THE SOCIAL AND ECONOMIC ROOTS OF THE SCIENTIFIC REVOLUTION

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THE SOCIAL AND ECONOMIC ROOTS OF THE SCIENTIFIC REVOLUTION

Texts by Boris Hessen and Henryk Grossmann

edited by

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Preface

The texts of Boris Hessen and Henryk Grossmann assembled in this volume are important contributions to the historiography of the Scientific Revolution and to the methodology of the historiography of science. They are of course also historical documents, not only testifying to Marxist discourse of the time but also illustrating typical European fates in the first half of the twentieth century. Hessen was born a Jewish subject of the Russian Czar in the Ukraine, participated in the October Revolution and was executed in the Soviet Union at the beginning of the purges. Grossmann was born a Jewish subject of the Austro-Hungarian Kaiser in Poland and served as an Austrian officer in the First World War; afterwards he was forced to return to Poland and then because of his revolutionary political activities to emigrate to Germany; with the rise to power of the Nazis he had to flee to France and then America while his family, which remained in Europe, perished in Nazi concentration camps.

Our own acquaintance with the work of these two authors is also indebted to historical context (under incomparably more fortunate circumstances): the revival of Marxist scholarship in Europe in the wake of the student movement and the professionalization of history of science on the Continent. We hope that under the again very different conditions of the early twenty-first century these texts will contribute to the further development of a philosophically informed socio-historical approach to the study of science.

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Rick Kuhn gave us hundreds of pages of photocopies of Grossmann's manuscripts. Jürgen Scheele lent us his personal photocopy of Grossmann's MS which became the basis of our edition. Rose-Luise Winkler gave us early drafts of her German translation of Hessen's paper and has constantly shared her knowledge of Russian-language sources along with a wealth of other information about Hessen. Tatiana Karachentsev assisted us at different stages with Russian sources.

Back in 1987 Gabriella Shalit translated Grossmann's essay of 1935 for *Science in Context*, Phillipa Shimrat has now newly translated Hessen's paper of 1931 for this volume. We thank them both for cordial cooperation.

For help in tracking down sources and for access to manuscript materials we would like to thank the the librarians of the Max Planck Institute for the History of Science (Berlin), the Archives for Scientific Philosophy at the University of Constance, the Archives of the Polish Academy of Sciences (NAUK), Warsaw, and the Universitäts- und Stadtarchiv, Frankfurt am Main.

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Classical Marxist Historiography of Science: The Hessen-Grossmann-Thesis

Gideon Freudenthal and Peter McLaughlin

Boris Hessen's "The Social and Economic Roots of Newton's 'Principia'" (1931) and Henryk Grossmann's "The Social Foundation of Mechanistic Philosophy and Manufacture" (1935) are the classic programmatic examples of Marxist historiography of science. The two works were produced completely independent of one another, but both scholars were working within the same intellectual tradition with the same conceptual tools on the same topic.[1] The positions they develop overlap and complement one another. They have enough in common that the enlarged thesis that emerges from their work may be called the "Hessen-Grossmann-Thesis."[2]

While many Marxists have contributed to the historiography of science, Hessen's and Grossmann's work displays a specifically Marxist approach: they conceptualize science as one kind of labor within the system of social production. Their discussions of the social context and the cognitive content of science are modeled on Marx's analysis of the labor process. Thus, whatever the merits of other Marxists' contributions to the history of science, from Friedrich Engels' *Dialectics of Nature* to various contemporary forms of social constructivism, Hessen's and Grossmann's work is integrally linked to their specific intellectual tradition and could only have been made by a scholar from that tradition.

Hessen's paper immediately caused a stir and was quickly applauded by enthusiastic supporters and held up as a negative paradigm of externalism by detractors who warned against "crude Marxist" explanations of science. Grossmann's paper, in many ways similar in thrust, has remained almost unknown to historians of science, published as it was in German in French exile. Around 1946, now in American exile, Grossmann completed a monographic study with the title (later changed) *Descartes' New Ideal of Science. Universal Science vs. Science of an Elite*. This manuscript is published here for the first time, along with some shorter materials

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[1] Grossmann (spelled Grossman in Poland) became aware of Hessen's paper somewhat later and mentions Hessen in in a 1938 book review of Georg Sarton's *The History of Science and the New Humanism* (1931) and G. N. Clark's *Science and Social Welfare in the Age of Newton* (1937).

[2] Freudenthal, 1984/1988.

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on related subjects also in English translation. Together with the two classic papers, these provide an introduction to the basic approach of Marxist historiography of science.

Boris Hessen's paper was originally published in an English translation in London at the Congress at which it was to have been read. Two Russian versions (with only minor differences) appeared later in the Soviet Union.[3] The original English version was done in a great hurry by the staff of the Soviet Embassy on the eve of the Congress[4] and thus, unsurprisingly, left something to be desired. Many of the mistakes are obvious to anyone with a serious knowledge of the subject matter, but the text has placed unreasonable demands on a general readership. Hessen's essay is here published in a new translation.

The purpose of the following introduction is to facilitate a fresh appraisal of the position argued for by Hessen and Grossmann. This reappraisal is necessary because what has come to be known to historians and philosophers of science as the "Hessen-Thesis" has little to do with the theses that Hessen and Grossmann actually propound, but is rather a projection based on misunderstandings and preconceptions of what a Marxist thesis ought to be. The reader will be able to ascertain what a Marxist analysis of science is by reading the texts themselves and can then judge it on its merits not its reputation.

Hessen's "The Social and Economic Roots of Newton's *Principia*" formulates three theses, the first of which was independently proposed by Grossmann and the second of which Grossmann also later assented to.[5]

- The first thesis concerns the relation of economic and technological developments in the early modern period and the relation of these two to the emergence of modern science: Theoretical mechanics developed in the study of machine technology.

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[3] Hessen 1933, 1934.

[4] See J. G. Crowther, *Fifty Years With Science*, London (Barrie & Jankins) 1970, pp. 76–88, for the details.

