Science as Labor

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The article takes the term "technoscience" literally and investigates a conception of science that takes it not only as practice, but as production in the sense of a material labor process. It will explore in particular the material connection between science and ordinary production. It will furthermore examine how the historical development of science as a social enterprise was shaped by its technoscientific character. In this context, in an excursus, the prevailing notion will be questioned that social relations must be conceived of as pure interactions. Finally, the article will go into the relationship between the epistemic dimension of science and its technoscientific character.

Introduction

The specific focus of this article is the technoscientific character of science itself. This character is obvious in the case of modern chemistry and all sciences that produce materially the objects that they investigate. But does it make sense to ascribe a technoscientific character to science in general? Can we perceive new features of its practice, its preconditions, its dynamics, and perhaps also its cognitive dimension, if we regard science in general in the light of our present experiences of the mutual penetration of science, technology, and ordinary production? These are the questions that motivate this article. In other words, I seize the discussion about "technoscientific productivity" as an occasion to discuss some aspects of a general conception of science that understands it not only as practice, but as production in the sense of a material labor process.

If we conceive of science as a material labor process, the question arises

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of how science relates to the ordinary social labor process. I will argue in this article that, after the Industrial Revolution, science itself became a sub-system of the social production process. But, rather than a starting point, this revolution was a turning point in the relationship between science and ordinary production which had shaped the former since the early modern period (Section 1). Another question concerns the significance of the technoscientific character of science for its development. I will argue that, because of its technoscientific character, the development of science shares striking features with that of the ordinary labor process (Section 2). Finally, I will discuss some issues in connection with the question of whether and how sciences' technoscientific character also shapes their epistemic dimension. The role of the material means of the scientific production process for cognition will constitute the center of this discussion (Section 3).

My attempt at an understanding of science as part of the social labor process, and as a specific kind of labor, presupposes conceptions of the large-scale structures and processes of modern societies that transgress the notions usually applied in social studies of science. Employing such large-scale categories only rarely and casually, scholars of science studies normally do not need to develop shared notions in this respect. This poses the dilemma that this article can neither rest on such notions in dealing with general categories such as the concept of the social labor process, nor develop itself those notions elaborately within the space given. To ensure at least an understanding about what the article is dealing with, keywords will be borrowed from a large-scale theory of social processes that is generally known and which, thus, can serve as a means of communication without obliging anybody to endorse it. The sociological theory used for this purpose is that of Karl Marx, certainly an expert with respect to the social labor process. An "Excursus on Marx, S- and N-terms, and Technological Determinism" will open the second section.[1]

1. Science as a Part of Economic Production

1.1 Science: A Factor of the Production Process

> "As the process of production becomes application of science, science, inversely, becomes a factor, a function so to speak, of the process of production" (Karl Marx[2])

1. For a more practically oriented attempt to capitalize on Marx' theory for an understanding of the relationship between science, technology, and the labor process, see (Levidow and Young 1981/1985). For a more recent interpretation of Marx's concept of sciences, see (Stachel 1994).

2. "Wie der Productionsproceß zur Anwendung der Wissenschaft, wird umgekehrt die

For a start, three points, though in no way unchallengeable ones, might be taken as points of departure for the discussion without submitting any further evidence:

- In the West, the social labor process has been essentially dependent on the results of the sciences since the nineteenth century. Beginning with single fields of mechanical engineering and extending to truly science-based branches like the electrical industries and the chemical industry at the turn of the twentieth century, the whole range of industrial production came to rest on science to different degrees over the course of this century. At the beginning of the twenty-first century, the same can be stated for agriculture, transportation, logistics, and communication.
- With regard to the material relations as distinguished from the economical ones, the present mutual dependency of scientific and economic production is principally of the same kind as that between different branches of the latter, for instance that between the manufacturing and the extractive industry. There is a continuous flow of materials, devices, know-how, ideas, and experts in both directions, which makes the dependency mutual. None of the branches can exist without the other.
- There is such a high degree of mutual dependency among the different scientific fields themselves that any attempt at dividing them into groups according to their practical relevance risks crediting particular fields with achievements of practical value that are actually results of synergetic patterns in many fields. Furthermore, singling out scientific fields according to the degree of their immediate relevance for the economic production process would fail to take into account the dynamics of the scientific production process. As recently evinced by microstructure physics' engenderment of modern nano-technology, fields that count as basic research with seemingly little practical value at one point in time can suddenly figure among the most promising ones with respect to the applicability of their results.

During the last century and a half in the developed countries, science has become as important a "factor of the production process," economically and strategically, as an economy's access to the world's raw materials.

Wissenschaft zu einem Factor, so zu sagen zu einer Function des Productionsprocesses." (MEGA) II/3.6 2060, my translation.

As a consequence, scientific production must be organized as such a crucial economic factor. The dependency of the economic production processes on science called for provisions to ensure that science actually produces and delivers what is needed for these processes. However, these provisions had to allow for the special nature of scientific production and, in particular, for the fact that discoveries and innovations can neither be anticipated nor planned beyond certain narrow limits. The uncertainties given by the openness of scientific production processes, and the immense costs (when the whole infrastructure necessary is taken into account) in turn set limits to the feasibility of running scientific research profitably under the direct control of private enterprises. Thus, a huge publicly-funded sector of science and technology proved indispensable both for economies based on private entrepreneurship and for socialistic economies. And because of the competition between private companies in the former, this sector must be organized in a way that prevents it from being openly subjected to particular private interests.

As a result of complex and ongoing interactions among all social parties involved—constitutional political boards, public service agencies, the military, associations of industrial and commercial companies, and traditional as well as newly-founded institutions for science and technology—intricate systems of formally independent, half-dependent, and directly controlled institutions and sites of research and scientific training have developed and are still developing. This type of complex system comprising scientific institutions of different organizational forms and status is characteristic of the modern industrial nations, notwithstanding peculiar features due to the particular historical development of each of these nations.[3] These institutional networks represent the social form of science as part and parcel of the social labor process.

The increasing dependency of economic production on science thus led to an evolving system of bonds, which tie science to the needs of the social labor process.[4] The consequences of these ties affect even the essentials of science, such as the free and rational exchange of thoughts. To give just one indication of this: According to the OECD,[5] more than half of the research in the West, in terms of money spent, is performed under direct

3. For the changes in the institutional design of connections and co-operation between political boards and research institutions in the US in the second half of the twentieth century, see, for instance, (Guston 2000, chaps. 1 and 6). For the structures of the European research policy at the turn of this century, see, for instance, (Trute 1994). See also part 3 of (Guzzetti 2000).

4. For the influence of the private research sector on the public one, see (Walsh 1998).

5. Compare the *Basic Science and Technology Statistics (BSTS) - 2001 edition* of the OECD.

control of the military[6] or private commercial companies and is therefore sealed off from free communication.[7] Furthermore, with regard to the capitalist structure of the social labor process in the developed countries, the non-profit character of a considerable part of science does not prevent it from becoming an element of this structure.[8]

However, the relationship between science and economic production cannot be considered simply a subjection of the former by the latter. Such a view would overlook an essential aspect of this relationship. Science has been intimately related to the sphere of economic production since its beginnings. That is, this relation predates the Industrial Revolution and the subsequent attempts to adapt science to the needs of this sphere. This relation consists in a material connection between science and economic production. Themselves comprising material production processes, natural sciences depend essentially on the economic production process, whatever the specific economic character of the latter. This dependency results not from subjection, but from the fact that the sphere of economic production is an essential prerequisite condition of science.

Natural science is essentially based on materials and equipment. The question of which materials are available and which equipment can be produced in a given society in a certain age is therefore of decisive importance for its development. This is well known not only to historians of science. Everybody recalls famous instances of the pivotal role that materials, devices, and apparatus played in the historical development of the sciences in the early modern period—the telescope for astronomy; the microscope for physiology; ovens, distillation apparatus and balances for chemistry; pendulum, prism, air-pump, and the Leyden jar for physics; the compass

6. For the increasing penetration of science and technology by the military during the last decades, see (Mendelsohn, Smith, and Weingart 1988).

