what might be involved in such an enterprise. I have no great confidence in its quantitative findings. Nevertheless, I suspect that a more sophisticated piece of work might find some of that chapter's tentative conclusions to be robust. In particular, my instincts are that it is indeed true that only a small proportion of fatalities are caused solely by "technical" faults in computer systems, and that many computer-related deaths are better attributed to "system accidents" in Charles Perrow's sense,[66] where the "system" involved is human and organizational as well as technical.

Chapter 10 (written with Graham Spinardi) seeks to reverse the focus of many of the preceding chapters and, indeed, of most of the social studies of technology. Its topic is what the processes of the development of technology can teach us about how it might be possible to do away with—to uninvent—particular technologies. The chapter seeks directly to confront the conventional wisdom that the invention of a technology such as nuclear weapons is an irreversible event. Drawing both on historical evidence and on interviews with designers of nuclear weapons, the chapter suggests that the development of nuclear weaponry depends in part upon tacit knowledge embodied in people rather than in words, equations, or diagrams. Therefore, if the designing of nuclear weapons ceases, and there is no new generation of designers to which tacit knowledge can be passed on from person to person, nuclear weapons will have been, in an important sense, uninvented. Their renewed development, though clearly possible, would have some of the characteristics of reinvention rather than mere copying.

There are some important considerations that force us to qualify this conclusion, and chapter 10 does not even mention a variety of other deep problems that would be faced by an attempt to uninvent nuclear weapons. Nevertheless, I hope that the chapter's arguments might help dispel some of the pessimism that too often, even nowadays, surrounds discussion of the future of nuclear weapons. The last few years have seen the sudden, unexpected disappearance of at least two social institutions that seemed permanent features of our world: the Cold War and apartheid in South Africa. Once we start to think about technologies, too, as social institutions—and that, for all the nuances in interpretation and differences in terminology, is the shared underlying theme of the social studies of technology—we can begin to imagine technologies, too, disappearing.

2

Marx and the Machine

As an aside in a discussion of the status of the concepts of economics, Karl Marx wrote: "The handmill gives you society with the feudal lord; the steam-mill, society with the industrial capitalist."[1] The aphorism has stuck; as a succinct précis of technological determinism it has few rivals. Apt and memorable (even if historically inaccurate)[2] as it is, it is nevertheless misleading. There is much in Marx's writings on technology that cannot be captured by any simple technological determinism. Indeed, his major discussion of the subject—occupying a large part of volume 1 of *Capital*—suggests a quite different perspective. Marx argues that in the most significant complex of technical changes of his time, the coming of large-scale mechanized production, social relations molded technology, rather than vice versa. His account is not without its shortcomings, both empirical and theoretical, yet it resonates excitingly with some of the best modern work in the history of technology. Even where these studies force us to revise some of Marx's conclusions, they show the continuing historical relevance of his account of the machine. Its possible political relevance is shown by an interesting connection between the practice of the "alternative technology" movement and an important way of studying the social shaping of technology.

Marx as Technological Determinist

Not so long ago Alvin Hansen's 1921 conclusion that Marxism is a "technological interpretation of history" was still widely accepted. Robert Heilbroner's celebrated 1967 paper "Do Machines Make History?" was headed by the famous "handmill" quotation, and Heilbroner clearly identified "the Marxian paradigm" as technological determinism. In Tom Burns's 1969 reader, *Industrial Man*, the section on Marx had as a head "Technology as the Prime Mover of Industrialization and Social Change."[3]

More recently, things have seemed not quite so clear. Many Marxists—and some non-Marxists—have been profoundly unhappy with the characterization of Marxism as technological determinism.[4] William Shaw complains: "All the friends of old Marx, it seems, have entered into a holy alliance to exorcise this specter [technological determinism]."[5] Yet the book that remains the best discussion of the different varieties of technological determinism, Langdon Winner's *Autonomous Technology*, can still be read as giving (with some crucial reservations) a technological-determinist interpretation of Marx: in changes in the forces of production, Winner writes, Marx believed he had "isolated *the* primary independent variable active in all of history."[6]

To be a technological determinist is obviously to believe that in some sense technical change *causes* social change, indeed that it is the most important cause of social change. But to give full weight to the first term in expressions such as "*prime* mover," a strong version of technological determinism would also involve the belief that technical change is itself uncaused, at least by social factors. The first of these theses we can describe, following Heilbroner,[7] as the thesis that machines make history. The second we might call the thesis of the autonomy of technical change.

The thesis that machines make history is certainly to be found in Marxist writing. Perhaps its most unequivocal statement is in Bukharin's *Historical Materialism*, where we find assertions like the following: "The historic mode of production, i.e. the form of society, is determined by the development of the productive forces, i.e. the development of technology."[8] Bukharin was far from alone in this claim,[9] and there are indeed passages from Marx's own writings that can be read in this way. The best known is the sentence from the *Poverty of Philosophy* quoted above. More weighty, though not so crisp, is the "1859 Preface":

> 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. It is not the consciousness of men that determines their existence, but their social existence that determines their consciousness. At a certain stage of development, the material productive forces of society come into conflict with the existing relations of production or—this merely expresses the same thing in legal terms—with the property relations within the framework of which they have operated hitherto. From forms of development of the productive forces these relations turn into their fetters. Then begins an era of social revolution.[10]

And there are several other statements, chiefly from the 1840s and the 1850s, which can be read as claims that machines make history.[11]

Alternative readings of at least some of these are possible. Rosenberg, for example, takes the "handmill" quotation and suggests that in its context it can be seen as not necessarily implying a technological determinism.[12] The "1859 Preface" is, however, where debate has centered. It was explicitly presented by Marx as "the general conclusion at which I arrived and which, once reached, became the guiding principle of my studies."[13] Echoes of it reappear throughout Marx's later works, and it has often been taken as the definitive statement of historical materialism. Anything approaching a careful reading of it quickly reveals two things. First, to make it into a statement that machines make history, the "forces of production" would have to be interpreted as equivalent to technology. Second, to make it into a strong technological determinism in the sense outlined above, the development of the forces of production would have to be taken as autonomous, or at least independent of the relations of production.

