998, 230.

[28]Descartes *The World*, Chapter 4; Descartes 1998, 87.

[29]Descartes *Principles of Philosophy*, II, 6 and 7; Descartes 1998, 225–226.

macroscopic objects in space, for Descartes' infinitely divisible matter that completely fills space it is the relations in a liquid and the vortices of matter which generate the movement of objects within it.

The fact that Descartes borrowed from experience in this way did not escape his contemporaries' attention, such that his rationalistic system had an ambivalent effect. On the one hand, after Descartes it was hardly possible for metaphysics to continue to avail itself of speculation as naively as had been characteristic for the pioneers of the previous generation. Yet on the other hand, his very attempt at a consistent, rationalistic justification of the foundations of natural science gave rise to doubts about the program of metaphysics, because it seemed no longer possible to rule out that any metaphysical justification would sooner or later run into conflict with the empirical orientation of modern science.

6.6 Newton's hidden atomism and the problem of force

Isaac Newton's attitude toward Descartes' rationalism can be regarded as representative for this awakening, fundamental doubt about the program of a metaphysical justification of natural science.

Newton's unfinished and unpublished manuscript *De Gravitatione ...*, in which he "venture[d] to dispose of [Descartes'] fictions,"[30] and in particular of the latter's identification of matter and space, already conveys not only a criticism of Descartes' specific assumptions about the relation between matter and space, but also a fundamental criticism of the very idea of a metaphysical foundation for such assumptions.

Newton wanted his own assumptions, which he formulated in a series of definitions and propositions, to be understood as being "either definitions of certain words; or axioms and postulates denied by none."[31] Newton avoided atomistic formulations of his assumptions, although the fact that they at least partly originated in atomistic theories could hardly be denied.

For instance, Newton defined a body as "that which fills place," and added the note:[32]

> I said that a body fills place, that is, it so completely fills it that it wholly excludes other things of the same kind or other bodies, as if it were an impenetrable being.

Further down he formulates:[33]

> […] I suppose in these definitions that space is distinct from body […].

Nevertheless, in the manuscript, Newton avoided any commitment concerning the question as to whether empty spaces exist.

In addition to such assumptions, which correspond to those of ancient atomism, Newton formulated further definitions and propositions which clearly reflect the historical distance to ancient atomism. He defined force (*vis*) as "the causal principle of motion and rest," tendency (*conatus*) as "resisted force," *impetus* as impressed force, *inertia* as "force within a body, lest its state should be easily changed by an external exciting force," pressure as the

[30] Newton 1978, 123.
[31] Newton 1978, 122.
[32] Newton 1978, 122.
[33] Newton 1978, 123.

tendency "of contiguous parts to penetrate into each others' dimensions," and gravity as "a force in a body impelling it to descend."[34]

Newton's definition of pressure, according to which pressure is only a tendency of two parts to penetrate each other, "[f]or if they could penetrate, the pressure would cease,"[35] especially brings out the contrast with an absolutized concept of impenetrability. In contrast to ancient atomism, the experience of impenetrability, that is, the experience that two bodies cannot be moved to the same place at the same time, is here brought into relation with the magnitude of resistance that a macroscopic body offers to a second body being in contact with it, a magnitude that is measurable in experiments.

In his *Principia* Newton makes clear that he regards his own determinations of matter, recorded by definitions and axioms, as the results of empirical experiences:[36]

> That all bodies are impenetrable we gather not by reason but by our senses. We find those bodies that we handle to be impenetrable, and hence we conclude that impenetrability is a property of all bodies universally. That all bodies are movable and persevere in motion or in rest by means of certain forces (which we call forces of inertia) we infer from finding these properties in the bodies that we have seen. The extension, hardness, impenetrability, mobility, and force of inertia of the whole arise from the extension, hardness, impenetrability, mobility, and force of inertia of each of the parts; and thus we conclude that any one of the least parts of all bodies is extended, hard, impenetrable, movable and endowed with a force of inertia. And this is the foundation of all natural philosophy.