7. For the secrecy policy of military research and development, see, for instance, (Reppy 1988, pp. 511ff.).

8. In this article, I cannot go into this aspect of the role science plays in the modern industrial societies of the West. However, a quotation from Marx's manuscript "Results of the Direct Production Process" (chap. 2, subsection "Mystification of Capital, etc.") may serve as an indication and reminder of what is left out here: "[. . .] the same naturally takes place with the forces of nature and science, the product of general historical development in its abstract quintessence—they confront the laborers as powers of capital. They are separated in fact from the skill and knowledge of the individual laborer—and although, in their origin, they too are the product of labor—wherever they enter into the labor process they appear as embodied as capital. [. . .] Science realized in the machine appears as capital in relation to the laborers. And in fact all these applications of science, natural forces and products of labor on a large scale, these applications founded on social labor, themselves appear only as means for the exploitation of labor [. . .]." See (MECW 34:455–460; (McLellan 1977, p. 430). See also part 2 of (MacKenzie and Wajcman 1999).

for geography; exotic animals and plants for zoology and botany. None of these things would have been available for the sciences without the economic development of early-modern Western societies. The devices and apparatuses owed their coming into being and refinement to the high standards achieved by the crafts in Western Europe at this age. And without international commercial relations and, in particular, without the colonial systems built up since the sixteenth century by the European nations, a systematic exploration of the Earth's surface would have been unimaginable. Chemists would have been confined to domestic raw materials and naturalists to domestic minerals, plants, and animals.

Furthermore, science required the sphere of economic production not only as a resource for building needed devices and providing interesting materials, but also as a source of inspiration. The wealth of experience accumulated and passed on in the sphere of production is certainly still underrated with respect to its significance for the development of the sciences. With his idea of an "experimental history," Francis Bacon pursued a plan to capitalize on just this wealth of knowledge systematically for the advancement of the sciences. In the sixteenth and seventeenth centuries, both the problems and the solutions of advanced technologies, such as pumping machinery in the mining industry, and artillery and fortification in the armaments industry, contributed essentially to pushing pre-classical mechanics to its limits[9] and beyond.[10] Chemistry is another example of the bearing that experiences and knowledge accumulated in the workshops had on the development of early modern sciences. In transgressing the Aristotelian-Paracelsian doctrines of element, principle, and mixt towards the modern conceptual system of chemical compound and reaction, eighteenth-century chemists at the Parisian *Jardin des Plants* rested, no less than on experiments, on their reflections of workshop experiences accumulated in sixteenth and seventeenth-century metallurgy and the iatrochemical production of medicines.[11]

9. See (Damerow et al. 1992).

10. See the classical studies by Henryk Grossmann: "Die gesellschaftlichen Grundlagen der mechanistischen Philosophie und die Manufaktur" (1935), English translation: (Grossmann 1987), and Edgar Zilsel: "The Social Roots of Science" (1942), new edition of Zilsel's writings (Zilsel 2000). For a standard assessment of the debate on the tradition of the workshops and the emergence of modern science, see (Cohen 1994, pp. 345ff.). In his review of the new edition of Zilsel's writings, N. Jardine discusses probable reasons for SSK scholars' usual neglect of these classic studies; see (Jardine 2003). See also the contribution by Gideon Freudenthal (this volume) who discusses the reception of Grossmann's essay and puts it in the context of the fate of Boris Hessen's famous essay "The Social and Economic Roots of Newton's *Principia*" from 1931.

11. See (Klein 1994a, 1994b).

It is a characteristic feature of the material relation between science and economic production before the Industrial Revolution that its benefits for the two sides were quite asymmetrical. Friedrich Engels, in notes that belong to the convolute of manuscripts published posthumously as *Dialektik der Natur,* pointed out the prevailing one-way character of this connection: "Up to now {it is} only bragged about what production owes to science; but science owes infinitely more to production" (MECW 25:465; my translation).[12] True, between 1500 and 1800, the contribution of the developing modern sciences to the advancement of the economic production was rather modest. In its main sectors, that is, agriculture, the handicrafts and manufactures, the economic production process remained largely untouched by science and proved able to do without it.[13] But in this period, there was also a steady increase of production sectors that made use of knowledge obtained scientifically. In mechanical arts such as construction, shipbuilding, machine engineering, ballistics and fortification, we encounter engineers, that is, new types of practitioners who regularly applied geometry, arithmetic, and mechanics when pursuing their tasks. An analogous development can be observed in chemical arts such as metallurgy, salt production, porcelain making, and the production of chemical medicines. Early modern chemists very much resembled engineers because of their characteristic combination of practical and theoretical expertise.[14] True, when focusing exclusively on high-level theories, one gets the impression that economic production could obtain little from the modern sciences. Genuine fruits of modern science, like the moon-tables that had become calculable on the basis of Newton's moon theory in the eighteenth century and truly represented a major contribution to navigation, were certainly exceptions. For a complete picture, however, one must take into account that science began to matter in an increasing number of advanced production sectors during this period, notwithstanding the fact that the sphere of economic production did, indeed, matter much more to science as a rich source of materials, instrumentation, inspiration, knowledge and experiences.

A close material connection between scientific and economic production thus existed long before the Industrial Revolution. What this revolution changed, however, was the until then prevailing one-way character of this relation which was replaced, step by step, by complex material relations of mutual dependency. Science's essential dependency on economic

12. "Bisher nur geprahlt, was die Produktion der Wissenschaft verdankt, aber die Wissenschaft verdankt der Produktion unendlich mehr" (MEW 20:457).

13. See part 1 of (Lefèvre 1978).

14. See the contribution by Ursula Klein (this volume).

production—from artisanship all the way up to high-tech processes—became even deeper with the development of modern industrial societies' infrastructure—from electrification to the Internet—in which science partakes. And the industrial production process became increasingly science-based. In the course of this development, science worked with and was shaped by materials and instruments provided by industries that were able to provide these goods thanks to science-based procedures and techniques. Thus, intertwined dependencies between technology and science arose from this development and constitute the background of today's technoscience.

1.2 Science: A Sub-System of the Economic Production Process

The term "technoscience" is used in a broader and in a more narrow sense. In the first case, the term denotes the intricate interlocking of economic and scientific production that developed starting in the nineteenth century and is now characteristic of the social production process in the West. Not only is each side a prerequisite condition of the other—the economic of the scientific, and the scientific of the economic—but, furthermore, each side is just as much a precondition as it is essentially based on the other: Modern high-tech production is not simply science-based, but rests on science which became possible only on the basis of these advanced production processes developed, that is, science which rests, for its part, on science-based production.[15] If one therefore regards this science-based high-tech production as a world of reifications of scientific conceptions and theories,[16] technoscience in this broader sense may appear as a self-referential process: today's science in action rests on high-tech production which is the reified science of yesterday, and engenders the conceptions and theories that will constitute tomorrow's technology when reified. But such a view of technoscience, which is quite reminiscent of the self-referentiality of Hegel's absolute mind, would not only reduce the economic production process to its scientific preconditions. It would also disregard the fact that the materials and equipment employed in economic production cannot simply be taken as embodiments of science. Even if such materials, machines, and technologic processes became employable and developable only because of scientifically gained insights, these means of production are more than reifications of scientific conceptions. As material things, they cannot be reduced to the concepts instrumental in the

15. This does not mean that science today is based exclusively on the most developed technologies. Co-operation with specialized craftsmen, for instance, is still indispensable even in high-tech laboratories.

16. For the problems involved with such a notion of reification, see the debate between Bloor and Rheinberger (this volume, next issue).

process in which they were produced. What is worse, such an idealistic view of technoscience would play down the essential tensions between scientific and ordinary material production also inherent in modern technoscientific production processes. Furthermore, it would deprive the very conception of technoscience of its heuristic value.

In a narrower sense, "technoscience" denotes sciences that are true hybrids of the ordinary and the scientific production process. These technosciences comprise not only technologic processes as each experimental science does. Rather, they literally produce the material objects that they study. Modern chemistry and physical fields like particle physics were our examples. It is probably superfluous to stress that producing is not creating. These hybrid sciences do not create their objects *ex nihilo* but produce them in exactly the same way as ordinary production processes, that is, by transforming given objects by means of given material agents.