Langdon Winner signals his ambivalence about the first point when he writes that "although there is some variation in the manner in which Marx uses these terms, *for our purposes* 'forces of production' can be understood to comprise all of physical technology." Furthermore, Winner also gives a broader definition of forces of production as "the instruments, energy, and labor involved in the active effort of individuals to change material reality to suit their needs."[14] Indeed, even orthodox Marxism has tended to follow the broader meaning. Stalin wrote: "The *instruments of production* wherewith material values are produced, the *people* who operate the instruments of production and carry on the production of material values thanks to a certain *production experience* and *labor skill*—all these elements jointly constitute the *productive forces* of society." The opponents of orthodox Marxism sharply criticized the reduction of the forces of production to technology. Lukács, attacking Bukharin's *Historical Materialism*, wrote: "Technique is a *part*, a moment, naturally of great importance, of the social productive forces, but it is neither simply identical with them, nor . . . the final or absolute moment of the changes in these forces."[15]

Interpretations of Marxism as technological determinism thus rest, in effect, on the equation "forces of production = technology." Yet even

defenders of the proposition that Marx was a technological determinist, such as William Shaw, find it difficult to impute this equation to Marx: "For Marx the productive forces include more than machines or technology in a narrow sense. In fact, labor-power, the skills, knowledge, experience, and so on which enable labor to produce, would seem to be the most important of the productive forces." So Shaw concedes that "technological determinism is a slight misnomer since Marx speaks, in effect, of productive-force determinism."[16] But much more is at stake than terminology. For if the forces of production include human labor power, then a productive-force determinism will look very different from a technological determinism as ordinarily understood. From his earliest writings on, Marx emphasized that what was specific about human work was that it was *conscious*:

> . . . free conscious activity is man's species character. . . . In *his work upon* inorganic nature, man proves himself a conscious species being. . . .
>
> A spider conducts operations which resemble those of the weaver, and a bee would put many a human architect to shame by the construction of its honeycomb cells. But what distinguishes the worst architect from the best of bees is that the architect builds the cell in his mind before he constructs it in wax. . . . Man not only effects a change of form in the materials of nature; he also realizes his own purpose in those materials.[17]

The inclusion of labor power as a force of production thus admits conscious human agency as a determinant of history: it is people, as much as or more than the machine, that make history.

The autonomy of technical change is likewise a proposition attributable to Marx only questionably, even if one accepts the equation between productive forces and technology. The "orthodox" position is that the productive forces have a tendency to advance but can be encouraged or held back by the relations of production. Stalin, for example, admitted that the relations of production "influence" the development of the forces of production, but he restricted that influence to "accelerating or retarding" that development. Not all Marxist writers have seen it like this, however. There is a change of terrain in the way the modern French Marxist Etienne Balibar shifts the metaphor away from "accelerate/decelerate": "The most interesting aspect of the 'productive forces' is . . . the *rhythm* and *pattern* of their development, for this rhythm is directly linked to the nature of the relations of production, and the structure of the mode of production." Lukács disagreed with the orthodox interpretation even more sharply: "It is altogether incorrect and unmarxist to separate technique from the other ideological forms and to propose for it a self-sufficiency from the economic structure of society. . . . The remarkable changes in the course of [technique's] development are [then] completely unexplained."[18]

The Difficulties of Determinism

In addition to the unclear meaning and questionable autonomy of the "forces of production," a further difficulty arises in reading the "1859 Preface" as technological determinism. That is the nature of the middle terms in the propositions it implies. Just what is the "determination" (or conditioning, or being the foundation of) exercised by the "totality of [the] relations of production"? What concept of determination is implied when it is said that the relations of production themselves are "appropriate" to "a given stage in the development of [the] material forces of production"?

On few topics has more ink been spilled. As Raymond Williams has pointed out, the verb "to determine" (or the German *bestimmen*, which is what the English translations of Marx are generally rendering when they write "determine") is linguistically complex. The sense that has developed into our notion of "determinism"—powerlessness in the face of compelling external agency—derives, Williams suggests, from the idea of determination by an authority (as in "the court sat to determine the matter"). However, there is a related but different sense of "to determine": to set bounds or limits (as in "the determination of a lease").[19]

If the determinative effect of the forces of production on the relations of production or of the relations of production on the "superstructure" can be read in this latter way, then our image of determination changes radically. It suggests not compelling causes but a set of limits within which human agency can act and against which it can push. It is an image fully compatible with another of Marx's aphorisms, that people "make their own history, but they do not make it just as they please; they do not make it under circumstances chosen by themselves, but under circumstances directly encountered, given and transmitted from the past."[20]

This is not an issue, however, that semantic debate alone can settle. Dealing with such topics, after all, we approach the conceptual core of a social science (any social science, not just Marxism). Variant readings of "determination" *are* possible, from simple cause-and-effect notions to G. A. Cohen's sophisticated defense of the thesis that the explanations

suggested by the "1859 Preface" are functional explanations ("to say that an economic structure *corresponds* to the achieved level of the productive forces means: the structure provides maximum scope for the fruitful use and development of the forces, and obtains *because* it provides such scope"). Erik Olin Wright argues, indeed, for making a positive virtue of diversity and incorporating different "modes of determination" into Marxist theory. Furthermore, debate on this issue can seldom be innocent. Profound political and philosophical differences entangle rapidly with matters of theory and methodology, as E. P. Thompson's essay "The Poverty of Theory" quickly reveals.[21]

Here we have reached the limits of the usefulness for our purposes of the exegesis of Marx's programmatic statements. The "1859 Preface" and similar passages will no doubt remain a mine, perhaps even a productive mine, for students of Marx's general theory and method. Students of technology, however, can turn their attention to a deposit that is both larger and closer to the surface: Marx's one extended and concrete discussion of technology.[22] Apart from its intrinsic interest (the main focus of what follows), this discussion throws interesting retrospective light on the more summary passages. In particular, it makes the thesis that Marx was a technological determinist in any strong sense extremely difficult to sustain, at least without invoking a peculiar and marked inconsistency between his general beliefs and his particular analyses.

