Cyborg History and the World War II Regime

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The Second World War was a watershed in history in many ways. I focus on the World War II discontinuity as it relates to the intersection of scientific and military enterprise. I am interested in how we should conceptualize that intersection and in offering a preliminary tracing of the "World War II regime" that has grown out of it—a regime that includes new forms of scientific and military practice but that has invaded and transformed many other cultural spaces, including—my primary example here—the industrial workplace. I exploit the figure of the cyborg to (1) thematize the social, material, and conceptual heterogeneity of the developments at issue; (2) specify a distinct range of cyborg objects and sciences that emerged from the World War II matrix; and (3) exemplify a historiographical approach that escapes the traditional master-narrative structures of science studies.

1. Introduction: Theory and History

The havoc interpretation wreaks in the domain of appearances is incalculable, and its privileged quest for hidden meanings may

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be profoundly mistaken. (JEAN BAUDRILLARD, "On Seduction" [1988, p. 149])

The grand narrative has lost its credibility. (JEAN-FRANÇOIS LYOTARD, *The Postmodern Condition* [1984, p. 37])

This is a preliminary essay in what I hope will prove to be a longer-term project, aiming to interrogate the intertwining of science, technology, and society in the constitution of what, for want of a better word, one can call postmodernity. The essay, like the project to follow, has two interconnected aims that need to be explained in advance. One is "theoretical"; the other, properly historical.

I begin with theory. My problematic originates in science studies—history, philosophy, sociology, and so on, of science—though it is by no means unique to that field. Science studies have traditionally been dominated by the three great master narratives of Nature, Reason, and Society. Accounting for science is taken to consist in the construction of more or less causal explanations for historical developments in terms of the behind-the-scenes operations of one (or more) of these great actors. Philosophy's job is to dig out the Reason (as Method) that has (or should have) controlled the history of the production of scientific knowledge, Sociology's job is to excavate the Social Interests behind the same, and so on. In common with an increasing number of scholars, in science studies and well beyond it, I have my doubts. My own studies of scientific practice convince me that, in various ways, the pursuit of the master narratives is a dead end, that such stories of science are, at best, necessarily retrospective, while I want to understand history in real time, as it happens, without recourse to endpoints located in the historical future. It seems to me that nothing is a fixed or reliable cause in history. Instead of looking to Nature, Reason, or Society in our accounting, we need to be aware that everything is at stake: the material, the conceptual, the technical, the human, and the social.[1] All of these cultural elements and strata are always open-endedly transformable into the future, and, furthermore, the actual trajectories of their extension are interactively determined in the production of alignments between them (in temporally emergent dialectics of resistance and accommodation that I call mangling; see Pickering 1995). This, at any rate, is what emerges from the study of scientific practice at the microlevel of individuals and small groups. And one aim of my project is thus to see whether and how this nontraditional

1. These are commonsense, not theoretical/foundational, categories, hence the disappearance of the capital letters.

perspective works when extended to the macrolevel. More remains to be said, however, about theory and questions of agency.

Traditional science studies are asymmetric about agency, recognizing genuine agency only in the human realm but not in nature, which is typically regarded as inert matter, passively awaiting representation. Thus philosophers of science have feared human agency (wants, desires, motives) and sought to police it via Reason, understood as Method. Sociologists of science have sought, instead, to understand human agency (Interests) as a genuine cause of belief and cultural extension. Again, in common with others, my studies convince me that this asymmetric distribution of agency is untenable, especially when issues of science and technology are at stake. Most obviously, it seems to me that machines *do things* that unaided human minds and bodies cannot. Machines, that is, are performative agents in a sense precisely analogous to disciplined human agents. Less obviously, perhaps, I think that we need to let agency rise to the surface in our understanding of science, technology, and society. On the one hand, instead of searching for hidden causes in the domain of human motivation, say, we need to think about the explicit performances of material objects and human beings; on the other, we need to see human motivations themselves as bound up in all sorts of ways with machines and disciplines—as themselves at stake in practice, as I put it above.[2]

My idea, then, is to explore the possibilities for a macrohistory of science, technology, and society in what I call the performative idiom, in terms of the interplay of human and nonhuman agency as temporally emergent in practice. There is, as it happens, a nice word for the intimate conjunction of the human and the nonhuman that, as it also happens, derives from one of the topics I want to explore historically. The word is "cyborg," an abbreviation for "cybernetic organism" and denoting a part-human, part-machine actor in which the two parts are constitutively coupled to one another.[3] I want to think how to do cy-

2. One referee suggests that I am trying, unsuccessfully, to "have it both ways" in imputing agency to machines while still speaking of human motivations. Against this, I would say that symmetry is not identity: I do not insist that all agents possess the same specific features. For more on how human goals might be conceptualized within my overall interpretive scheme, see Pickering (1993*a*, 1995).

3. When I wrote this essay I thought that the word "cyborg" came originally from science fiction: I thank Donna Haraway and Chris Hables Gray for correcting me, and the latter for sending me a copy of Clynes and Kline (1960)—a summary of a technical paper presented at a conference sponsored by the U.S. Air Force in which the term appears to have been used for the first time. Donna Haraway's "Manifesto for Cyborgs" (1985) put cyborgs into circulation in science studies. A referee asks about the relation between "cyborgs" and "networks." The latter is, of course, a key term of art in actor-

borg history. I should add that cyborg history is not just about human and nonhuman performances. It has to be about knowledge and representation, too. But the idea is to explore how knowledge and systems of representation fit into the performative field rather than study them as autonomous objects.

I will make one last general comment on theory and historiography before I turn to my specific project. Traditional master narratives have a way of drawing attention to themselves. They isolate and invite us to contemplate the invariant skeleton behind the flux of appearances: history as the working out of Reason, or the play of a standard list of Interests—the endless repetition of the same. Actual historical developments appear as props to such master narratives, not the thing (hidden, to be revealed) itself. Of course, something similar might be said of cyborg history. I have just sketched in, very crudely, my own general picture of history—as the open-ended transformation of culture in all of its heterogeneous dimensions in an ever-evolving play of human and nonhuman agency. The point to stress, however, is that despite this generality and the sameness that it implies, cyborg history continually returns us to historical specifics. It does not invite us to imagine a story behind what visibly happened; it does not invoke hidden substances as explanations. History *is* the open-ended extension of culture in fields of agency, and all that cyborg history has to offer is the specifics of this process, at particular places and particular times. Cyborg history thus fosters a kind of double vision, thematizing the general and the particular both at once. Furthermore, in cyborg history the particular is a heterogenous assemblage of the material, the social, the conceptual, and so forth. Cyborg history, then, requires us to pay attention to all of these strata of culture and their evolution at once. It implies a *rebalancing* of historiography away from its traditional obsession with homogeneous categories like Reason.

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I suggest that we forget about writing the history of Nature or Man (Reason and Society) as theorized in terms of their hidden properties. We should write instead a history of cyborgs—situated, heterogeneous couplings of the human and the nonhuman in their visible performa-

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network theory (e.g., Latour 1987) to which the present analysis owes much. I prefer to use the term cyborg here because (1) it immediately conjures up the heterogeneity at issue, and (2) the image of a network is topologically inadequate to get at the complexity of some of the transformations to be discussed: it cannot, for example, do justice to the concept of "enfolding" introduced in the next section.

tivity. But the question remains: which cyborgs? If one insists that the evolution of the human, the social, the material, and the conceptual are all truly open-ended, there can be no principled answer to that question: one can find cyborgism everywhere. But one can choose specific sites, recommended by their historical importance—for understanding our postmodern condition, for example. And I want to examine the construction of an especially significant scientific-military cyborg in World War II and its subsequent evolution (mutation, dispersal, recombination, proliferation, cross-breeding) into our present, as what I call, echoing Foucault, the World War II regime.[4]

Thus, my theoretical and historically specific interests and aims are as follows. In Section II, I discuss the social, material, technical, and conceptual conception and birth in World War II of the cyborg in question. I am particularly concerned with the ways in which the prewar boundaries between science and the military were breached, with what flowed through the breaches, and with transformations in scientific and military practice that sustained and were sustained by those breaches and flows. In Section III, I both narrow the focus, discussing a range of cyborg objects and cyborg sciences that owed their genesis to World War II—objects and sciences that in different ways destabilized the boundary between the human and the nonhuman—and widen it again, indicating very briefly some material, social, and conceptual lines along which the World War II regime propagated itself into our present. Section IV follows one of those lines in a little more detail, via some observations on the automation of the industrial workplace. This article is, then, about three layers of cyborgism: the overall hybridization of science and the military in World War II; the birth of cyborg objects and sciences in World War II and their subsequent evolution; and the cyborgization of industry.

4. The question of periodization arises here. I think that the heterogeneous cultural transformations effected in World War II were sufficiently far-reaching that one can regard World War II as a discontinuity, marking off an increasingly postmodern postwar world from all of the worlds that preceded it. But this is not the only discontinuity that cyborg history needs to register. Obviously, the Industrial Revolution of the late eighteenth and nineteenth centuries is crucial. The birth of industrial and governmental research laboratories and the development of scientific management in the late nineteenth and early twentieth centuries mark another discontinuity. Earlier, Mary Voss's (1994) analysis of the intertwining of practical mathematics with the concerns of bombardiers at the birth of modern physics is a persuasive argument that the Scientific Revolution itself marks a significant date in cyborg (as well as representationalist) history. In this sense, to focus on World War II is to start in midstream. My suggestion is not that cyborgism began in World War II; it is simply that it took on new forms and a new intensity then.

I have two final introductory remarks. First, especially in writing Sections II and IV, a literary image from William Gibson's (1984) novel *Neuromancer* has never been far from my thoughts. In relation to the profusion of computers and computer networks in 1980s science fiction, the great originality of *Neuromancer* is that the human action takes place inside a computer database—cyberspace, as Gibson calls it.[5] This is a topological image, of the rearrangement of actors and events in a literal or metaphorical space, and much of what we will be examining needs, I think, to be understood in similarly topological terms. To get to grips with this, I appeal to biological imagery in Section II; in Section IV I invoke cyberspace itself. Second, I should make it clear that what follows is based upon other people's historical research, not my own. I have, in fact, drawn upon a range of academic and popular historiographic genres: history of ideas, history of technology, institutional, and military history, biography, and autobiography. My contribution, such as it is, is to observe that these diverse sources can be combined to construct a "big picture" that seems to go unremarked by all of them, the picture of the multiply interlinked heterogeneous assemblage that I call the World War II regime.[6]

II. Science and the Military in World War II

> War is the father and king of all. (HERACLITUS, quoted in Guthrie [1962, p. 444])

> Suppose we considered the war itself as a *laboratory?* (THOMAS PYNCHON, *Gravity's Rainbow* [1975, p. 49])

> We were into the Navy more deeply than anyone had thought possible for civilians, and I felt we could penetrate more deeply still. (PHILIP MORSE, *In at the Beginnings* [1977, p. 187])

5. Since I find myself repeatedly mentioning cyberspace—equivalently, virtual reality—as the essay goes on, I should explain what it is. Crudely, a virtual reality is an all-encompassing computer-generated environment. One can think of the typical arrangement in which the cybernaut wears a pair of goggles to view an artificial 3-D computer-generated space and moves through this space by pointing with a glove (see Benedikt 1991; McCaffery 1991; Rheingold 1991). I indicate some lines leading from World War II into cyberspace below, but I should note that I ignore the important intertwinings of computer technology and the entertainment industry (Rheingold 1991).

6. On the renewed interest in, and heightened awareness of the perils of, macrohistoriography in the history of science, see Secord (1993). The claim that there is a big picture of the World War II regime that remains to be delineated is at once a critique of the genres on which I draw and of the microdisciplinarity that goes with them (Pickering 1993*b*); that many of my sources are richly contextualized indicates that contextualism alone is no antidote to tunnel vision. The master-narrative blueprints are the prob-

In this section I want to thematize some key developments centered upon the intersection of scientific and military enterprise in World War II, especially as they were manifested in the United States. My principal text is the classic overview of these developments, Kevles ([1978] 1987, chaps. 19 and 20). Recalling that my interest is in understanding the intertwined evolution of human, social, conceptual, and material cultural strata, I begin with the material technoscientific inputs to the fighting of World War II, then turn to the social and technical transformations of science and the military that accompanied the scientific construction and military use of these new gadgets, and then talk about one of the new conceptual technologies that also served to engage science with the military in this period. In this way, I want to arrive at a crude delineation of the material, social, and conceptual scientific-military cyborg that was a principal product of World War II.

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When people think about the intersection of scientific and military enterprise in World War II they tend to think first about hardware, about novel technoscientific objects—above all, about atom bombs, but perhaps as well about radar and hi-tech electronics, and about rockets and the V–2s that fell on the south of England before the end of the war. All of these objects left their marks not just on the battlefield, but also—in an amazing proliferation of descendants—on the peace that followed (as well as on subsequent wars). I focus upon radar here, since it was at the heart of the social and conceptual transformations at issue.[7]

Since radar is a familiar enough technology, I do not need to say much about it here as a material device. Briefly, the radar technology of World War II was modeled upon the sonar technology of World War I.[8] Sonar is a technique for determining the range and direction

lem. (In Pickering [1992] I discuss the peculiar figure/ground, content/context switches of gestalt that the best contextual history can induce in the reader.)

7. While it was the most spectacular scientific product of science in World War II, the atom bomb strikes me as a singularity; its history, from the Manhattan Project and the Los Alamos Laboratory up to the conspicuous nonuse of thermonuclear weapons in the Cold War, reflects upon little except itself. Rocketry was a German specialty in World War II, though it would be interesting to study its postwar recontextualization (complete with V–2 rockets and Wernher von Braun) in the United States (see DeVorkin 1987 and McDougall 1985).

8. The reference here and below to "models" and "modeling" point to an interpretive scheme I have developed elsewhere (at greatest length in Pickering 1995) and which I will not elaborate in this essay. The basic idea is that practice should be understood in

of material objects (ships) by measuring the elapsed time between emission of a sound pulse and the return of its echo: the distance of the reflecting object follows immediately from a knowledge of the speed of sound. Radar works similarly, but using pulses of electromagnetic radiation instead of sound. Primitive radar sets were developed in the 1930s (Kevles 1987, pp. 290–91), and much of the scientific work on radar during World War II (and after) was devoted to the development of high-powered sources of high-frequency radiation, in an effort to achieve precise location of distant targets with compact sets (tailored to particular uses). Two points about radar are worth stressing. First, radar sets are, in my terms, *material agents*. Their entire significance lay in the fact that they did things that naked humans could not: seeing beyond the range of human sight or in conditions that severely limited human vision (through fog, clouds, smoke, in the dark, etc.). Second, the performativity of radar was of a specific kind. Unlike bombs, say, radar sets were agents of representation and surveillance; instead of dismembering human beings or property (the prototypical activity of warfare), radar sets produced maps.[9]

If everyone thinks of the World War II intersection of science and the military in terms of the material contributions of the former to the latter, few people—except some historians and Thomas Pynchon—think about the social transformations that accompanied these material flows. But, as I shall now attempt to explain, social and material transformations hung together and reinforced one another. As a baseline, we can note that before World War II, science and the military in the United States were more or less decoupled. To introduce a biological image that I find helpful in keeping track of the topological transformations involved, the two institutions were like two complex cellular organisms, each with its own cell wall or boundary across which little was transported from one to the other (fig. 1).[10] The armed ser-

general as a process of open-ended modeling, taking existing culture as its point of departure but having no determinate advance destination. Trajectories of cultural extension then take the form of real-time dialectics of resistance and accommodation in relation to captures of agency and the production of alignments within a multiple and heterogeneous cultural field.