The broader and the narrower understandings of "technoscience" focus on phenomena that are interdependent: these hybrid sciences were and are particularly instrumental for the development of twentieth-century high-tech production; and this production was and is a decisive precondition for the further development of such hybrids, as can be taken from the emergence of modern bio-technology. Bio-technology is a particularly suitable example to highlight a further feature of technoscientific sciences, namely the striking similarity between the processes performed in high-tech production and in the laboratories of such hybrid sciences. It is often difficult to tell the difference between these processes. When observing only the technical procedure of cell cloning, for instance, one cannot know whether it is being carried out in a science lab or as a step in the production chain of a high-tech agricultural enterprise. Indeed, without knowledge about the different contexts in which the procedure is actually performed in the two cases, it must be regarded as essentially the same operation. But it is obviously an artifact that we cannot distinguish the procedure performed at the one place from the other. Our inability to distinguish is a result of our abstraction from the contexts and, in particular, from the functions the operation has in each case.[17]

Not only single operations appear undistinguishable when their actual function is left out of consideration, but this abstraction seems to fuse the production processes of entire technosciences with those of high-tech industries. However, the processes, as similar as they may be in terms of their physical nature, serve different ends in the two cases. Even if run as part of a company, departments for research and development are clearly

17. This is an example of the well-known limits of the ethnologic approach in science studies.

distinguishable from those for production proper by their function. They neither produce commercial goods nor parts or components of goods that must be finished in other departments of the company. It is their aim and task to improve and enrich the knowledge preconditions of the economic production process.[18] And it is exactly this purpose which generally differentiates scientific production from economic production in the social production process as a whole. Whether or not its results are temporarily kept secret or restricted in their application by patents, scientific production contributes to and enlarges the common stock of knowledge that eventually can be applied by a society in the material production process. This common character of the stock of applicable knowledge to which science contributes was probably the reason why Marx called science "universal labor."[19] Contributing to this common stock is the specific function of science in the social labor process, which renders it a branch of this process that is distinguishable from other branches.

Science is not only a distinguishable part and factor of the advanced system of social labor processes, but must also be considered a sub-system thereof with a life of its own within certain limits. This relative autonomy becomes apparent indirectly through a rather paradoxical phenomenon that still demands better understanding. Though mainly funded, supported, institutionally entertained and controlled, stimulated, and driven by the expectation of its needed contributions to the stock of applicable knowledge,[20] science seems to a considerable extent successful in dodging all attempts to govern its development from the outside. Only by and large, and apparently by chance rather than by design, does the development of science fulfill the expectations and desires of the society. The concept of a "finalization of science," that is, the idea that science has achieved a developmental stage that allows it to adjust its development to the needs

18. A commercial company exclusively dedicated to the production of practically employable and patentable knowledge would be an interesting border-line case between economic and scientific production. Another such case would be a scientific laboratory that produces material objects not only to subject them to investigation but for sale as well, for instance, to other laboratories. Many of the laboratories of early modern times were of such a hybrid nature: they were at the same time workshops, as we will see below in the case of Galileo's Padua laboratory.

19. "Universal labor is all scientific labor, all discovery and all invention. This labor depends partly on the co-operation of the living, and partly on the utilization of the labors of those who have gone before" (MECW 37:105). By stressing that science is accomplished partly in co-operation among contemporaries and partly by building on results of the past, Marx highlights by implication as one dimension of its "universality" that it can be applied in completely different contexts at different times and places.

20. There are also social interests in science as a pure spiritual enterprise. In the context of a discussion on technoscience, however, the omission of these interests may be excusable.

of the society as a whole,[21] is almost forgotten and today must seem like some kind of bureaucratic dream.

It has not the appearance that the recalcitrance that the development of science brings to bear against attempts at steering it is due above all to the relative institutional autonomy granted to parts of the publicly funded science sector in order to protect them from direct subjugation to private interests. In a socialistic society, attempts at planning science would probably face exactly the same problems that concern the boards, committees, and councils of governments or public and private funding organizations in the West. These boards have to distribute huge and at the same time limited means to a spectrum of research fields with seemingly promising and desirable prospects, with no guarantee that those prospects will be realized. Specific aspects of research policy, such as strategies of evaluating the potencies of research fields or of setting priorities, are not at issue here.[22] Rather, it is the essential unpredictability of science, which, to all appearances, can be lessened but not eliminated, that is of interest in our context. Science cannot tell in advance which insights, least of all which useful ones, can be gained through a certain research device or setting, but must discover this. To let science find this out, society must take the risk of providing the equipment in question without any security. Having chosen among different seemingly promising research perspectives according to a society's priorities and to what it can afford, research policy can improve the chances of its choice only by granting to the sciences unrestricted use of the research means provided.[23] In the long run, the unpredictable outcome of this unrestricted use may be much more decisive for the development of the sciences than the trial-and-error strategies of which the bulk of science policy apparently consists.

2. Science as a Social Labor Process

So far we have discussed science in its relations to the sphere of economic production and, in particular, in its present state as an integral part of the social labor process. However, science is not only part of a socially performed process, but is itself a social production process. Science is essentially a collective enterprise whatever its particular social forms. Private science, taken *strictu sensu,* seems to be a contradiction in terms. The certainty of observations, the generality of experiences, the likelihood of con-

21. The most important contributions to the debate on the finalization of science are selected in (Schäfer 1983).

22. For a discussion of such strategies with respect to basic research, see, for instance, (Max-Planck-Gesellschaft 2002), particularly parts 4 and 6.

23. The third part of this article will come back to this unrestricted use of the material of research means as an essential characteristic of science.

jectures, the convincing power of conclusions, the truth of conceptions and theories—none of those items can be established privately. Scientific methods and insights are not only engendered as results of co-operation among contemporaries, but build on the efforts of preceding generations and must be transmitted to the subsequent ones. The forms of co-operation between scientists vary from mere reception and communication all the way to direct collaboration in the laboratory. They also vary with the forms of division of labor that have developed in the course of the history of science.

These observations are hardly controversial. Today, the social character of science is not only generally acknowledged, but considered a trivial fact. Arguments arise only when it comes to the consequences of this fact and, particularly, to the claim that science is shaped by social relations not only externally, but also in its essential structures, the epistemic ones included. In such disputes, almost all parties involved usually share an understanding of social relations that conceives of them as interactions, that is, pure human-human relations that engender a self-referential social world. The popular references to scientists' "negotiations" about observations, conjectures, conclusions, or concepts are indicative of this understanding of the social relations among scientists. However, is it really plausible to take the relations of tradesmen on the market place as standard for the social relations of scientists? If we applied this model exclusively, science could no longer be considered as labor. For, as I will argue, the social relations that humans enter in labor processes are those of co-operation according to the given division of labor. Because the forms of division of labor and co-operation are shaped not by human-human relations alone, they thus cannot be reduced to pure interaction.

We encounter here a principal aspect of the conception of science as labor. Upon first glance, it seems of little relevance whether one considers science to be a social practice or a labor. After further contemplation of this distinction, the latter view may even seem disadvantageous. Labor is a kind of practice. Thus, an understanding of science as a practice rather than labor seems to promise a less narrow perspective. But is this really true? As indicated, an understanding of science as social practice can easily entail a reduction of the social process of scientific production to pure interaction. It is the contention of this article that an understanding of science as labor allows a conceptualization of its social nature that avoids such a reduction. However, it may be not at all self-evident that the notion of labor stands for this irreducibility. An excursion to Marx might therefore be helpful to further clarify the assumption that the social nature of science can most adequately be understood when conceiving of science as labor.

2.1 Excursus on Marx, S- and N-terms, and Technological Determinism

In the *Preface* to his *Critique of Political Economy* from 1859, Karl Marx wrote:

> "The general conclusion at which I arrived and which, once reached, became the guiding principle of my studies can be summarized as follows. In the social production of their existence, men inevitably enter into definite relations, which are independent of their will, namely relations of production appropriate to a given stage in the development of their material forces of production. The totality of these relations of production constitutes the economic structure of society, the real foundation, on which arises a legal and political superstructure and to which correspond definite forms of social consciousness. The mode of production of material life conditions the general process of social, political and intellectual life. [. . .] At a certain stage of development, the material productive forces of society come into conflict with the existing relations of production [. . .]. Then begins an era of social revolution. [. . .] In studying such transformations it is always necessary to distinguish between the material transformation of the economic conditions of production, which can be determined with the precision of natural science, and the legal, political, religious, artistic or philosophic—in short, ideological forms in which men become conscious of this conflict and fight it out" (MECW 24:262f).