[5] As Grossmann's original title "Universal Science versus Science of an Elite" suggests, he refers to two respects in which modern science is universal in contrast to previous forms of knowledge. In the first place the universality of its method, modeled on mathematics, makes it applicable to all subject matter and thus undermines the guild-like knowledge of specialists. Secondly, there is no secret knowledge in science, no skills that are handed down only in personal contact between master and apprentice. Universal method is accessible to all and thus gives everyone the key to participation in the scientific endeavor. The universal and democratic aspects of science are hence intertwined. At the end of his *Universal Science* Grossman quotes Descartes' address to the reader in his *Discours de la Méthode* in which he explains why he wrote the essay in French rather than in Latin: "The last sentences of the *Discours* constitute an open challenge to the specialists. Descartes addresses his work not to them but to the broad intelligent public, to every man with good sense, and is convinced that these men are better able to appraise his work than the specialists" (127–128). However, Grossmann supports these ideas mainly by references to declarations of intention by Descartes and others, whereas his own research, documented in this work, concentrates on the relation between technological practice and concept formation in science. Grossmann seems to have realized this discrepancy himself since he changed the name of the work in later manuscript versions to "Descartes and the Social Origins of the Mechanistic Concept of the World."

- The second thesis draws the converse conclusion: In those areas where seventeenth-century scientists could not draw on an existing technology (heat engines, electric motors and generators) the corresponding disciplines of physics (thermodynamics, electrodynamics) did not develop.
- The third thesis concerns the ideological constraints placed on science in England at the time of the "class compromise" or "Glorious Revolution" (1688): Because of this compromise Newton drew back from fully endorsing the mechanization of the world picture and adapted his concept of matter so as to be able to introduce God into the material world.

1 Economics, Technology and Science

The titles of the essays by Hessen and Grossmann published in this volume refer to different topics. Hessen's paper of 1931 addresses a specific book: Newton's *Principia*.[6] Grossmann's essay of 1935 refers to the "Mechanistic Philosophy" in general and his essay of 1946 names a different person in its title: Descartes. Nonetheless all three papers have one shared topic and cover much the same historical ground. Hessen's and Grossmann's topic is the Scientific Revolution that culminated in the seventeenth century, which in their view had been prepared by developments since the thirteenth or fourteenth century. The great scientists and philosophers, Galileo, Descartes, Huygens and Newton (and many others, of course), represent its peak of achievement. Grossmann therefore stresses that the Scientific Revolution was *completed* in the period of Galileo and Newton but that it had begun much earlier. Both Hessen and Grossmann view mechanics and not cosmology (e.g. the Copernican Revolution) to be the core of the scientific revolution. This is in itself significant inasmuch as they thus focus not on the conflict between a geocentric and a heliocentric worldview, but rather on the mechanization of the world picture, in which natural phenomena are explained, like machines, by mechanical laws of motion only.

1.1 Economic Needs and Technical Problems

The point of departure of Hessen's argument is the correlation between problems in economics, technology and science in the time up to Newton. Certain economic demands or needs are correlated with certain technical problems or developments, which in turn are correlated with fields of scientific study:

> Consequently, we shall first investigate the historical demands presented by the emergence and development of merchant capital. Then we shall consider what technical problems were posed by the newly developing economy and what complex of physical problems and knowledge, essential for solving these technical problems, they generated (p. 5).

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[6] The Russian title is: "The Socio-Economic Roots of Newton's Mechanics."

Economics is said to *present* demands, which *pose* technical problems, which *generate* scientific problems. Each of these steps must be explained. Considering three major social areas: industry or general production, transportation and war, Hessen presents lists of examples of correlated technological and scientific endeavors.

Let us examine some examples: Hessen notes that the further development of trade ("merchant capital") depended on improved transport. The favorite, that is, most efficient means of transport for goods was naturally by water. Economic development, he says, "set transport the following technical problems":

1. to increase the tonnage capacity of vessels and their speed,
2. to improve the floating qualities of ships,
3. to develop means for better navigation,
4. to improve the construction of canals and docks.

Now the technical problems 1, 2 and 4 based on this economic need correspond to the scientific fields of study, hydrostatics and hydrodynamics; technical problem 3, improving navigation (the determination of longitude), involved the development of chronometers and was hence also correlated with studies in mechanics.[7]

Or take industry: mining in particular involved raising the ore from down in the mines. This technical task was tackled with the aid of various complex machines compounded out of the simple machines – which are studied by statics. Ventilating and draining the mines was accomplished by air and water pumps, which are studied by aerostatics and hydrostatics. The use of artillery in war involved determining the trajectory of projectiles and can hence be related to some of the most celebrated work by Galileo and Newton.

Such correlations do not yet present a thesis on the emergence of modern science. The correlations have to be explicated and explained. There would seem to be two alternatives to explain the correlation. The first takes technology to be the *goal* of science and perhaps the *motive* for pursuing science in the first place. The second takes technology to be the *precondition* of science and conjectures nothing about motives:

A. Technology was developed *in order to* facilitate economic development, and science studied the particular problems that it studied *in order to* improve technology.
B. Technology was developed *in order to* facilitate economic development, and science developed *by means of* the study of the technology that was being applied or developed.

Both share the first, but not the second, proposition. These two positions (A and B) are significantly different in their conceptualizations of the relation of science

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[7] Hessen is not asserting that our distinct disciplines existed at the time but rather that these disciplines are what arose out of the study of these problems.

to technology. Is technology the goal of seventeenth-century science or rather its subject matter? The first expresses the position usually attributed to Marxist historiography of science – and emphatically rejected by Koyré, Hall and other traditional internalists in the history of science. The second alternative (B) is a formulation of the Hessen-Grossmann-Thesis. Let us briefly explicate both views. The first view (A) involves four steps of argument which develop a more or less strong form of economic determinism:

1. a (causal) connection is established between economic interests and technical projects;
2. it is shown that the technical projects involve technological problems;
3. it is shown that these technological problems correspond to fields of study in science;
4. it is asserted that scientists were *motivated* by economic (or technical) interests to solve the technological problems and therefore also to study the corresponding fields of science.

Proposition (1) seems problematic since it seems to imply that economic or, more broadly conceived, social interests or needs determine technological solutions to the problems of society. Yet it is fairly easy to see that many needs go unfulfilled and many demands call forth no corresponding supply. This is a point made by R.K. Merton with reference to explaining technological invention on the basis of economic needs and scientific discovery on the basis of technological needs. While technological inventions often responded to needs,

> it is equally true (wrote Merton) that a multitude of human ‘needs’ have gone unsatisfied throughout the ages. Moreover, countries which are generally considered to be the most needy of inventions, such as Amazonia and India, have, in fact, relatively little invention. In the technical domain, needs, far from being exceptional, are so general that they explain little. Each invention *de facto* satisfies a need or is an attempt to achieve such satisfaction.[8]

Merton here also points to a significant asymmetry in discussions of needs and their fulfillment: Basic needs tend to be more general, the means to their fulfillment more particular. Some needs (e.g. nourishment) are common to all societies, but each fulfills these needs in a different way. And needs can go unfulfilled, while means (inventions) always satisfy some need or other, or we go back to the drawing board. Thus before a perceived need can generate an action calculated to satisfy it, it must be made more specific with regard to the means available. A key element of Marx’s analysis of the labor process was that the *will* of the producer must be subordinated to a concrete *purpose* before anything gets done.[9] And this concrete purpose

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[8] Merton 1938, 157. Moreover, “where an observer from a culture which has an established tradition of attempts to improve material welfare and to control nature may often detect a need in another society, that need *may not exist* for the members of the society under observation, precisely because of a difference in values and aims.”