The Labor Process and the Valorization Process

The chapter entitled "The Labor Process and the Valorization Process"[23] is the pivot of *Capital.* Marx, who up to that point had been analyzing chiefly the phenomena of the commodity, exchange and money, employed the full power of his skill as a writer to set the scene for the chapter: "Let us therefore . . . leave this noisy sphere, where everything takes place on the surface and in full view of everyone, and [enter] into the hidden abode of production, on whose threshold there hangs the notice 'No admittance except on business.' Here we shall see, not only how capital produces, but how capital is itself produced."[24] After the chapter, his argument built architectonically to the crescendo of "The General Law of Capitalist Accumulation" some 500 pages further on. While we will not follow him that far, this little chapter is central to an understanding of his discussion of machinery.

First, says Marx, we "have to consider the labor process independently of any specific social formation." He lists the "simple elements" of the labor process: "(1) purposeful activity, that is work itself, (2) the objects on which that work is performed, and (3) the instruments of that work." The labor process is a cultural universal, "an appropriation of what exists in nature for the requirements of man"; it is "common to all forms of society in which human beings live."[25] But it develops and changes through history.

Marx does not, as the technological-determinist reading would lead us to expect, turn now to the development of "the instruments of work." (It is interesting, indeed, that he subsumes technology, in the narrower meaning of "instruments," under the broader head of "the labor process.") Instead, he moves from the labor process in general to the labor process under capitalism, and from labor as a material process of production to labor as a social process. The process of production under capitalism is not just a labor process; it is also a valorization process, a process of adding value. The capitalist "wants to produce a commodity greater in value than the sum of the values of the commodities used to produce it, namely the means of production and the labor power he purchased with his good money on the open market."[26] He wants to produce a commodity embodying surplus value.

The distinction between the labor process and the valorization process is not a distinction between two different types of process, but between two different aspects of the same process of production. Take a simple example, the production of cotton yarn. Looking at that as a labor process means looking at the particular, concrete ways in which people work, using particular technical instruments, to transform a given raw material into a product with given properties. In any society that produces yarn it would be meaningful to examine in this way how it is done. But that is not all there is to the production of yarn under capitalism. The production of yarn as a valorization process is a process whereby inputs of certain value give rise to a product of greater value. The concrete particularities of the inputs and product, and the particular technologies and forms of work used to turn the inputs into the product, are relevant here only to the extent that they affect the quantitative outcome of the process.[27] Capitalist production processes, but not all production processes in all types of society, are valorization processes. The valorization process is the "social form" of the production process specific to capitalism.

Were Marx's theory technological determinism, one would now expect an argument that the labor process—the technology-including "material substratum"—in some sense dominated the "social form."

Quite the opposite. In his general statements on the matter (most of which are to be found in the unpublished chapter of *Capital*, "Results of the Immediate Process of Production"), Marx repeatedly argues that "the labor process itself is no more than the instrument of the valorization process."[28] And in *Capital* itself he presents an extended historical and theoretical account of the development of the capitalist production process—an account in which the social form (valorization) explains changes in the material content (the labor process). From this account let us select one central thread: Marx's history of the machine.

The Prehistory of the Machine

The history begins strangely, in that its central character is absent. The origins of capitalism, for Marx, lay not in a change in technology, but in a change in social relations: the emergence of a class of propertyless wage laborers.[29] "At first capital subordinates labor on the basis of the technical conditions within which labor has been carried on up to that point in history."[30] Archetypally, this took place when independent artisans (say textile workers), who previously produced goods on their own account, were forced through impoverishment to become employees. So instead of owning their spinning wheels or looms and buying their own raw materials, they worked (often in their own homes, under the "putting out" system) on wheels or looms belonging to a merchant, spinning or weaving raw materials belonging to him into a product that would be his property and which would embody surplus value. The social relations within which they worked had thus changed drastically; the technical content of their work was unaltered. This Marx describes as the "formal subordination" of labor to capital.[31] It was formal in that it involved a change in social form (the imposition of the valorization process) without a valorization-inspired qualitative alteration in the content of the labor process—without "real subordination."

Inherited labor processes were, however, severely deficient vehicles for the valorization process. Within their bounds, capitalists could increase surplus value primarily by the route Marx calls "absolute surplus value"—lengthening the working day. But that was not easily achieved. As Marx points out, the earliest statutes in Britain regulating the working day extend it, rather than limit it. But they were largely ineffective. It was often difficult to get workers to turn up for work at all at the beginning of the week (the tradition of "Saint Monday"). The intense, regular work required for valorization was a habit hard to impose. And outworkers without direct supervision had an effective form of disvalorization available in the form of embezzlement of raw materials, as historians more recent than Marx have emphasized.[32]

The ways capitalists sought to overcome these deficiencies in the labor process from the point of view of valorization are the subject of part 4 of volume 1 of *Capital*. The first that Marx discusses is "simple cooperation." This occurs when capital brings individual workers together "in accordance with a plan."[33] There is nothing specific to capitalism about simple cooperation: in all societies it will, for example, offer advantages in the performance of simple physical tasks, two people working together being able to lift a weight each individually could not. Nevertheless, simple cooperation offers definite advantages from the point of view of valorization.

The nature of these advantages highlights an important feature of valorization: it is not simply an economic process; it involves the creation and maintenance of a social relation. Certainly productivity is increased ("the combined working day produces a greater quantity of use-values than an equal sum of isolated working days"[34]), and the centralization of work can lead to savings in fixed capital. But, equally important, the authority of the capitalist is strengthened. For cooperation necessitates coordination. If you are lifting a weight, someone has to say "one, two, three . . . hup." Because the individual workers who are brought together by capital are subordinate to capital, that role of coordination becomes, in principle, filled by capitalist command—by capitalist *management*, to use an anachronism. The consequence Marx describes as follows: "Hence the interconnection between their [the workers'] various labors confronts them; in the realm of ideas, as a plan drawn up by the capitalist, and, in practice, as his authority, as the powerful will of a being outside them, who subjects their activity to his purpose."[35] A form of alienation is involved here—not psychological alienation, nor alienation from a human essence, but the literal alienation of the collective nature of work. That collective nature is here seen as becoming the power of another—of the capitalist. In addition, the physical concentration of workers under the one roof greatly facilitates the down-to-earth tasks of supervision: enforcing timekeeping and preventing embezzlement.[36]

Marx intended "simple cooperation" as an analytic category rather than as a description of a historical period in the development of the labor process (although more recent writers have specified a historical phase in which it was crucial).[37] The form of cooperation typical of the

period immediately prior to mechanization Marx describes as "manufacture."[38] (Marx, of course, uses the term in its literal sense of making by hand.) Crucially, manufacture, unlike the most elementary forms of cooperation, involves the differentiation of tasks, the division of labor. It arises in two ways. One is the bringing together of separate trades, as in the manufacture of carriages, where wheelwrights, harness makers, etc., are brought together under the same roof, and their work specialized and routinized. The other, and perhaps the more significant, is where the production of an item formerly produced in its entirety by a single handicraft worker is broken down into separate operations, as in the manufacture of paper, type, or (classically) pins and needles.