Marx's large-scale theory of society is not our topic here. Therefore, rather than spelling out the theory indicated with these words by its author, aspects of a particular bearing on the argument of this article will be discussed.

A suitable start is provided by a sentence that probably sounds strange in the ears of many sociologists: "In the social production of their existence, men inevitably enter into definite relations, which are independent of their will, namely relations of production appropriate to a given stage in the development of their material forces of production." One of the many problems involved in this statement concerns the very question of whether social relations constitute a whole that is self-referential; that is, a whole, the structures of which result solely from the mutual interactions between humans without being conditioned by non-social factors.

Marx took the very mundane position that no society can exist without entertaining a relation to nature that warrants the physical survival of its members or, at least, of a number of them sufficient for reproduction. Being themselves natural beings, a certain species of animals, as it were, humans cannot subsist on interaction alone but must acquire natural entities necessary for their life—matter and energy, to put it most abstractly. To a considerable part, the "production of their existence" is therefore an activity that can legitimately be described in terms provided by the life sciences and other natural sciences. But it is at the same time a social activity, a "social production of their existence," which engenders social relations among the individuals, "relations of production," which Marx regarded as the bedrock of a society's system of social relationships. These basic social relations are taken to be not only "inevitable" but also "independent of the will" of the individuals which enter into them.

Insofar as interaction among humans and, thus, their social relations, are conceived of first and foremost as an expression of humans' capacity for judgment, decision, and free action, social relations "independent of the will" might sound like a contradiction in terms. Marx had in mind not only the fact that a new generation enters into already established social relationships that are independent of the newcomers' will. Such established relations might prove, in a final analysis, to originate in free interaction. Rather, the point Marx wanted to make is that the core structure of a society's social relations cannot be reduced to free will and interaction. In Marx's view, the basic structure of these social relations, namely the relations of production, consists of human-human relations that are conditioned by human-nature relations, which are a matter of choice or will to only a very limited degree.

It is important to see that Marx did not replace the self-determination of interaction and social relations with a determination by nature. Indeed, the usual distinction and opposition of the social and the natural does not work here. Production, human labor, though not at all preternatural, is not a natural event but the activity of a human society. This activity is, however, shaped not only by the human actors but also by the materials worked upon and, above all, by the material means worked with. It is therefore a process that defies the familiar opposition between social and natural, self-determined and determined by nature, and appears as a true hybrid of the two spheres.[24] Thus, Marx questioned, on a basic level, a conception of the social as a merely self-referential sphere.

The disagreement that can be expected at this point might have to do with the situation that the study of sociology is usually divorced from that of economy. As a basis and a result of this disciplinary separation, often

24. It is probably superfluous to remark that this hybrid of the social and the natural has nothing to do with Bruno Latour's assumption of an initial stage of not yet developed discriminations between the social and the natural from which more stable and refined distinctions gradually emerged; see (Latour 1992).

only those relations or institutions are taken to be of a genuine social nature which are engendered and sustained by pure interaction and thus can be considered self-referential. An example may be helpful to clarify this point.

Take any concrete division of labor, for instance, that between the sexes in a pastoral tribe of the stone age, and let us assume for the time being that all work in connection with the flock and stock is the task of the male part, and things like gardening, pottery and so on a female affair. This form of division of labor would be due primarily to the half-nomadic form of life of such tribes, and one can focus on the concrete material conditions of this form of life in a given case to obtain an understanding of the concrete division of labor. But it is also possible to take this material side of the social phenomenon for granted and to focus on how this division is realized morally by ascribing tasks, duties, obligations as well as merits, honors and so on to the members of the tribe which enforce the fulfillment of their respective social roles. This choice of a focus is absolutely legitimate. It would, however, become a source of error if anybody contended that it was this social distribution of roles that created the division of labor at hand.

No question, it would be equally wrong if anybody believed that moral institutions like an obligation or a merit could be taken as a mere outcome of the material conditions underlying the division of labor in question. These institutions must also be established by means of interaction. Thus, we have two sides to any division of labor: on the one hand, its material shape and structure, which is not a result of, but an adaptation to the material conditions of labor, and on the other, its moral enforcement which cannot be derived from these conditions. But is this moral side really self-referential? Or does it only appear so because of its separation from the material side, or, to put it more generally, because this side is abstracted from the economic dimension, as is the rule rather than the exception in today's sociological studies?

Linguistic approaches to social phenomena, that is, approaches that conceive of social entities as grounded in speech-acts, seem to be *a fortiori* threatened by the danger of misconceptions of the social because of a neglect of its material conditions. Terms with reference to social entities, that is, S-terms as opposed to N-terms with reference to physical entities,[25] appear to these approaches as self-referential in an ultimate analysis.

25. It is probably superfluous to state that the use of the abbreviations "S-terms" and "N-terms" refers to theories of the Edinburgh school of SSK. For the abbreviations, see (Barnes 1983, pp. 525f.). These theories are reminiscent of the conception of social institutions that Mary Douglas developed in the course of her anthropological work—see (Douglas 1975), particularly the introduction to part II; see also (Douglas 1995).

And, consequently, so do the social entities themselves. True, the meaning of S-terms is created linguistically; but this holds for all kinds of terms, N-terms no less than S-terms. However, whether the referent of a S-term is created linguistically as well seems to be a question that cannot be decided *a priori* by a linguistic theory; rather, it should be subjected to empirical sociological investigations in each particular case. To give an example: Contrary to Marx's assumption,[26] money was taken to be such a linguistically engendered social object to which, thus, a self-referential character could be ascribed.[27] This understanding may seem plausible. But would it also seem plausible to conceive of social labor processes as such linguistic creations? It appears that one would have to strip these processes of all their material components to attain such a view. As a consequence, the seeming self-referentiality of its remaining social form would probably boil down to an analytical artifact as a result of this privation.

The hybrid character of the production process observed above comprises an aspect of particular interest in our context. The blending of the social and the natural, of what is man-made and what is determined by nature, is especially characteristic of the means of production, the "material forces of production," as Marx put it.[28] In what sense are the natural and the social blended in the material means of the labor process? It is the human actor who renders a stone a tool; but this does not rob the stone of its natural properties. Its effective role in the labor process is determined by its natural properties as well as by the human actor. As long as they are used as instruments or preserved for future use, instruments of labor have both social and natural characteristics and maintain this double-faced nature until they are cast out of the realm of labor instruments. Moreover, the material means of production not only act upon the object in question, but also react back on the human laborers and their actions, the social organization of these actions included.

To give a well-known example from the Industrial Revolution for the

26. The most elaborated exposition of Marx's theory of money can be found in his *Critique of Political Economy* of 1859.

27. See (Bloor 1999, pp. 108f.); see also (Bloor 1997, pp. 29ff.).

28. Marx considered not only tools, instruments and other technical equipment of the labor process "material forces of production" but also all kinds of material conditions of the production process—available materials, agriculturally usable soils, plants, and animals, access to the sea, and so on—and, moreover, the personal productive forces of humans, from physical strength over skill to mental abilities. No question, these personal forces, although in some basic features endowments bestowed by nature, were created and developed culturally in the course of history. But it seems equally clear that this historical development was narrowly tied to that of the instruments of the labor process. This issue will be discussed in more detail in the third part in connection with the scientific labor process.

connection between the material means applied in production and the social organization of the production process: The invention and introduction of new machinery for the textile industries in the decades before and after 1800—in particular spinning machines like the water-frame and the mule—marked not only technological advancements but triggered a revolution in the social organization of labor.[29] Needless to say, none of the historical actors could anticipate, let alone plan, the social consequences of these inventions. Furthermore, as is evident in the empathetically understandable but by and large not terribly effective revolts of the workforce against such machinery which accompanied the Industrial Revolution, one cannot combine *à la carte* means of production of a certain kind, e.g., machinery like the self-acting mule, with favored social relations of production, for instance, with a workshop of the traditional crafts or with domestic production. Indeed, introducing machinery of this kind in any case meant introducing social forms of the labor process that are as incompatible with the traditional ones as the modern factory system which ultimately emerged under the concrete historical circumstances.