[9] *Capital*, Chapter 7, Section 1, The Labour-Process or the Production of Use-Values. “At the end of the labour-process, we get a result that at its commencement already existed ideally in the representation of the workman. He not only effects a change of form in the natural material on

is itself formulated with the help of the available means. In fact, means developed for one purpose (and need) may also allow other needs to become purposes or make previously unrealistic purposes realistic.

The simple straightforward view, that needs determine their fulfillment abstracts from the question of whether the means to satisfy the needs are available, but it also makes a second mistake, in that it takes the needs or interests to be just given, thus overlooking the extent to which the needs themselves are concretized with respect to the means of their possible satisfaction. While some needs may be formulated fairly generally, say transportation, any particular need must be formulated somewhat more precisely before any action can be taken to satisfy it: The means available progressively concretize the wish to an ever more concrete purpose (e.g., first to improve transport, improve shipping, improve the hydrodynamic properties of the ships, improve the shape of the bow).

The need or desire to expand commerce, ascertained by Hessen, is not of itself a need to improve shipping. Merchants could have turned to transport by land or adapted to merely local commerce; they could have switched to handling smaller merchandize, developed new kinds of commodities, or substituted local products for imported ones. The decision to improve shipping for the purpose of expanding commerce, which constitutes the concretized form of the need for the appropriate technology, presupposes the consideration of possible concrete projects characterized by the means for their realization. Furthermore, the fact that an economic need is conceptualized as a *technological* problem is not self-evident. Again Merton reflected on this problem:

> Economic and military needs, then, may be satisfied by other than technologic means. But given the routine of fulfilling these wants by technologic invention, a pattern which was becoming established in the seventeenth century; given the prerequisite accumulation of technical and scientific knowledge which provides a basic fund from which to derive *means of meeting the felt need*; and it may be said that, in a limited sense, necessity is the (foster) mother of invention.[10]

Grossmann deepens these reflections by considering the difference between the economies of Roman antiquity and the late medieval European town. Only in the latter did a need to expand production involve the need to devise a machine or technical device to do something. Grossmann suggests that technology was marginal as long as production could depend on a social perpetuum mobile, slavery. With the rise of the medieval town the situation changed: urban labor costs money and therefore the search for an artificial perpetuum mobile begins: Although experience shows that a perpetuum mobile in the strict sense cannot be found (Grossmann, 1935b, 67–68; 1946, 106), machines can indeed replace human labor. (Grossmann, 1946, 69) Whereas a shortage of labor in Roman antiquity would have been formulated

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which he works, but he also realizes in that material a purpose, that he knows, that determines as a law the way he acts, and to which he must subordinate his will." MEW 23, 193 (our translation).

[10] Merton 1938, 158. Cf. also pp.155–59. See also "Science and Economy of seventeenth Century England," pp. 6–7. The peculiar notion that needs cause their own fulfillment is so strongly embedded in everyday culture that even Merton slips into it at one point (1938, 148).

as a need for more slaves, in early modern Europe such a shortage was formulated as a need for more and better machines. This latter need of course presupposes that machines are already used in production, so that the experience made with them can be used in conceptualizing such a need. However, whereas machines were at first used primarily to do things that human labor power could not do or to apply force beyond the capacity of a human to provide (stamping mills; iron-production) (Grossmann, 1946, 89–90), they later also replaced regular human labor. Descartes' announcement in the *Discourse on the Method* that science and technology would diminish human labor could look back on a long tradition (Grossmann 1946, 78).

The thesis may be generalized: the means available are decisive in conceptualizing a need. Now this notion seems to turn the widespread understanding of Marxist "externalism" upside down. Means are not developed in order to satisfy existing needs (or interests), but the concrete conception of needs, purposes which may explain action, depends on the means available, that are then used to satisfy them. To a certain extent then, the means available can determine the possibility or at least the reasonableness of certain needs, interests and desires. Thus when Hessen speaks of the "needs of the rising bourgeoisie" or the "demands of the economy and technology" these are of course mediated by the available means to their fulfillment.

These qualifications do not mean that economic developments may not be used as a factor in the explanation of technical developments. On the contrary, they indicate that to explain an action, we should refer to a concrete *purpose,* not to an abstract wish or need. The purpose of an action presupposes a need and plausible means for its satisfaction. The synthesis of both forms a purpose. Similarly, a wish (e.g., to improve transport, or even the more concrete wish to build better boats) does not account for the course of action taken. This depends on the circumstances involved, especially on the available means for action.

1.2 Technical Problems and Science

Now that we have a basic idea of the relation of economic needs to technological problems that both of the above-mentioned interpretations of Hessen's first thesis seemed to share, we can take up the second step, the relation of science to technology, in which the two versions openly differ. The first version (A) maintained that science studied the particular problems that it studied *in order to* improve technology. This was formulated as the proposition:

4. that scientists were *motivated* by economic (or technical) interests to solve the technological problems and therefore also to study the corresponding fields of science.

If we abstract from the special case of explicitly biographical studies in which the individual scientist is the focus of attention, it is questionable whether the personal motives of scientists are at all relevant to the historical understanding of science.

Just as economic needs must be further specified with regard to the technical possibilities of their realization before they can be acted upon, so too must scientific goals be further specified in terms of the means available (methods, techniques, instruments). Thus what it means to pursue this or that concrete scientific problem depends on the means available in the arsenal of science of the time. Given a certain state of knowledge with its material and symbolic means, with its instruments, experimental systems and theories, its open questions and common methods, scientists on the whole will engage in similar activities irrespective of their personal motivations: they will look for solutions to the open questions, search for salient points and innovative ideas etc., whether their motivation is ambition, greed or the quest for truth. A motivation to engage in science is required, but the particular nature of the motives would seem to be of no great importance since it does not determine the particular course of action taken. This specific activity is determined by the state of science, the methods and means available. Neither Hessen nor Grossmann addressed the motivations of scientists since they did not consider them to be relevant to understanding the development of science.