The division of labor involved in manufacture was often extreme. Marx spends nearly a page listing a selection of the trades involved in the manufacture of watches, and points out that a wire on its way to becoming a needle passes "through the hands of seventy-two, and sometimes even ninety-two, different specialized workers." The advantages from the viewpoint of valorization of this division of labor are clear. Labor is cheapened, according to the principle enunciated by Babbage in 1832: "The master manufacturer, by dividing the work to be executed into different processes, each requiring different degrees of skill or of force, can purchase exactly that precise quantity of both which is necessary for each process; whereas, if the whole work were executed by one workman, that person must possess sufficient skill to perform the most difficult and sufficient strength to execute the most laborious, of the operations into which the art is divided." Productivity is increased through specialization and the increased continuity and intensity of work, although at the cost of "job satisfaction": ". . . constant labor of one uniform kind disturbs the intensity and flow of a man's vital forces, which find recreation and delight in the change of activity itself."[39]

In addition, the division of labor in manufacture reinforces the subordination of the worker to the capitalist. Craft workers able to produce an entire watch might hope to set up independently; the *finisseurs de charnière*, "who put the brass hinges in the cover," could hardly hope to do so. Even more strikingly than in simple cooperation, under manufacture the collective nature of work, the interdependence of the different labor processes involved, confronts workers as the capitalist's power. The manufacturing worker, unable to perform or even understand the process of production as a whole, loses the intellectual command over production that the handicraft worker possessed. "What is lost by the specialized workers is concentrated in the capital which confronts them. It is a result of the division of labor in manufacture that the worker is brought face to face with the intellectual potentialities of the material process of production as the property of another and as a power which rules over him." The alienation of the collective nature of work has advanced one stage further, and the division of head and hand that typifies modern capitalism has begun to open up decisively. Marx quotes from a book written in 1824 a lament that the radical science movement of the 1960s and the 1970s would easily recognize: "The man of knowledge and the productive laborer come to be widely divided from each other, and knowledge, instead of remaining the handmaid of labor in the hand of the laborer to increase his productive powers . . . has almost everywhere arrayed itself against labor. . . . Knowledge [becomes] an instrument, capable of being detached from labor and opposed to it."[40]

And yet manufacture was not a fully adequate vehicle for valorization. The basis of the manufacturing labor process remained handicraft skill, however fragmented and specialized, and that skill was a resource that could be, and was, used in the struggle against capital. So "capital is constantly compelled to wrestle with the insubordination of the workers," and "the complaint that the workers lack discipline runs through the whole of the period of manufacture."[41] But, by one of the ironies of the dialectic, the most advanced manufacturing workshops were already beginning to produce . . . the machine.

Enter the Machine

Up to this point in his discussion, Marx makes effectively no mention of technical change, instead focusing exclusively on the social organization of work. It was not that he was ignorant of the technical changes of the period of manufacture. Rather, his discussion is laid out in the way it is to argue a theoretical point: that preceding organizational changes created the "social space," as it were, for the machine; and that the limitations of those changes created the *necessity* for it.

But what is a machine? Marx's chapter "Machinery and Large-Scale Industry" opens with what appears to be a rather pedantic discussion of the definition of "machine." Yet this little passage is highly significant because of the nature of the definition that Marx chose.

Marx rejected definitions that saw a continuity between the "tool" and the "machine"—definitions typical of "mathematicians and experts on mechanics." While it is true that any machine is analyzable as a

complex of more basic parts, "such as the lever, the inclined plane, the screw, the wedge, etc.," this "explanation is worth nothing, *because the historical element is missing from it.*" Nor does it suffice to differentiate the tool from the machine on the basis of the power source (human in the case of the former, nonhuman in the case of the latter): "According to this, a plough drawn by oxen, which is common to the most diverse modes of production, would be a machine, while Claussen's circular loom, which weaves 96,000 picks a minute, though it is set in motion by the hand of one single worker, would be a mere tool."[42]

Instead, Marx offers the following definition: "The machine . . . is a mechanism that, after being set in motion, performs with its tools the same operations as the worker formerly did with similar tools." This *is* a historical definition in two senses. First, Marx argues that of the three different parts of "fully developed machinery"—"the motor mechanism, the transmitting mechanism and finally the tool or working machine"—it was with innovations in the third that "the industrial revolution of the eighteenth century began." Changes in the source of motive power were historically secondary and derivative. Second, and more important, it is a historical definition in that it points up the place of the machine in the process that Marx was analyzing. The machine undermined the basis on which manufacturing workers had resisted the encroachments of capital: "In manufacture the organization of the social labor process is purely subjective: it is a combination of specialized workers. Large-scale industry, on the other hand, possesses in the machine system an entirely objective organization of production, which confronts the worker as a pre-existing material condition of production."[43]

Essentially, in machinery capital attempts to achieve by technological means what in manufacture it attempted to achieve by social organization alone. Labor power is cheapened, for example, by the employment of women and children. This is not merely a technical matter of the simplification of labor or of "machinery dispens[ing] with muscular power." Under manufacture, the division of labor had already created a wealth of jobs requiring neither particular skill nor particular strength; in any case, it is clear that these attributes are not naturally the exclusive preserve of adult males. Rather, the tendency to the employment of women and children had been "largely defeated by the habits and the resistance of the male workers."[44]

In the long run, the machine contributes to valorization crucially through the medium of "relative surplus value": the reduction in the labor time required to produce the equivalent of the worker's wage, with consequent increase in the surplus value accruing to the capitalist. In the short run, however, the machine also sets capital free to accrue absolute surplus value. By undermining the position of key groups of skilled workers, by making possible the drawing of new sectors into the labor market, and by threatening and generating unemployment, the machine "is able to break all resistance" to a lengthening of the working day.[45] And because work can now be paced by the machine, its intensity can be increased.