This last sentence was phrased very deliberately. I do not understand Marx[30] as saying that machines such as Arkwright's water-frame or Roberts' mule brought about the factory system. Rather, he claimed that their application was incompatible with the social organization of labor developed in Western Europe up to that time. To stick with their application therefore meant developing new, suitable forms of the organization of labor. The form eventually found, the factory system of the early nineteenth century with all its brutality, was not a compulsive and inevitable consequence of the machines applied. Equally instrumental for the emergence of this system was the fact that capitalists applied these machines for the exploitation of laborers. But these capitalists could not impose a labor organization at odds with this machinery; and the same would have held for the "association of free producers" Marx dreamed of. This seems to me the background of his statement that the "relations of production [are] appropriate to a given stage in the development of their material forces of production" and, furthermore, that, "at a certain stage of development, the material productive forces of society come into conflict with the existing relations of production [. . .] Then begins an era of social revolution." Against this background, these statements should not be taken as indica-

29. For the invention of these machines, see (Usher 1954, pp. 295ff.), and for their social consequences, (Berg 1985, pp. 254ff.).

30. Marx's most elaborate discussion of the Industrial Revolution can be found in chap. 13 of the first volume of his *Capital.*

tions of a crude technological determinism.[31] Rather, they indicate a social theory which conceives of the material means of labor given and used in a certain age as essential conditions of the social production process that provide a horizon of possible social relations of production, that is, material conditions that make such relations possible and at the same time set limits to them.

2.2 Historical Development as a Labor Process

When conceiving of the scientific production as labor *strictu sensu,* one should expect that its social form and organization depends by and large on the material means, just as they do in other branches of the social labor process. And this is indeed the case. This becomes particularly clear when we look at experimental research.

The sites of experimentation in early modern times resemble strikingly the workshops of the age. Galileo's laboratory in Padua is a good case in point.[32] This laboratory not only served scientific research but was actually a workshop in which an appointed smith, Messer Marcantonio Mazzeloni, fabricated mostly military and surveying compasses under Galileo's direction. It also was used for private lectures on fortification and related mechanical and mathematical topics.[33] The fact that Galileo actually ran his laboratory as a real workshop for the production of instruments is telling but not the decisive point in our context. Rather, this laboratory could be run like a workshop with its flat hierarchy and low degree of division of labor, since this form of organization fit the instruments in question, which were ordinary craftsmen's tools. For the same reason, such laboratories could be set up and entertained by private persons with some fortune or, as the case of Galileo proves, only some cleverness with respect to business.

In early modern times, thus, we encounter a situation where all ex-

31. In their introductory essay, MacKenzie and Wajcman (1999) distinguish two kinds of technological determinism: one that is a theory of society and one that is a theory of technology. The latter, which regards the development of technology as autonomous, clearly contradicts Marx's views. The former, which stresses the social effects of technologies, conforms with his views, however not in their "hard" form as a "simple cause-and-effect technological determinism" (p. 4). For an elaborate discussion of Marx's stance in this respect, see (MacKenzie 1984). For the debate on technological determinism, see also (Rosenberg 1981) and (Staudenmaier 1985, chap. 4). For a comprehensive conception of the development of technology, see (Basalla 1988).

32. See above all the bookkeeping accounts regarding "L'officina di strumenti mathematici in Padova" in (Galilei 1890–1909, 19:131–149). See also (Valleriani 2001, pp. 284ff.).

33. On the similarity between eighteenth-century chemical laboratories and workshops, see Ursula Klein's contribution in this volume.

change, communication, and co-operation between scientists was essentially colored by the basic fact that the proper research process was performed by separated and, to a certain degree, even autonomous scientific actors. The complex process of transforming individual assumptions, hypothesis, and so on, into shared opinions and convictions of smaller or larger groups of scientists therefore rested essentially on communication rather than co-operation proper. Accordingly, the social infrastructure and resources of communication—travel, the exchange of materials, personal letters, the gradually emerging periodicals of scientific communities—played an outstanding role in the formation process of scientific knowledge.

Notwithstanding earlier attempts to initiate and entertain more direct forms of co-operation among scientists at courts, mercantilist enterprises, and in particular at the newly founded academies of all kinds,[34] this situation did not begin to change substantially until the emergence of large laboratories in the course of the nineteenth century. The development of the laboratories of experimental physiology in nineteenth-century Germany is a good case in point.[35] These laboratories were situated in major cities like Leipzig and Berlin where the technical infrastructure changed dramatically in the course of the century, in particular through the installation of extensively branched networks of underground pipelines for water and gas supply. Against the background of this infrastructure, new technical laboratory equipment could be employed. Of special significance in this respect proved to be a gas-motor, the Otto motor, which had been developed to serve smaller workshops as a substitute for the large and costly steam engine. The introduction of this machine into the laboratory allowed the development of experimental apparatus with unprecedented effects, in terms of both technical performance and consequences for the labor process in the laboratory. The latter began to resemble labor processes in factories. Now, mechanical devices performed the traditional operations of the experimenter who, for his part, had to operate those devices. Traditional skills and competences were replaced by new ones.

As result of this development, which was not restricted to experimental physiology but gradually expanded over the whole range of experimental sciences,[36] one encounters a type of research laboratory that resembles a

34. Practical institutions such as military academies, mining academies (*Berg-Akademien*) or construction academies (*Bau-Akademien*) were not of less significance in this respect than famous savant academies such as the Royal Academy in London or the Académie des Sciences in Paris.

35. For the following, see (Dierig 2003).

36. For this development, see, for instance, (James 1989) and (Fox and Guagnini 1999).

factory more than the workshop of a craftsman. Gaston Bachelard plainly called this entity the "factory laboratory" (*l'usine-laboratoire*) (Bachelard 1953, p. 78). Its size and equipment were no longer designed to serve just one single scientist. Rather, it could be used by an indefinite number of scientists in a variety of modes—successively or alternately, with or without a staff of assistants, and even co-operatively at the same time. It thus allowed teams of scientists to evolve with a variety of hierarchical structures.[37] Needless to say, such laboratories, whatever their origin, could not be entertained over time by individual scientists but required a broader social fundament, be it provided by scientific societies, by the framework of a state's educational or research support system, under the roof of large commercial companies or behind the fences and walls of military sites. This holds *a fortiori* for today's large science laboratories like the CERN in Geneva, which is used by research teams from all over Europe on the basis of leasing contracts.[38] The characteristic experimental instruments in these laboratories are of course no longer the craftsmen's tools or engine-driven apparatuses of nineteenth-century laboratories (some of which are still used), but modern machine systems. These laboratories therefore strikingly resemble modern high-tech factories with their specific forms of the division of labor.[39]

There is no doubt that, even in the age of big science, the social process of forming scientific knowledge and convictions is still essentially a matter of communication and, thus, highly susceptible to the dramatic changes and developments in the means of communication today. But in modern experimental science, communication no longer primarily links individual scientists, but for the most part teams of scientists who discuss and develop assumptions and interpretations collectively as part of research performed collaboratively. Moreover, based on the new means of communication, research co-operation has become possible for teams working at different sites all over the world.[40]

The forms of co-operation and communication among scientists and, along with this, the relations between experimental research and the formation of shared understandings, thus prove to be highly dependent on

37. For the relation of instrumentation and division of labor in modern laboratories, see (Shinn 1998).

38. For details, see (Hermann and Krige 1987–1996).

39. On the development of large science laboratories in the second half of the twentieth century, see (Westfall 2001).

40. A impressive instance of such a worldwide collaboration among teams of scientists is the European South Observatory (ESO), the organization that joins European astronomical and astrophysical research institutes and observatories strategically placed in South America and connected by modern communication technology.

the instruments used in the research process. Equally important is the role of the material means of scientific production in the development of large-scale divisions of labor within science—from the processes of dividing or uniting fields of research up to the emergence, formation or decay of disciplines. It is not possible to go into this here, and I can therefore merely contend the following: just as the instruments used engender the object of scientific research—without the Leyden jar, no eighteenth-century science of electricity, without the cyclotron, no particle physics—scientific fields develop around promising research strategies which are, for their part, essentially dependent on the instruments available.