9. Surveillance is a theme that runs through this section (and reappears in Sec. IV) but that I will leave undeveloped in this essay. It indicates another angle, I think, at which one could approach my topic. Irving Elichirigoity (1994) talks about the development of a distinctive "machine vision" running from radar in World War II up to the global satellite surveillance of the present.

10. Each of these cells (science and the military) had an inner cyborg structure in which social, material, and conceptual elements were reciprocally tuned to one another

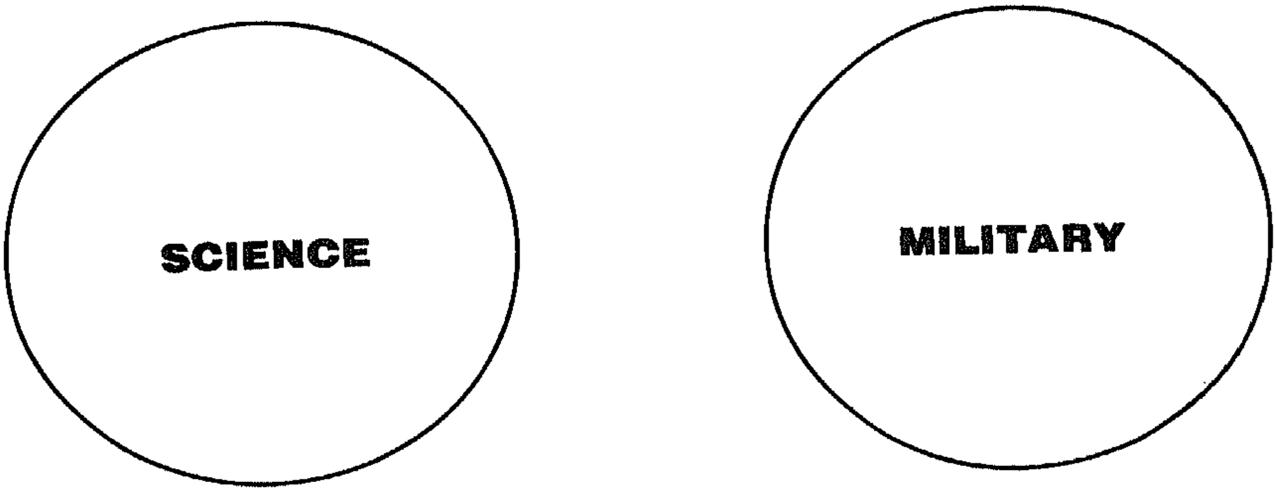

Figure 1. Science and the military before World War II

vices did have their own technical bureaus, but their effectiveness was circumscribed by "small budgets, lack of interservice cooperation, and limited contacts with civilian science" (Kevles 1987, p. 290).

In the eighteen months before the United States entered the war in December 1941, however, this situation had already begun to change. The impetus for the transformation came from civilian scientists who felt that they had more to contribute to the war effort than the military recognized, and its institutional vehicles were first the National Defense Research Committee (NDRC) and then the more powerful Office of Scientific Research and Development (OSRD).[11] These novel social formations were, I want to say, loci of fusion of science and the military,

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(on science, see Pickering 1995), but I am concerned here with the transformations that eventually linked them together.

11. Two points can be added. First, in writing this essay, the distinctive contribution of mathematicians to the war effort has become more apparent to me. Here one would need to think about the work of the Applied Mathematics Panel (AMP) of the NDRC, formed in late 1942 (headed by Warren Weaver, assisted by Mina Rees). Leonard (1992, pp. 62–67) gives a useful overview of the work orchestrated by the AMP. Second, I can note that in all of the sources I have consulted, the progressive entanglement of science with the military in World War II is told as a seduction narrative in which scientists took the lead against the resistance of the military. It is interesting that scientists and the military respectively took up classically feminine and masculine positions in this seduction. The military went out to fight, of course, while the scientists stayed "at home"; but also, part of the scientists' seduction strategy was to take no credit for their contribution to the fighting, trying to enmesh the military in scientific research to such an extent that the military could believe that innovations actually originated with them, and so on. At the same time, the military often regarded the scientists as stereotypically feminine: wild, unpredictable, dangerous, unreliable, mad—out of control. These observations prompt me to wonder about the apparently complex sexuality of many of the key scien-

in the sense that they were staffed and run jointly by scientists and military men.[12] The image is that of the two cells extending small polyps that coalesced at their tips. The linkage, however, functioned asymmetrically, acting largely upon science but not upon the military.

One of the first tasks undertaken by the NDRC was that of surveillance, namely, the survey-mapping of the contemporary scientific resources of the United States (Kevles 1987, p. 298).[13] This mapping was not undertaken for its own sake; instead it generated an archive (as Foucault [1972] used the term) on which the NDRC and OSRD could act. And the action took the form of a kind of tuning of the technical practice and performativity of science as a macroactor, via the letting of research contracts and the establishment of new laboratories. To see how this worked, we can look briefly at one of the most successful of the new scientific institutions established by the NDRC, the Radiation Laboratory set up at MIT for research and development on radar technologies—the Rad Lab, as it was known. Scientific practice at the Rad Lab was tuned and aligned with military enterprise in several senses. First, it was oriented to specific objects (power sources for radar sets, etc.) that were of no special interest to science (in its prewar evolution) but that were valued for their peculiar performativity (see Forman 1987 on the distinctive wartime and postwar turn to objects and "technique"). Second, scientific practice around these objects was organized in the then-novel form that we now call big science, characterized by the formation of mission-oriented, hierarchically organized, interdisci-

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tists involved. This all-male cast typically portrays itself in autobiographies as successful with and delighting in the company of attractive women (see the photo of von Kármán at age 80 in von Kármán and Edson 1967). At the same time, these men often do not marry, or marry unsuccessfully, and their relations with one another often seem to me best described as love (Alvarez and Lawrence; Morgenstern and von Neumann). I have no idea where to go with this line of thought. ("John Williams, head of RAND's math division, adored Johnny von Neumann, and was thrilled when ... he convinced von Neumann to join RAND," "John Williams' mentor and idol, Warren Weaver . . . delivered the opening address" [Kaplan (1983) 1991, pp. 64, 72].)

12. These organizations were modeled upon the prewar National Advisory Committee for Aeronautics, of which Vannevar Bush became chair in 1939 before he became chair of the NDRC and Director of the OSRD (Kevles 1987, pp. 292–301). Although Kevles says that the NDRC included "a delegate each from the army and the navy" (p. 297), Paul Forman warns me not to exaggerate the military presence on it and the OSRD.

13. There was a degree of symmetry here, in that "Karl Compton made the rounds of the military agencies and compiled a list of critical projects" (Kevles 1987, p. 298).

plinary teams of scientists, engineers, and technicians.[14] And third, returning to the orientation to objects, we can note that the tuning of scientific practice in alignment with the military was even more precise than so far acknowledged.

The NDRC and OSRD could let contracts to encourage scientists to work on devices judged to have military potential, but the effort was in vain if such devices did not, in fact, *circulate* from the wartime labs into military use, and such circulation was intrinsically problematic. For instance, the Rad Lab initially focused on the development of an aircraft-detection radar system called the AI–10, but the services declined to put this system to use. At this point the Rad Lab as a social institution came close to collapse, and it was only kept in existence by John D. Rockefeller, Jr., who anonymously underwrote Rad Lab salaries. Eventually, however, the lab switched its attention to antisubmarine warfare (ASW) in the air to surface vessel (ASV) project, and the navy agreed to try these sets out—thus guaranteeing the future of the Rad Lab itself (Kevles 1987, pp. 304–5).[15]

So, in terms of my biological and topological image, the tuning of science by the NDRC and OSRD polyps served to transform science's inner economy, causing it to secrete certain substances (enzymes?) that would circulate across the cell boundaries into the military and be consumed there. The point to remember, of course, is that the transformations in question are not truly organic ones; they are cyborg transformations, involving the mutual transformation and adjustment of the social (the establishment of the NDRC, the OSRD, and the Rad Lab), the technical (the rise of big science), and the material (the development of specific radar technologies, as circulated). Figure 2 attempts to schematize this first stage in the cyborg coupling of science and the military.

With ASV and other wartime successes, in radar and elsewhere, the scientists began to press for a more intimate engagement in military affairs. Their argument was that they should be allowed to make their own assessment of military needs, and that they should also be al-

14. E. O. Lawrence's prewar Radiation Laboratory at the University of California in Berkeley was an influential model in the World War II proliferation of big science. See Heilbron and Seidel (1990) on Lawrence's lab, and Galison and Hevly (1992) on the history of big science more generally. For important and detailed historical studies of what he calls "reconstituting the civilian [scientist]" during and after World War II, see Dennis (1990, 1994).

15. "By the end of 1942 the Rad Lab . . . budget had reached $1,150,000 monthly, and its staff had multiplied to almost two thousand people. By 1945 it would contain almost four thousand, about one quarter of them academics, almost five hundred of them physicists" (Kevles 1987, p. 307).

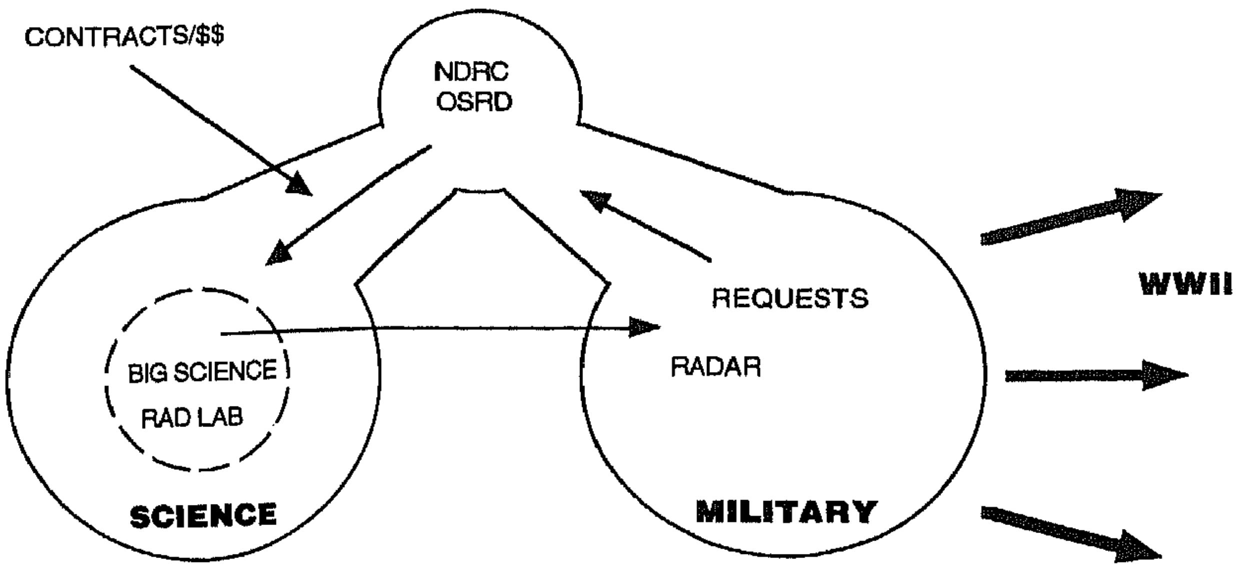

Figure 2. Science and the military as a protocyborg

lowed more involvement in the conduct of military operations than that of simple purveyors of equipment. At a high level of authority, the first objective was initially met in the establishment in April 1942 of the Joint Committee on New Weapons and Equipment (JNW), composed of a rear admiral, a brigadier general, and, as chair, a civilian scientist (Vannevar Bush, the head of the OSRD) (Kevles 1987, p. 309). Like the NDRC and OSRD, the JNW amounted to a further breach in the boundaries around science and the military and a further site of fusion. Unlike the earlier breaching institutions, however, the JNW was symmetric in that it was intended as a two-way window, a double panopticon, through which scientists could scan the military for problems that they might hope to address, while military men could scan science for resources they would like to see developed.[16] Less formally, the MIT Rad Lab came to fulfill a similar function: "After Pearl Harbor and the success of the ASV . . . scores of army and navy officers established residence at MIT to keep their respective services up to date on the military possibilities of microwave systems and to inform the physicists of current military needs" (Kevles 1987, p. 306).

16. "Panopticon" is a gesture toward Foucault's (1979) discussion of one-way surveillance as a technique of power. The interesting thing about the JNW is that it worked both ways. The MIT Technology Plan, established in 1920, is an early example of double panopticism, intended, in that instance, to make the interior of the research university visible to industry, and vice versa (Noble 1979, pp. 142–44). This is as good a place as any to note that MIT was the heart of the beast as far as the cyborg coupling of science and the military was concerned. Four of the central characters in this essay—Vannevar Bush, Philip Morse, Norbert Wiener, and Jay Forrester—were MIT professors (though Bush left MIT before the war).

The establishment of the JNW intensified the coupling of science and the military at the highest levels of authority, but even before its creation scientists were pressing for a closer engagement in the day-to-day conduct of military affairs. As Philip Morse put it, "Of course, Bush and Compton and Conant, who were running NDRC, were in touch with the highest military authorities and were undoubtedly contributing to the overall [military] plans. But there must be [a] need for mathematicians and theoretical physicists to work at lower command levels, to forge multiple links between new technology and military requirements" (Morse 1977, pp. 170–71). This desire led to the construction of a new *conceptual* stratum of the scientific-military cyborg that became known as operations research (OR). I now want to describe the substance of OR and, at the same time, to emphasize the social transformations of the World War II formation that were integral to its development. My text is the autobiography of Philip Morse (1977), the key figure in the development of OR in the United States during World War II and one of the leading proselytizers and organizers in the worldwide spread of OR after the war. This semipopular set of recollections written years after the events at interest is a flawed source; still, it conjures up the developments at issue, especially concerning the intertwining of the conceptual and the social, better than any other I know.[17]

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Operations research was born in Britain and, as its name suggests, had to do initially with the engagement of scientists in the planning and evaluation of military operations, especially as these involved the new technoscientific hardware we have been discussing—radar. Rather than review the British experience, though, we can just as well pick up the story in its transplantation to American soil. In early 1942, the U.S. Navy established an operational Antisubmarine Warfare (ASW) Unit, whose chief, Captain Wilder Baker, invited Morse to set up an OR group to be attached to the unit. Morse agreed, and by the end of 1942, he had assembled a thirty-man (I think) multidisciplinary team largely made up of physicists and mathematicians (Morse 1977, p. 183)—the ASW OR Group, or ASWORG. In a moment I will to try to characterize what this group did—that is, what OR was. But first I want to comment on the group's social location.