Most important, the alienation of the collective and intellectual aspects of work, already diagnosed by Marx in simple cooperation and manufacture, achieves technical embodiment in the machine. For "along with the tool, the skill of the worker in handling it passes over to the machine." The machine, increasingly a mere part of an automated factory, embodies the power of the capitalist: "The special skill of each individual machine operator, who has now been deprived of all significance, vanishes as an infinitesimal quantity in the face of the science, the gigantic natural forces, and the mass of social labor embodied in the system of machinery, which, together with these three forces, constitutes the power of the 'master.'"[46]

In the labor process of machino-facture, capitalist social relations thus achieve technical embodiment. It is characteristic of capitalism in all its stages that "the conditions of work," the means of production in their social form as capital, employ the worker, instead of the worker employing the means of production. "However, it is only with the coming of machinery that this inversion first acquires a technical and palpable reality." Before the machine, the worker still commanded the tool—and used this command as a source of countervailing power. From the viewpoint of the worker, the machine is thus a direct threat. It is "capital's material mode of existence."[47]

So class struggle within capitalism can take the form of "a struggle between worker and machine." Workers, of course, directly attacked machines (and still do, even if organized machine breaking has given way to less overt forms of "sabotage").[48] But the struggle, Marx emphasized, is two-sided. Capital uses machinery not only strategically, as outlined above, but also for precise tactical purposes. Where workers' (especially skilled workers') militancy poses a threat to valorization, capital can counter by promoting the invention and employment of machinery to undermine workers' power.

The theorist of this waging of class struggle by technical means was Andrew Ure, who concluded in his 1835 *Philosophy of Manufactures* that

"when capital enlists science into her service, the refractory hand of labor will always be taught docility." Marx cited inventions discussed by Ure—coloring machines in calico printing, a device for dressing warps, the self-acting spinning mule—as means of doing this, and he suggested that the work of inventors such as James Nasmyth and Peter Fairbairn had apparently been motivated by the exigencies of defeating strikers. "It would be possible," Marx judged, "to write a whole history of the inventions made since 1830 for the sole purpose of providing capital with weapons against working-class revolt."[49]

Marx's Account and the Historical Record

Capital was published in 1867. How well does Marx's account stand up in the light of over a century of historical scholarship? There is considerable agreement with his characterization of the overall process of the mechanization of production, even from those who would not regard themselves as standing in any Marxist tradition. David Landes writes: "For many [workers]—though by no means for all—the introduction of machinery implied for the first time a complete separation from the means of production; the worker became a 'hand.' On almost all, however, the machine imposed a new discipline. No longer could the spinner turn her wheel and the weaver throw his shuttle at home, free of supervision, both in their own good time. Now the work had to be done in a factory, at a pace set by tireless, inanimate equipment."[50]

The close connection between class conflict and technical innovation in nineteenth-century Britain has been noted moderately often in more recent historical writing. Landes writes that "textile manufacturers introduced automatic spinning equipment and the power loom spasmodically, responding in large part to strikes, threats of strikes, and other threats to managerial authority."[51] Nathan Rosenberg argues that "the apparent recalcitrance of nineteenth-century English labor, especially skilled labor, in accepting the discipline and the terms of factory employment provided an inducement to technical change," and lists particular innovations in which this process can be identified. Rosenberg's list largely follows Marx's, but he adds such items as the Fourdrinier paper-making machine.[52] While denying that the spread of the self-acting mule to America can be accounted for in this way, Anthony F. C. Wallace echoes Ure and Marx on its technical development: "The goal of inventors, from Crompton's time on, was to make the mule completely automatic so as to reduce to a minimum the manufacturer's dependence on the highly skilled, highly paid, and often independent-minded adult male spinners."[53] Tine Bruland argues that, in the case of the mule (and also in those of calico-printing machinery and devices for wool combing), it was indeed true that "industrial conflict can generate or focus technical change in production processes which are prone to such conflict."[54]

For a different historical context (Chicago in the 1880s), Langdon Winner draws on the work of Robert Ozanne to provide another example. Newly developed pneumatic molding machines were introduced by Cyrus McCormick II into his agricultural machinery plant to break the power of the National Union of Iron Molders. "The new machines, manned by unskilled labor, actually produced inferior castings at a higher cost than the earlier process. After three years of use the machines were, in fact, abandoned, but by that time they had served their purpose—the destruction of the union."[55]

The obverse of the capitalists' use of machinery in class struggle, workers' resistance to the machine, is too well known in the case of Britain to require special documentation. Interestingly, though, historians have begun to interpret that resistance differently. Luddism, it has been argued, was neither mindless, nor completely irrational, nor even completely unsuccessful.[56] The working-class critique of machinery, of which machine breaking was the most dramatic concrete expression, left a major mark on British thought. Maxine Berg has shown the extent to which the science of political economy was formed in Britain by the debate between the bourgeois proponents of machinery and its working-class opponents—and also its landed Tory opponents.[57]

Historians are also beginning to find resistance to the machine where it was once assumed that there had been none. Merritt Roe Smith's justly celebrated *Harpers Ferry Armory and the New Technology* shows that the "American system of manufactures"—the distinctive contribution of nineteenth-century America to the development of mechanized mass production—was resisted. The highly skilled armorers, and many of the institutions of the still essentially rural society in which they lived, opposed, often bitterly and on occasion violently, changes which meant that "men who formerly wielded hammers, cold chisels, and files now stood by animated mechanical devices monotonously putting in and taking out work, measuring dimensions with precision gauges, and occasionally making necessary adjustments."[58] The struggle documented by Smith between "the world of the craftsman" and "the world of the machine" at Harpers Ferry significantly modifies the assumption that "American workmen welcomed the American system."[59]