For the existence of an absolute space independent of matter, Newton gave empirical proof with what is known as his 'bucket experiment'. According to his view the water propelled upward by centrifugal force in a rotating bucket shows that one can distinguish between the rotating bucket and a bucket at rest; as such it proves the existence of absolute space in reference to which the rotation takes place. Likewise he invoked arguments for the existence of empty spaces, for instance the negligible resistance the celestial bodies experience in their movements,[37] as well as the possibility of rarefying matter to an unlimited extent.[38]

Newton attempted to avoid basic assumptions of atomism (such as the assumption of the absolute impenetrability of matter), because by their very nature they could not be confirmed directly in experimental experience. However, this attempt proved difficult to sustain. There is a great variety of evidence that Newton often tacitly accepted the validity of such assumptions. Newton was an atomist, but the basic assumptions of atomism were introduced into his work rather incidentally.

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[34]Newton 1978, 148. In Newton 1978, *conatus* is translated as 'endeavour', not as 'tendency'.

[35]Newton 1978, 148.

[36]Newton *Principia*, Book III, "Rules for the study of natural philosophy," Rule 3; translation taken from Newton 1999, 795–796.

[37]Thus, in his *Opticks* Newton writes: "[…] to make way for the regular and lasting Motions of the Planets and the Comets, it's necessary to empty the Heavens of all Matter, except perhaps some very thin Vapours, Steams, or Effluvia, arising from the Atmospheres of the Earth, Planets, and Comets, and from such an exceedingly rare Æthereal Medium as we described above" (Newton 1979, 368).

[38]Thus, Newton writes: "But if the quantity of matter in a given space could be diminished by any rarefaction, why should it not be capable of being diminished indefinitely?" (Newton *Principia*, Book III, Proposition 6, Corollary 3; Newton 1999, 810)

So, for instance, in his *Opticks* Newton explained chemical reactions as rearrangements of particles, which were caused by attractive forces between them. But such an explanation presupposes atomistic matter and impenetrability, such that Newton here was led to note:[39]

> All Bodies seem to be composed of hard Particles [...]. And therefore Hardness may be reckon'd the Property of all uncompounded Matter. At least, this seems to be as evident as the universal Impenetrability of Matter.

Tacit assumptions were associated also, and above all, with Newton's concept of force. Through Newton's *Principia* the concept of force became a central concept of the theory of nature, which, in the form of attractive forces like gravitation, was intimately related to novel basic assumptions about the properties of matter. Changes in the motion of material bodies are caused by forces, and the material bodies for their part affect other bodies through forces.

The concept of the impenetrability of matter could not remain unaffected by such a substantial expansion of the concept of matter. In the atomistic tradition the changes in the motions of two colliding bodies were attributed to the impenetrability of matter. According to Newton's axioms every change in motion is necessarily caused by forces. This then raises the question as to the nature of the forces that act upon the colliding bodies as a consequence of the absolute impenetrability of matter.

Newton never supplied his contemporaries with an answer to such questions. He never presented the foundations of his theory of matter in a form that would have been comparable with Descartes' *Principles of Philosophy*.

6.7 Euler's solution

There was certainly no shortage of attempts to reconcile Newton's findings with Descartes' rationalistic foundation of science. Leonhard Euler's foundations of mechanics constituted an important attempt of this kind. On the high technical level of eighteenth-century analytical methods, Euler created a mathematically formulated Cartesian theory of matter and its motion in space, which was based on three basic metaphysical determinations of matter held to be apodictic: its *extension*, its *inertia*, and its *impenetrability*.[40] The occurrence of forces, in contrast, Euler conceived to be a phenomenon derived from impenetrability:[41]

> The impenetrability of bodies, therefore, contains the real origin of the forces, which are continually changing their [i.e., the bodies'] state in this world; and this is the true solution of the great mystery, which has perplexed philosophers so grievously.