From the considerations above, some important conclusions follow. First, personal motivations of scientists are irrelevant to the project of explaining scientific development on a social scale. Scientific developments depend on the material and symbolic means which determine both the concrete problems and their possible solutions, not on the personal motivations of the scientists. This of course does not exclude the possibility that on a social scale social and economic interests may directly and indirectly exert pressure on institutions and individuals to favor among possible projects those which are socially desired or of immediate economic utility. The history of science in the seventeenth century is full of such examples,[11] as is contemporary funding policy. Second, the actual relation of science and technology in the seventeenth century can be reformulated in the light of the considerations above. Two questions should be considered: First whether the technology of the seventeenth century belonged to the "means" of scientific inquiry and thus made some scientific endeavors possible (and excluded others); and second, whether it was not precisely the specific difference between science and technology that made science possible. This difference is the fact stressed by critics of the "Hessen-Thesis", namely that scientific research was not subordinated to the service of practical ends. In the framework of the Hessen-Grossmann thesis this can be formulated in the following way: Scientists could explore the possibilities contained in the scientific means at hand (whatever their provenience) and had no need to subordinate their inquiry to finding solutions to pressing social or economic problems. The suggestion that science was dependent on a distance from practical pressures that made room for activities that can be viewed as the disinterested quest for truth, does not presuppose that science is an endeavor *sui generis*, but rather attempts to achieve

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[11] For a short discussion see Robert K. Merton, "Science and the Economy of Seventeenth Century England."

a deeper understanding of science through its specific difference to technological invention. We shall discuss these two questions in the next section.

The view formulated in version (A), often referred to as Baconian Utilitarianism, explicates a widespread misunderstanding of the first Hessen thesis as a claim about the personal motives of individual scientists: that they pursued science to advance technology, production and economic gain. Most critics therefore have believed they must deny the argument concerning the motivation of the scientists involved and that this denial refutes Hessen. This position is just as flawed as the position it criticizes. It presupposes that what is at issue is the *real* motivation of the scientists involved: economic interest, a disinterested quest for truth, or the glorification of God through the study of his works. Critics of Hessen, arguing that the motives of scientists were not in fact utilitarian, have implicitly accepted the presupposition that if the motives had been utilitarian, this would bear significantly on the explanation of the Scientific Revolution. And they seem to presuppose that the determination of technology by economic needs, which they do not deny, is similarly to be explained by the motives of the economic actors involved. In technology as opposed to science, economic motives are not considered implausible or disreputable. But it is not just Marxists of the 1930s who are accused of questioning the motives of seventeenth century scientists; Francis Bacon in particular was accused of this by Alexandre Koyré, who distinguished a "propagandist" of science like Bacon or a craftsman interested in building something from real scientists like Galileo and Descartes "who seldom built or made anything more than a theory."[12] Koyré argued further that the wish to create technology cannot have been the motive of scientists to pursue science because key areas of technology were already in place before and independent of science; thus technology cannot have determined science in any way at all.[13]

However, even Bacon's famous dictum that "Nature to be commanded must be obeyed"[14] need not be read as saying merely that if we want to dominate nature better, we should learn more about its laws. It can just as well be read to assert that in those places where we have in fact succeeded in commanding nature (technology), we must have been obeying nature's laws. Thus, studying successful technology is the key to scientific knowledge of nature. Hessen on more than one occasion appeals to this alternative form of Baconianism, for instance, when he reports that Galileo began his *Discorsi* "with an address to the Venetians praising the activity of the arsenal at Venice and pointing out that the work of that arsenal provided *a wealth of material for scientific study*."[15] It is the critic's assumption that the only conceivable relation of technology to science is that of a motive in the mind of a scientist that blinds them to the possibility that practice with technology might influence ideas about nature. Although, as we shall see below, the disciplinary reception of Hessen

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[12] Koyré 1943 ("Galileo and Plato") 400–401; A.R. Hall (1952, 163) joins the critique of Bacon saying (without citing evidence or explaining what a seventeenth-century scientist is) "Few of the public apologists for science were themselves scientists."

[13] Koyré [1948] 1961, 308.

[14] *Novum Organum* I, §2.

[15] Hessen 165 (our italics); see also the quotation from Galileo in Hessen's Appendix (no. 1).

is particularly influenced by postwar anti-communism, there is in much of it also a deeper-lying basic inability to consider any materialistic explanation at all.

2 The First Thesis: Technology Opens Horizons for Science

The first thesis, advanced by both Hessen and Grossmann, asserted that science developed by means of the study of existing technology. This means first that the concept of *nature* changed. As the feudal mode of production was gradually replaced by the capitalist mode of production, as the towns became increasingly more important and the country increasingly less, as artisan production and manufacture increased in importance vis à vis agriculture, the concept of nature changed as well. Traditional agricultural labor was supportive of natural processes. Nature turned seed into grain on its own but could do this better when supported by human labor. But machines are not products of nature but man made. Once machines, which were traditionally seen as ways to outwit nature, began to be conceived as natural agents, two consequences ensued. Machines were understood to obey natural laws not to abrogate them. Second, the world was conceived as an ideal machine and natural phenomena as its operations. This has been called the "mechanization of the world picture." Thus both the concepts of *nature* and of *machine* or *mechanics* change. Nature is no longer conceived as an organism governed by teleology, and mechanics no longer as a collection of contrivances to outmaneuver nature. Rather nature and mechanics coincide. A consequence of this unification for the theory of motion is first that the Aristotelian distinction between "natural" and "forced" motion loses its basis and its sense: natural motion is conceived as if produced by a machine, the laws governing the exertion of power of a machine are the laws of nature. To study nature hence means to study man-made machines, not nature untouched. The *machina mundi* is now conceived as an automatic machine (a clock) which functions according to the laws of nature.[16] The science of mechanics, which investigates the laws governing the functioning of machines thus became the science par excellence, a universal science exploring the function of all machines, natural and artificial alike.

The increase of the economic importance of technology and its associated activities was followed by an improved social position of those involved. As remarked by Hessen and Grossmann in passing and discussed by Merton in detail, economic, technical and scientific occupations improved their social positions in the seventeenth century, such that the social elite, which earlier went into other fields of occupation, now went in significantly larger numbers into science.[17] Of course, the establishment of scientific societies, the financial support of scientific endeavors etc. should also be considered the effects of this economic and technical development.