Marx's views on one particular key technology—the steam engine—have also found confirmation in G. N. von Tunzelmann's recent work. Marx's analysis, writes Tunzelmann, "is spare and succinct, encapsulating what emerge in my study as the truly significant links between steam-power and cotton." Von Tunzelmann finds himself in extensive agreement with Marx's argument that technical changes in the steam engine resulted from changing capital-labor relations in mid-nineteenth-century Britain. It may not have simply been the Ten Hours Act, restricting the length of the working day, that induced employers and designers to increase boiler pressures and running speed, but the need "for squeezing out more labor in a given time" was certainly important.[60]

This way of proceeding—comparing Marx's theory with more recent historical accounts—can, however, too easily become an exercise in legitimation, or an argument that, to quote Paul Mantoux, Marx's "great dogmatic treatise contains pages of historical value."[61] It also ignores real problems of evidence concerning the origins of certain innovations. It is indeed a fact, as Rosenberg notes, that in early nineteenth-century Britain it was widely agreed that "strikes were a major reason for innovations."[62] But the extent of that agreement is a different matter from whether it described the actual state of affairs. Neither the "discovery accounts"[63] of inventors such as Nasmyth nor the anecdotes and inferences of contemporaries such as Andrew Ure or Samuel Smiles, are necessarily to be taken at face value. Yet, in the still-common absence of historical research addressing such questions for particular innovations, more recent writers are often no better placed than Marx in terms of the sources open to them. Studies such as *Harpers Ferry Armory*, alive equally to the detail development of particular technologies and to the social relations of production, are still too rare to allow confident generalization.

Further, it would be quite mistaken to see Marx's account of the machine as completed. His account contains difficulties and ambiguities, and these need to be clarified in parallel with, and in relation to, its testing against "actual history." It is actually a theory, not a putative description of events. It is not a history of the Industrial Revolution, or even of the Industrial Revolution in Britain, but an attempt to develop a theory of the social causes of organizational and technical changes in the labor process. Uniform, unilinear developmental paths cannot properly be deduced from its premises. Actual history will inevitably be more complicated. Thus Marx himself had to turn, immediately after his discussion of machine production, to the very considerable continuing areas of domestic outwork and manufacture. Raphael Samuel's

major survey of the balance between "steam power" and "hand technology" in Marx's time shows the slowness of the process of mechanization. Indeed, Marx was arguably wrong to assume that outwork and small-scale manufacture were necessarily forms "transitional" to "the factory system proper."[64] A century after his death outwork still flourishes, even in some technologically advanced industries.[65] On occasion, valorization may be better served by decentralized rather than centralized labor processes.[66]

This example illustrates a general issue that became important as interest in Marx's theory revived during the 1970s. In the rush of theoretical reflection and empirical research about the labor process, writers sometimes conflated particular strategies that capital employs to further valorization with the goal of valorization itself. Capitalists were seen as *always* pursuing the deskilling of labor, or as *always* seeking maximum direct control over the labor process. But neither assertion is even roughly correct empirically, nor is either goal properly deducible from the imperative of valorization alone. "Skill" is not always a barrier to valorization; only under certain (common but not universal) circumstances does it become one. Direct control over the labor process is not always the best means of valorization.

Marx himself seems on occasion to postulate something close to a thesis of continual deskilling and of the creation of a homogeneous work force: "In place of the hierarchy of specialized workers that characterizes manufacture, there appears, in the automatic factory, a tendency to equalize and reduce to an identical level every kind of work that has to be done by the minders of the machines."[67] The outcome of the extensive research and debate occasioned by Harry Braverman's influential elaboration of the "deskilling" thesis can in part be summarized by saying that deskilling and homogenization are precisely "a tendency"—no more.[68] The imperative of valorization does bring about changes in the labor process that do away with capital's dependence on many human competences that once were necessary, these changes do undermine the position of groups of workers who owe their relatively high wages or ability to resist capital to their possession of these competences, and technology is crucial to this process. But these changes in the labor process also create the need for new competences, create new groups of "skilled" workers, and create types of work that are far from exemplifying the real subordination of labor to capital.[69] The very creation of these is often the obverse of the process of deskilling other occupations: computer programming is a contemporary example.[70]

Similarly with control. From a twentieth-century perspective, too much weight is placed in *Capital* on what Andrew Friedman calls a "direct control" strategy on capital's behalf. This strategy, of which Taylorism is the obvious example for the period after Marx's death, "tries to limit the scope for labor power to vary by coercive threats, close supervision and minimizing individual worker responsibility" and "treats workers as though they were machines." But "direct control" hardly captures the range of strategies for the management of labor power. Management can also involve a "responsible autonomy" strategy, trying "to harness the adaptability of labor power by giving workers leeway and encouraging them to adapt to changing situations in a manner beneficial to the firm . . . [giving] workers status, authority and responsibility . . . [trying] to win their loyalty, and co-opt their organizations to the firm's ideals."[71]

Again, there is nothing in Marx's theory to suggest that capital will seek maximum control over the labor process as a goal in itself, or that capitalists will necessarily prefer direct over indirect forms of control. A degree of control over the labor process is clearly a prerequisite for valorization, but the theory does not lay down how that control can best be achieved, nor does it imply that control should be pursued regardless of its costs. Supervisors, after all, cost money, and techniques of production that maximize direct control over labor power may be fatally flawed in other respects.