When two bodies collide, according to Euler, their impenetrability causes the exertion of a force that changes their motions. Euler solved the problem Newton left unresolved, that the magnitude of this force cannot be determined from impenetrability alone, by introducing

[39] Newton 1979, 389.
[40] Euler *Letters to a German Princess*, Letter no. 121 (21 April 1761); Euler 1823, Vol. 2, 17, in this edition it is letter no. 6 of Vol. 2.
[41] Euler *Letters to a German Princess*, Letter no. 77 (18 November 1760); Euler 1823, Vol. 1, 233.

a supplementary principle: The force that occurs is the smallest possible force that is able to prevent the penetration of matter.[42]

Connecting Cartesian principles with Newtonian dynamics inevitably led to an elaboration and change in the Newtonian concept of force. As Euler pointed out, because Newton's inertia was not a force in the sense of the Newtonian axioms, the designation as a force was misleading.[43] A further result was the differentiation between absolute forces and forces of constraint, with which matter resists forces acting upon it. In this manner Euler's mechanics became the point of departure for later attempts to formulate a generalized principle of inertia and, using this principle, develop a forceless, consistently kinematic mechanics; the mechanics of Heinrich Hertz serves as an example from the nineteenth century.

6.8 Kant's anti-atomistic solution

Immanuel Kant's concept of matter represents a break in so far that with it the distinction of matter from space through its impenetrability was for the first time principally challenged. For Kant this distinction was inacceptable:[44]

> Absolute impenetrability is in fact nothing more nor less than an occult quality. For one asks what the cause is for the inability of matters to penetrate one other in their motion, and one receives the answer: because they are impenetrable.

What did Kant have to set against this? From the difficulty of reconciling the assumption of the impenetrability of matter with the implications of Newtonian dynamics, Kant drew conclusions that were diametrically opposed to those of Euler, bringing him in extreme opposition to the mechanistic foundation of natural science.[45] Instead of presupposing the impenetrability of matter and asking about the forces that result from this impenetrability in the case of the collision of material bodies, as Euler did, he assumed conversely that the bodies appear to us to be impenetrable only because a force counteracts the penetration. In Kant's view, what actually distinguishes matter from space are "original forces," which constitute its essence, namely an attractive force, which we perceive as gravity, and a repulsive force, which appears to us as its impenetrability. He writes:[46]

[42] Euler *Letters to a German Princess*, Letter no. 78 (22 November 1760); Euler 1823, Vol. 1, 233–236; see also: Euler *Theoria motus corporum solidorum sev rigidorum*, §134; Euler 1765, 50, Euler 1948, 65; for a German translation, see Euler 1853, 59.

[43] Euler *Mechanica*, Praefatio; Euler 1912, 10, for a German translation, see Euler 1848, 5.

[44] Kant *Metaphysical Foundations of Natural Science*, Chapter 2, Explication 4, Remark 2; Kant 2004, 39.

[45] "The mechanical mode of explanation [...] has, under the name of *atomism* or the *corpuscular philosophy*, always retained its authority and influence on the principles of natural science, with few changes from Democritus of old, up to Descartes, and even to our time. What is essential therein is the presupposition of the *absolute impenetrability* of the primitive matter, the *absolute homogeneity* of this material, leaving only differences in the shape, and the *absolute insurmountability* of the cohesion of matter in these fundamental particles themselves" (Kant *Metaphysical Foundations of Natural Science*, Chapter 2, "General Note to Dynamics"; Kant 2004, 72).