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[16] See on this point Freudenthal 1986, 59–66 and McLaughlin 1994. More specifically, the machine studied in scientific mechanics until and including Newton and the generation following him were "transmission machines." The importance of this issue will be discussed below.

[17] Merton 1938, Chapters II–III.

Second, the rise in social prestige of technology (due to its increased economic significance) made the progressive merging of two traditions possible which, for social reasons, were earlier segregated from one another: the mechanical and the liberal arts, the knowledge of craftsmen and the knowledge of the learned.[18] On the one hand, the new group of sophisticated craftsmen (architects, instrument makers etc.), so-called *virtuosi*, were better educated and occupied higher social positions than ordinary craftsmen. On the other hand, the improved social locus of the mechanical arts made it possible for the learned now to engage in their study. The learned profited from the knowledge of the craftsmen (either directly or from the new technical literature) and also gained a field for their own observation and experimentation (Grossmann 1935a, 187–88). It seems reasonable to conjecture that the new experimental-mathematical science was born out of the fusion of the experimental tradition of the craftsmen with the systematic and mathematical tradition of the learned.[19]

The main thesis common to Hessen and Grossmann builds on these considerations. It says that the science of mechanics (so-called "theoretical" mechanics) developed in the study of contemporary technology, of "practical" mechanics. This thesis is diametrically opposed to the wide-spread view, which is also regularly attributed to Hessen, that practical mechanics was guided by the science of mechanics and that theoretical mechanics was pursued in order to apply it in practice. More or less the opposite is the case. Both Hessen and Grossmann maintained that the primary occupation of scientific mechanics in the early modern period was to study already *existing* technology and understand how it functions, not to improve it – however much the one or other scientist personally may in fact have wanted to do just this.

Third, since scientific mechanics developed through the study of practical mechanics and its tradition, it owed much of its theoretical structure and conceptual character to practical mechanics. The Hessen-Grossmann-Thesis addresses the determination of the cognitive content of science, which was traditionally shunned by sociologists of science (Merton included). The thesis attempts to explore the horizon of cognitive possibilities on the basis of the material and symbolic means employed. One corollary concerning early modern science is Grossmann's contention that the origin of essential conceptual presuppositions of mechanics is to be found in practical mechanics. This will be discussed in the next section.

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[18] At one point Grossmann (1946, 70) dates the first beginning of modern science with this merger, the subsumption of mechanics under geometry as part of the liberal arts in the *De divisione* of Gundisalvus (12th century).

[19] This thesis is usually associated with the work of Edgar Zilsel, "The Sociological Roots of Science," *American Journal of Sociology*, *47* (1942), 245–279, but it is also present in Hessen's and Grossmann's papers.

2.1 Grossmann on the "Real Abstraction" in Transmission Machines

Grossmann scrutinized the genesis of the general, abstract and quantitative concept of motion. Simple observation does not offer us pure motion. In everyday life and in technical practice, motion always occurs together with other phenomena: friction, heat, force etc.; and it is always a qualitatively specific motion: straight, curved, upwards, downwards etc. The traditional Aristotelian conceptualization of motion as "natural" or "forced" shows that a process of abstraction can go in different ways from the modern direction. Grossmann's studies of the genesis of the abstract concept of motion, in which all these concrete forms of motion are left out of consideration, took up the question of what recommended or favored one kind of abstraction over another: What made it possible to replace the quite intuitive and traditionally sanctioned concepts of motion with entirely different concepts, which had earlier seemed abstruse?

From the perspective of everyday human practice, scientific concepts of motion are extremely counter-intuitive. In our experience bodies do not move in uniform inertial motion. This does not preclude the possibility of our forming laws for counter-factual cases, but it may very well render them implausible and raise philosophical doubts as to whether they are merely *entia rationis* or have a *fundamentum in re* and an application in experience. Grossmann's thesis, which will be elaborated in more detail below, claims that the new concept of motion was acquired in the study of technical, mechanical practice.

Grossmann's thesis may be read as a cognitive-psychological or as a philosophical thesis. The psychological thesis attempts to explain the plausibility or credibility of a particular conceptualization in spite of everyday experience and in spite of traditional learning by pointing out a sphere in which such concepts could seem plausible. The philosophical thesis attempts to explain why such concepts can be taken to have reference and where the referents are to be found. Together, Grossmann's considerations may be applied to explain why the rise of technology also gave rise to a new conceptualization of natural phenomena, why these new concepts did indeed find reference in the real world by way of technology, and finally also why this conceptualization of nature seemed plausible within certain strata of society.

Grossmann refers in his paper to some ideas of Marx concerning the introduction of machines into production.[20] Marx pointed out that the introduction of engines into production presupposed that the function of a motive power had been separated practically from the various specific operations performed on the object worked upon. Once an automated tool, a "machine" in Marx's terminology, is introduced instead of a tool guided by the skilled hand of the craftsman, human labor is reduced to the function of a motive force of this machine. Only then can it be replaced by an animal or some other natural power (wind, water, gravity).

Consider a grain mill. It may be seen to consist of three parts: the engine or "motor mechanism" on the one end and the grinding device ("tool or working machine") on the other. These two are connected by a transmission mechanism

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[20] *Capital* I, MEW 23: 401–407 CW 35, 384–89.

("transmitting machine"), which transmits and sometimes transforms the motion produced by the engine to the grinding device. Sometimes the transmission machine transforms circular motion into rectilinear or vice versa. One power source can be replaced by another which fulfils the same function. It may be a water wheel or a windmill, a human or an animal. Similarly, the same engine may be attached to different devices: It can drive a mill, a lathe, or some other device. These instruments, which directly form the working piece, may be automatic or guided by hand. Marx called "working machine" such an automatic instrument whether moved by an engine or a human worker (in contradistinction to an artisan working with a tool). He insisted that the crucial step in industrialization was the invention of such machines, that is, automatic instruments. He argued that the introduction of motor mechanisms presupposes that the labor process has been emancipated from its artisan form, in which the functions of the instrument and of the engine are inseparably intertwined. Only when the movement of the hand, which both drives and guides a tool, has been broken up into the function of an automatic instrument (which needs no guidance) and a power source producing a standard motion, can human power be replaced by an engine. Only when what once was skilled labor is performed by a machine, can an engine also replace human physical power. Once different kinds of labor are performed by different machines driven by the same kind of motion, these different machines could be attached to the same kind of engine. Only then could such engines be introduced into the process of production, and indeed they were so introduced.