17. A comparison of Morse's and Kevles's history of OR suggests that, as the previous quotation indicates, Morse was ignorant of some of the higher-level maneuvering that lay behind the developments we will be discussing. It would be easy enough to

Two points need to be stressed. First, the members of ASWORG remained civilians. They were paid by the NDRC through a contract with Columbia University. But, second, ASWORG was nevertheless lodged within the navy, "imbedded in a military staff" (Morse 1977, p. 183). This can be taken in a quite literal sense: from August 1942, ASWORG was housed in the Navy Building on Constitution Avenue in Washington, D.C. The navy made a space for the civilian scientists within its institutional body and, as it were, *enfolded* the scientists, wrapping itself around them, in what, as will become clear, was a process aimed at optimizing military performativity. And one can think about this enfolding in a social and technical as well as a geographical sense: ASWORG was given access both to secret Naval information and to the command of ASW itself, and it was ordered "to work solely for the Navy and to disclose no information even to NDRC except when specifically authorized by the Navy" (Morse 1977, p. 183). More on this in a moment, but first let me note that this enfolding of OR scientists by the military was far more intimate and detailed than that achieved at the Rad Lab or the various sites of fusion so far described. Biological metaphors beckon again. In ASWORG, the civilian scientific/mathematical organism had extruded a polyp, not into the empty social space of newly formed institutions, but into the interior of the military body, a polyp that, like a biological symbiont, could only survive (and grow) in that alien environment. This was an unprecedented evolutionary development in U.S. scientific and military history—as Morse remarked (1977, p. 187), "We were into the Navy more deeply than anyone had thought possible"—and one that is iconic of the scientific-military cyborgization that I am trying to get hold of.[18]

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construct a sizable bibliography on the history of OR, especially of its technical aspects; Fortun and Schweber (1993) is an interesting recent study.

18. In a fuller treatment, it would be necessary to talk about the various resistances that emerged in the encounter of the OR scientists and the military, and the various accommodations that eventually delineated their social and technical alignments. See Kevles (1987, passim), and Morse (1977, p. 182): "It must have been traumatic for an old-line naval officer to see, as part of the staff of Admiral King, the Commander in Chief of the U.S. Fleet, an ASW Operations Research Group . . . made up of civilian scientists who were neither officers nor civil servants and who were not even paid by the Navy." The singularity of this enfolding of science by the U.S. military can be emphasized in two ways. First, by Morse's remark that on a NATO visit to Europe in 1959, proselytizing for OR, "A day in Bonn spent talking to the military was not . . . heartening. They listened and asked questions, but appeared uncertain as to how O/R could be adapted to the German Staff System. There seemed to be no place in the military organization chart for a civilian group, particularly one containing academicians" (Morse 1977, p. 325). And second, by noting that in World War I, Thomas Edison had actually per-

But now, what did the OR scientists of ASWORG do? Morse offers a nice description of his group's first major project. As he tells it, "as soon as we arrived . . . [w]e were shown a room full of reports of all actions by or against enemy submarines, real or imagined" (Morse 1977, p. 177). This sentence immediately suggests a way of unraveling the character Pointsman's suggestion in *Gravity's Rainbow* (Pynchon 1975, p. 49) that we might consider "the war itself as a *laboratory*." In the internal surveillance of military activity, the war generated an enormous amount of data of a specific kind, reports of military engagements, and so on—its own distinctive archive, in Foucault's sense. And, in classically Foucauldian fashion, OR grew as a discipline in this archive. Faced with the room full of reports, Morse continues, "We went into a one-week huddle to work out a theory of the process of antisubmarine warfare" (Morse 1977, p. 177). The aim was to think what one might do with the operational archive, and one theme that emerged was that one might try to optimize ASW in relation to airborne radar searches.[19] To this end, Morse's group started writing down mathematical equations to express the area of sea that a plane could search in a given time, in order to calculate how many planes would be needed to have a given probability of finding a surfaced

formed an OR-style analysis of how to counter the U-boat threat, but Edison reported to "a civilian official, the secretary of the Navy, who did not have operational responsibility for the deployment of ships and shipping," and his recommendations had little impact (Fortun and Schweber 1993, p. 635, n. 28). As with double panopticism, however, there were precedents for analogous couplings in the relations between science and industry. In the late nineteenth century and throughout the twentieth century, scientific research was enfolded by industry in the establishment of industrial and governmental research laboratories (see Noble 1979; van den Belt and Rip 1987; and Hounshell 1992). Van den Belt and Rip's essay on the establishment of the synthetic dye industry in Germany documents fascinating mutual adjustments in the technical practice of science, its specific products (different dyestuffs), the institutional coupling of science to industry, the relation between different sectors of the dyeing and cloth-producing industries, and the law (German patent regulation).

19. A simple OR calculation generates the context for the opening moves in *Gravity's Rainbow*. Roger Mexico divides the south of England into unit squares and plots the frequency of V–2 hits in each square, which turns out to be a Poisson distribution. This implies that the V–2s are falling at random, just as likely to strike one square as any other, which in turn implies that there is no strategy to evade them. However, there is another archive in the story, the record of Tyrone Slothrop's sexual adventures, which do turn out to predict where the next V–2 will fall, thus creating an opening for some other (weirdly transformed) scientific (and other) approaches, including the Pavlovian behaviorism of Pointsman. (An interesting historical connection between behaviorism and military enterprise lies at the heart of the development of cybernetics; see the next section.)

submarine in a given region. Many parameters entered these equations, including the effective range of radar vision as well as the speed, altitude, and range of the planes to be used (as well as the optimum search pattern, which ASWORG also set out to determine). Many of these parameters were already known (or could be adjusted in the light of ASWORG's findings—planes could fly higher, for example), but often only from what Morse called "test stand" data (Morse 1977, p. 178). The Rad Lab researchers, for example, had made measurements of the range of radar, but not under operational conditions. Morse's team thus hoped to extract such parameters from the operational archive itself: one could, they imagined, make a statistical analysis of the ranges at which submarines had been located in prior missions and thus arrive at some meaningful average, perhaps, of the distance at which reliable identification was possible in military use.

So, ASWORG returned to the archive hoping to carry out the program just outlined and, as Morse tells us, "immediately ran into an obstacle that was to hinder us in all our work" (Morse 1977, p. 179). The data were inadequate: quantities of interest either had not been reported or appeared to have been reported carelessly. And this, of course, set in train a characteristic set of disciplinary developments: the archive had to be reformed; more focused and accurate data needed to be collected. As far as Morse was concerned, "We wanted technical data collected by technical men," and this meant delicate "negotiations" to place OR scientists outside naval headquarters (HQ) and into operating units. Field representatives of ASWORG were soon in place at Eastern Sea and Gulf Sea HQs and "at Argentia, Newfoundland, learning about Atlantic convoy problems" (Morse 1977, p. 180). These representatives talked to officers and men and "went out on occasional flights and began to see for themselves the details that had never got into the reports" (Morse 1977, p. 181). In consequence, the kind of data that ASWORG wanted began flowing back to Washington. Morse reports that "soon we were able to report back to [the] Radiation Lab some of the reasons why the radar was performing so poorly and to suggest some ways in which the defects could be remedied. Very shortly we could present to the ASW Unit a set of search plans that, when implemented, noticeably increased the number of submarine sightings per week. Data coming back from the bases began to be accurate enough for us to use it to spot changes in U-boat tactics" (Morse 1977, p. 181).

As cyborg history, this last paragraph deserves some commentary. First, in the dispatch of OR scientists from Washington to operational HQ we see an intensification of the embedding of civilian scientists in the military body, a further degree of the enfolding of the former by the latter. The symbiont polyp of OR had extruded subpolyps deeper into the body of its host. Second, we can see that the OR scientists in the operational HQ constituted a surveillance unit in several senses. On the one hand, they reported back to Washington ASWORG on observed operational deficiencies in radar as performative hardware, whence the news was propagated out of the military body back to the Rad Lab, where it set in train a further tuning of scientific practice, thus in turn intensifying the coupling of science to the military via the flow of objects, as discussed above. On the other hand, by improving the overall data collection exercise, the scientists in the field helped to constitute the kind of archive in which quantitative calculations and optimizations could be performed.[20] And these, third, fed into a tuning and optimization of military tactics, a transformation of the inner military practices of war-fighting precisely analogous to the earlier transformations of the inner practice of science at the Rad Lab. It is evident from the above quotation that the ASWORG calculations and recommendations were acted upon by the ASW command and, furthermore, that these recommendations were performatively successful ("noticeably increased the number of submarine sightings per week").[21] The up-

20. Continuing with the theme of surveillance, Morse insisted that members of his group had to be returned to HQ after six-month tours of operational duty. This was to make sure that they would bring back the latest operational information from the field and to ensure that they could periodically familiarize themselves while at HQ with the latest technoscientific developments, preparatory to carrying them back to military operations. As well as the flow of radar technologies and OR techniques from science into military operations, then, there was a continual circulation within the scientific-military cyborg of OR personnel between ASWORG HQ and service units (Morse 1977, p. 189).

21. This is not very spectacular in itself. In Morse's autobiography, he goes on to discuss what happened when ASWORG turned its attention from search to attack: "Within two months it was apparent that . . . the number of attacks resulting in sub sinkings [had increased] by a factor of about five" (Morse 1977, p. 182). But the overall social, material, and conceptual configuration of developments is what interests me here more than the details of particular OR exercises and their success or failure. One can also note that, since it quickly "took over the record-keeping for the whole U.S. antisubmarine war" (Morse 1977, p. 184), ASWORG in effect evaluated itself (Latour [1983, 1987] thematizes this point of scientific self-surveillance). Another angle on cyborg transformations and the breaching of disciplinary boundaries comes into sight here: "A complete IBM data-processing system was installed; we hired a [mechanical] computer expert and several insurance actuaries to work up the programs to analyze and tabulate the data that were now pouring in." One of the perils of working with semipopular sources also becomes clear here: another semipopular history tells an almost identical story about the success of OR in improving submarine sinkings, but ascribes it to Blackett's OR group in Britain (Kaplan 1991, p. 53). Kevles (1987) is undoubtedly a work of

shot of this success and others was a further proliferation of OR groups throughout the military body.[22]

After this first pass through OR, I can sum up by noting that the World War II coupling of science and the military was more intense, heterogeneous, and symmetric than it appeared in figure 2. In a series of open-ended social, technical, material, and conceptual developments, the civilian/scientific and military communities redefined themselves around endpoints that were interactively stabilized against and reciprocally dependent upon one another. The inner technical practices of both science and the military were radically transformed in World War II, science (especially the physical sciences) turning into object-oriented multidisciplinary big science, and the military moving from traditionally structured tactics and strategy to scientifically planned warfare deploying the new technoscientific objects. These transformations were tuned to and aligned with one another via the establishment of new institutions of surveillance and control (NDRC, OSRD, JNW), by the creation of new technoscientific artifacts (like radar) and their circulation into military practice and by the development of OR, a new conceptual apparatus that invaded military practice carried by a civilian vector (physicists and mathematicians). As shown in figure 3, what had been largely separate and autonomous institutions before World War II—science and the military—had become profoundly transformed and locked together as a complex social, material, and conceptual cyborg entity by the end of it.

III. Cyborg Objects, Cyborg Sciences, and the World War II Regime

At this point I can think of two ways to proceed. One is transversely, exploring the constitution of the World War II scientific-military cyborg beyond the realms of radar. The other is to track the evolution of the beast in time into the present, the trajectory of what I call the World

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more than reputable historical scholarship: he discusses how Edward Bowles—yet another MIT professor, also lodged in the Pentagon as Expert Consultant to the Secretary of War (i.e., above the hierarchy of the professional military)—drew upon the work of ASWORG to recommend the centralization of ASW around army aircraft (Kevles 1987, pp. 309–12).

22. Morse (1977, chap. 7) surveys U.S. naval OR activity but gives no statistics. In a different arena of the war, Kevles notes that "in January 1943 there had been only one operations analysis section in the entire U.S. Army Air Force; by January 1945, in USAAF commands around the world, there were seventeen such groups, employing 32 mathematicians, 21 radio and radar engineers, 14 terminal ballisticians, 11 physicists, and some 100 other analytic experts. . . . By V-J Day, from Africa to Southeast Asia and on to the Aleutians, civilian scientists were in vogue as strategic and operational advisers to a degree without precedent in the annals of American military history" (Kevles 1987, p. 320).

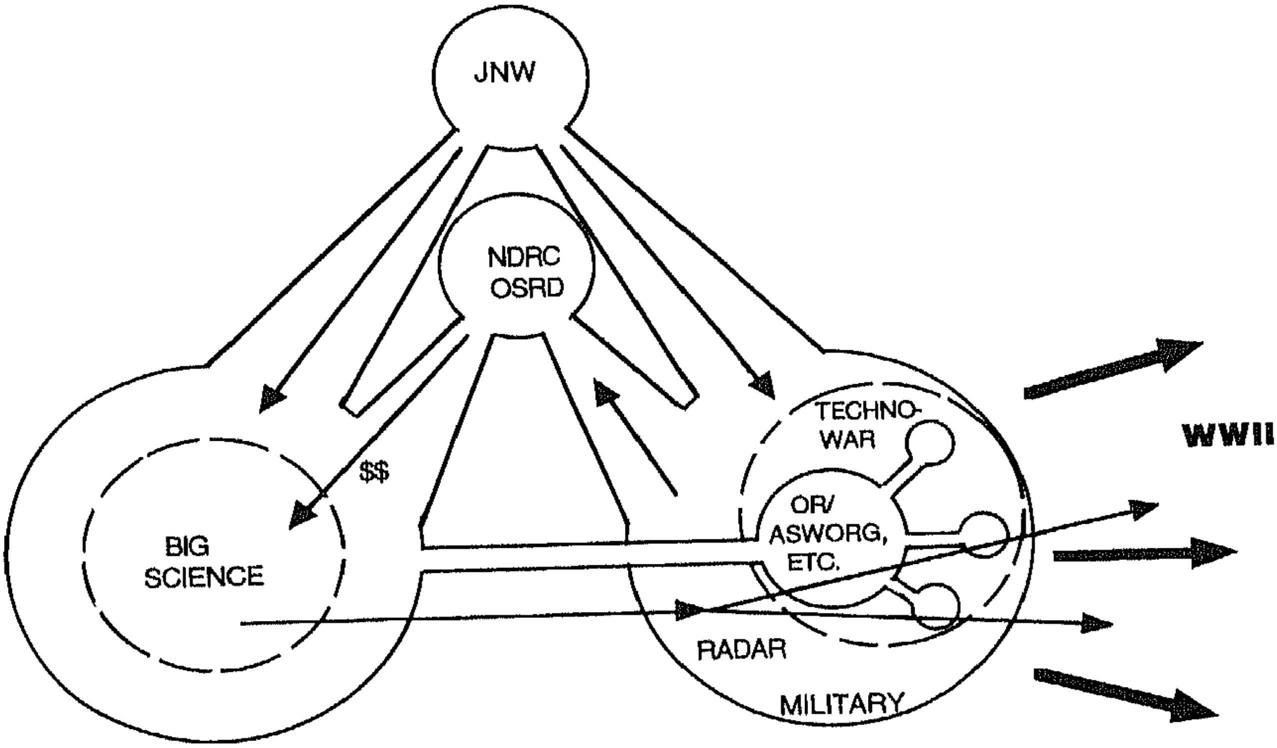

Figure 3. The science-military cyborg in its mature World War II form

War II regime. In this section, I offer some very brief and preliminary sketches of how one might think about both. I begin with the World War II formation as so far described, indicating—really just naming—some of the lines of its subsequent development. I then discuss the sense in which OR itself was a distinctively cyborg science. This is the point of departure for my transverse cut across World War II. It seems to me that a whole range of cyborg sciences were born in World War II, often taking specific cyborg objects as their surface of emergence. I point to some interesting examples and indicate their importance by referring to their later history.