To present Marx's theory as hinging around valorization rather than deskilling or control points to the relevance to it of the traditional concerns of those economic historians who have made technology a central focus of their work.[72] The level of wages, the rate of interest, the level of rent, the extent of markets—all these would be expected to influence the choice of technique, and there are passages in Marx that show his awareness of this.[73]

Where the Marxist and the "neoclassical" economic historian would diverge, however, is in the Marxist's insistence that "factor costs" ought not to be treated in abstraction from the social relations within which production takes place. This is a persistent theme throughout *Capital.* Capital, Marx wrote, "is not a thing"; it is not a sum of money or commodities; it is "a social relation between persons which is mediated through things."[74] The relation between capitalist and worker is not simply a matter of wages and hours of work; it is also a matter of law and the state (in, for example, the worker's legal status as "free citizen" or otherwise), of supervision, discipline, culture, and custom, of collective forms of organization, power, and conflict.[75]

William Lazonick, in his study of the choice of technique in British and U.S. cotton spinning, argues that, although factor prices mattered, their effect was conditioned by the very different nature of production relations in such spinning centers as Oldham in Lancashire and Fall River in Massachusetts. Such facts as the preference of Lancashire mill owners for spinning mules and that of their New England counterparts for ring spinning have to be understood in the context of the different historical evolution of relations within the work forces and between workers and capitalists.[76]

Lazonick's work, though, is far from an uncritical confirmation of Marx. Indeed, it points up a major inadequacy in Marx's account—one that ties in closely with the problem of evidence mentioned above. Marx's reliance on sources such as the writings of Ure meant that he had quite plausible evidence for what class-conscious capitalists hoped to achieve from the introduction of the machine. But what they hoped for was not necessarily what happened. Marx quoted Ure's judgment on the self-acting mule: "A creation destined to restore order among the industrious classes." Lazonick's work shows that the mule had no such dramatic effect. In Lancashire, "adult male spinners (now also known as 'minders') retained their positions as the chief spinning operatives on the self-actors," developed a strong union, achieved standardized wage lists that protected their wage levels, and kept a fair degree of control over their conditions of work. Such was the failure of the self-acting mule in increasing capital's control that when ring spinning was introduced in New England it was talked about in precisely the same terms as the self-actor had once been—as a curb on "obstreperous" workers—only this time these were the minders of self-acting mules![77]

In part, the failure of capitalists to achieve their goals can be put down to workers' resistance; to the extent that it can be explained in this way, it offers no fundamental challenge to Marx's account. Workers are not passive clay in capital's hands; quite the opposite. Even highly automated factories with close, harsh labor supervision offer major opportunities both for individual acts of noncompliance and for collective action to change conditions.[78] Further, the very fact that the labor process, however much it is affected by the valorization process, remains a material process of production constrains what capital can achieve. In his work on automatically controlled machine tools, David Noble found that, despite all their efforts, managements were unable to do without skilled machinists. As one machinist put it: "Cutting metals to critical tolerances means maintaining constant control of a continually changing

set of stubborn, elusive details. Drills run. End mills walk. Machines creep. Seemingly rigid metal castings become elastic when clamped to be cut, and spring back when released so that a flat cut becomes curved, and holes bored precisely on location move somewhere else. Tungsten carbide cutters imperceptibly wear down, making the size of a critical slot half a thousandth too small." Experienced machinists were needed to make sure that "automatic" machines did not produce junk parts or have expensive "smashups."[79]

The intractability of both workers and the material world is, however, not fully sufficient to explain the type of development described by Lazonick. Here we come to an area where Marx's account clearly requires modification. The social relations of production within which technology develops are not simply between worker and capitalist, but also between worker and worker. Crucially, they include relations between male workers and female workers, between older workers and younger workers, and, sometimes at least, between workers of different ethnic groups.

Marx was of course aware of the division of labor by age and sex, but he slid far too readily into a facile description of it as "natural."[80] Lazonick's account of the history of the self-acting mule, for example, shows that adult male minders in Britain retained their position not through any "natural" attributes, nor because of their power to resist capital, but because British employers found useful, indeed indispensable, the hierarchical division in the work force between minders and "piecers," whose job it was to join the inevitable broken threads. And this relation within the work force conditioned technical change. It made it rational for capitalists to work with slightly less automated mules than were technically possible, so that failures of attention by operatives led not to "snarls" that could be hidden in the middle of spun "cops" but to the obvious disaster of "sawney," where all of the several hundred threads being spun broke simultaneously, with consequent loss of piecework earnings for the minder.[81]

Of the divisions within the work force that affect the development of technology, that between women and men is perhaps the most pervasively important. Marx's account captures only one of the (at least) three ways in which this division interacts with change in the technology of production. He focuses on the very common use of machinery plus low-paid, less unionized women workers to replace skilled men. Ruth Schwartz Cowan, in her review of "women and technology in American life," shows this process at work in American cigar making.

But she also points to the very different situation of the garment industry, arguing that there the sewing process had not been automated (beyond the use of the sewing machine) in large part because of the availability of "successive waves" of immigrant women. Their undoubted skills cost employers nothing extra. Those skills were learned largely in the home, rather than at the employers' expense. And because sewing is "women's work," it is defined as unskilled (Phillips and Taylor argue that this, not the opposite as commonly assumed, is the real direction of causation) and thus is poorly paid.[82]

A third form of the interaction between gender divisions and workplace technology is that identified by Cynthia Cockburn in her study of the history of typesetting technology in Britain. Up to a point, the process was exactly parallel to that described by Marx. Employers sought to invent a machine that could "bypass the labor-intensive process of hand typesetting," thus undermining the well-paid, well-unionized male hand compositors. By the end of the nineteenth century several such mechanized typesetters had become available, and the compositors and their employers struggled over their introduction. But here the story diverges from Marx's archetype. The male compositors (like the mule spinners) were able to retain a degree of control over the new technology, and the machine that became the dominant means of mechanizing typesetting, the Linotype, was the one that offered least threat to their position. Unlike its less successful predecessor, the Hattersley typesetter, the Linotype did not split the process of typesetting into separate parts. As the men's union, the London Society of Compositors, put it, by not splitting up the process "the Linotype answers to one of the essential conditions of trade unionism, in that it does not depend for its success on the employment of boy or girl labor." The choice of the Linotype, backed up by vigorous campaigning by the union to exclude women, eventually left the composing room still "an all-male preserve." Technology, according to Cockburn, can thus reflect male power as well as capitalist power.[83]

The Politics of Design and the History of Technology

Perhaps the most intriguing question of all those that are raised by Marx's account of the machine is one that Marx neither put clearly nor answered unequivocally: Does the design of machinery reflect the social relations within which it develops? Do capitalists (or men) merely abuse machinery for their own purposes, or do those purposes somehow shape the machine?