Grossmann takes this idea a step further into the cognitive realm and asks what the origin of an abstract concept of *motion* or *work* produced by *force* was.[21] Evidently it makes no sense to form a general concept of motion if instances of this motion cannot be transformed into various specific motions known from experience. "Motion in general" does not exist aside from its different individual forms. In light of the discussion of Marx above, the question can be put this way: Under what circumstances does the concept of *motion* or *work* (a homogeneous form of motion against resistance) make sense? Evidently, such a concept does not make sense when we study the work of a craftsman: here the aspects of a purposeful modification of the object by a special form of motion (dependent on the nature of the material and the purpose of the craftsman and on his instruments), cannot be separated from the application of physical force that is moving the instrument. Motive force, skill, purpose and instrument form a unity. It does, however, make sense to *distinguish* between these aspects as soon as they are in fact *separated* or when it seems possible to separate them. This separation of motive force from the purposeful guidance of the hand in the process of labor is the same that was conceived by Marx as a presupposition for the introduction of motor mechanisms into the labor process. Grossmann conceived it to be also the starting point for conceptualizing "motion"

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[21] Marx, too, extended this idea to the cognitive realm, but did not develop it further. He suggested that difficulties in the use of transmission machines connecting the motive force and the mechanical tool led to the study of friction and the flywheel. "In this way, during the manufacturing period, were developed the first scientific and technical elements of modern mechanical industry" (*Capital* Chapter 15, CW 35, 80; MEW 23: 397).

in an abstract and quantitative fashion. When (1) various different kinds of labor have been separated from the motive power applied in performing them, then motive power could also be conceptualized separately, and when (2) various kinds of the motion (circular, straight) produced by various motive powers (e.g. water, animal, man) could also be transformed one into the other by appropriate transmission machines, then it also made sense to form concepts of abstract motion and force, referring exclusively to the faculty of performing labor as such, i.e., moving heavy bodies against resistance, especially raising heavy bodies in the gravitational field of the Earth.

> It is evident that man, in all these technological upheavals, acquired new, important material for observing and contemplating the actions of forces. In the machines, in the turning of the water wheels of a mill or of an iron mine, in the movement of the arms of a bellows, in the lifting of the stamps of an iron works, we see the simplest mechanical operations; those simple quantitative relations between the homogeneous power of water-driven machines and their output, viz. those relations from which modern mechanics derived its basic concepts. Leonardo da Vinci's mechanical conceptions and views are only the result and reflection of the experiences and the machine technology of his time, when one new technical invention follows the other or the previous inventions are improved and rationalized. (Grossmann, 1935a: 193–194)[22]

Grossmann's use of "reflection" in this context should not be taken to mean that scientific mechanics derived its concept of homogeneous motion simply from observation of working machines. In the footnote to this passage, Grossmann refers to technical literature, which emerged in the middle of the fifteenth century; and Hessen points to a new kind of expert: scientific engineers who had been working in the mines since the 15th century (Hessen, 161, 169).

Hence the process of concept formation in scientific mechanics refers back to practical mechanics in two ways: *first,* by the direct study of machines, and *second,* by appropriating the knowledge contained in practical mechanics, whether through personal contact with practitioners, or through the technical literature. Indeed, it is easy to show that some concepts of practical mechanics were adopted by scientists and were still used even after scientific knowledge has superseded them (e.g. *force* for *momentum*).[23]

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[22] Hessen reasons in a similar way: "Since the time of the Crusades industry had developed enormously and had a mass of new achievements to its credit (metallurgy, mining, the war industry, dyeing), which supplied not only fresh material for observation but also new means of experimentation and enabled the construction of new instruments" (169).

Hessen adds an important consideration. The concept of "abstract work" abstracts not only from its specific form of motion in space, but also from the transformation of work from one form (mechanical kinetic and potential energy) into others (e.g. thermal and electric energy).This even more demands an explanation as to the direction abstraction took.

[23] In the Preface to the *Principia* Newton also extensively referred to practical mechanics in order to demonstrate the wide range of applicability of the third law of motion (see Scholium to the laws of motion; Newton 1999, 424–430); there, too, we find a typical expression adopted from the technical literature can be found: "The effectiveness and usefulness of all machines or devices consists wholly in our being able to increase the force by decreasing the velocity and vice versa." (Newton 1999, 429) Compare this with John Wallis' pre-Newtonian concept of force, which recurs

2.2 The Differing "Purposes" of Science and Technology

The question of the origin of concepts of classical mechanics can be also differently formulated: We can ask why the concepts used in scientific mechanics did in fact have reference and why they were *believed* to apply to the world in general and to technology in particular. Why did the laws of statics and dynamics, as developed by using mathematical representations apply to inclined planes, pulleys etc., or why did the laws of motion of bodies (later: "point masses") refer to real bodies and real machines? And why did no scientist in the seventeenth century doubt that statics and dynamics refer to the real world and have application to machines and projectiles in spite of empirical evidence that they did not? The discovery of the parabolic trajectory of projectiles, which is explicitly and recurrently heralded as the solution to an essential problem of ballistics, is far from an adequate description of the trajectory of a shell shot from a cannon. In fact, without some previous reason to believe that theories are about the real world, an experimental test with artillery would more likely refute than confirm such a theory. This question deserves some elaboration because the discrepancy between practical and theoretical mechanics was put forward in what is arguably the most serious criticism of Hessen, by A.R. Hall,[24] but it seems that his arguments prove the exact opposite of what he believes they prove.

The discussion above showed a very close connection between science and technology: technology was not only presented as the direct object of study of mechanics, but also as a determinant of its concepts in significant ways. What could and could not be conceived was discussed in reference to what could and could not be learned from contemporary technology. These considerations have to be followed by an examination of the specific differences between the points of view of science and technology. If indeed both technicians and scientists studied the same field, often the same machines, in what does their knowledge differ?[25]

This difference is the main concern of A.R. Hall's study *Ballistics in the Seventeenth Century*. Hall studied ballistics – one of the techniques to which Hessen

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to the five "common" machines: "And this is the foundation of all machines for facilitating motion. For in whatever ratio the weight is increased, the speed is diminished in the same ratio; whence it is that the product of the weight and the speed for any moving force is the same." (Wallis, letter to Oldenburg, November 15, 1668; *Oldenburg Correspondence*, 1966ff: V, 168)

[24] Hall 1952 (*Ballistics*). Hall in fact mentions Hessen only once in the book and doesn't include his name in the index or bibliography, but the text is a sustained argument against the utility thesis.