* * *

If one wanted to get at the constitution of postmodernity, it would be nice to start with the World War II formation described in the previous section and propagate it forward. Topics that one would find oneself discussing would include those listed below.

1. The first topic one might consider would be the expansion and rise to dominance of the big-science form of scientific life (with the MIT Rad Lab, etc., as models). One would be struck, I think, by its resolute multidisciplinarity, by the ways in which big-science projects proved refractory to traditional disciplinary

boundaries in the natural sciences and engineering.[23] Conversely, one would note that the big sciences inserted themselves into the academic body via the construction of new institutional spaces, outside the traditional disciplinary structure. One would also note the continuing links of these nontraditional endeavors to military sponsors, and that they have largely come to dominate U.S. universities by virtue of the large "overhead" components in their supporting grants and contracts (Forman 1987; Leslie 1987; Galison and Hevly 1992). This is all part of what Michael Dennis (1990, 1994) calls "reconstituting the civilian."

2. Following the military rather than the scientific line, one would be concerned with the continuing technoscientification of military practice and its sporadic eruption into hi-tech warfare (Vietnam [Gibson 1986] and the Gulf War spring to mind).[24]
3. One would also want to think about the institutional couplings of science and the military as they have continued to evolve within the World War II regime. Among these, funding bodies like the Office of Naval Research (ONR)—the postwar stand-in for the OSRD and NDRC—have so far commanded the most attention, but others are interesting, too. I think of the various advisory committees set up by the services toward or shortly after the end of World War II to sustain the intimate enfolding of science, such as the Science Advisory Board (SAB) of the air force (Gorn 1988; Gray 1989; von Kármán and Edson 1967).[25] These committees sought to capture the imagination of civilian scientists in dreaming the future of technoscientific warfare and hence to bring that future into existence, and they dreamed of cyborgs. The "smart cockpit" became virtual reality, and so on. Along similar lines, one would want to examine the post-Sputnik military

23. On the distinctively pragmatic orientation of wartime and postwar big science, see Schweber (1986); on the emergence of a new breed of science administrators linking big science to the federal government, see Needell (1987).

24. Thinking in terms of the evolution of material objects, it is worth noting how vast arsenals of nuclear weapons hung together with the high modernism of superpower rivalry, and the appropriateness of the high-tech electronics line (smart bombs, etc.) to the postmodern, post-Cold War, new world order of unpredictable, small-scale (relative to global annihilation) conflicts (and the new concern with the proliferation of small numbers of small atomic bombs: viz. North Korea).

25. Gorn (1988) discusses the postwar purification of air force planning, as civilians were progressively excluded from military councils. This did not reflect any loss of faith in science; it reflected a yet more intimate enfolding in which a significant cadre of air force officers themselves received high-level scientific training (at places like MIT)—another axis of "reconstituting the military" as Michael Dennis would put it.

Advanced Research Project Agency (ARPA, later DARPA), which was also at the heart of developments in computer networking (up to our very own Internet) as well as computer imaging and artificial intelligence, all lines that led into cyberspace as well as to Operation Desert Storm and other destinations (Norberg and O'Neill 1992). And I think of the RAND Corporation, established by the air force at the end of World War II as its think tank. RAND, above all, was the place where thermonuclear warfare came closest to reality, where natural and social scientists dreamed of megadeath, where the new rationalities of systems analysis and game theory delineated the ultimate scenarios of Cold War geopolitics (Kaplan 1991; Smith 1966; Helsel 1993; Poundstone 1993).

4. One would also need to talk about the subsequent history of OR itself, spilling out of military enterprise into industrial and governmental planning, giving birth to systems analysis (at RAND: Smith 1966; Leonard 1991) as a more open-ended and all-embracing future-oriented dream matrix, which once more spilled out into the wide world (Bugos 1993), and so on.

These are all topics worth contemplating, but I cannot develop them. Instead, I want now to stress a specific feature of OR as a way of thematizing a transverse linkage across World War II. I said above that I think it is useful to describe OR as a cyborg science, and now I should explain what that means. The point is simple enough. Unlike the traditional natural sciences that find their ontological foundation in the material world, or the traditional social sciences that speak of the distinctively human (or social), the ontology of OR was the operation: the performance of a heterogeneous assemblage of humans and nonhumans, of planes, submarines, radar sets and radar operators, pilots, depth charges, and so on.[26] As a science concerned with the

26. To get a fix on U.S. social science around the time of World War II and its resolutely humanist ontology, one can consult Heims (1991, chap. 1) and Buck (1985). To mention a couple of relevant examples (taken from Kaplan 1991, pp. 68–70), a key figure in establishing a social science division at RAND in 1947 was Leo Rosten, who trained in political science and economics at the University of Chicago and the London School of Economics: "When the war broke out, Rosten joined the Office of War Information and supervised analyses of public opinion, enemy morale, how to deal with enemy interrogation if captured, the sociology of Nazism and other aspects of psychological warfare. But his most important position . . . was key point of liaison between Washington and Hollywood, convincing the government to use the expressive medium of the movies to educate the public on what the war was all about, and persuading studio executives to join the effort as well. . . . Rosten also got Walt Disney to make animated propaganda and instructional films." The first head of social science at RAND was Hans

business of fighting wars (and, later, running factories and so on), OR was indifferent to the traditional distinctions between people and things that define both (a form of) modernist common sense and the boundaries between the classic academic disciplines. The ASW OR Group constructed a unitary mathematical model of antisubmarine warfare from which, in conjunction with its surveillance operations, issued, in one direction, suggestions for improving the material technologies of radar and, in the other, suggestions for the human conduct of ASW. This lumping together of the human and the nonhuman and the unprincipled working of both sides of the boundary in the name of overall performativity is what I want to point to in naming OR a cyborg science.[27]

One point that fascinates me in this connection is that OR was not the only cyborg science to emerge from World War II, and in the rest of this section I want to point to some other examples. These examples (except the last) revolve in different ways about another new object that was born in the World War II intersection of science and the military, the electronic computer, so before I get into the details I want to make two general remarks about the computer itself. First, the computer is a paradigmatically cyborg object. It unsettles the boundary between the human and the nonhuman by externalizing and materializing the business of thought.[28] Second, I am struck by how much the development of the computer in World War II, in the several guises to be discussed, revolved around gunnery control—the mundane business of pointing guns (heavy ones, not sidearms) in the right direction,

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Speier, who "worked on a Rockefeller Foundation project analyzing totalitarian propaganda and, during the war, published a widely read book on German radio propaganda."

27. To find precedents for the cyborgism of OR, the place to look is not within the traditional academic disciplines, but in the management of industrial labor. Thus there is a cyborg strand to Taylorism and scientific management in the early twentieth century. Taylor's goal was to tune machines and human working practices to one another for the sake of industrial productivity. My impression is, however, that by World War II, the theorization of the human side of production had largely been taken over by humanist social scientists (Noble 1979; Graham 1992). Fortun and Schweber (1993) agonize about whether OR was something special or really just Taylorism. I would emphasize that OR was historically disconnected from Taylorism; that it marked an entry point for natural scientists, mathematicians, etc., into the traditional preserve of managers and social scientists; and that, despite its similarities to scientific management, it at least marked an intensification and extension of the range of the latter.

28. Again, the electronic computer is not without precedent. Its appearance in World War II marked a discontinuity in the project of mechanical computation going back to Babbage's difference and analytical engines (on which see Schaffer 1994).

around the specific cyborg coupling of men and artillery. There is a historiographic black hole here—a wonderful history of gunnery control as the surface of emergence of great swaths of material, social, and conceptual transformations that has never, as far as I know, been written.

* * *

The line of computer development to which I will pay least attention is the easiest one to explain. Just before World War II, several individuals had set to work building electronic number-crunching devices, glorified calculating machines. In a historical review, Bernard Cohen notes that such initiatives found themselves heavily supported by the military when hostilities broke out and that, further, "the most significant wartime development in computing was ENIAC (Electronic Numerical Integrator and Computer). . . . It became operational at the Moore School [of the University of Pennsylvania] in the spring of 1945 and was later shipped to Aberdeen. By the time it was taken out of service on 2 October 1955, it had probably done 'more arithmetic than had been done by the whole human race prior to 1945'" (1988, pp. 135–36). "Aberdeen" is the Army Ordnance Department Ballistic Research Laboratory at the Aberdeen Proving Ground in Maryland. The ENIAC's arithmetic had presumably to do with the detailed computation of shell trajectories and the like—with aiming guns, as just mentioned.[29]

As far as this sheer number-crunching aspect is concerned, I have little more to say, except to note some ways in which postwar increases in computer power have transformed the natural sciences. Thus Fred Suppe (work in progress) speaks of a "scientific data revolution" brought about by the ability of computers to handle much more data than was once thought possible. He has a wonderful plot of "numbers of discrete data points used in testing an hypothesis," which takes off from 10^4 in 1960 and arrives at 10^{12} in the year 2000. He explains the break at 1960 in terms of the introduction of the IBM 1620, the first machine to make electric computation widely available in U.S. universities. At the same time, computer-imaging methods have been developed to make such enormous data sets surveyable by humans (Suppe's particular interest; see also Lynch 1991 on the "topical contextures" of "opticism" and "digitality"), and these imaging techniques have in turn been crucial to the emergence of entirely new fields of science and

29. So the computer was born in the same matrix in which physical science had been born 500 years earlier (this takes us back to Voss [1994]). On the conception of ENIAC as a ballistics calculator, see Goldstine (1993).

mathematics like chaos theory (Kellert 1993; Beyerchen 1989). These postmodern sciences, as Norton Wise (and no doubt others) calls them, are interesting in at least two connected ways. On the one hand, they are cyborg sciences, in the sense that the practitioners of chaos theory, say, claim to find the same chaotic behavior in inorganic, organic, and human systems. On the other hand, in contrast to the traditional sciences, they are nonreductive. Like this essay but in a different register, they look for patterns *in* phenomena and abstain from the traditional attempt to go behind the scenes in pursuit of underlying causes.[30]

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Like most people, I suspect, my tendency has been to think that the computer evolved primarily under the above description, as a number cruncher, and only later took on the multiple roles that it has today (word-processing, graphics, voice-mail, E-mail, virtual reality, automobile control, robotics). But this turns out to be a mistake. Many of the present-day roles of the computer were already foreshadowed at its birth in World War II. In several respects, the computer emerged within, and as part of, the cyborg projects of World War II. I will discuss two of these projects (both based at MIT) to indicate what is at stake—the history of the Whirlwind computer and of Norbert Wiener's antiaircraft predictor.[31]

To understand the history of Whirlwind (Redmond and Smith 1980; Noble 1986) one has to go back to gunnery control. To put it crudely, there has always been a problem with the motor control of heavy artillery. It is difficult to get a motor to point a gun accurately in the desired direction. And since at least World War I, the solution has been the use of servomotors, in which the difference between the present orientation of the gun and its intended orientation is somehow measured and fed back to the motor itself. However, feedback systems and servomotors are not without their own problems. Since their industrial development in the nineteenth century, it has been clear that they are prone to pathologies like "hunting"—a condition in which the orientation of the gun oscillates around the intended direction instead of sticking there—and a great deal of material and theoretical effort has subsequently been devoted to controlling such phenomena (Richard-

30. One should also really discuss here the development of the computer industry and of computer science (and its variants) as a new academic discipline. On the latter, see Mahoney (1990*a*, 1990*b*).

31. For the following paragraphs running from Whirlwind to planet management I am indebted to many conversations with Irving Elichirigoity.

son 1991, pp. 17–32). Let me just note that servomotors are themselves cyborg objects that destabilize the boundary between the human and the nonhuman by seeking to download everyday human skills into machines, and that feedback and control theory are in this sense cyborg sciences, before passing onto the particular developments that interest me.

Sometime in the winter of 1940–41, the Electrical Engineering Laboratory of MIT set up a Servomechanisms Laboratory (hereinafter, the Servo Lab), originally sponsored by the Sperry Gyroscope Company in connection with their development of AA gun control, designed to help protect British shipping from German dive-bombers (Redmond and Smith 1980, p. 9). It appears that the Servo Lab continued to focus on gun control mechanisms in the following years, and certainly Jay Forrester, one of the initial intake of graduate students, did (Redmond and Smith 1980, p. 15). In 1944, however, Forrester became the leader of the ASCA (Airplane Stability and Control Analyzer) project, funded at the Servo Lab by the navy. The ASCA was intended to be an all-purpose flight simulator, a device intended to simulate the experience of flight—for pilot training and plane development—without using expensive real planes. And to simulate the behavior of flight in real time, the Servo Lab engineers—led by Jay Forrester—sought to do two things: to translate the pilot's actions (opening the throttle, say) into airplane motions by solving a complicated set of simultaneous equations, and then to translate these motions back to the pilot, both as a set of instrument readings and as physical motions of the simulated cockpit via jacks controlled by servomotors (hence the involvement of the Servo Lab). Early development of ASCA aimed at an electromechanical solution via the construction of an analogue model of plane behavior, but by the 1950s the project had shifted to the construction of a digital computer—Whirlwind—as its computational heart.[32]

I can continue with the story of Whirlwind in a moment, but first two remarks. It is notable that in the story so far ASCA comes first and Whirlwind second. Whirlwind, that is, was not conceived first as a number-cruncher and then put to use in a flight simulator; the computer was conceived from the beginning as part of a performative material agent, coupled into the material world via servomotors. Here, then, we touch on one of the origins of robotics. Second, it is worth noting the cyborgism of ASCA/Whirlwind. The very word "simula-

32. Forrester first started thinking seriously about what it took to simulate flight in November 1944, and "his preliminary survey indicated that 92 quantities and 33 simultaneous equations were involved, just to describe the aircraft response" (Redmond and Smith 1980, p. 16).

tor" suggests the way in which Whirlwind destabilized the boundaries around not just the natural world but around the world of built objects like airplanes, too. The Whirlwind project aimed precisely to construct a virtual reality, in the space of material performances as well as representations. And, at the same time, it aimed to conform human beings to that virtual reality, to discipline them in specific ways in alignment with the performance of specific machines—this was (and is), of course, the significance of the use of such simulators in flight training.[33]

So, the Whirlwind project was an exercise in cyborgism, but it never achieved its dreams. The navy lost faith in MIT's ability to deliver what it had promised. Forrester moved first, as director, to the MIT Digital Computing Laboratory, and then to MIT's Lincoln Laboratory, where, as head of the Digital Computers Division, "he directed the military and operational planning of the SAGE system for continental air defence" (Bloomfield 1986, p. 3). The SAGE (Semi-Automatic Ground Environment military early-warning radar) system was a sophisticated machine surveillance system, and Whirlwind was its centerpiece.[34] Other uses were found for Whirlwind, too, including one on the robotics line that I will pursue in Section IV. To complete the present discussion, though, I want to stay with Forrester a little longer.