[46] Kant *Critique of Pure Reason*, A265, B321; translation taken from Kant 1996, 327. The impenetrability of matter is traced back to the interaction of forces not only in Kant's writings during his critical period (after 1781), but also in a relatively early tract, the *Monadologia physica* of 1756, yet with a decisive difference: Here matter exists as an entity independent of forces. It consists of the smallest, indivisible components, which Kant called *monads* in keeping with Leibniz's terminology, and which, as for Leibniz, are granted the capability to exert forces. Each monad is surrounded by a *sphaera activitatis*, a sphere of activity through which it keeps other monads away (Satz VI; Kant 1907, 351), and the repulsive force with which this occurs is perceived empirically as impenetrability (Satz

> We are acquainted with substance in space only through forces that are active in space: either in propelling other substances toward the substance (attraction), or in preventing them from penetrating into the substance (repulsion and impenetrability); we are not acquainted with other properties making up the concept of the substance that appears in space and that we call matter.

As a consequence of this reduction of the concept of matter to the concept of force, for Kant it followed that matter, like space, was infinitely divisible[47] and "originally elastic."[48] It retreats from attacking forces until the growing repulsive forces are able to resist the attacking forces.[49]

According to this theory, solid bodies are constituted by the coaction of the attractive and repulsive forces. The boundary between two bodies is that surface on which the repulsive forces of the respective matters balance each other.[50] In the case of a single body in empty space, a comparable boundary of the border results from the fact that the attractive force of matter, according to Newton's law of gravitation, decreases in inverse proportion to the square of the distance, while the repulsive force, according to Kant's assumption, decreases in inverse proportion to the cube of the distance. This means that the repulsive force predominates in the vicinity, but decreases more rapidly with distance than the attractive force. Thus, for every isolated body in space there must be a closed surface in which the repulsive and the attractive forces of the body balance each other. According to Kant, this surface is the boundary of the body; for the penetration of this surface is resisted by the repulsive force, while outside this surface the repulsion cannot be perceived, because it is smaller than the attraction.[51]

Through Kant's redefinition of the concept of matter, not only impenetrability as the characteristic property of matter was traced back to the concept of force, but so was the concept of matter itself. Matter in its conventional form was declared to be a metaphysical relic that does not stand up to the *Critique of Pure Reason*. In opposition to the concept

VIII; Kant 1907, 353). Here Kant apparently tried to establish a connection with Newton's theory by physically reinterpreting Leibniz's monads.

[47] "Matter is *divisible to infinity*, and, in fact, into parts such that each is matter in turn" (Kant *Metaphysical Foundations of Natural Science*, Chapter 2, proposition 4; Kant 2004, 40).

[48] Kant *Metaphysical Foundations of Natural Science*, Chapter 2, proposition 2; Note 1; Kant 2004, 36–37.

[49] "Matter can be compressed to infinity, but can never be penetrated by a matter, no matter how great the compressing force of the latter may be" (Kant *Metaphysical Foundations of Natural Science*, Chapter 2, proposition 3; Kant 2004, 37). Kant writes in summary: "The *action* of the universal attraction immediately exerted by each matter on all matters, and at all distances, is called *gravitation*; the tendency to move in the direction of greater gravitation is *weight*. The action of the general repulsive force of the parts of every given matter is called its *original elasticity*. Hence this property and weight constitute the sole universal characteristics of matter, which are comprehensible a priori, the former internally, and the latter in external relations. For the possibility of matter itself rests on these two properties" (Kant *Metaphysical Foundations of Natural Science*, Chapter 2, proposition 8, Note 2; Kant 2004, 56–57).

[50] "Physical contact is the interaction of repulsive forces at the common boundary of two matters" (Kant *Metaphysical Foundations of Natural Science*, Chapter 2, Explication 6, Remark; Kant 2004, 50).

[51] "Thus the original attraction of matter would act in inverse ratio to the squares of the distance at all distances, the original repulsion in inverse ratio to the cubes of the infinitely small distances, and, through such an action and reaction of the two fundamental forces, matter filling its space to a determinate degree would be possible. For since repulsion increases with the approach of the parts to a greater extent than attraction, the limit of approach, beyond which no greater is possible by the given attraction, is thereby determined, and so is that degree of compression which constitutes the measure of the intensive filling of space" (Kant *Metaphysical Foundations of Natural Science*, Chapter 2, Proposition 8, Remark 1; Kant 2004, 59).

of matter from atomism or corpuscular theory, in which matter represents the presupposed carrier or causer of forces, Kant's concept of matter consequently eliminated any substrate that was assumed prior to the original forces of attraction and repulsion. Matter then consists of nothing more than forces operating in space.