At this point, of course, the issues raised by Marx's theory converge with a central question—perhaps the central question—of the history of technology. George Daniels posed it when he organized his essay "The Big Questions in the History of American Technology" around the "nature and the direction of causation" in the relationship between technology and society, asserting his belief that "the direction of the society determines the nature of its technological innovations." "The influence of economics, politics, and social structure on technology" is among the topics mentioned by Thomas Hughes in his survey "Emerging Themes in the History of Technology." According to Carroll Pursell, arguments about the neutrality of technology—whether "the purposes (ethics and values) of our society are built into the very form and fabric of our technology"—have "grave implications . . . for the way in which the history of technology is studied and taught." If the history of technology needs to be rescued, as David Hounshell believes, from becoming "increasingly internalistic" in its approach, then pursuit of this question offers a way of combining attention to technical detail with concern for broader issues of social history.[84]

Replying to Hounshell, Darwin Stapleton notes that Karl Marx "has always been in the background" of the history of technology.[85] Unfortunately, Marx himself equivocated on this crucial question. Sometimes he appears to treat machines as subject to abuse by capital but not in their design inherently capitalist: "It took both time and experience before the workers learnt to distinguish between machinery and its employment by capital, and therefore to transfer their attacks from the material instruments of production to the form of society which utilizes those instruments." Marx also writes, however, that a "specifically capitalist form of production comes into being (at the technological level too)."[86] While it seems to me that extending Marx's theory to the level of detailed technical design would be a natural step, we have no unequivocal evidence that Marx took it. *A priori*, it would not be unreasonable (indeed, as outlined above, it would be orthodox) to accept that the *pace* of technical change was affected by social relations—that mechanization was hastened by valorization-imposed needs to undermine the power of skilled workers, for example—while denying that those relations affected the actual design of technical artifacts. Without clear information about what Marx believed, we can but turn to the more important question of what actually is the case.

Fortunately, historians have found it possible to obtain at least partial, tentative answers to the question of the effect of social relations on technical design. Perhaps the most straightforward way of doing this hinges on documenting the *contingency* of design, identifying instances where "things could have been different," where, for example, the same artifact could have been made in different ways, or differently designed artifacts could have been constructed. Having identified contingency, the historian can then ask why one way, or one design, was chosen rather than another. In that way the question of the effect of social relations becomes a matter for empirical inquiry as well as for theory.[87]

Langdon Winner's stimulating essay "Do Artifacts Have Politics?" provides a rudimentary but clear example. Robert Moses could have had the bridges over Long Island's parkways constructed with a wide range of clearances. He chose to build them low, with "as little as nine feet of clearance at the curb." The reason, Winner argues, was that the buses which might otherwise take poor people along the parkways to Moses's "widely acclaimed public park" at Jones Beach were 12 feet high![88] (Why contingency is important is obvious here. If it had not been clearly possible for Moses to choose to build higher overpasses, we would have no way of assessing the relevance of his social prejudices to his bridge design.)

There is of course nothing new about the approach of identifying contingency,[89] nor is identifying contingency in itself enough.[90] An explanation of the causes of the choices actually made is necessary too. But here Marx's theory *is* useful, because it does suggest where to look for such an explanation—in the area of the technology of production, at least. In any society, the design of production technology will reflect the need for that technology to be part of a labor process that is a functioning whole. This implies obvious physical constraints: the instruments of production must be compatible with the raw materials available. But it also implies social constraints. The labor process in a capitalist society must function effectively not simply as a material process of production but also as a valorization process. Production technology will thus be designed with a view to ensuring successful valorization, and valorization will typically not simply be a matter of "profit maximizing" but will involve the creation and maintenance of desired social relations.

David Noble's analysis of the automation of machine tools can be seen as an attempt to apply this perspective to technical design. Noble identifies contingency in that development. There were *two* ways to automate—record-playback and numerical control—and it is far from clear that only numerical control was *a priori* viable. Noble also identifies a

problem of valorization: the capacity of skilled machinists to control the pace of production, or indeed to disrupt it completely. He suggests that the choice of numerical control reflected its perceived superiority as a solution to this problem of valorization. As one engineer central to the development of both systems put it: "Look, with record-playback, the control of the machine remains with the machinist—control of feeds, speeds, number of cuts, output; with N[umerical] C[ontrol] there is a shift of control to management. Management is no longer dependent upon the operator and can thus optimize the use of their machines. With N.C., control over the process is placed firmly in the hands of management—and why shouldn't we have it?"[91]

Contingency and the Politics of Technology

There is of course one major objection to making contingency the way into the study of the social relations embodied in the actual design of artifacts and of the technologies of production: we may not be able to identify contingency. The most obvious way to legitimate any particular design decision or choice of technique is to say it is "technically necessary." A vested interest thus typically arises in disguising the actual extent of contingency. Even more serious, particular ways of designing things and making things can become so routine and habitual that our minds may be closed to the possibility of doing things otherwise. Though Seymour Melman may be right that choice in production techniques and the consciousness of choice among engineers and designers are pervasive, the parameters within which choice operates may well be much narrower than those within which it could operate.[92]

Several attempts have been made to reveal the extent of contingency by designing "alternative technologies." Best known are the efforts to embody in technology the virtues of small scale, decentralization, and ecological awareness. But there have also been attempts from within high-technology industry to alter in fundamental ways both what is produced and how it is produced. In Britain this was best exemplified by the "alternative plans" put forward by the work force at Lucas Aerospace. These plans involved attempts to shift production from military to "socially useful" products, and also to change the nature of production—to reverse deskilling and the separation of head and hand. The Lucas employees' work in this latter sphere seems to have been informed explicitly by Marx's analysis of the machine.[93]

Whatever the eventual success or failure of efforts to alter the nature of technology, our understanding of how technology changes can only

profit from them. By making contingency and choice actual rather than merely hypothetical, they throw into ever-sharper light the ways in which social relations shape technical development. Perhaps, too, the process can be dialectical rather than one-way. Perhaps understanding how existing technology has been and is being socially shaped can help in reconstructing it. If that can be so, and if Marx's account of the machine is useful to that understanding, then the shade of Marx will surely be happy, for it was of the essence of the man that he believed not simply in understanding the world but also in changing it.[94]