In 1956, Forrester moved to MIT's Sloan School of Management (established in 1952). At the Sloan School, Forrester developed his distinctive "systems dynamics" approach to thinking about industrial dynamics. Crudely, systems dynamics was OR plus feedback loops, formulated as a computer model intended to describe the evolution of systems in time. The connections back to Forrester's wartime and postwar military experiences are clear: feedback in gunnery control, the solution of sets of simultaneous equations with time-varying inputs (ASCA), the computer (Whirlwind), management (the SAGE project).

33. This helps us to understand why NASA eventually took the lead (alongside the military, still) in the development of virtual reality techniques (Rheingold 1991).

34. SAGE also generated a rationale for the social expansion of computer programming: "a huge demand for programmers was created by the American government, which wanted to double the number of programmers from 2,000 to 4,000 in order to prepare the early-warning radar network code-named SAGE. . . . Early in the program's history the Systems Development Corporation was created to produce the programming workforce" (Galison 1985, p. 348). The Systems Development Corporation was a spin-off of the RAND Corporation (Kraft 1977, p. 27). In this example we can note an interesting feature of the World War II regime. Although different elements of the World War II megacyborg evolved in a quasi-autonomous fashion, one finds them continually recombining in strange and wonderful patterns along the way: thus radar, computers, feedback control, and RAND all coalesced into the novel cyborg formation that was SAGE.

And out of these emerged systems dynamics as a classically cyborg science. Forrester's models were indifferent to the traditional distinctions between the human and the nonhuman components of industry, simulating them as a whole and aiming at joint optimization, just like OR as described above. An interesting thing about systems dynamics, however, was that, unlike OR or even systems analysis, Forrester sought to expand its range endlessly, moving in 1968 to modeling what he called the urban dynamics of the city, and then to the world (Forrester 1961, 1969, 1971). Figure 4 is the flow diagram of WORLD2 (from Forrester 1971), Forrester's global model, which grew out of his encounter with members of the Club of Rome in 1970. The following MIT model, WORLD3, was the basis for the famous *Limits to Growth* report (Meadows et al. 1972).

With *Limits to Growth,* the component of the World War II regime that began with gunnery control, servomotors, and flight simulators had grown to take over the world.[35] And, as Irving Elichirigoity (1992, 1994) shows, *Limits to Growth* was itself a key moment in the construction of a "discourse of globality," a "planet management" approach to "governmentality" (Foucault) that effaces traditional boundaries (like those around the nation state, or between the human and the nonhuman) in emphasizing the global interconnectedness of social, ethical, military, ecological, economic, political, and industrial issues. This is one of the many axes along which the World War II regime has become almost all-pervasive.[36]

I close this part of my essay with an observation. Cyborg sciences like OR and systems dynamics, as already indicated, mark encroachments primarily by natural scientists, engineers, and mathematicians upon the terrain of the traditional social sciences (and not the reverse). And one of the striking features of the World War II regime is the

35. Systems dynamics approaches to computer modeling have, of course, been applied to all sorts of heterogeneous problems on all sorts of scales. See, for example, Taylor (1992) for a critical account of MIT's socioecological modeling of nomadic pastoralists.

36. Another route into planet management must have been the development of satellite global surveillance techniques. Here one would have to think about the rocketry line as it evolved out of the World War II science-military cyborg and also, I suspect, about the development of techniques for processing the kind of data that satellite surveillance generates. Operations research techniques, as described above in connection with ASWORG, might constitute a substrate for this; evidently computer imaging (above, this section) must eventually have become important; I wish I knew more about the Strategic Bombing Survey, which perhaps played a key role. In any event, here we have another recombination of otherwise more or less autonomous lines of development within the World War II regime.

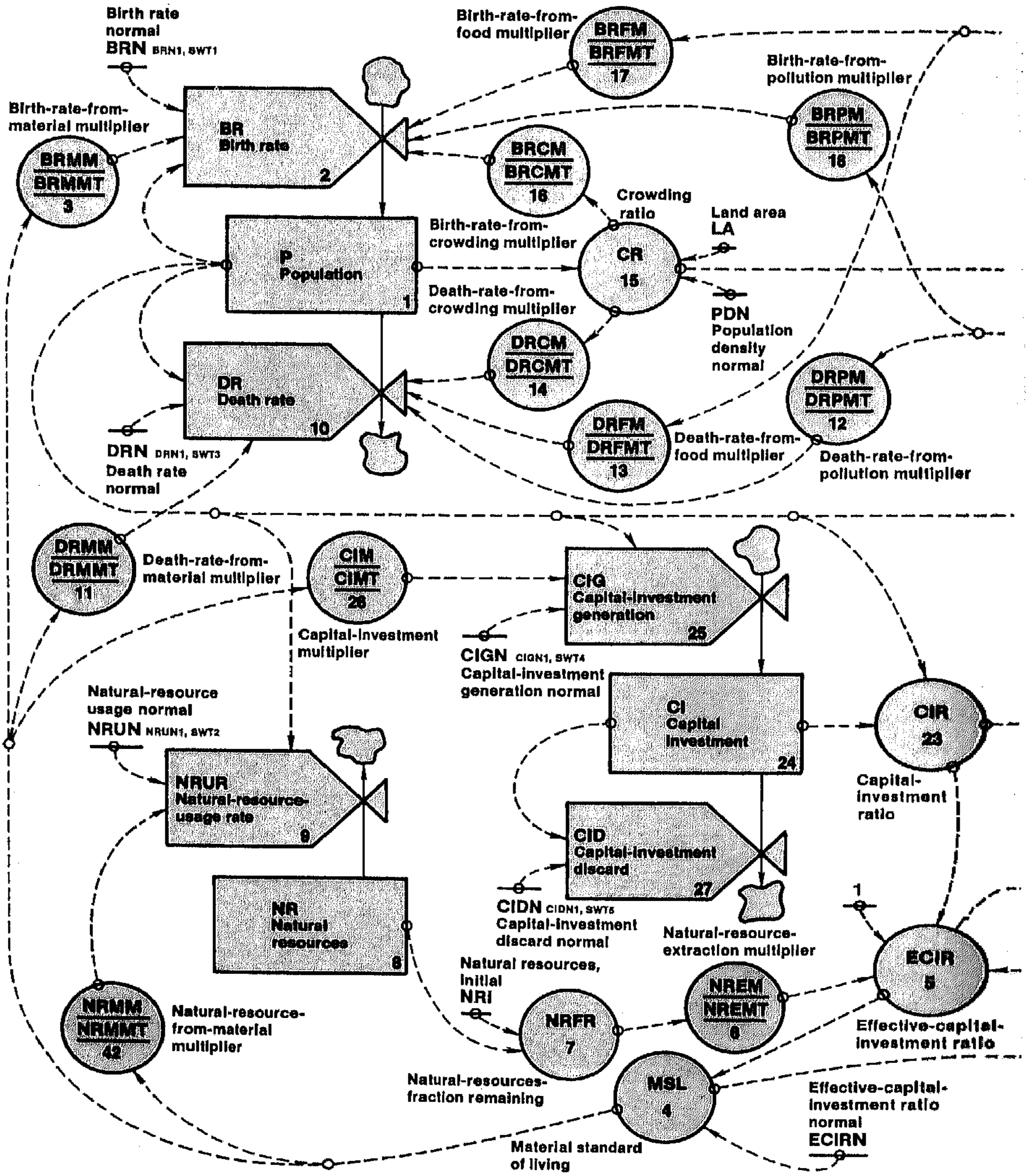
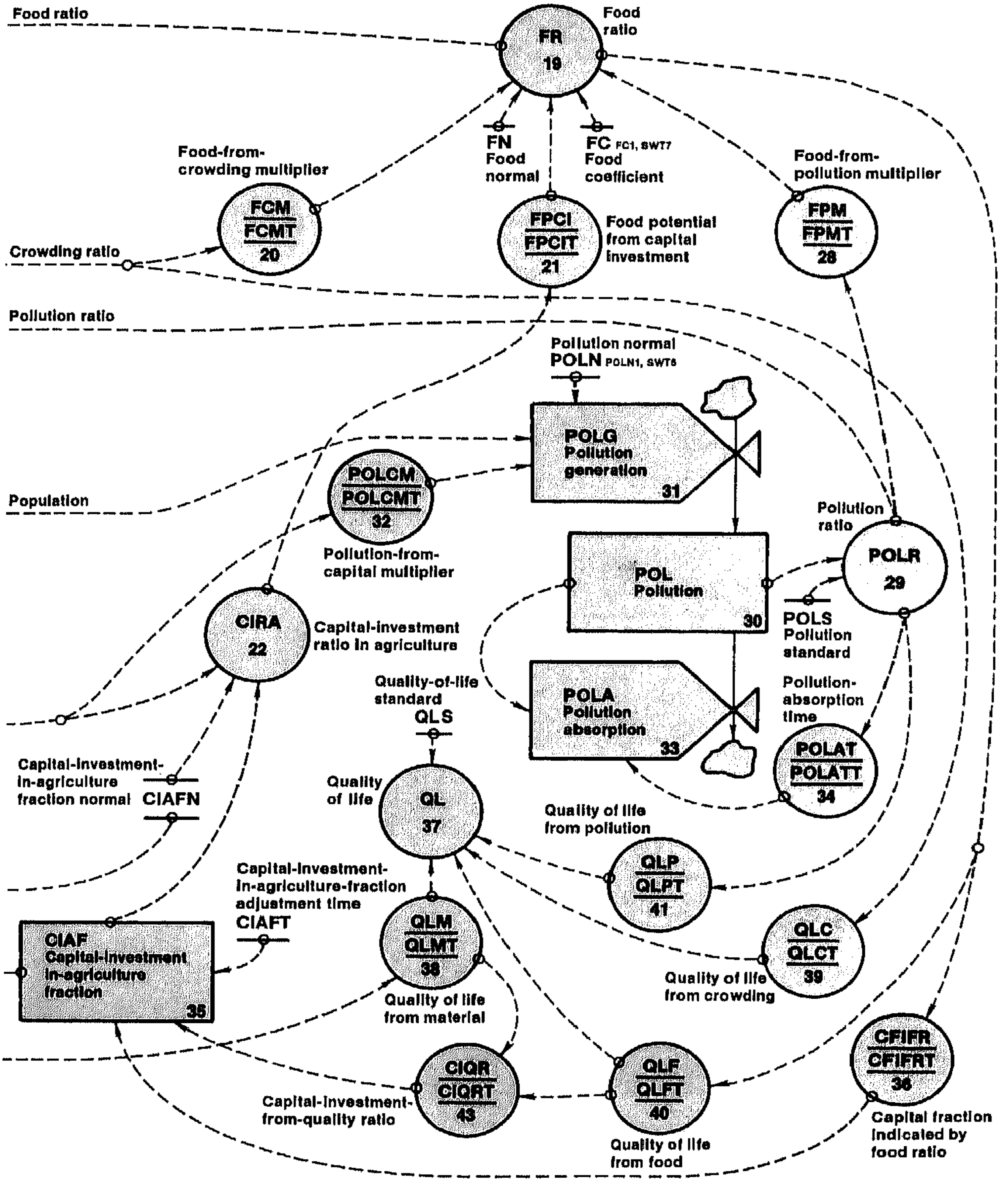


Figure 4. Jay Forrester's WORLD2 global model, interrelating the five level variables—population, natural resources, capital investment, capital-investment-in-agriculture fraction, and pollution. (From *World Dynamics* by Jay W. Forrester. Copyright © 1971 by Wright-Allen Press, Inc. Available only through Productivity Press, Inc., P.O. Box 13390, Portland, Oregon 97213-0390, (800) 394-6868. Reprinted by permission.)



Food ratio
FR
19
Food ratio
FN
Food normal
FC FC1, SWT7
Food coefficient
Food-from-crowding multiplier
FCM
FCMT
20
FPCI
FPCIT
21
Food potential from capital investment
Food-from-pollution multiplier
FPM
FPMT
28
Crowding ratio
Pollution ratio
Pollution normal
POLN POLN1, SWT6
POLG
Pollution generation
31
Population
POLCM
POLCMT
32
Pollution-from-capital multiplier
POL
Pollution
30
Pollution ratio
POLR
29
POLS
Pollution standard
CIRA
22
Capital-investment ratio in agriculture
Quality-of-life standard
QLS
POLA
Pollution absorption
33
Pollution-absorption time
POLAT
POLATT
34
Capital-investment-in-agriculture fraction normal
CIAFN
Quality of life
QL
37
Quality of life from pollution
QLP
QLPT
41
Capital-investment-in-agriculture-fraction adjustment time
CIAFT
CIAF
Capital-investment in-agriculture fraction
35
QLM
QLMT
38
Quality of life from material
QLC
QLCT
39
Quality of life from crowding
CFIFR
CFIFRT
36
Capital fraction indicated by food ratio
CIQR
CIQRT
43
Capital-investment-from-quality ratio
QLF
QLFT
40
Quality of life from food

extent to which this encroachment has taken place—not, it has to be said, in the total effacement of the traditional humanist social sciences, but, topologically, in the layering of cyborg sciences over the traditional social sciences, a process that continues today. Thus, for example, Forrester was by no means alone in reconstructing the theory of the factory, the city, and the world in terms of engineering notions of feedback. There is even a book (that deserves to be better known) on *Feedback Thought in Social Science and Systems Theory* (Richardson 1991), which traces the history of many significant postwar incursions of "the engineer's concept of feedback" (p. 1) into the social sciences. Richardson follows what he calls "two threads" of feedback thought. One is the "servomechanisms" thread, exemplified here in the work of Jay Forrester. The other is the "cybernetics" thread, to which we can turn, staying close to the inventor of the word "cybernetics," Norbert Wiener.

* * *

I turn back to gunnery control. As early as 1940, Norbert Wiener—child prodigy, then MIT mathematician—was thinking about building an Anti Aircraft Predictor (AAP) (Galison 1994, p. 231), a device intended to process time-series observations on flight paths in order to predict where guns should be aimed to bring planes down. An important point is that information would be fed back to the AAP on the behavior of the plane under attack, so that the AAP would, as it were, learn about its target in a goal-oriented fashion. This device never worked; Wiener felt it needed more computer power for information processing than was then available (hence a connection forward in time to the electronic computer, again), but it evidently functioned as a source for the scientific and mathematical imagination. It could be seen as a protocyborg, with its purposeful learning abilities serving as a model of, or substitute for, human and, more generally, biological characteristics. It thus spawned the field of cybernetics, a prototypically cyborg [*sic*] science in which, eventually, the entire world as well as its material, biological, and human parts, including the human brain, were to receive a unified analysis as learning systems with feedback. Although the term "cybernetics" itself has fallen somewhat into desuetude in the West, under its heading one can find important and distinctive developments continuing to the present in psychology, anthropology, sociology, political science, and management science, as well as chess playing, artificial intelligence, engineering, biology, and mathematics, not to mention robot warfare (Heims 1980, 1991; Richardson 1991; De Landa 1991). I think, for example, of Donna Haraway's wonderful studies (1981–82, 1991) of the roots of sociobiology within cybernetics—E. O. Wilson started by thinking of the foraging behavior of fire ants on the model of Wiener's AAP—and of current conceptions of the immune system as a quasi-military command-and-control system.