3. Instruments of Labor and Knowledge

The assertion that the instruments used in the scientific labor process engender objects and even entire realms of research objects certainly requires further clarification. Such a clarification seems particularly necessary in the context of this article since, provided it holds for science in general, this assertion suggests a further dimension of the technoscientific nature of modern sciences. Indeed, it seems possible to claim such general validity if one distinguishes between a strong and a weak sense in which research objects are engendered by the material means used in the research process. Electricity and particle physics are instances of research fields with objects that are engendered in a strong sense, namely literally produced by the laboratory machinery. But it also makes sense to speak of such engendering in cases where the employed equipment grants access to and allows the investigation of given objects. In this weak sense, one can state that Galileo's telescope "engendered" the Jupiter moons.

The technoscientific dimension of science that becomes visible in this way could be characterized as that of a technologic transcendentalism of scientific cognition, albeit an historical one. According to this transcendentalism, scientific objects would appear as always being given and, thus, mediated by the material means employed at a certain point of time; objects independent of such mediation would have to be considered as unrecognizable as Kant's "things in themselves." Even the cognitive dimension of the scientific process would prove to be fundamentally shaped by the technologic nature of the research process and, more precisely, by the material means used in this process. A closer look at the relationship between material means and knowledge in general, and scientific knowledge in particular, seems to be necessary.

3.1 Knowledge: Precondition and Result of Labor

Nothing deserves the name of a means that is not used or intended to be used to fulfill an end. It is the end that renders something a means. One can, thus, state that means are determined by ends. However, whether or not something is a suitable means for a purpose depends not only on the end but also on its physical properties, which are determined by the end only in part, even in the case of fabricated means. Being determined by an end only in part, that is, due to their irreducibly material nature, over time, means can be used in the social labor process for ends different from the original one.[41] Taking into account that these new ends were uncovered in the process of handling the means under different circumstances, these ends turn out to be conditioned by the means. Ends not only determine means, but prove to be determined by them in turn. Apart from wishes that are mere negations of existing states, it is questionable that humans can even envision ends other than those that anticipate possibilities presumed in or actually given with extant means.

How does this relate to knowledge? Knowledge[42] is always a precondition for the application of a means in a given way—knowledge of the means' make-up or of the way it functions when employed to achieve the end in question. However, by applying a material means in the labor process, its material nature can reveal new ways of application and employment, which were not given along with the original ends. Thus, in the practical use of material means, new experiences may occur and new purposes can emerge. Such new experiences and purposes, in turn, stimulate improvements of the original means. And, in a renewed process of application, these altered means may again lead to new experiences and purposes, and occasionally to the invention of new means. Some of the latter can open up a new horizon of unforeseen possibilities for the physical and mental activities of humans. We have, thus, a co-evolution of material means and knowledge of which a surplus of knowledge is characteristic. This surplus is due to the simple but rarely sufficiently acknowledged fact that humans can gain more knowledge from the use of a means than was needed to invent it in the first place.[43]

Among the material means of the labor process, one can distinguish between means of production properly so called, that is, means that act

41. It is probably superfluous to stress that the social nature of the labor process is always presupposed, regardless whether or not it is explicitly stated. True, this very principal discussion about the interrelation between knowledge and labor instruments abstracts from all specific social forms of the labor process. But it does not abstract from this form itself.

42. For the following, see (Damerow and Lefèvre 1996).

43. From these observations, some philosophical conclusions could be drawn with respect to the notion of experience and in particular with respect to its reduction to sensory perception. True, there is no experience without sensory perception; but equally true, no experience, not even sensory perception, without acting and, except for pure interaction, without the means of acting.

physically on the object in question, and means of anticipating or planning. The latter may be called material "means of thinking." Maps, drawings, geometrical constructions, means of counting, writing systems, etc., come immediately to mind. What is true of material means in general is also true of these material means of thinking. They, too, develop along with knowledge in a co-evolution that characteristically engenders a surplus of knowledge. However, it should be added that it is these means of thinking in particular that set up a horizon of what can be accomplished by thought and what cannot. Presupposing social conditions favorable to realizing the spectrum of possibilities inherent in a material means of labor at a certain stage of development, it depends specifically on the material means of thinking to what extent and in what way the experiences made through acting with the means of labor can be transformed into established knowledge; and, furthermore, what systems of knowledge, that is, what deep structures of inference, can be built.

3.2 Material Means of Scientific Thinking

So far, we have regarded the interrelation of knowledge and acting with material instruments only in economic labor processes. Is such an interrelation also characteristic of the scientific labor process? Can we suppose that scientific findings, insights, propositions, and theories emerge in such a co-evolution of material means and knowledge? As I will argue, this supposition can, indeed, be justified, provided that a comprehensive notion is formed of what belongs to the material means of scientific thinking.

It is probably not at all contentious to call observational instruments or experimental devices "material means of the sciences." And probably nobody will question the dependency of certain scientific concepts and theories on such instruments and devices. However, it may seem less obvious to also denote languages, symbolic systems, or diagrammatic representations "material means." Such means of representation are usually taken to be mere externalizations of thoughts, the materiality of which does not really matter. And even when they are acknowledged as indispensable means of memorizing and communicating, their function as material means of thinking is often missed, that is, their function as means that decide what can be achieved by thinking.

Numerical notations are a good case in point. In a culture like ancient Egypt with a system of numerical notation that does not include a place value system, we do not find algorithms for multiplication and division that are in any sense comparable to ours. With regard to these elementary arithmetical operations, the most gifted and accomplished mathematicians of such a culture would not be able to keep up with average people of our culture. The "superiority" of the latter rests solely on the employed notation system, which allows these algorithms. Another instructive example is provided by chemical formulas.[44] Their function as a kind of shorthand is hardly the extent of their usefulness. Rather, they serve chemists as means of reconstructing complex chemical reactions and as building blocks of formula models, without which modern organic chemistry would not have developed. Thus, they were rightly called "paper tools," that is, graphic means, the materiality of which matters no less than that of ordinary tools. It therefore makes sense to call also seemingly non-physical things like syntactical ordered systems of signs, chemical formulas, tables, diagrams, etc. "material means of thinking." Like other material means of thinking, they delineate a horizon of what results scientists can achieve and even what results are conceivable or probable.

It therefore seems quite reasonable to assume that the co-evolution of knowledge and material means of production discussed above for the labor process in general, including its characteristic surplus of knowledge yielded, holds for the process of scientific production as well. This conclusion is suggested when the material character of such "paper tools" is acknowledged and, on this basis, the cognitive performances of scientists as well are, realistically, considered to rest essentially on the spectrum of material means of thinking available in a given society in a certain age.

The material means of thinking used in science are not entirely different from those used outside science. The kinds of instruments applied are not the primary means by which scientific labor distinguishes itself from other sorts of labor.[45] Many of the material means of scientific thinking were invented neither by scientists nor for scientific purposes, but emerged and developed in practical contexts. This holds not only for instruments like the telescope or the centrifuge, but also for less tangible means such as a society's system of numerical notation which was invented, developed and used in various domains of planning, administration, etc., long before science came into being. Even in contemporary science, the material means taken over from the outside world, with or without adaptations, probably outnumber those invented and developed specifically for science. Furthermore, the flow of materials and instrumentation occurs not only from the sphere of economic production into science, but also the other way around. Materials and apparatuses produced and developed in laboratories turned out to be of relevance for economic

44. For the following, see (Klein 2003).
45. For the following, see (Joerges and Shinn 2001).

production and triggered the development of analogous instruments and techniques on a scale suitable for their employment in the sphere of the economic labor process. Thus, it is not the nature of the means themselves but their *use* for purposes of cognition that renders them scientific means. To give an example:[46] The inventors of Greek geometry did not invent the compass and ruler on which this geometry essentially rests. Living in a society that used these instruments in several practical domains, they rendered them scientific instruments by making a specific use of them. They employed them not to design the ground plan of a temple or for another practical goal, but to gain insight in the regularities of constructions that can be accomplished by compass and ruler.