If we allow ourselves an anachronistic comparison, Kant's concept of matter resembles the later concept of the field; and his theoretical aspiration is reminiscent of Einstein's unachieved goal of a unified field theory, in which the source terms of the field equations disappear, i.e., the fields are no longer generated from matter independent of the fields.[52]

Yet Kant's goal was not to erect a new theory of physics. Rather, with his *Critique of Pure Reason* he wanted to counter metaphysical speculation with the methodically controlled, precise determination of the most general theoretical statements of science, statements founded in reason and not in experience. He hoped, through the self-reflection of the reasonable subject (*vernünftiges Subjekt*), to extract those criteria that would permit him to distinguish between the metaphysical illusion and the apodictic truth of general judgments (*Allgemeinurteile*) independent of experience.

Kant criticized the metaphysical argumentations of his day not because he did not share the goal of grounding the theoretical framework of empirical knowledge on the principles of reason, but rather because they did not live up to this program. Kant's question was not the question of the empiricists: 'How can metaphysics be avoided in science?' but rather: 'How is metaphysics possible as a science?'

Kant formulated this program in his *Critique of Pure Reason*, and elaborated it for the field of natural science in the *Metaphysical Foundations of Natural Science*. In particular, he concluded that the following ideas do not originate from experience:

- space and time and, thereby, the laws of kinematics;
- the general properties of matter, which is constituted by attraction and repulsion, originally elastic and infinitely divisible;
- the law of conservation of mass (in Kant called "quantity of matter");
- the first and third Newtonian axioms, i.e. the law of inertia and the principle of the equivalence of acting and reacting forces (but not the proportionality of force and acceleration); the consequence for Kant was
- a law of collision (albeit an erroneous one); and
- the non-existence of Newton's absolute space.

6.9 The impact of Kant's criticism

The above listing alone makes clear that Kant's metaphysical foundation of natural science, too, would not bear the test of time. Nearly all of his supposedly apodictic assumptions, obtained from a critique of reason, have subsequently turned out to be of only limited validity or even wrong.

In fact, Kant's concept of matter, too, like those of his predecessors, was based on conceptual models. What distinguishes Kant's foundation, however, is the fact that his conceptual models for the conceptualization of the microscopically small hardly incorporated any categories of everyday experience unreflectively, but were based almost exclusively on

[52] Einstein 1992, 71 ff. see also Einstein's letter to Felix Pirani, 2 February 1954 (Einstein Archives 17-447.00).

categories of the most advanced areas of contemporary natural science. Compared with the particles of matter and the ethereal fluids of corpuscular theoreticians, Kant's centers of force thus appear as an extraordinarily modern theoretical construct. Indeed, in the post-Kantian theories of matter such theoretically constructed conceptual models were further developed into powerful methodological instruments of modern natural science.

In contrast, the program of a metaphysical foundation for natural science was directed toward other objectives and doomed to failure. To pursue this agenda, the protagonists of modern science, as was here demonstrated for the case of the concept of matter, brought forth an enormous variety of metaphysical systems, whose simultaneous incompatibility and claim to universality represent the clearest indication for the failure of metaphysics.

Kant subjected the presuppositions of metaphysical systems to a systematic critique. He did not see that his own assumptions about judgments independent of experience were just as problematic as those against which his critique of reason was directed. In the *Metaphysical Foundations of Natural Science* he leveled the accusation at Newton that he[53]

> by no means dared to prove this law a priori, and therefore appealed rather to *experience*.

History has shown that Newton's caution in this point was all too justified.

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[53] Kant *Metaphysical Foundations of Natural Science*, Chapter 3, Proposition 4, Remark 1; Kant 2004, 88.

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