Cybernetics then, took computer-controlled gun control and layered it in an ontologically indiscriminate fashion across the academic disciplinary board—the world, understood cybernetically, was a world of goal-oriented feedback systems with learning. It is interesting that cybernetics even trumped the servomechanisms line of feedback thought by turning itself into a universal metaphysics, a Theory of Everything, a TOE, as today's physicists and cosmologists use the term—a cyborg metaphysics, with no respect for traditional human and nonhuman boundaries, as an umbrella for the proliferation of individual cyborg sciences it claimed to embrace (Bowker 1993). Possibly the most familiar instances of this line of thought in the present are to be found in Maturana and Varela's work (1980, 1992) on autopoiesis and self-organizing systems.[37]

I will make one parting comment on Wiener's AAP. As far as I can make out, it was never clear whether Wiener intended this as an aid to human gunners or to replace them, whether it was intended to *augment* human performances, as a prosthesis, or to *automate* them away (I borrow this distinction from Rheingold [1991]). This tension between augmentation and automation runs through the subsequent evolution of the material cyborgs and cyborg sciences of World War II, as will become clear in Section IV.

* * *

My last stop in this cut across World War II concerns game theory, a mathematical field whose origins actually owed nothing to the computer or gun control.[38] The key event here was the publication in 1944

37. One referee writes that "the paper interprets the science of cybernetics as giving a metaphysics for the world. No reasons are given as to why we should interpret cybernetics and other talk of cyborgs in this fantastic way." I am not endorsing the particular metaphysical claims mentioned in this paragraph; I am reporting their existence as a distinctively philosophical strand of the World War II regime, layered upon all sorts of continuing metaphysical discourses. For the theoretical considerations that motivate my present attempt to understand history in terms of the figure of the cyborg, I cite again Pickering (1995) where, to complicate the issue immensely, I found myself citing Maturana and Varela (1992) sympathetically. This seems to be an instance of the collapse of theory into its object that Jameson (1991) discusses as a symptom of postmodernity.

38. To stick with the computer, in a fuller treatment it would also be necessary to talk about code breaking in World War II. Hodges's (1983) wonderful biography of Alan Turing is the great work here. Computers did eventually become the substrate for game theory. Thus, Mirowski (1991, p. 242) notes that "the Princeton/ONR connection also

of von Neumann and Morgenstern's *Theory of Games and Economic Behavior.* In one sense, game theory was a continuation of the traditional philosophical project of externalizing thought and decision making via the articulation of a formal/mathematical logic (a project that, of course, intersected in World War II with that of materializing thought in the electronic computer). The novelty, however, was that in game theory, thought was socialized: game theory was about rational actors competing in a field of the actions of other rational actors. Its paradigmatic application was to the well-known Prisoner's Dilemma, in which two prisoners have to decide independently whether to rat on one another.[39] As the second half of the title of von Neumann and Morgenstern's book indicates, their intention was to address the social rationality of distinctly economic actors (Weintraub 1992; Leonard 1993, 1994), but economists displayed an almost total lack of interest, and game theory found its first significant following at RAND, where it constituted a mathematical basis for the "rationalization" of Cold War thermonuclear geopolitics (Mirowski 1991; Leonard 1991).

I can think of three reasons for describing game theory as a cyborg science. First, like the computer, in externalizing thought it destabilized the boundary between the human and the nonhuman. Against this, it could be said that game theory still referred to something distinctly and properly human, namely, thought. But, second, in use game theory typically functioned as part of a heterogeneous assemblage indifferent to the human/nonhuman divide. This is nicely expressed by Heims (1991, p. 27): "Even such anthropocentric social scientists as [Margaret] Mead and [Lawrence] Frank became proponents for the mechanical level of understanding, wherein life is described as an entropy-reducing device and humans characterized as servomechanisms, their minds as computers, and social conflicts by mathematical game theory." More specifically, Kaplan (1991, p. 67) discusses the use of social scientists at RAND to fill in the "utility functions" in game-theory payoff matrices, themselves used to explore the structure of heterogenous material, social, and conceptual performances (like thermonuclear strikes by or against the Soviet Union).[40] And third, it is

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seems to have been a major stimulant to the building of computers explicitly dedicated to the solution of games for the military, by as early as 1951."

39. Poundstone (1993, p. 103) says that the Prisoner's Dilemma itself was first formulated in connection with experiments conducted at RAND in 1949 by Merrill Flood and Melvin Dresher.

40. Along this same line, Rider (1992) notes that OR practitioners considered game theory to be part of their own mathematical arsenal, and Leonard (1992, p. 65) describes two applications of game theory by ASWORG.

worth noting that in the past decade or so game theory has lost its specific reference to human thought. After its expulsion from the garden—the RAND Mathematics Department was dissolved in the mid–1960s as insufficiently mission-oriented (Leonard 1991, p. 277)—game theory successfully invaded not just economics, sociology, and international relations theory (and the Pentagon: Leonard 1991) but also, in the 1980s, genetics, population ecology, evolutionary biology, and the study of animal behavior. Under rubrics such as that of the "evolutionary stable strategy," game theory became ontologically promiscuous, yet another classically cyborg science (Poundstone 1993, chap. 12; Sigmund 1993).

IV. The Automatic Workplace

In the previous section I tried to map out some of the lines along which the scientific-military World War II cyborg evolved into the present, in the hope of indicating the historical importance and current ubiquity of the World War II regime. In this section I follow one particular line in a little more detail, moving from the military to industry, another key site for the coupling of people and machines. My focus is on the computerization of the workplace, and the story starts, as usual, back at MIT.

Flight simulators are very complex pieces of equipment, and, after the navy withdrew its support, Forrester and the Servo Lab found a simpler project for Whirlwind. Funded now by the air force, in the early 1950s the MIT engineers turned their attention to the computer control of industrial machines, especially to the development of what were called numerically controlled machine tools (N/C). The idea was to program computers to drive servomotors that would guide the motions of machine tools along precisely specified paths, thus, in effect, making shop-floor labor obsolete (the programming would be done by white-collar personnel away from the factory floor). The classic historical account of this process is David Noble's book, *Forces of Production* (1986), in which he establishes that, from the perspective of the Servo Lab, industrial management and engineers in general, the object of N/C was to begin the automation of the factory (rather than an augmentation of human labor, in terms of the distinction made in Sec. III).[41] Unlike the flight simulator project, this one eventually bore the intended kind of fruit: N/C prototypes were constructed at the Servo

41. It would be interesting to see how far one could go in characterizing the World War II regime in terms of the automation project: the automation of shopping (all of the computer interfaces, algorithms, and networks of the plastic economy; the data superhighway); the automation of sex (virtual reality again: Rheingold 1991, chap. 16).

Lab and began to move outward into industry. And what interests me here is what transpired in this outward movement as the World War II regime invaded the factory. I will not try to tell the whole history of industrial automation in a few pages. Instead I will concentrate on two moments: the introduction of N/C equipment at the GE Aero Engine plant at Lynn, Massachusetts, in the mid-1960s and 1970s (Noble 1986, chap. 11), and the transformation of the Caterpillar plant at Decatur, Illinois, in the 1980s (Miller and O'Leary 1994). These are sufficient to point to significant elaborations of my cyborg theme, and the second points to some interesting topological transformations that have accompanied this line of postwar development.

So, N/C was first introduced at the GE Lynn plant under the Servo Lab conception as essentially a substitute for human labor. The use of N/C was seen as a material solution to a management problem in controlling skilled human labor by more or less effacing the latter. Thus, N/C destabilized the boundary between the human and nonhuman by locating what had traditionally been human performances within machines. Human labor did not quite disappear in the N/C shop, but the machine operators were expected to act as humble prostheses of the machine. The humans would turn the machines on and off, feed them with materials, set their speeds, and so on, but the traditional skills of machine tool operators would be replaced by computer programs and servos.

However, things did not go as planned at GE. As described in detail by Noble, as soon as N/C was introduced, production and labor relations went to pieces: the hi-tech N/C shop became the "bottleneck" in aero engine production. And, after struggling for a while within the usual system of labor relations, GE management found a novel accommodation. In 1968, a group appointed to look into the problems of N/C production reported that "the Task Force believes the principal reason for this lack of motivation [among N/C operators] is that management has been too steeped in traditional concepts of industrial engineering. These concepts . . . which served us well with older equipment and with the workforce of earlier generations seem to be at the source of our problems" (Noble 1986, p. 280). In effect, the recommendation was for a retheorization of the workforce, away from a traditional Taylorism that construed workers as simple material agents to be disciplined within the usual framework of rewards and punishments, and toward a recognition of the intelligence of shop-floor labor, in the hope of more successfully aligning workers and the N/C machines.

The upshot of this recommendation was the establishment of the so-called Pilot Program at GE in late 1968. Within the Pilot Program, many of the traditional disciplinary restraints on labor were withdrawn, and the N/C operators were encouraged to take over at least some of the functions of management in orchestrating production. The new Pilot Program regime would be "unique in that there was to be no foreman, no scheduled lunch periods, and flexible starting and personal times" (Noble 1986, p. 281). Further, the classification of the operators would be "unlimited" (p. 281), meaning that they would be free to start to take over responsibilities usually held by others (pp. 280–81): "The leaders (senior N/C machinists) . . . would [for example] assign N/C machinists in debugging new equipment, tools, and methods; schedule equipment start-up; work with planning in developing, implementing, and controlling new methods and procedures; approve programming from the viewpoint of good machine shop practice; review and make suggestions about changes in workstations, tools, and fixtures; assume responsibility for quality in the unit and interface with quality control; [and] monitor the area for availability of all materials and check equipment to insure safe and proper functioning."

In short, in a drastic shift of policy, GE management now expected the pilots effectively to act like traditional management consultants and, moreover, to implement their own recommendations, blurring their roles into the traditional roles of foremen, planners, programmers, quality controllers, and so on. And, as Noble shows, this process went further and further at GE, with the pilots taking on more and more of the responsibilities surrounding N/C production—until, that is, the Pilot Program was unilaterally terminated by GE management in 1975 (reinstituting a Taylorite disciplinary regime that encoded what had been learned about the use of N/C over the preceding eight years).

I cannot go into more historical detail, but I want to emphasize two general features that emerge from this early encounter between the World War II regime and the factory. On the one hand, the antihumanist, automation wing of the World War II regime has continually emerged as problematic in practice. The attempt to efface human labor, in this example as elsewhere, failed. On the other hand, this antihumanist wing has nevertheless been highly consequential in making the contemporary world. As just described, automation here involved the introduction of a new set of performative material objects in the workplace, which, in turn, precipitated not the intended effacement of the human, but a complex and open-ended set of interrelated heterogenous transformations. Within the Pilot Program, shop-floor labor was reconceptualized as a response to problems centered on the new technology—the properties of the human, that is, were redescribed in relation to computerized machines; new work practices, tuned to the new machines, were established by the pilots; and social relations between workers, and between workers and management, were reconfigured in the same process (the blurring of the boundary between labor and management). Pre-N/C machine shops were no doubt already cyborg formations, but with the coming of N/C the internal economy of this cyborg was radically—conceptually, technically, materially, socially—reconfigured.[42]

As mentioned, the Pilot Program at GE ended in 1975. The old disciplinary boundaries between workers and management and so on were reintroduced, though in a way that reflected what had been learned in the intervening period. And, according to Noble, the search for new ways more thoroughly to automate the factory went on at GE as elsewhere. The cure for the early failure of automation was more automation. The antihumanist World War II regime was, paradoxically, almost strengthened by failure; its failures served to delineate yet more scope for the work of the automaters. And now I turn to where the automation project had got to by about 1990. I cannot survey the entire scene, so I will talk about a single example that seems perspicuous, taken from Peter Miller and Ted O'Leary's (1994) fascinating study of the transformation of manufacturing at Caterpillar during the 1980s.

* * *

In response to a financial crisis in the early 1980s, Caterpillar, one of the world's largest manufacturers of heavy earthmoving equipment, sought to redesign its entire manufacturing operation, and Miller and O'Leary follow this process up to the opening of Caterpillar's new "Assembly Highway" at Decatur, Illinois, in 1989. This new highway (and its associated spurs, discussed below) incorporated much sophisticated N/C equipment, descendants of the GE machines discussed above. But this is not the point I want to dwell upon. Instead, I begin with the material and spatial reconfiguration of production instanti-

42. Within this reconfigured cyborg, labor even developed new interests, unrepresentable within the Taylorite scheme: "For some of them, as they [the pilots] later reflected, the Pilot Program was the most exciting thing they had ever been involved in, at work anyway, and they were loathe to give it up without at least a fight. As one pilot remembered, 'Some of the guys really didn't want to see it go. They were even willing to sacrifice the bonus—just don't bring back the foreman!'" (Noble 1986, p. 315). Noble offers an interpretation of the history of N/C at GE in terms of the interests of GE management and "limits" upon the flexibility of those interests; I develop a critique of this style of temporally nonemergent and humanist analysis in Pickering (1995, sec. 5.3).

ated at Decatur and symbolically represented in figure 5 (Miller and O'Leary 1994, p. 30, fig. 1).