[25] Newton clearly saw that his subject matter was the same as that of practical mechanics. He just as clearly underestimated the difference between scientific and practical knowledge seeing it merely in the degree of precision: "Practical mechanics is the subject that comprises all the manual arts, from which the subject of mechanics as a whole has adopted its name. But since those who practice an art do not generally work with a high degree of exactness, the whole subject of mechanics is distinguished from geometry by the attribution of exactness to geometry and of anything less than exactness to mechanics. Yet the errors do not come from the art but from those who practice the art. Anyone who works with less exactness is a more imperfect mechanic, and if anyone could work with the greatness exactness, he would be the most perfect mechanics of all" (Newton 1999, 381).

referred (161–164) – but he generalized his conclusions to science and technology in general.[26]

A general formula for the curve of a projectile was found by Evangelista Torricelli (1608–1647), but it was not for the use of gunners. For these, Hall tells us, "Torricelli published tables of ranges and altitudes from which, the range at any one angle having been measured, the rest could be found by the rule of three."[27] By presenting both his theory and practical rules for guns side by side, Torricelli acknowledged the existing gap between theory and practice. Confronted with the fact that the trajectory of real projectiles was not a parabola, Torricelli claimed that his study *De Motu Projectorum* was purely theoretical.

According to Hall, in presenting his formula Torricelli demanded to be treated as a philosopher and a mathematician, not as someone talking about application in the real world: "the tables and instruments he had described were not for measuring the ranges of cannon balls, but certain geometric lines associated with geometric parabolas."[28] However, Hall admits that Torricelli explicitly spoke in his essay of guns shooting shells at walls of cities, that he printed tables giving measurements in paces, and that his readers might easily have supposed that "when he talked of guns he meant real guns."[29]

Hall distinguishes three different stages in the relation between gunnery and scientific ballistics since the Renaissance: With Leonardo practical and theoretical mechanics were not yet separated; they separated with the development of scientific mechanics (as in the work of Galileo and Torricelli); and they met again under different conditions after the work of Newton and Jean Bernoulli, through which science could much better explain and describe the real trajectory of projectiles.[30]

We can now suggest answers to the questions formulated above.

Idealizations and counter-factual assumptions are indispensable in science. Inertial motion, point masses, uniform acceleration in free fall and the parabolic trajectory of projectiles – all these blatantly contradict experience. Real canon balls are not point masses and do not move like them, they are not shot in a vacuum but in the resisting medium of the air. The inertial motion of the projectile cannot be observed nor can a parabolic trajectory. This difference between idealization and reality immediately implies that the results of science cannot be directly applied to experience. And the other way around: The purposes of

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[26] Hall 1952, 163.

[27] Hall 1952, 95.

[28] Hall 1952, 97.

[29] Hall 1952, 99.

[30] "By the third quarter of the century everyone in the van of the scientific movement admitted that the primary principles of dynamics laid down by Galileo were fundamental to all future work, but it was also apparent that in their simple form they were not true for the world of experience. . . . It was necessary to discover the complex mathematical rules which link the world of scientific abstraction to the world of nature, if it was to be proved that the one was indeed appropriate to the other . . ." (Hall 1952, 128).

science (in the sense discussed above) were not adopted from technology but rather formulated within science. Scientific knowledge developed only when it was not required to give immediate solutions to existing problems. It required on its part freedom to concretize its own problems and develop its impractical solutions in order to develop concepts that transcend immediate technical knowledge and necessities.

In Torricelli's time, the gap between gunnery and science was indeed sensible. This is another way of saying that specific scientific knowledge had already developed considerably and independently of practical technical knowledge.

And yet, there was no doubt in the mind of its practitioners that both kinds of knowledge, the technical and the scientific, were about the same empirical matters of fact. The Hessen-Grossman thesis explains why: because science studied – albeit in its specific way – real technology. This thesis was formulated and substantiated for one historical case by Hessen's critic, A.R. Hall. Only the terminology and the ideological prejudices are different:

> Philosophers from Galileo to Newton . . . used the problems of ballistics as a gymnasium in which to develop their powers for larger and more important researches (Hall, 1952, 158).

The gap between science and technology opened because science developed in a different direction from its starting point in practical knowledge (this was the foundation of its subsequent strength), it progressively closed as science advanced enough to explain and predict existing technology much better than the most experienced practitioners. The gradual rapprochement was achieved by a superposition of additional laws (motion in a resistant medium applied to the motion as determined by force, inertia and gravity) and by the improvement of technology that rendered its functioning more standardized.

The growing success demonstrated not only the success of the science of mechanics in solving this particular problem, but also that science's analytical procedure is adequate. This procedure rests on the presupposition that the innumerable observed phenomena consist of a limited and small number of basic law-governed processes independent of each other and their composition. On this assumption, the first task of science was to analyze the phenomenon in question into its constituents. In a second step the laws governing these single processes were to be determined, and finally the initial phenomenon had to be explained as resulting from a composition of the different processes. Newton's success in determining the trajectory of a projectile under the complex conditions on the surface of the Earth proved not only that his theory was adequate, but also that the analytical approach of science (the "analytic-synthetic method") was adequate. Thus were the initial idealizations and counter-factual assumptions justified in retrospect. But we should also note that scientists in this age were aware of the technical origin of their problems and therefore never doubted the reference of their concepts or the applicability of theoretical mechanics to practical mechanics. The Hessen-Grossman thesis that science developed in the study of contemporary technology does not mean that it served technology, but on the contrary, that it put technology in the service of its own enquiry – and it did not itself contribute to technology for decades, if not for centuries.[31] And nevertheless, there was never any doubt that scientific mechanics is *about* real machines and that *in principle* it will finally explain how they function better than the practitioners can.

2.3 Grossmann on the Mechanization of Mathematics

Grossmann's ideas about the development of mathematics and of universal method as found in Descartes are expressed in the original subtitle of his monograph, *Universal Science vs. Science of an Elite. Descartes New Ideal of Science* (renamed after 1946 as *Descartes and the Social Origins of the Mechanistic Concept of the World*). The "New Ideal of Science" refers on the one hand to a science that becomes active, replacing the contemplative ideal of science in antiquity and promising together with technology to dominate nature in the service of mankind. On the other hand the "new ideal" refers to a universal science, a universal method, appropriate for investigation in all areas of inquiry. The original title of the book expresses a complimentary concern: the new science is not the science of an elite because the means developed and employed in it do not require any specialized knowledge, being powerful enough that even non-specialists could achieve significant results with them. On these questions, Grossmann pursues his ideas concerning the cognitive import of technology for contemporary science in general. The introduction of machines makes the virtuoso superfluous; specialized, highly trained craftsmen are not required any more to ensure the quality of the product. Similarly, the mechanization of mathematics makes mathematics a universal method and hence makes science in general accessible to all.