There is another significant difference with respect to the use of such means in scientific and practical contexts. In the latter case, the purposes aimed at and economical considerations of all kind impose narrow limits on the use that can be made of the employed means. Handling these means in an unrestricted manner is out of the question as is, thus, free exploration of the possibilities they present. However, such free exploration constitutes the core of science. The purpose pursued in science is this very exploration of what knowledge can be gained using such means. Of course, in the scientific labor process as well, care must be taken not to waste materials or abuse instruments. And scientific research cannot be taken as a playful way of trying out what can be achieved with the given equipment. In contrast to tendencies to depict the laboratory as the site of heroic activities or of a fancy as well as brilliant playing around, the greater part of laboratory work consists, like ordinary labor, of exhausting and boring routine operations that apply materials and instruments as effectively and economically as possible. But this down-to-earth view of laboratory work by no means denies that successful research needs to have the freedom to pursue unforeseen results and traces, to shift the focus of attention to unexpected by-products of the process under investigation, in other words, to yield to the drive of promising digressions that emerge in the course of the work. It is for this openness of science, on which its fertility rests, that unrestricted use of the research means is absolutely essential. With science, the realization of potential knowledge inherent in given means is transformed into a systematically performed social enterprise.

3.3 Nature in the Light of Technology

In the light of the arguments put forward so far, the technologic character of science may have become more tangible. A conception of science that

46. For the following, see (Netz 1999).

focused chiefly on observation and induction without allowing for the material means that enable perception and cognition would seem to overlook the reality of science. And even if one added negotiation to observation and induction, only a small improvement would be achieved. Scientific production is a labor process that employs, like all other kinds of labor, material means. It is based on such means not only occasionally or in some exceptional cases, but generally. Accordingly, the results achieved are always the outcome of an equipped production process and, thus, shaped by the equipment actually employed. In other words, these results are mediated by material means which function as "conditions of the possibility" of such results, like the "pure forms of intuition" and the "pure concepts of the understanding" in Kant's epistemology—"conditions of the possibility," however, that are genuinely historical.

A part of the material means that shape science supports the natural faculties of the scientists. Observatory instruments enable the senses of the scientific laborers to discern and discriminate details that lie far beyond the limits of their natural perception capacity. Algorithms and calculating devices allow extrapolations of attained data, which cannot be performed by the unequipped mind. But such supporting means are hardly neutral. Even mathematical algorithms always yield only representations that are as selective as all other kinds of representations and models. As is well-known, observatory instruments are not pure media that merely magnify or amplify phenomena. Rather, they transform them and thus necessitate an appropriate understanding of how they work as precondition for interpreting their productions. Instruments of observation such as radio telescopes or machinery for scanning tunneling microscopy, finally, cannot be conceived of as aids for our senses but must be understood as devices that produce, through interaction with the objects in question, traces and data that are transformed into representations perceptible to us.

Observatory instruments of this kind constitute the bridge to the material means of the scientific production process which render it technoscientific *strictu sensu,* namely to instruments such as a chemical distillation apparatus that acts physically upon natural objects. Such means ultimately cease to comply with the view of science as observation plus induction, which permits activity on part of the scientist only on the mental level and prescribes purely receptive passivity towards the object. Rather, these intervening means show the physical interaction between employed means and natural objects as the foundation of the scientific labor process. Its object is not the untouched natural things but their behavior in such interactions. Furthermore, because of their materiality, the behavior of the instruments employed in such interactions is, in principle, just as genuine an object of investigation and source of insights as the behavior of the objects acted upon. Actually, understanding the way the instrument works was and still is a favored access to the understanding of nature.

It is therefore not by chance that, in the beginning, science developed by studying instruments from the sphere of economic production. For instance, up to the eighteenth century, mechanics was essentially the science of mechanical instruments. Statics was originally a science of the balance and was called very adequately "science of weights" in the Middle Ages. Optics originally dealt with the properties of lenses and mirrors. Early modern dynamics rested essentially on the investigations of machine parts like the pendulum and of ballistics. The same could be shown for chemistry and other natural sciences. The reason why insight into nature can be gained by studying the operation of certain instruments of labor lies principally in the fact that such instruments draw in and make use of "forces of nature" for the labor process. One can thus study nature in these instruments as in a mirror: "Art has always been a highly selective mirror of nature" (White 1966, p. 110).[47]

Later on, such intervening instruments with significance for science came into being and were developed in the sphere of scientific production itself. The air-pump and certain chemical reagents may serve as examples. Furthermore, in this sphere, a new type of material means of the scientific labor process emerged; means that are more than just intervening instruments but rather technoscientific ones of a particular kind, namely instruments that first generate the object of investigation. The sequence from the Leyden jar up to the cyclotron could be adduced once more. However, even natural history, usually considered purely descriptive, proves upon closer inspection to be such a technoscience. In botany and zoology, for instance, the stabilization of plant and animal specimens includes not only collecting, ordering, and preserving but also producing in a literal sense. For the reduction of varieties to species, an essential precondition of classification, cannot be performed mentally but requires growing and breeding.[48] Against the background of the observed role that material means of the ordinary labor process played and play for science, the employment of production instruments in sciences may no longer appear as exceptional as before. They form one extreme pole in a spectrum of material means of scientific labor extending all the way down to simple observation instruments like magnifying glasses.

47. In a paper from 1978 (Ruben 1978), Peter Ruben suggested that the epistemological theory of mirroring, notorious in Lenin's version, might be quite reasonable if separated from a sensualistic understanding of perception as well as from a mentalist understanding of cognition and taken instead literally to be a process mediated by material entities.

48. (Müller-Wille 1997) discusses this practice in the case of Linnaeus' botany.

At least since the early modern period, the technologic character of science has left traces in the understanding of what science does, though most of these traces are indirect. The gradual dismissal of the traditional opposition of nature and art is one such trace. This opposition was instrumental for Aristotle's distinction between mechanics and physics,[49] which separated technologic knowledge from knowledge of nature as such. As is well known, this separation was not only a matter of classifying fields of knowledge but had institutional consequences: in the Middle Ages and the early modern period, physics, a sub-discipline of philosophy, was taught at the universities whereas mechanics developed outside of this sphere of higher education.[50] Still an unsettled issue in the sixteenth century, the demarcation between physics and mechanics began to vanish with Galileo and the seventeenth-century natural philosophers who followed his example. The new understanding of technology and science manifested itself when Newton conceptualized the paths of the planets as ballistic trajectories, and no less, when, at the same time, chemists began to treat vitriols synthesized in the laboratory in the same way as natural vitriols. Along with the development of the early modern sciences, a clear understanding emerged that humans' technology is neither unnatural nor outwits nature but makes use of her laws and powers. As Francis Bacon put it classically: *natura non nisi parendo vincitur* (*Novum Organum* I, aphorism 3).

This paradigm change was not confined to considering devices and machines as acting in conformity to nature. Rather, such artifacts even became models of nature—the mechanistic conception of the universe as a clock is probably the most prominent instance of modeling nature after technical devices. Although the principal inadequacy of such models is generally acknowledged, science seems to be unable to refrain from making use of them—taking the sun as a fusion reactor or a H-bomb, the DNA as a code, the brain as a computer, and so on. This modeling should not be dismissed as a matter of popularizing and illustrating scientific conceptions that has nothing to do with science proper. Rather, it deserves attention as an indicator of a deep structure of scientific reasoning. It indicates an essentially technologic character of scientific explanations. On a basic level, explaining a phenomenon means deriving it from an actual or imaginable process that would produce it. The "logic" of explanation is that of production. It thus has the appearance that our modern sciences are technosciences even at their very epistemic core.

49. For this distinction, see (Hoykaas 1963).

50. Jordanus Nemorarius' science of weights must be considered an exception that confirms the rule.

References

Bachelard, Gaston. 1953. *Le matérialisme rationnel.* Paris: Presses Universitaires de France.

Barnes, Barry. 1983. "Social Life as Bootstrapped Induction." *Sociology,* 17(4):524–545.

Basalla, George. 1988. *The Evolution of Technology.* Cambridge: Cambridge University Press.

Berg, Maxime. 1985. *The Age of Manufactures: Industry, Innovation and Work in Britain 1700–1820.* London: Fontana Press.

Bloor, David. 1997. *Wittgenstein, Rules and Institutions.* London and New York: Routledge.

———. 1999. "Anti-Latour." *Studies in History and Philosophy of Science,* 30(1):81–112.