The upper diagram (labeled "Today") of figure 5 depicts a traditional mode of manufacture. Subcomponents are made from parts held in an inventory of stock—"storage"—and then delivered to and held in another storage location. It is important to note that the various operations involved in "machining and fabricating" are separated according to the nature of the machines and processes involved, so that materials often travel by long and circuitous routes on their trajectories from one storage location to another. From the final storage depots, finished subcomponents are taken to an assembly line, where the end product is constructed, ready for shipping out of the factory. The lower diagram is labeled "PWAF," for "Plant with a Future" in Caterpillar-speak. The Decatur plant was a functioning PWAF, and it was distinguished from traditional plants by a reconfiguration of its material geometry. There are no storage areas in the PWAF. Instead, "out-

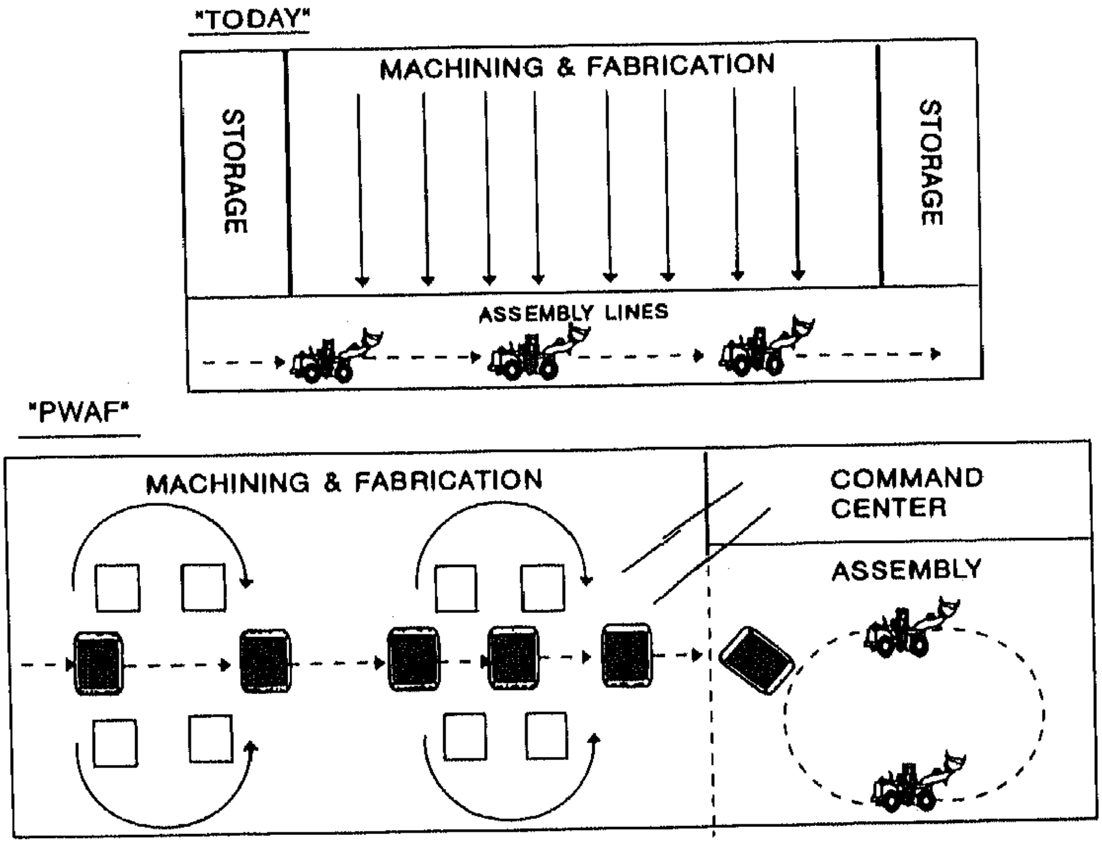

Figure 5. The transformation of the factory. (Reprinted from *Accounting, Organizations and Society* 19, Peter Miller and Ted O'Leary, "Accounting, 'Economic Citizenship' and the Spatial Reordering of Manufacture," pp. 15–43, Copyright 1993, with kind permission from Elsevier Science Ltd., The Boulevard, Langford Lane, Kidlington 0X5 1GB, UK.)

sourced" materials from external suppliers travel as required down an assembly highway—the dotted line down the middle of the left-hand box of the PWAF diagram—and are diverted down various spurs for assembly into subcomponents, whence they are returned to the highway—around the looping arrows in the left-hand box. Each of these spurs groups the required heterogeneous machines and processes required to produce a given class of subassemblies (differential gears, say). Finally, the highway spills into the assembly area, where all of the items coming down it are put together as finished earthmovers. Figure 6 is a more detailed representation of the Decatur plant itself (Miller and O'Leary 1994, p. 34, fig. 2).

The Decatur PWAF, then, is an example of a striking reorganization of the material topology of production. But even more striking, I think, is the fact that this spatial transformation is part and parcel of a massive realignment of production to the automation wing of the World War II regime. The key observation is that figure 6 is, by design, not just an icon, but a map of computer hardware and software. In fact, the PWAF concept in general and the Decatur plant in particular were

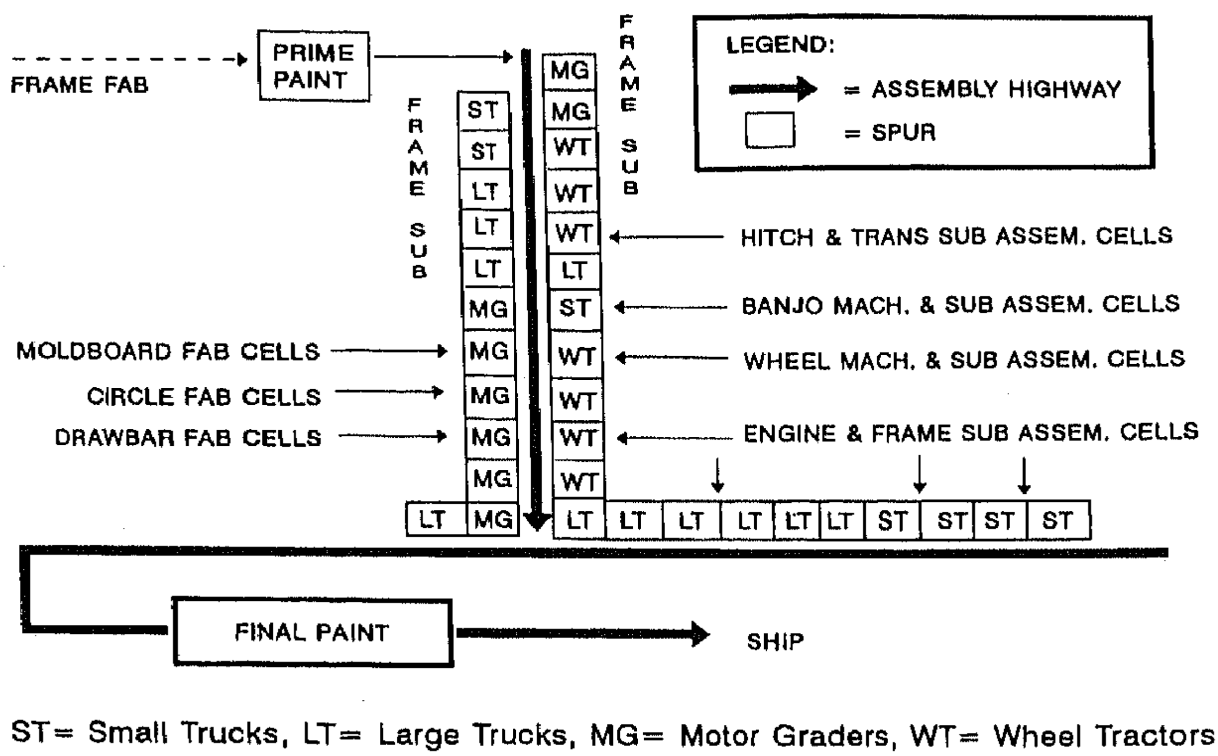

Figure 6. The Assembly Highway, Decatur, Illinois. (Reprinted from *Accounting, Organizations and Society* 19, Peter Miller and Ted O'Leary, "Accounting, 'Economic Citizenship' and the Spatial Reordering of Manufacture," pp. 15–43, Copyright 1993, with kind permission from Elsevier Science Ltd., The Boulevard, Langford Lane, Kidlington 0X5 1GB, UK.)

conceived as sites of computer-controlled manufacture. This is the computer-as-material-agent line coming down from World War II and Whirlwind taken to a new pitch of intensity. Not only are individual machines computer controlled, but so are flows of materials between them. The PWAF reconfigurations of material flows are intended precisely to make this kind of computer command and control possible (including control of the automated guided vehicles [AGVs] that move materials along the highway; Miller and O'Leary 1994, p. 26). And, descending on Decatur on a different but related line from World War II, this overall reconfiguration of the space of production was undertaken within an overall "systems analysis" approach, itself a descendant of OR and elaborated first at the RAND Corporation (as mentioned above).[43] And there is yet another angle on the PWAF plant as a map of a computer system. Beyond computer control, the PWAF was designed for detailed economic surveillance, to make the inputs and outputs of each part of the plant visible. The highway-and-spur system achieves this by its isomorphism with accounting software (developed for the purpose). It is based on "cells" or "modules" of production (individual spurs, for example), constructed just so their expenses and productivity can be measured independently of other cells.

So, the material reconfiguration of the factory in this instance amounts to an interlocking set of computer systems and models laid out in iron and steel, concrete and silicon. In contrast to Section II, where biological metaphors seemed appropriate, here we are in a peculiar version of William Gibson's cyberspace. The space of production, as far as Caterpillar was concerned, had, by the late 1980s, become the space of computer command and control made flesh—a kind of virtual reality environment in reverse—a simulation of a simulation, where the former is more real than the latter, as Jean Baudrillard (1983) might point out, though absolutely dependent upon it.

But still, one might ask, what happened to the people? Has the dream of the automatic factory at last achieved itself in Decatur, Illinois? It has not, in fact. The spurs on the highway are still populated with human labor, but, interestingly, by humans once more retheorized and reconfigured. In line, it seems to me, with the 1970s experience with N/C, shop-floor labor appears in the PWAF as a kind of optimized prosthesis to the computer, optimized, that is, to conclusions about what computers and people respectively do best—or, more accurately, where the distinctive attributes of humanity are conceived in

43. Miller and O'Leary (1994) talk a lot about "systems," though they do not explicitly mention "systems analysis"—some investigation is called for here.

terms of what it has turned out computers do badly. PWAF'ed "Humanity" is the electronic computer's Other as delineated in the temporally emergent trajectory of the antihumanist automation project.[44] Thus workers are now relied upon to fill in the gaps of the automated factory. They function, for instance, as troubleshooters, authorized to hold up production on their spurs in the name of quality control; completed parts are supposed only to leave spurs, never to return because of subsequently revealed problems. More impressively, workers are encouraged to experiment with the organization of production within their spurs, with the object of cumulative gains in productivity.[45] The idea is that workers should regard themselves as quasi-autonomous "proprietors" of their "cells."[46] At the same time, however, they remain enmeshed within a disciplinary apparatus. They are required to orchestrate their own production within a field of information on future orders and stocks relayed to computer terminals via computer networks (ex-ARPA and DARPA), and the production rate and quality of each cell is monitored by the downstream cells that are dependent upon it.[47]

The image that emerges, then, is of the postmodern factory as a

44. Miller and Rose (1993) trace out the history of the "quality of working life" movement, which from the 1950s aimed at a new alignment of "the government of the workplace, the political problems of democracy and the ethics of subjectivity" (p. 18). Something like this clearly lurks in the background of the Pilot Program at GE and the Decatur PWAF. The reconceptualization of the human as the computer's Other is not, of course, confined to the factory. The poor showing of computerized pattern-recognition projects, for example, has served to thematize specific human performances as specifically human (at least temporarily) and thus to feed back into the posthumanist augmentation thread of the World War II regime as a concern with visual computer interfaces (Rheingold 1991).

45. "After months of study and experiment, for instance, 'proprietors' of the motor grader 'circle' cell at [the] Decatur plant brought intractable and long-standing process difficulties into the open. They implemented a crucial change in the order of certain machine processes. 'Circles are now easier and more quickly assembled. [The] binding of circles during assembly testing has been eliminated. . . . Customers now have greater moldboard accuracy while the machine is operating'" (Miller and O'Leary, 1994, p. 37, n. 52, quoting the Caterpillar Decatur plant newspaper *Cat Blade*).

46. Rather than "prisoners" thereof—Caterpillar's metaphors get mixed at times. Miller and O'Leary (1994) are interested in the heterogeneous "expertises" that invade the factory in developments like this one (this is what one would think about if one wanted to continue with the biological imagery of Sec. II), and I think what has happened is that "cell" is a computer modeler's term, while "proprietor" emanates from somewhere in the depths of personnel management.

47. This is the old trick of using the assembly line to make worker performance visible (the line stops when some worker fails to complete the assigned task) and hence to discipline workers that fail, but it is extended now to non-assembly-line tasks.

giant cyborg in which, as in the World War II alignment of science with the military, the material, the human, the social and the conceptual strata of production have been complexly tuned to one another, with the World War II regime occupying a central role in this tuning. The material and social spaces of production have been reconfigured in accommodation to a set of computer-based techniques of surveillance, command, and control, themselves evolving in a process that serves to determine at once the properties of humans and nonhumans.[48] My suggestion is that we should take this transformation of the factory as iconic of the way in which the World War II regime has made the postmodern world as it has grown and transformed itself in the half-century since its birth.

* * *

I have one remark in conclusion: Miller and O'Leary's study thematizes the achievement of certain novel material, conceptual, and social alignments, within the factory, between the factory and customers and suppliers, and to ideas of "new economic citizenship" (the worker as "proprietor" in a precisely documented competitive space). They end their study, however, by noting that nothing guarantees the stability of these alignments. Alignments engineered in one place tend to cut across alignments already engineered elsewhere. They note, for example, that "a reorganization of the firm into divisions or profit centres, and the argument that each division has potentially different kinds of customers and operates in different market situations, can be used to support the view that 'patterned' labor bargaining is an anachronism" (Miller and O'Leary 1994, p. 42). Pattern bargaining is an established form in which, in a given year, labor unions within a given industry bargain with a single manufacturer, with the other manufacturers agreeing to grant labor contracts to their workers in conformity with whatever gets fought out at the first. As it happens, the Decatur PWAF was the site at which pattern bargaining was made an anachronism. Caterpillar declined to accept the upshot of the latest round of negotiations on wages and working conditions on the ground that the roles of labor at Decatur were simply not comparable to traditional roles at other plants (back to the two parts of fig. 5). The upshot was a long and bitter strike, lockouts, and so forth, and an eventual return to work by the labor force on management conditions.

48. In the Foucauldian schema, apparatuses of surveillance are surfaces of emergence for sciences of command and control. It is worth noting that in the World War II regime the computer performs all three roles at once. (In military contexts one speaks of a unitary C^3I assemblage, for command, control, communication, and information.)

Here, it seems to me, we have left the World War II regime, its objects, institutions, and conceptualizations, behind. We are back in the old, familiar, and enduring realm of class conflict. And this, I suspect, is the typical situation. It reminds me of the recent spectacular display of hi-tech weaponry in the Gulf War in relation to modernist and nationalist politics (the autonomy of states; the supply of strategic materials), and threats of the same in Yugoslavia, where the threat is of intervention in a struggle over the boundaries of almost premodern states. The collapse of the Cold War (itself multiply and heterogeneously constructed, at least in part, within the World War II regime) seems to have exposed a situation in which the World War II anti- or posthumanist cyborg regime—intensely and spectacularly dynamic, always changing in unpredictable ways—is overlaid upon, and constitutes new spaces for, quasi-timeless modernist/humanist struggles: bosses against labor, nations against nations. I feel as if I am watching two movies at once: the World War II regime movie fast-forwarding on one screen, while the other is stuck or even spiraling backward (the rise of religious fundamentalism). I cannot say I like either of them very much.[49]

References

Baudrillard, J. 1983. *Simulations*. Translated by P. Foss, P. Patton, and P. Beitchman. Foreign Agent Series. New York: Semiotext(e).

———. 1988. "On Seduction." Pp. 149–65 in *Jean Baudrillard: Selected Writings*, edited by M. Poster. Stanford, Calif.: Stanford University Press.