The mechanization of mathematics refers to three different factors: (1) the use of mechanical devices in mathematics (slide rules, logarithms etc.); (2) the use

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[31] Hall believed that the gap between technology and science refuted Hessen: Science did not in fact contribute much to technology in the seventeenth century, and this proves, Hall believed, that the improvement of technology cannot have been the motivation for scientists to engage in research (Hall 1952, 163–64).

This argument is mistaken in two regards. First, it misunderstands the Hessen-Thesis and construes it as referring to the motivations of individual scientists. Second, it presupposes that because an expectation was not fulfilled, it cannot have been a motivation.

Hall's ideological commitments are obvious. He believes that sociological history of science as such reduces great scientific discoveries to "no more than the response of a quick mind to the most pressing need of the moment" (162) wrenched from science "by the strong hand of economic necessity" (165). In contrast, Newton's work on the trajectory of projectiles in resisting media in the second book of the *Principia* does not mean that he "was *guilty*... of allowing himself to be dominated by the technological problems of his own day" (Hall 1952, 129, our italics) but rather that he solved an ancient philosophical problem. The philosopher studies science "in order to satisfy his intellectual curiosity" (p. 4). In short: scientists had "higher" motives than economic gain. This motivation is evident in many writings on the topic. See again Hall 1963, 15: The social studies of science has created says Hall "a certain revulsion from the treatment of scientists as puppets."

of propositions of mechanics in mathematics (as in determining a tangent by the inertial component of the curved trajectory of a body); and (3) the "mechanical" performance of a mathematical algorithm without reflection, just as a machine can be operated by a worker who does not understand its structure. This latter characteristic of machines and algorithms alike bears on Grossmann's view that modern science is not the science of an elite. A machine can guarantee invariably high quality that is independent of the virtuosity of the workman. Grossmann emphasized the analogous democratic aspect of this development in science (1946, 13), namely that science becomes accessible to all, not the secret of a few virtuosi (1946, 121–2). He believed that this was the reason why Descartes did not conceal his method from the masses, but rather propagated it, even including women in the intellectual endeavor (1946, 125–126). Grossmann enthusiastically celebrated Descartes as someone who a century and a half before the French Revolution proclaimed the fundamental equality of humans in respect to reason (1946, 126) and saw in his decision to write in the vernacular instead of scholarly Latin, another manifestation of this democratic stance (1946, 128).[32]

In our context it is important to emphasize the similarity of Grossmann's conception of labor to his concept of scientific work and the decisive role he ascribes to the means employed. As is well known, Marxism ascribes the means of production a decisive role in social life, but Grossmann focuses on the claim that a worker does not himself have to possess the knowledge embodied in the means he uses. The qualification of the worker in mechanical production may vary inversely as the quality of the means. With the universal language of ideas conceived by Descartes, a peasant might do better than a contemporary philosopher (1946, 19, 22).

The idea of the universality of the means refers to both sides of the labor process: to the subject and to the object. On the side of the subject, it means that anyone can operate them; on the side of the object, it means that they are applicable to every object. The reason for this is that science examines the simple *relations* and *proportions* between things, not the multifarious *natures* of the things themselves (1946, 25–27). Before the universal method can be applied, the various objects must be first reduced to common dimensions, analogous to spatial dimensions, which are common to all material objects and are studied by geometry (1946, 26–27, 30–34).

Now, this comparison of Cartesian universal method to machines is not an arbitrary analogy suggested by Grossmann. In fact, Descartes himself praises his geometry with the same words with which he praises his machines for grinding lenses. The universal method should be an algorithm that can be operated mechanically, without mathematical thought. An external mechanism should likewise be able to perform these operations. Thus Descartes' project loses its eccentric flair and appears as a step in a long development which worked on the mechanization of mathematics by means of mechanical calculation devices such as sliding rules

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[32] Grossmann also believed that Descartes may also assume contemporary significance as he "foresaw the great intellectual crisis of today," that is, specialization because of which nobody can understand "social and intellectual life as a whole" (1946, 21).

and logarithms and finally led to Descartes' attempt to automate the intellectual processes themselves (1946, 49–52).

We discussed above Grossman's idea that the abstract and mathematical concept of motion resulted from the study of machines. We concentrated on the transformation of one form of motion into another which enabled the formation of the concept of motion as such, abstract motion. We can now enrich the picture and address the mathematical character of the new concept of motion, resulting from the application of new mathematical methods to abstract motion, and vice versa, the formation of new mathematical concepts resulting from the study of new forms of motion in machines. Not only did mathematics study motion and use mechanical devices, but mathematical teachings were also conceptualized in mechanical terms. The conceptualization of the infinitesimal calculus in terms of motion ("fluxions") and the analysis of motion by means of the infinitesimal calculus is an obvious example. It can be shown at least for some cases that the conceptualization of the infinitesimal in mathematics and of the mathematical concept of motion in mechanics were developed in one and the same argument and were dependent on the same experience with mechanical devices.[33]

3 The Second Hessen-Thesis: The Limited Horizon of Science

Whereas Grossmann concentrated on the positive contribution of practical mechanics to science in the form of prerequisites and fundamental concepts, Hessen also pointed to the limits to theoretical mechanics drawn by practical mechanics. Hessen's second thesis is the converse of the first: if theoretical mechanics was made possible by mechanical technology, then other fields of physics, that did not figure prominently in the 17th century may not have developed because the requisite technology had also not yet been developed. Specifically, Hessen maintains that the primitive state of steam-engine technology did not permit a science of heat and its relations to mechanical forms of energy.[34] Thus, for instance, the conservation of energy could only take the form of the conservation of *mechanical* energy. Other forms of energy such as heat and electromagnetism as well as the transformation of one form into another could only be fully integrated into experimental science after their practical transformation in the steam engine and generator. This argument has been almost universally ignored. Hessen (rightly) gives some credit for the idea to Friedrich Engels, and this reference has been interpreted as another sign

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[33] Grossman did not present specific cases to substantiate his claim that the formation of the general and abstract conception of motion was dependent on the study of machines, nor did he analyze specific mathematical examples. For a case study that shows on the example of Giambattista Benedetti (1530–1590) the dependence of conceptualization of mathematics and the concept of motion on experience with treadles, which transform rectilinear into circular motion, see Freudenthal 2005.

[34] Hessen, 193–203.