Cohen, H. Floris. 1994. *The Scientific Revolution.* Chicago: The University of Chicago Press.

Damerow, Peter, Gideon Freudenthal, Peter McLaughlin, and Jürgen Renn. 1992. *Exploring the Limits of Preclassical Mechanics.* New York: Springer.

Damerow, Peter, and Wolfgang Lefèvre. 1996. "Tools of Science." Pp. 395–404 in *Abstraction and Representation.* Edited by P. Damerow. Dordrecht: Kluwer Academic Publishers.

Dierig, Sven. 2003. "Engines for Experiment: Laboratory Revolution and Industrial Labor in the Nineteenth-Century City." Pp. 116–134 in *Science and the City.* Edited by S. Dierig, Jens Lachmund and Andrew Mendelsohn. Chicago: University of Chicago Press.

Douglas, Mary. 1975. *Implicit Meanings: Essays in Anthropology.* London: Routledge & Kegan Paul.

———. 1995. *How Institutions Think.* Syracuse N.Y.: Syracuse University Press.

Fox, Robert, and Anna Guagnini. 1999. *Laboratories, Workshops and Sites: Concepts and Practices of Research in Industrial Europe, 1800–1914.* Berkeley: Office for History of Science and Technology, Univ. of California.

Galilei, Galileo. 1890–1909. *Le opere di Galileo Galilei.* Firenze: Barbera.

Grossmann, Henryk. 1987. "The Social Foundations of Mechanistic Philosophy and Manufacture." *Science in Context,* 1(1):129–180.

Guston, David H. 2000. *Between Politics and Science. Assuring the Integrity and Productivity of Research.* Cambridge: Cambridge University Press.

Guzzetti, Luca, ed. 2000. *Science and Power: The Historical Foundations of Research Policies in Europe.* Luxembourg: Office for Official Publ. of the European Communities.

Hermann, Arnim, and John Krige. 1987–1996. *History of CERN.* 3 vols. Amsterdam: Elsevier.

Hoykaas, R. 1963. *Das Verhältnis von Physik und Mechanik in historischer Hinsicht.* Wiesbaden: Franz Steiner.

James, Frank A. J. L., ed. 1989. *The Development of the Laboratory: Essays on the Place of Experiment in Industrial Civilisation.* New York: American Institute of Physics.

Jardine, Nicholas. 2003. "Zilsel's Dilemma." *Annals of Science,* 60:85–94.

Joerges, Bernward, and Terry Shinn, eds. 2001. *Instrumentation between Science, State and Industry.* Dordrecht: Kluwer Academic Publsihers.

Klein, Ursula. 1994a. *Verbindung und Affinität. Die Grundlegung der neuzeitlichen Chemie an der Wende vom 17. zum 18. Jahrhundert.* Basel: Birkhäuser.

———. 1994b. "Origin of the Concept of Chemical Compound." *Science in Context,* 7(2):163–204.

———. 2003. *Experiments, Models, Paper Tools.* Stanford CA: Stanford University Press.

Latour, Bruno. 1992. "One more Turn after the Social Turn: Easing Science Studies into the Non-modern World." Pp. 272–292 in *The Social Dimension of Science.* Edited by E. McMullin. Notre Dame: Indiana University of Notre Dame Press.

Lefèvre, Wolfgang. 1978. *Naturtheorie und Produktionsweise.* Darmstadt: Luchterhand.

Levidow, Les, and Bob Young, eds. 1981/1985. *Science, Technology and the Labour Process: Marxist Studies.* 2 vols. Atlantic Highlands: Humanities Press.

MacKenzie, Donald. 1984. "Marx and the Machine." *Technology and Culture,* 25:473–502.

MacKenzie, Donald, and Judy Wajcman, eds. 1999. *The Social Shaping of Technology.* Buckingham and Philadelphia: Open University Press.

Marx, Karl. 1887. *Capital.* 3 vols. Vol. I. Moscow: Progress Publsihers.

Max-Planck-Gesellschaft, ed. 2002. *Innovative Structures in Basic Research.* München: Max-Planck-Gesellschaft.

McLellan, David, ed. 1977. *Karl Marx: Selected Writings.* Oxford: Oxford University Press.

MECW. 1975ff. *Marx/Engels Collected Works.* 49 vols. Moscow: Progress Publsihers.

MEGA. 1975ff. *Marx/Engels Gesamtausgabe.* 107 vols. Berlin: Dietz.

Mendelsohn, Everett, Merritt Roe Smith, and Peter Weingart. 1988. "Science and Military: Setting the Problem." Pp. Xi–xxix in *Science, Technology and the Military.* Edited by E. Mendelsohn, M. R. Smith and P. Weingart. Dordrecht: Kluwer Academic Publishers.

MEW. 1959–1990. *Marx Engels Werke.* 49 vols. Berlin: Dietz.

Müller-Wille, Staffan. 1997. *Varietäten auf ihre Arten zurückführen : zur Begründung eines natürlichen Systems der Pflanzen durch Carl von Linné (1707–1778).* Berlin: VWB.

Netz, Reviel. 1999. *The Shaping of Deduction in Greek Mathematics.* Cambridge: Cambridge University Press.

Reppy, Judith. 1988. "The Government of Military R&D: A Comparative Perspective." Pp. 507–514 in *Science, Technology and the Military.* Edited by E. Mendelsohn, M. R. Smith and P. Weingart. Dordrecht: Kluwer Academic Publishers.

Rosenberg, Nathan. 1981. "Marx as a Student of Technology." Pp. 8–31 in *Science, Technology and the Labour Process: Marxist Studies.* Vol. 1. Edited by L. Levidow and B. Young. Atlantic Highlands: Humanities Press.

Ruben, Peter. 1978. "Wissenschaft als allgemeine Arbeit." Pp. 9–51 in *Dialektik und Arbeit der Philosophie.* Edited by P. Ruben. Köln: Pahl-Rugenstein.

Schäfer, Wolf, ed. 1983. *Finalization in Science: The Social Orientation of Scientific Progress.* Dordrecht: Reidel.

Shinn, Terry. 1998. "Instrument Hierarchies: Laboratories, Industry and Division of Labour." Pp. 102–121 in *The Invisible Industrialist: Manufactures and the Production of Scientific Knowledge.* Edited by J. P. Gaudillière and I. Löwy. London: Macmillan.

Stachel, John. 1994. *Marx´s critical concept of science.* Berlin: Max-Planck-Institut für Wissenschaftsgeschichte. (Preprint 10 of the Max Planck Institute for the History of Science.)

Staudenmaier, John. 1985. *Technology's Storytellers. Reweaving the Human Fabric.* Cambridge MA: MIT Press.

Trute, Hans-Heinrich. 1994. "Comparative Analysis of European Research Policy Structures." Pp. 3–27 in *European Research Structures—Changes and Challeneges. Institutional Aspects of European Research Policy.* Vol. 1. Edited by Max-Planck-Gesellschaft. München: Max-Planck-Gesellschaft.

Usher, Abbott Payson. 1954. *A History of Mechanical Inventions.* Revised Edition. New York: Dover.

Valleriani, Matteo. 2001. "A View on Galileo's Ricordi Autografi: Galileo Practitioner in Padua." Pp. 281–291 in *Largo Campo di Filosofare. Eurosymposium Galileo 2001.* Edited by J. Montesinos and C. Solís. La Orotava: Fundación Canaria Orotava de Historia de la Ciencia.

Walsh, Vivien. 1998. "Industrial R&D and Its Influence on the Organization and Management of the Production of Knowledge in the Public Sector." Pp. 301–344 in *The Invisible Industrialist: Manufactures and the*

Production of Scientific Knowledge. Edited by J.-P. Gaudillière and I. Löwy. London: Macmillan.
Westfall, Catherine, ed. 2001. *Proceedings of the Second Conference on Laboratory History.* Newport News VA: Jefferson Laboratory.
White, Lynn jr. 1966. “Pumps and Pendula: Galileo and Technology.” Pp. 96–110 in *Galileo Reappraised.* Edited by C. L. Golina. Berkeley and Los Angeles: University of California Press.
Zilsel, Edgar. 2000. *The Social Origins of Modern Science.* Dordrecht: Kluwer Academic Publishers.