Benedikt, M., ed. 1991. *Cyberspace: First Steps*. Cambridge: MIT Press.

Beyerchen, A. D. 1989. "Nonlinear Science and the Unfolding of a New Intellectual Vision." *Papers in Comparative Studies* 6:25–49.

Bloomfield, B. 1986. *Modelling the World: The Social Constructions of Systems Analysts*. New York: Blackwell.

49. Some readers have been puzzled by this last paragraph, so I stress that it does not mean, for example, that I think that the World War II regime has come to an end and been replaced by, say, class struggle. The image I intend to evoke is one of cultural multiplicity, with the World War II regime constituting just one kind of contemporary cultural space alongside (and sometimes, as at Caterpillar, interfering with) others—spaces that one can label "class struggle," "nationalism," "religious fundamentalism," etc. This labeling, I add, in response to one referee, need not constitute a covert concession to the historiographic master narratives I mentioned at the beginning of this essay. My proposal is not to understand strikes, lockouts, and so on in terms of some behind-the-scenes Marxist theory; I simply observe that such performances are historically disjoint from the World War II regime; they obviously have their own, much longer, trajectory of evolution, going back to the Industrial Revolution.

Bowker, G. 1993. "How to Be Universal: Some Cybernetic Strategies, 1943–70." *Social Studies of Science* 23:107–27.

Buck, P. 1985. "Adjusting to Military Life: The Social Sciences Go to War, 1941–1950." Pp. 203–52 in *Military Enterprise and Technological Change: Perspectives on the American Experience*, edited by M. R. Smith. Cambridge, Mass.: MIT Press.

Bugos, G. E. 1993. "Manufacturing Certainty: Testing and Program Management for the F–4 Phantom II." *Social Studies of Science* 23:265–300.

Cohen, I. B. 1988. "The Computer: A Case Study of the Support by Government, Especially, the Military, of a New Science and Technology." Pp. 119–54 in *Science, Technology, and the Military: Sociology of the Sciences Yearbook*, vol. 12. Edited by E. Mendelsohn, M. R. Smith, and P. Weingart. Dordrecht: Kluwer.

Clynes, C. F., and N. S. Kline. 1960. "Cyborgs and Space." *Astronautics* (September): 26–27, 74–75.

De Landa, M. 1991. *War in the Age of Intelligent Machines.* New York: Zone Books, Swerve Editions.

Dennis, M. A. 1990. "A Change of State: Political Cultures of Technical Practice at the MIT Instrumentation Laboratory and the Johns Hopkins University Applied Physics Laboratory, 1930–1945." Ph.D. dissertation. Johns Hopkins University.

______. 1994. "'Our First Line of Defense': University Laboratories and the Making of the Postwar American State." *Isis* 85:427–55.

DeVorkin, D. 1987. "Organizing for Space Research: The V–2 Rocket Panel." *Historical Studies in the Physical and Biological Sciences* 18:1–24.

Elichirigoity, I. 1992. "Towards a Genealogy of Planet Management." Paper presented at the workshop, "The Components of Practice," London School of Economics, November 6, 1992.

______. 1994. "Towards a Genealogy of Planet Management: Computer Simulation, Limits to Growth and the Emergence of Global Spaces." Ph.D. dissertation. University of Illinois at Urbana-Champaign.

Forman, P. 1987. "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940–1960." *Historical Studies in the Physical and Biological Sciences* 18:149–229.

Forrester, J. 1961. *Industrial Dynamics.* Cambridge, Mass.: MIT Press.

______. 1969. *Urban Dynamics.* Cambridge, Mass.: Productivity.

______. 1971. *World Dynamics.* Cambridge, Mass.: Productivity.

Fortun, M., and S. S. Schweber. 1993. "Scientists and the Legacy of World War II: The Case of Operations Research." *Social Studies of Science* 23:595–642.

Foucault, M. 1972. *The Archaeology of Knowledge.* New York: Pantheon.

———. 1979. *Discipline and Punish: The Birth of the Prison.* New York: Vintage.

Galison, P. 1985. "Bubble Chambers and the Experimental Workplace." Pp. 309–73 in *Observation, Experiment, and Hypothesis in Modern Physical Science,* edited by P. Achinstein, P. Hannaway, and O. Hannaway. Cambridge, Mass.: MIT Press.

———. 1994. "The Ontology of the Enemy: Norbert Wiener and the Cybernetic Vision." *Critical Inquiry* 21:228–66.

Galison, P., and B. Hevly. 1992. *Big Science: The Growth of Large-Scale Research.* Stanford, Calif.: Stanford University Press.

Gibson, J. 1986. *The Perfect War—the Technowar in Vietnam.* New York: Atlantic Monthly Press.

Gibson, W. 1984. *Neuromancer.* New York: Ace.

Goldstine, H. H. 1993. *The Computer: From Pascal to von Neumann.* Princeton, N.J.: Princeton University Press.

Gorn, M. H. 1988. *Harnessing the Genie: Science and Technology Forecasting for the Air Force 1944–1986.* Washington, D.C.: Office of Air Force History.

Graham, L. 1992. *Lillian Moller Gilbreth's Extensions of Scientific Management into Women's Work, 1924–1935.* Ph.D. dissertation. University of Illinois at Urbana-Champaign.

Gray, C. H. 1989. "The Cyborg Soldier: The US Military and the Postmodern Warrior." Pp. 43–71 in *Cyborg Worlds: The Military Information Society,* edited by L. Levidow and K. Robins. London: Free Association.

Guthrie, W. K. C. 1962. *A History of Greek Philosophy.* Vol. 1. *The Early Presocratics and the Pythagoreans.* Cambridge: Cambridge University Press.

Haraway, D. 1981–82. "The High Cost of Information in Post-World War II Evolutionary Biology: Ergonomics, Semiotics, and the Sociobiology of Communication Systems." *Philosophical Forum* 13:244–78.

———. 1985. "A Manifesto for Cyborgs: Science, Technology, and Socialist Feminism in the 1980s." *Socialist Review* 80:65–107. Reprinted as "A Cyborg Manifesto: Science, Technology, and Socialist-Feminism in the Late Twentieth Century," in *Simians, Cyborgs, and Women: The Reinvention of Nature* (London: Free Association, 1991), pp. 149–81.

———. 1991. "The Biopolitics of Postmodern Bodies: Constitutions of Self in Immune System Discourse." Pp. 203–30 in *Simians, Cyborgs, and Women: The Reinvention of Nature.* London: Free Association.

Heilbron, J. L., and R. W. Seidel. 1990. *Lawrence and His Laboratory: A*

History of the Lawrence Berkeley Laboratory. Vol. 1. Berkeley and Los Angeles: University of California Press.

Heims, S. J. 1980. *John von Neumann and Norbert Wiener.* Cambridge, Mass.: MIT Press.

______. 1991. *The Cybernetics Group.* Cambridge, Mass.: MIT Press.

Helsel, S. 1993. "Employing the Dialectic of Faith and Reason as a Means to Describe the Interminable Dynamism of Kahn's Futurological Method." Paper presented at the Center for Science Studies, Northwestern University, October 29, 1993.

Hodges, A. 1983. *Alan Turing: The Enigma.* New York: Simon & Schuster.

Hounshell, D. A. 1992. "Du Pont and the Management of Large-Scale Reasearch and Development." Pp. 236–61 in *Big Science: The Growth of Large-Scale Research,* edited by P. Galison and B. Hevly. Stanford, Calif.: Stanford University Press.

Jameson, F. 1991. *Post Modernism, or, The Cultural Logic of Late Capitalism.* Durham, N.C.: Duke University Press.

Kaplan, F. (1983) 1991. *The Wizards of Armageddon.* New York: Simon & Schuster.

Kellert, S. H. 1993. *In the Wake of Chaos: Unpredictable Order in Dynamical Systems.* Chicago: University of Chicago Press.

Kevles, D. J. (1978) 1987. *The Physicists: The History of a Scientific Community in Modern America.* New York: Vintage.

Kraft, P. 1977. *Programmers and Managers: The Routinization of Computer Programming in the United States.* New York: Springer.

Latour, B. 1983. "Give Me a Laboratory and I Will Raise the World." Pp. 141–70 in *Science Observed: Perspectives on the Social Study of Science,* edited by K. D. Knorr-Cetina and M. Mulkay. Beverly Hills, Calif.: Sage.

______. 1987. *Science in Action: How to Follow Scientists and Engineers through Society.* Cambridge, Mass.: Harvard University Press.

Leonard, R. J. 1991. "War as a 'Simple Economic Problem': The Rise of an Economics of Defense." *History of Political Economy* 23:261–83.

______. 1992. "Creating a Context for Game Theory." Pp. 29–76 in *Toward a History of Game Theory,* edited by E. R. Weintraub. Durham, N.C.: Duke University Press.

______. 1993. "'In the Spirit of Exact Science': von Neumann, Morgenstern and the Transformation of Economic Theory. Part I: From von Neumann to Nash: Economics, Game Theory and Social Process." Unpublished paper.

______. 1994. "Reason, Ethics and Rigour: The 'Education' of Oskar

Morgenstern, 1928–1944." Paper prepared for the History of Economics Society meeting, "The Theory of Games on the 50th Anniversary of von Neumann and Morgenstern," Boston, January 3, 1994.

Leslie, S. W. 1987. "Playing the Education Game to Win: The Military and Interdisciplinary Research at Stanford." *Historical Studies in the Physical and Biological Sciences* 18:55–88.

Lynch, M. 1991. "Laboratory Space and the Technological Complex: An Investigation of Topical Contextures." *Science in Context* 4:51–78.

Lyotard, J.-F. 1984. *The Postmodern Condition: A Report on Knowledge.* Minneapolis: University of Minnesota Press.

Mahoney, M. S. 1990*a*. "The Roots of Software Engineering." *CWI Quarterly* 3:325–34.

______. 1990*b*. "Cybernetics and Information Technology." Pp. 537–53 in *Companion to the History of Modern Science,* edited by R. C. Olby et al. London: Routledge.

Maturana, H. R., and F. J. Varela 1980. *Autopoiesis and Cognition: The Realization of the Living.* Dordrecht: Reidel.

______. 1992. *The Tree of Knowledge: The Biological Roots of Human Understanding.* Rev. ed. Boston: Shambala.

McCaffery, L., ed. 1991. *Storming the Reality Studio: A Casebook of Cyberpunk and Postmodern Science Fiction.* Durham, N.C.: Duke University Press.

McDougall, W. A. 1985. *The Heavens and the Earth: A Political History of the Space Age.* New York: Basic.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens III. 1972. *The Limits to Growth.* New York: Universe.

Miller, P., and T. O'Leary. 1994. "Accounting, 'Economic Citizenship' and the Spatial Reordering of Manufacture." *Accounting, Organizations and Society* 19:15–43.

Miller, P., and N. Rose. 1993. "Production, Identity and Democracy." Unpublished manuscript. London School of Economics.

Mirowski, P. 1991. "When Games Grow Deadly Serious: The Military Influence on the Evolution of Game Theory." *Journal of Political Economy* 23:227–55.

Morse, P. M. 1977. *In at the Beginnings: A Physicist's Life.* Cambridge, Mass.: MIT Press.

Needell, A. A. 1987. "Lloyd Berkner, Merle Tuve, and the Federal Role in Radio Astronomy." *Osiris* 3:261–88.

Noble, D. F. 1979. *America by Design: Science, Technology and the Rise of Corporate Capitalism.* Oxford: Oxford University Press.

______. 1986. *Forces of Production: A Social History of Industrial Automation.* Oxford: Oxford University Press.

Norberg, A. L., and J. E. O'Neill. 1992. *A History of the Information Processing Techniques Office of the Defence Advanced Research Projects Agency.* Minneapolis: Charles Babbage Institute.

Pickering, A. 1992. "The Rad Lab and the World." *British Journal for History of Science* 25:247–51.

———. 1993*a*. "The Mangle of Practice: Agency and Emergence in the Sociology of Science." *American Journal of Sociology* 99:559–89.

———. 1993*b*. "Anti-discipline or Narratives of Illusion." Pp. 103–22 in *Knowledges: Historical and Critical Studies in Disciplinarity,* edited by E. Messer-Davidow, D. Shumway, and D. Sylvan. Charlottesville: University Press of Virginia.

———. 1995. *The Mangle of Practice: Time, Agency and Science.* Chicago: University of Chicago Press.

Poundstone, W. 1993. *Prisoner's Dilemma.* Oxford: Oxford University Press.

Pynchon, T. 1975. *Gravity's Rainbow.* London: Picador.

Redmond, K. C., and T. M. Smith. 1980. *Project Whirlwind.* Bedford, Mass.: Digital.

Rheingold, H. 1991. *Virtual Reality.* New York: Simon & Schuster.

Richardson, G. P. 1991. *Feedback Thought in Social Science and Systems Theory.* Philadelphia: University of Pennsylvania Press.

Rider, R. 1992. "Operations Research and Game Theory: Early Connections." Pp. 225–39 in *Toward a History of Game Theory,* edited by E. R. Weintraub. Durham, N.C.: Duke University Press.

Schaffer, S. 1994. "Babbage's Intelligence: Calculating Engines and the Factory System." *Critical Inquiry* 21:203–27.

Schweber, S. S. 1986. "The Empiricist Temper Regnant: Theoretical Physics in the United States 1920–1950." *Historical Studies in the Physical and Biological Sciences* 17:55–98.

Secord, J. A., ed. 1993. "Special Issue: The Big Picture." *British Journal for History of Science* 36, no. 4.

Sigmund, K. 1993. *Games of Life: Explorations in Ecology, Evolution, and Behaviour.* Oxford: Oxford University Press.

Smith, B. L. R. 1966. *The RAND Corporation: A Case Study of a Non-profit Advisory Corporation.* Cambridge, Mass.: Harvard University Press.

Taylor, P. J. 1992. "Re/constructing Socio-Ecologies: System Dynamic Modeling of Nomadic Pastoralists in Sub-Saharan Africa." Pp. 115–48 in *The Right Tools for the Job: At Work in Twentieth-Century Life Sciences,* edited by A. Clarke and J. Fujimura. Princeton, N.J.: Princeton University Press.

van den Belt, H., and A. Rip. 1987. "The Nelson-Winter-Dosi Model and Synthetic Dye Chemistry." Pp. 135–58 in *The Social Construction* *of Technological Systems: New Directions in the Sociology and History of Technology*, edited by W. Bijker, T. P. Hughes, and T. Pinch. Cambridge, Mass.: MIT Press.

von Kármán, T., and L. Edson. 1967. *The Wind and Beyond: Theodore von Kármán, Pioneer in Aviation and Pathfinder in Space.* Boston: Little, Brown.

von Neumann, J., and O. Morgenstern. 1944. *Theory of Games and Economic Behavior.* Princeton, N.J.: Princeton University Press.

Voss, M. 1994. "Niccolo Tartaglia: A Maestro d'Abbaco between the Cannon and the Book." Paper presented at History Department seminar, Princeton University, February 10, 1994.

Weintraub, E. R., ed. 1992. *Toward a History of Game Theory.* Durham, N.C.: Duke University Press.